Thesis

by

Tigran Saidnia

Emission kernel of parton shower

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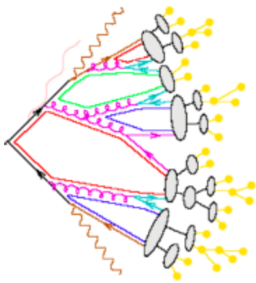

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statement of originality

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.

Karlsruhe, March 20, 2019

Tigran Saidnia

Contents

0.1 Brief history of particle physics

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 chapter 4 ; 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 that matter cannot 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. Wilhelm Capelle: Die Vorsokratiker, Leipzig 1935, S. 399.
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. A New System of Chemical Philosophy, Band 1, Teil 1, Manchester, London 1808,
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.
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 M. Plank, the founder of quantum physics. However, one of the most important steps in the atomic model was taken by the British physicist E. 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 we knew that the alpha particles were positively charged, we could assume the electric repulsive force of two positive charges. In 1911, RUTHERFORD created the planetary model of the atom, which was developed a year later by his pupil NIELS BOHR (1885-1962) into a model known as the Bohr atom model. At first, however, it remained unclear what this core should consist of. 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 [**?**].

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. 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 procession 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 showed that the electrons were scattering quasi-free point-like constituents inside the proton which were soon identified with quarks. This was the first time that quarks were shown to be dynamical entities, instead of bookkeeping devices to classify the hadrons (Gell-Mann's eightfold way).

0.2 Standard model

0.3 Quantum chromo dynamics

Nowadays, we know there are four types of interactions, see below:

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

Otherwise, it's clear meanwhile that nucleons are made up of quark and gluons. Whereby, the gluons are the exchange bosons for this short interaction. To explain the short range of strong interaction Yukawa (1934) postulated mesons as a mediator for this force by the exchange of this massive field quanta. Three years later a candidate (π meson) was found in cosmic rays. Later on it was shown that Massive gauge field quanta break the gauge symmetry though so that the mediator must consequently be massless. But if they are based on the SU(3) gauge symmetry of the QCD[1] Lagrangian massless how can

[1] The quantum field theory which describes this area is called Quantum chromo dynamics short QCD.

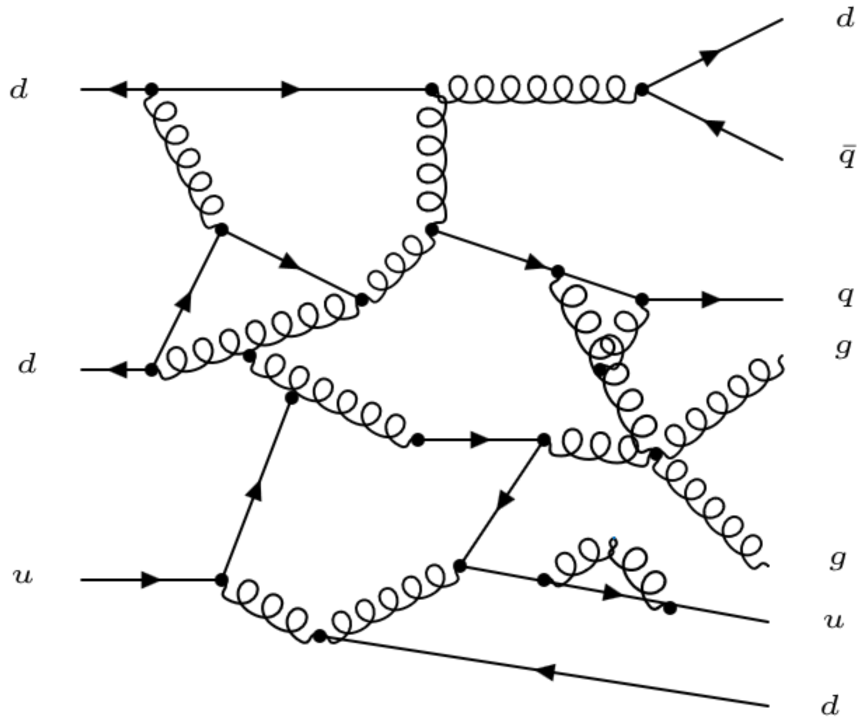


Figure 1: That's a schematic picture of neutron structure. at the left side of the diagram is the low-resolution to see. The 3 quarks picture allows us to interpretate the quantum numbers of the neutron in the valence band. We also obtain a high-resolution picture for a large Q^2. Here we have a lot of gluons (gluon sea) and quarks pair.
The interesting thing is, it doesn't matter in which energy scale we observe the quantum number of a neutron, because it is always the same.

the strong sector be short range? Another question came from a series experiments at SLAC. Through high-energy electron-proton scattering could make evidence of 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 the propagator loop correction in QCD we have to consider both quark loops (negative contribution $\rightarrow$ screening) and gluon loops (positive contribution $\rightarrow$ anti screening).

Figure 2: Running coupling compared for QED, with a positive and QCD with a negative beta function

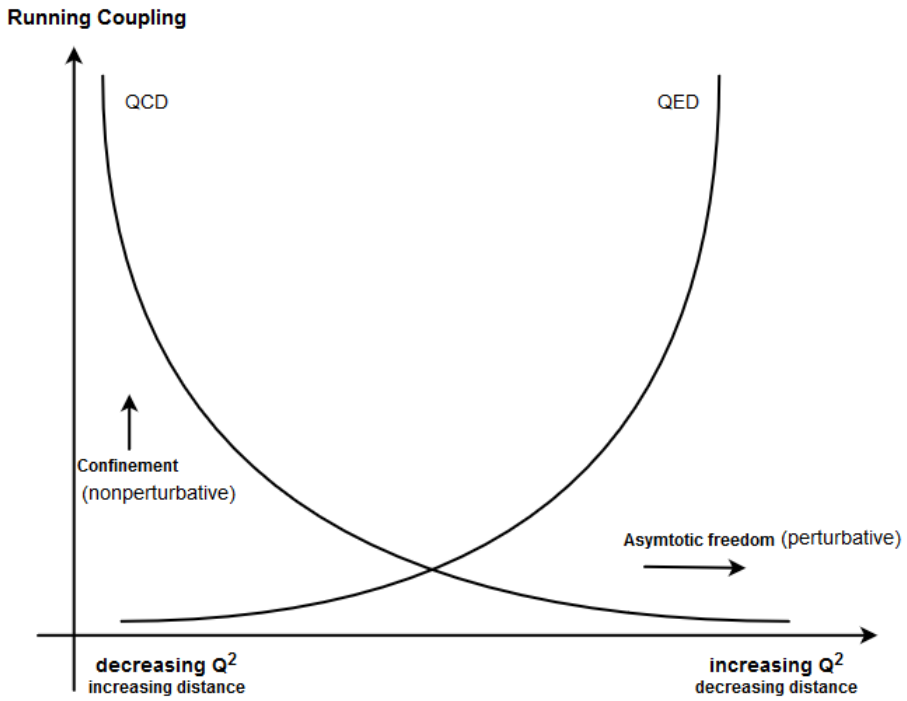
The one loop running coupling in QCD is:

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

Where $\beta_0 = \dfrac{11N_c - 2n_f}{12\pi}$, n_f comes from the first diagram and causes screening. n_f is the number of quarks and N_c the number of colours and comes from the second diagram (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:

$$\beta(\alpha) = -(\beta_0\alpha^2 + \beta_1\alpha^3 + \beta_2\alpha^4 + ...) = \frac{d\,\alpha(Q^2)}{d\,ln(Q^2)} \tag{2}$$

e.g. $-(\beta_0\alpha^2) < 0$ will be negative, which is actually the opposite of QED with $\beta_0 = -\dfrac{\pi}{3} \rightarrow -(\beta_0\alpha^2) > 0$! That means coupling constant in QCD will increase with decreasing Q^2 (increasing distance), In QED vice versa.



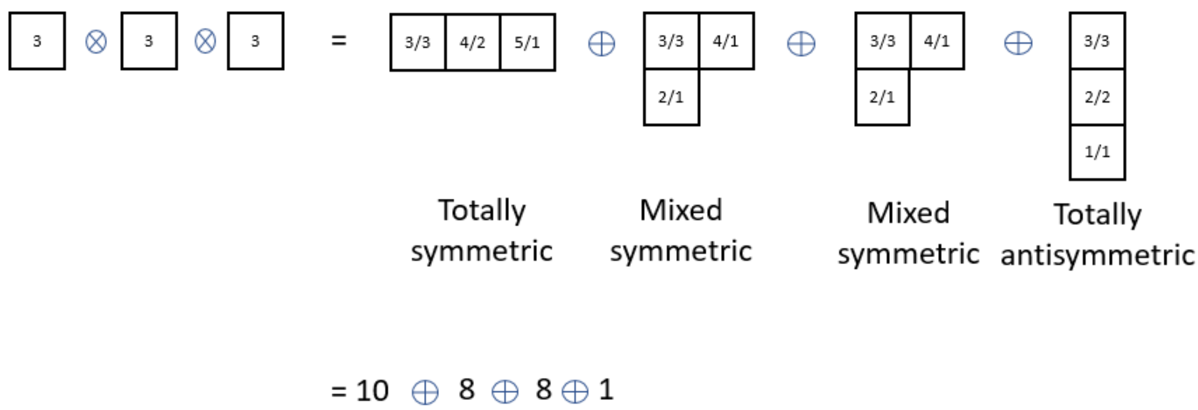
Asymptotic freedom allows us to use perturbation theory [2]. Quarks have not yet been observed as free particles. With increasing separation it will be easier to produce quark-antiquark pair than to isolate quark because the coupling between them too strong is. This

[2]Actually there is need of two more things, if we want to make the connection between theory and experiment: either infrared safety or factorisation. That will be discussed in the next chapter

mechanism is called confinement. Confinement It has been confirmed in Lattice QCD, but not yet mathematically. It belongs to nonperturbative theory. Quarks prefer to bind into hadrons what can be classified to baryons with three quarks state and mesons with a quark-antiquark state. As we know, the wave function of fermions must be antisymmetric according to Pauli exclusion principle under the exchange of two quarks. Interestingly, there are resonance states with spin $\frac{3}{2}$ like Δ^{++}. 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 is solved with the additional degree of freedom, the so-called color charge. Each quark comes in one of three colours red, green or blue and also anticolour $\bar{r}, \bar{b}, \bar{g}$ for antiquarks. The hadrons are colour singlets in regard with the hypothesis, , they are invariant under rotations in colour space. The colour hypothesis describes the existence of mesons with $q\bar{q}$ and baryons with qqq. because if the wave function is odd in color, we have solved the spin statistical problem. The total wave function for each particle can be expressed in terms of:

$$\begin{array}{c} \Psi_{3q} = \psi_{space} \times \chi_{spin} \times \theta_{colour} \times \phi_{flavour} \\ O(3) \quad SU(2) \quad SU(3) \quad SU(6) \end{array} \tag{3}$$

Now we can compute all possible States in regard to colour With Young Tableaux. One uses group theory methods, for instance the Young Tableaux technique, to decompose products of irreducible representations into sums.



After using The same procedure for SU(2) and SU(6) for spins and flavours of the three quarks we will get:

$$\begin{array}{l} 2 \otimes 2 \otimes 2 = 4 \oplus 2 \oplus 2 \oplus 0 \\ 6 \otimes 6 \otimes 6 = 56 \oplus 70 \oplus 70 \oplus 20 \end{array} \tag{4}$$

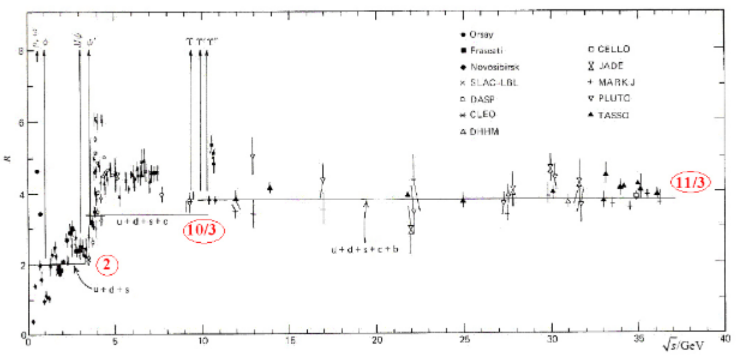
As we can see, the total wave function is most complicated in the QCD area. That's the reason why the Lagrangian of QCD is always given in the short form. I'll get to the bottom of Lagrangian in QCD later. Before the QCD is formulated as a gauge theory, an experiment should be pointed out which makes clear why there is an additional degree of freedom in the QCD and why there is no U(1)-symmetry here. Looking at the electron-positron scattering again, it is important to realize that not only $\mu^+\mu^-$, but also e^+e^-,$\tau^+\tau^-$ and also $q\bar{q}$ can arise, where the quark pairs fragment into hadrons. For the ratio:

$$R = \frac{\sigma(e^+e^- \to Hadronnen)}{\sigma(e^+e^- \to \mu^+\mu^-)} \tag{5}$$

one would expect, due to the fact that the coupling takes place over the charge, that only the sum over the square of the quark charges (because ${e^2}_\mu = 1$) contributes. However, there is an additional factor N_C that can be determined experimentally

$$R = N_C \sum_q e_q^2 \tag{6}$$

Without this factor one would expect 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 respective results though (i.e. $N_C = 3$):



0.4 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 interactions terms. The Lagrangian of QCD is invariant under $U(3) = U(1) \times SU(3)$ global trafo. I'm just going to look into $SU(3)$. We can replace the three Pauli matrices from $SU(2)$ in the Yang-Mills theory by the eight Gell-Mann matrices λ^a with following relation:

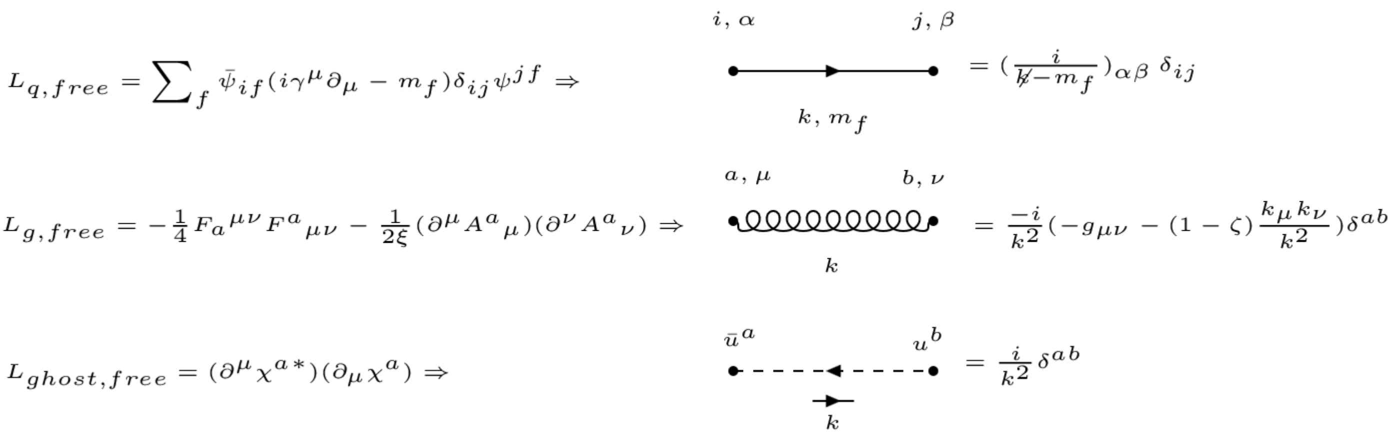
$$\begin{aligned} &T^a = \frac{1}{2}\lambda^a \\ &[T^a, T^b] = i f^{abc} T^c && \text{fundamental representation} \\ &({T^a}_{adj})_b c = -i f^{abc} && \text{adjoint representation} \end{aligned} \tag{7}$$

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

$$
\begin{aligned}
&\mathscr{L} = \mathscr{L}_{free} + \mathscr{L}_{int}\\
&\mathscr{L} = \sum_f \bar{\psi}_{if}(i\gamma^\mu\partial_\mu - m_f)\psi^{if} - \frac{1}{4}F_a{}^{\mu\nu}F^a{}_{\mu\nu} - \frac{1}{2\xi}(\partial^\mu A^a{}_\mu)(\partial^\nu A^a{}_\nu) + (\partial^\mu\chi^{a*})(\partial_\mu\chi^a)\\
&-g_s\bar{\psi}_i T^a{}_{ij}\psi_j\gamma^\mu A^a{}_\mu - \frac{g_s}{2}f^{abc}(\partial_\mu A^a{}_\nu - \partial_{nu}A^a{}_\mu A_b{}^\mu A_c{}^\nu) - \frac{g_s{}^2}{4}f^{abc}(A_b{}^\mu A_c{}^\nu f^{ade}(A^d{}_\mu A^e{}_\nu)\\
&-g_s f^{abc}(\partial^\mu\chi^{a*})\chi^b A^c{}_\mu
\end{aligned}
\tag{8}
$$

Here i,j are color indices in the fundamental representation, a color index in the adjoint representation of SU(3) respectively. f labels the six flavours of quarks. g_s describes the strong coupling constant and $A^a{}_\mu$ is the gluon field and it corresponds to anon-abelian gauge theory with structure constants f^{abc}. χ^a is a scalar field under Lorenz group, but anti commuting. With The field-strength tensor for QCD by:

$$F^a{}_{\mu\nu} = \partial_\mu A^a{}_\nu - \partial_\nu A^a{}_\mu - g_s f_{abc}A^b{}_\mu A^c{}_\nu \tag{9}$$



It can be shown that the above Lagrangian is invariant under the following $SU(3)$ gauge transformations:

$$
\begin{aligned}
&\psi'(x) \to exp(i\,\eta_a(x)\,T^a)\,\psi(x)\\
&D' \to \partial_\mu + ig_s T_a\,A'^a_\mu\\
&A'^a_\mu \to A^a{}_\mu - \frac{1}{g_s}\partial_\mu\eta^a(x) + f^{abc}\eta_b(x)A_{c\nu}(x)
\end{aligned}
\tag{10}
$$

0.5 Colour factor calculation

In this section we will calculate the Casimir operators of the respective diagrams for later goals. Fundamental representation in $SU(3)$ are given by:

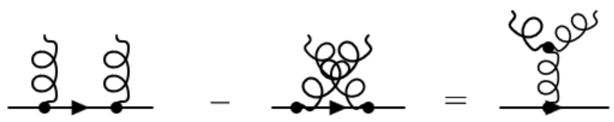
$$T^a = \vartheta^a \equiv \frac{\lambda^2}{2} \qquad \textit{with Gell} - \textit{Mann matrices}\ \lambda^a \tag{11}$$

$$\lambda^1 = \begin{pmatrix} 0 & 1 & \\ 1 & 0 & \\ & & 0 \end{pmatrix},\ \lambda^2 = \begin{pmatrix} 0 & -i & \\ i & 0 & \\ & & 0 \end{pmatrix},\ \lambda^3 = \begin{pmatrix} 1 & & \\ & -1 & \\ & & 0 \end{pmatrix},\ \lambda^4 = \begin{pmatrix} & & 1 \\ & 0 & \\ 1 & & \end{pmatrix}$$
$$\lambda^5 = \begin{pmatrix} & & -i \\ & 0 & \\ i & & \end{pmatrix},\ \lambda^6 = \begin{pmatrix} 0 & & \\ & 0 & 1 \\ & 1 & 0 \end{pmatrix},\ \lambda^7 = \begin{pmatrix} 0 & & \\ & 0 & -i \\ & i & 0 \end{pmatrix},\ \lambda^8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & & \\ & 1 & \\ & & -2 \end{pmatrix} \tag{12}$$

As we can see, λ^3 and λ^8 are diagonal. These generators satisfy:

Or in the adjoint representation:

$$[T^a, T^b] = if^{abc}T^c \Rightarrow .$$



$$T^aT^b \quad - \quad T^bT^a \quad = \quad if^{abc}T^c$$

$$[F^a, F^b] = if^{abc}F^c \Rightarrow .$$

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

$$\sum_{c,d} f^{acd} f^{bcd} = N\delta^{ab} \tag{13}$$

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

$$[T^a, [T^b, T^c]] + [T^c, [T^a, T^b]] + [T^b, [T^c, T^a]] = 0 \tag{14}$$

If we write this in terms of the structure constant, we'll get:

$$f^{axd} f^{bcx} + f^{cxd} f^{abx} + f^{bxd} f^{cax} = 0 \tag{15}$$

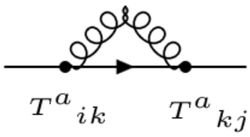
So we are able to compute:

$$f^{abc} = -2i\, tr(T^a[T^b, T^c]) \tag{16}$$

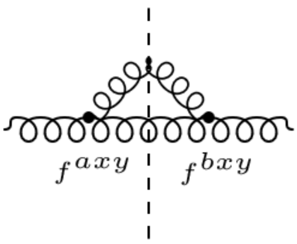
generalize to:

$$f^{abc} f^{xcd} = 4i\, tr(T^a[T^b, [T^c, T^d]]) \tag{17}$$

With this relations we can calculate all Casimir operators:



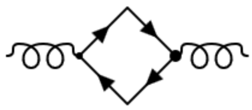
$$(T^a T^a)_{ij} = C_F \delta_{ij} = \frac{N_c^2 - 1}{2N_c} = C_F \sim \frac{N_c}{2}$$



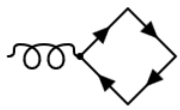
$$\sum_{xy} f^{axy} f^{bxy} = C_A \delta^{ab}$$

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

$$C_A = N_c = 2C_F \sim 2(\frac{N_C}{2}) \tag{18}$$



$T_f \, \delta^{ab}$

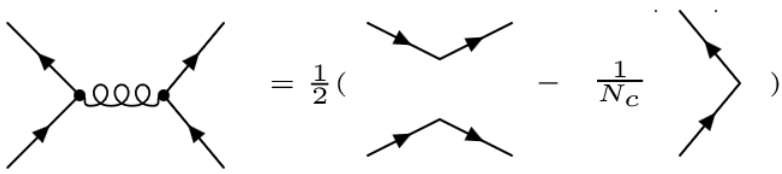


$tr(T^a) = 0$

One of the most important relation in this case is the Fierz identity. It shows the difference between QED and QCD!

$$\sum_a T_{ij}{}^a T_{kl}{}^a = \frac{1}{2}(\delta_{il}\delta_{kj} - \frac{1}{N}\delta_{ij}\delta_{kl}) \tag{19}$$

Graphically it means: The charge transfer in QED takes place along the Fermion line



because photons cannot transport charges. On the other hand, the gluons can transfer color charges because they have color charges themselves.
The main relation we will use later for SU(N):

$$tr(T^a T^b) = T_{ij}{}^a T_{ji}{}^b = T_F \delta^{ab} \tag{20}$$

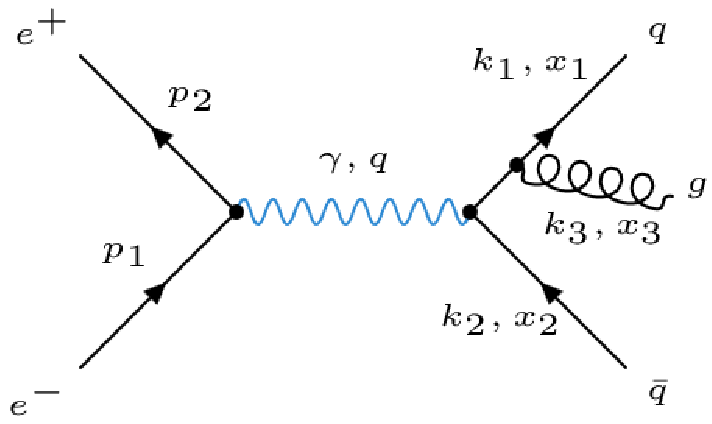
$$\sum_a (T^a T^a) = C_F \delta^{ij} \tag{21}$$

$$f^{acd} f^{bcd} = C_A \delta^{ab} \tag{22}$$

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

0.6 IR and Collinar Divergences

Beyond the LO (Leading order) diagrams it happens singularities. To discuss about these consider first the process $e^- e^+ \to q\bar{q}g$



In order to calculate the cross section of this diagram, we have to consider the gluon emission from the antiquark. Since the calculation is quite long, we concentrate on the final result:

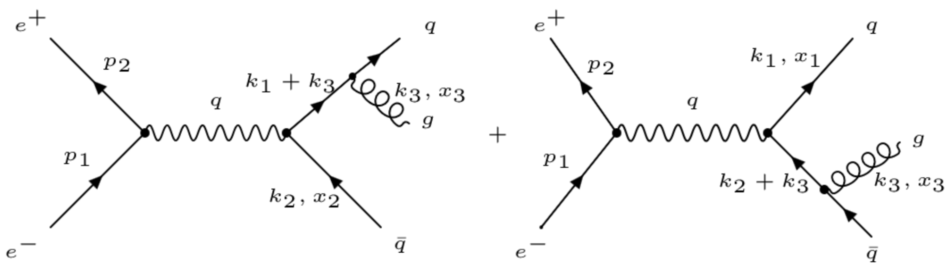


Figure 3: Left diagram $e^- e^+ \to qg\bar{q}$ and right $e^- e^+ \to q\bar{q}g$

$$
\begin{aligned}
A =& \frac{\bar{u}(k_1)(-ig_s\gamma^\nu \times T^a)[-i(\not{k}_1 + \not{k}_3)](-iee_q\gamma^\mu)v(k_2){\epsilon_\mu}^{\lambda_1}{\epsilon_\nu}^{\lambda_2 *}}{(k_1+k_3)^2} \\
-& \frac{\bar{u}(k_1)(-iee_q\gamma^\mu)[i(\not{k}_2 + \not{k}_3)](-ig_s\gamma^\nu \times T^a)v(k_2){\epsilon_\mu}^{\lambda_1}{\epsilon_\nu}^{\lambda_2 *}}{(k_1+k_3)^2} \\
\Rightarrow A =& -g_s T^a [\frac{\bar{u}\ \not{\epsilon}\,(\not{k}_1 + \not{k}_3)\,\Gamma\, v}{(k_1+k_3)^2} - \frac{\bar{u}\,\Gamma\,(\not{k}_2 + \not{k}_3)\ \not{\epsilon}\, v}{(k_2+k_3)^2}] \quad \text{with } \Gamma = (-iee_q\gamma^\mu){\epsilon_\mu}^{\lambda_1}
\end{aligned}
\tag{23}
$$

Under consideration that the partons are on-shell, we get:

$$
A = -g_s T^a [\frac{\bar{u}\ \not{\epsilon}\,(\not{k}_1 + \not{k}_3)\,\Gamma\, v}{2k_1 \cdot k_3} - \frac{\bar{u}\,\Gamma\,(\not{k}_2 + \not{k}_3)\ \not{\epsilon}\, v}{2k_2 \cdot k_3}]
\tag{24}
$$

In the soft limit with $k_0 \to 0$ we can factorize A_{soft} the amplitude in two parts:

$$
A = -g_s T^a [\frac{k_1\ \epsilon}{k_1 \cdot k_3} - \frac{k_2\ \epsilon}{k_2 \cdot k_3}] A_{born} \qquad \text{with } A_{born} = \bar{u}\,\Gamma\, v
\tag{25}
$$

Which one contains all information about colour and momenta and A_{born} with all spin information. If one calculates the cross section for it, one gets:

$$
\begin{aligned}
A =& C_F g_s^2 \sigma^{born} \int \frac{d^3k}{2k_0(2\pi)^3} 2 (\frac{k_1 \cdot k_2}{(k_1 \cdot k_3)(k_2 \cdot k_3)}) \\
& C_F g_s^2 \sigma^{born} \int dcos\,\theta\, \frac{dk_0}{k_0} \frac{4}{(1 - cos\,\theta)(1 + cos\,\theta)}
\end{aligned}
\tag{26}
$$

We define the energy fraction by:

$$
x_i = \frac{2E_i}{\sqrt{s}} = \frac{2q\ \cdot\ k_i}{s}
\tag{27}
$$

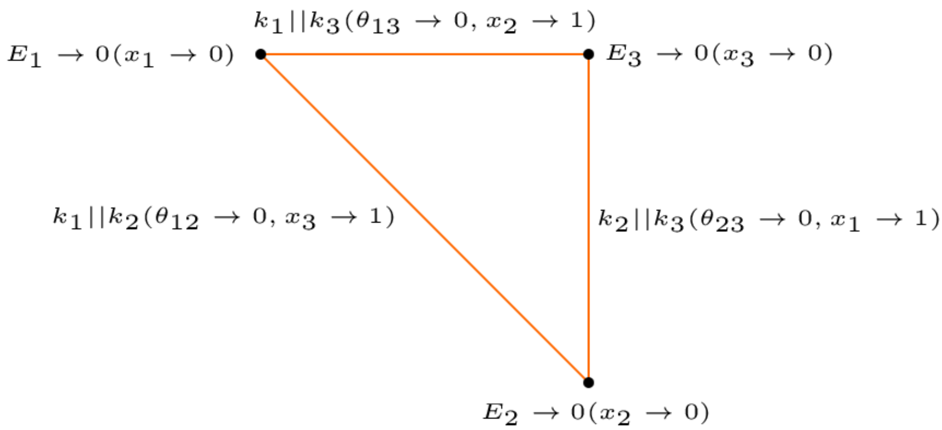
One can show that $\sum x_i = 2$ and thus, that only two of the xi are independent.
The final result is:

$$
\frac{d^2\sigma}{dx_1 dx_2} = (\frac{4\pi\alpha}{s}) \sum {e_i}^2 \frac{2\alpha_s}{3\pi} \frac{{x_1}^2 + {x_2}^2}{(1-x_1)(1-x_2)}
\tag{28}
$$

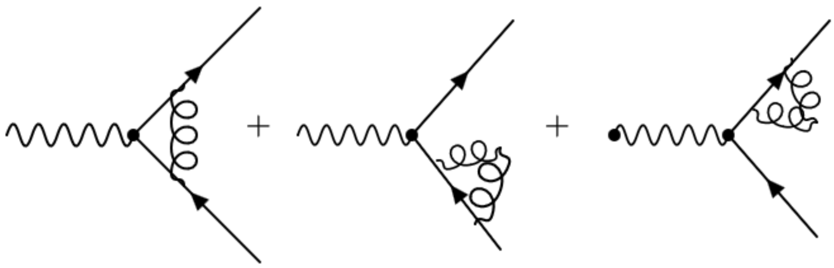
There are three singularities in regard with the final result. If the emitted photon is collinear to the outgoing quark or anti-quark ($x_1 \to 1$ or $x_2 \to 1$) and When the emitted gluon is very soft ($x_1 \to 1\,\text{and}\, x_2 \to 1$). The singularities come from the quark propagator in each diagram. The denominators contain according Feynmann rules terms with $\sim \frac{1}{(k_i+k_j)^2}$. We can eliminate the quark mass under on-shell condition so that:

$$
\frac{1}{(k_i+k_j)^2} = \frac{1}{2k_i \cdot k_j} = \frac{1}{2E_iE_j(1 - cos\theta_{ij})} = \frac{1}{s(1-x_k)}
\tag{29}
$$

One can show all possibilities for three partons through a triangle:



fortunately, According to KLN-Theorem one can eliminate the real singularities by adding the virtual contributions to them. The sum over real and virtual contributions in the phase space integral must be finite. We will use deep inelastic scattering (DIS) to show how the



infrared singularities are absorbed in the parton distributions.

0.7 Subtraction method

$$|A|^2 = |A^{(0)}{}_n|^2 + |A^{(0)}{}_{n+1}|^2 + 2Re(A^{(0)*}{}_n A^{(1)}{}_n) \tag{30}$$

Whereby, $|A^{(0)}{}_n|^2$ is the tree level contribution from Lo and has no divergences, $|A^{(0)}{}_{n+1}|^2 + 2Re(A^{(0)*}{}_n A^{(1)}{}_n)$ comes from the NLO and they are separately divergent. The problem in this case is that Integrations cannot be combined due to different phase space dimensions:

$$\sigma^{NLO} = \int_{n+1} \partial\sigma^R + \int_n \partial\sigma^V \tag{31}$$

To tackle this problem one can use the subtraction method in that way one add and subtract the terms $\partial\sigma^A$ to the integral. $\partial\sigma^A$ approximates soft and collinear singularities of $\partial\sigma^R$.

$$\sigma^{NLO} = \int_{n+1}[\partial\sigma^R - \partial\sigma^A] + \int_n[\partial\sigma^V + \int_1 \partial\sigma^A] \tag{32}$$

The virtual contribution must be UV-finite:

$$\int_n[\partial\sigma^V = \int_n[\int_{loop} \partial\sigma^V{}_{bare} + \sigma^V{}_{Counter\,term}] \tag{33}$$

The addition of $\int_1 \partial\sigma^A$ to the $\int_n[\partial\sigma^V$ 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:

$$\int_n \partial\sigma^V + \int_{loop} \partial\sigma^L - \int_{loop} \partial\sigma^L = \int_n \int_{loop}[\partial\sigma^V{}_{bare} - \partial\sigma^L] + \int_n[\sigma^V{}_{Counter\,term} + \int_{loop} \partial\sigma^L] \tag{34}$$

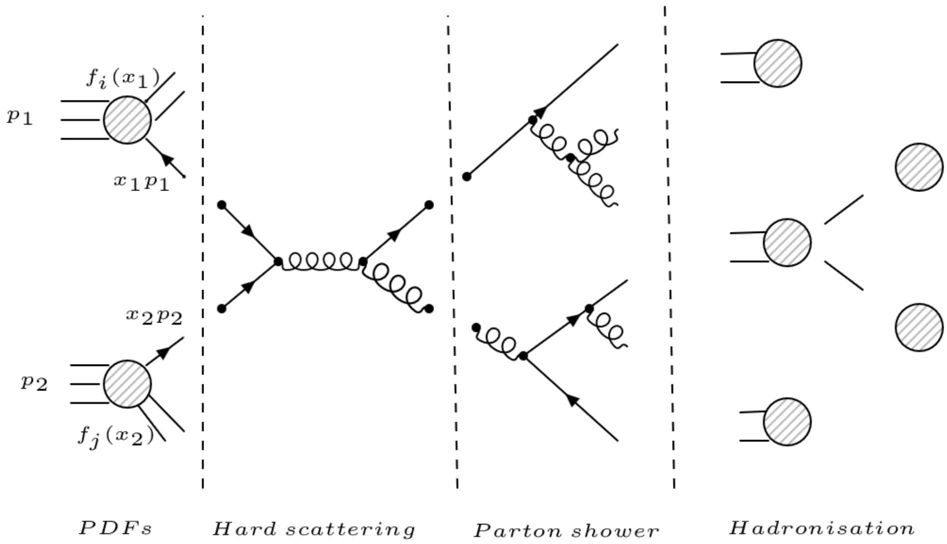
$$\sigma^{NLO} = \int_{n+1}[\partial\sigma^R - \partial\sigma^A] + \int_n \int_{loop}[\partial\sigma^V{}_{bare} - \partial\sigma^L] + \int_n[\sigma^V{}_{Counter\,term} + \int_{loop} \partial\sigma^L + \partial\sigma^A] \tag{35}$$

0.8 Factorisation

The hadron hadron scattering can be written as:

$$\sigma = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \sigma_{ij}(x_1, x_2, Q^2/\mu^2 ...) \tag{36}$$

Here the (arbitrary) factorisation scale μ can be thought of as the scale which separates



the long and short-distance physics. Roughly speaking, a parton with a transverse momentum less than μ is then considered to be part of the hadron structure and is absorbed in the parton distribution. Partons with larger transverse momenta participate in the hard scattering process with a short-distance partonic cross-section. The factorisation theorem also applies to deep inelastic scattering. The DIS cross section can be written as:

$$\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}[(1-y)F_2(x, Q^2) + xy^2 F_1(x, Q^2)] \tag{37}$$

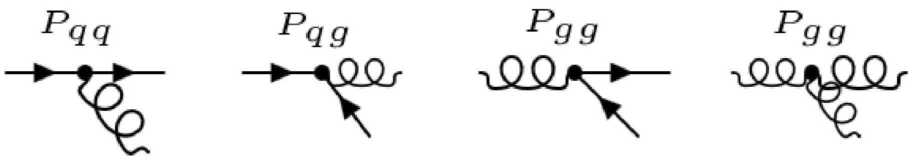
In this case we need to introduce the structure function, is defined as the charge weighted sum of the parton momentum densities, the probability that the parton carries a momentum fraction x. The index i denotes the quark. flavour.

$$F_2{}^{exp}(x) = \sum_i e_i{}^2 x f_i(x) \tag{38}$$

The evolution of a quark distribution due to gluon radiation and is called the DGLAP evolution equation.

$$\frac{\partial f(x, \mu^2)}{\partial\, ln\, \mu^2} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dy}{y} f(y, \mu^2) P_{qq}(\frac{x}{y} + O(\alpha_s{}^2) \tag{39}$$

There three more spiriting possibilities according to below diagrams.



$$\left.\begin{aligned}
\langle\, \hat{P}_{qq}\rangle &= C_F[\frac{1+z^2}{1-z} - \varepsilon(1-z)] \\
\langle\, \hat{P}_{gq}\rangle &= T_R[1 - \frac{2z(1-z)}{1-\varepsilon}] \\
\langle\, \hat{P}_{qg}\rangle &= C_F[\frac{1+(1-z)^2}{z} - \varepsilon z] \\
\langle\, \hat{P}_{gg}\rangle &= 2C_A[\frac{z}{1-z} + \frac{1-z}{z} + z(1-z)]
\end{aligned}\right\} \text{splitting functions} \tag{40}$$

0.9 splitting/subtraction method

0.10 Catani-Seymour Formalism

0.11 Old parametrisation

$$\left.\begin{aligned}
&{q_i}^{\mu} = z{p_i}^{\mu} + y(1-z){p_j}^{\mu} + \sqrt{zy(1-z)}m_{\perp}\\
&q^{\mu} = (1-z){p_i}^{\mu} + yz{p_j}^{\mu} - \sqrt{zy(1-z)}m_{\perp}\\
&{q_j}^{\mu} = (1-y){p_j}^{\mu}\\
&y = \frac{q_i q}{p_i p_j}\\
&q_i + q = p_i + yp_j\\
&q_j + q = (1-z){p_i}^{\mu} + (1+yz-y){p_j}^{\mu} - \sqrt{zy(1-z)}m_{\perp}\\
&q_i \cdot q = y(1-2z+2z^2)(p_i \cdot p_j)\\
&q_i \cdot q_j = z(1-y)(p_i \cdot p_j)\\
&q_j \cdot q = (1-z)(1-y)(p_i \cdot p_j)
\end{aligned}\right\}\ \text{parametrisation} \tag{41}$$

0.12 new kinematic

$$\begin{aligned}
&{k_l}^{\mu} = \alpha_l \alpha {\Lambda^{\mu}}_{\nu}{p_i}^{\nu} + y\beta n^{\mu} + \sqrt{y\alpha_l\beta_l}{n^{\mu}}_{\perp,l} \qquad l = 1, ..., m\\
&{q_i}^{\mu} = (1-\sum_{l=1}^{m}\alpha_l)\alpha {\Lambda^{\mu}}_{\nu}{p_i}^{\nu} + y(1-\sum_{l=1}^{m}\beta_l)n^{\mu} - \sqrt{y\alpha_l\beta_l}{n^{\mu}}_{\perp,l}\\
&{q_k}^{\mu} = \alpha {\Lambda^{\mu}}_{\nu}{p_k}^{\nu} \qquad k = 1, ..., n \qquad k \neq i
\end{aligned} \tag{42}$$

0.12.1 useful relations

$$
\begin{aligned}
{q_i}^2 = {p_i}^2 = {q_k}^2 = k_l^2 = p_j^2 = p_k^2 = n^2 = 0 \quad & \text{All hard momenta are on-shell} \\
Q^\mu = {q_i}^\mu + \sum_{l=1}^{m} k_l^\mu + \sum_{k=1}^{m} q_k^\mu = {p_i}^\mu + \sum_{k=1}^{m} p_k^\mu \quad & \text{total momentum} \\
n^\mu = Q^\mu - \frac{Q^2}{2p_i \cdot Q} p_i^\mu \quad & n^\mu \text{ is the recoil}
\end{aligned}
$$

$$
\begin{aligned}
{q_i}^\mu + \sum_{l=1}^{m} k_l^\mu &= \alpha \Lambda^\mu{}_\nu {p_i}^\nu + y n^\mu \\
\alpha \Lambda^\mu{}_\nu Q^\nu &= Q^\mu - y n^\mu \\
{n^\mu}_{\perp,l} \Lambda^\mu{}_\nu {p_i}^\nu &= n_{\perp,l} \cdot n = n_{\perp,l} \cdot Q = 0 \\
{n^\mu}_{\perp,l} \cdot p_k &\neq 0 \\
n_{\perp,l}^2 &= -2\alpha \Lambda^\mu{}_\nu {p_i}^\nu n_\mu \\
n_{\perp,1}^2 &= -2 p_i \cdot Q \\
\alpha_1 &= 1 - \beta_1 \\
\alpha &= \sqrt{1-y}
\end{aligned}
\tag{43}
$$

Lorenz trafo

$$
\begin{aligned}
\alpha \Lambda^\mu{}_\nu = {p_i}^\mu p_{i\nu} \frac{-y^2 Q^2}{4(p_i \cdot Q)^2 (1 + \sqrt{1-y} - \frac{y}{2})} + {p_i}^\mu Q_\nu \frac{y(1+\sqrt{1-y})}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \\
+ Q^\mu p_{i\nu} \frac{(y^2 - y - y\sqrt{1-y})}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} + \sqrt{1-y}\, \eta^\mu{}_\nu
\end{aligned}
\tag{44}
$$

$$
\begin{aligned}
\hat{p_i}^\mu = \alpha \Lambda^\mu{}_\nu {p_i}^\nu = {p_i}^\mu p_{i\nu} {p_i}^\nu \frac{-y^2 Q^2}{4(p_i \cdot Q)^2 (1 + \sqrt{1-y} - \frac{y}{2})} + {p_i}^\mu Q_\nu {p_i}^\nu \frac{y(1+\sqrt{1-y})}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \\
+ Q^\mu p_{i\nu} {p_i}^\nu \frac{(y^2 - y - y\sqrt{1-y})}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} + \sqrt{1-y}\, \eta^\mu{}_\nu {p_i}^\nu
\end{aligned}
\tag{45}
$$

$$
\begin{aligned}
\hat{p_i}^\mu &= {p_i}^\mu (Q \cdot p_i) \frac{y(1+\sqrt{1-y})}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} + \sqrt{1-y}\, {p_i}^\mu \\
&= {p_i}^\mu \Big[\frac{y(1+\sqrt{1-y})}{(2 + 2\sqrt{1-y} - y)} + \sqrt{1-y} \Big] = {p_i}^\mu
\end{aligned}
\tag{46}
$$

$$
\boxed{\hat{p_i}^\mu = \alpha \Lambda^\mu{}_\nu {p_i}^\nu = {p_i}^\mu}
\tag{47}
$$

$$\hat{p_k}^{\mu} = \alpha \Lambda^{\mu}{}_{\nu} {p_k}^{\nu} = {p_i}^{\mu} p_{i\nu} {p_k}^{\nu} \frac{-y^2 Q^2}{4(p_i \cdot Q)^2(1+\sqrt{1-y}-\frac{y}{2})} + {p_i}^{\mu} Q_{\nu} {p_k}^{\nu} \frac{y(1+\sqrt{1-y})}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})}$$
$$+ Q^{\mu} p_{i\nu} {p_k}^{\nu} \frac{(y^2 - y - y\sqrt{1-y})}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})} + \sqrt{1-y}\eta^{\mu}{}_{\nu} {p_k}^{\nu} \tag{48}$$

$$\begin{aligned} \hat{p_k}^{\mu} = \alpha \Lambda^{\mu}{}_{\nu} {p_k}^{\nu} = {p_i}^{\mu} [\frac{-y^2 Q^2 (p_i \cdot p_k)}{4(p_i \cdot Q)^2(1+\sqrt{1-y}-\frac{y}{2})} + \frac{y(1+\sqrt{1-y})(Q \cdot p_k)}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})}] \\ + Q^{\mu} [\frac{(y^2 - y - y\sqrt{1-y})(p_i \cdot p_k)}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})}] + \sqrt{1-y} {p_k}^{\mu} \end{aligned} \tag{49}$$

$$\begin{aligned} &\hat{p_k}^{\mu} = \alpha \Lambda^{\mu}{}_{\nu} {p_k}^{\nu} = {p_i}^{\mu} [\frac{-y^2 Q^2 (p_i \cdot p_k)}{4(p_i \cdot Q)^2(1+\sqrt{1-y}-\frac{y}{2})} + \frac{y(1+\sqrt{1-y})(Q \cdot p_k)}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})}] \\ &\quad + Q^{\mu} [\frac{(y^2 - y - y\sqrt{1-y})(p_i \cdot p_k)}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})}] + \sqrt{1-y} {p_k}^{\mu} \\ &\text{with} \\ &A_1 \equiv \frac{-y^2 Q^2 (p_i \cdot p_k)}{4(p_i \cdot Q)^2(1+\sqrt{1-y}-\frac{y}{2})} + \frac{y(1+\sqrt{1-y})(Q \cdot p_k)}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})} \\ &A_2 \equiv \frac{(y^2 - y - y\sqrt{1-y})(p_i \cdot p_k)}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})} \end{aligned} \tag{50}$$

$$\boxed{\hat{p_k}^{\mu} = A_1\, {p_i}^{\mu} + A_2\, Q^{\mu} + \sqrt{1-y} {p_k}^{\mu}} \tag{51}$$

$$\begin{aligned} &\hat{Q}^{\mu} = \alpha \Lambda^{\mu}{}_{\nu} Q^{\nu} = {p_i}^{\mu} [\frac{-y^2 Q^2 (p_i \cdot Q)}{4(p_i \cdot Q)^2(1+\sqrt{1-y}-\frac{y}{2})} + \frac{y(1+\sqrt{1-y}) Q^2}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})}] \\ &\quad + Q^{\mu} [\frac{(y^2 - y - y\sqrt{1-y})(p_i \cdot Q)}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})}] + \sqrt{1-y} Q^{\mu} \\ &\text{with} \\ &S_1 \equiv \frac{Q^2}{2p_i \cdot Q} [\frac{-y^2}{2(1+\sqrt{1-y}-\frac{y}{2})} + \frac{y(1+\sqrt{1-y})}{(1+\sqrt{1-y}-\frac{y}{2})}] = \frac{Q^2}{2p_i \cdot Q} y \\ &S_2 \equiv \frac{(y^2 - y - y\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})} + \sqrt{1-y} = 1 - y \end{aligned} \tag{52}$$

$$\boxed{\hat{Q}^{\mu} = \tfrac{Q^2}{2p_i \cdot Q} y\, {p_i}^{\mu} + (1-y)\, Q^{\mu}} \tag{53}$$

0.13 Single emission part

$$
\begin{aligned}
{k_1}^{\mu} &= (\alpha_1 - y\beta_1(\frac{Q^2}{2p_i \cdot Q}))p_i{}^{\mu} + y\beta_1 Q^{\mu} + \sqrt{y\alpha_1\beta_1}n^{\mu}{}_{\perp,1} \\
{q_i}^{\mu} &= (\beta_1 - \alpha_1 y(\frac{Q^2}{2p_i \cdot Q}))p_i{}^{\mu} + y\alpha_1 Q^{\mu} - \sqrt{y\alpha_1\beta_1}n^{\mu}{}_{\perp,l} \\
{q_k}^{\mu} &= \alpha\Lambda^{\mu}{}_{\nu}{p_k}^{\nu} \qquad\quad k = 1, ..., n \qquad k \neq i
\end{aligned} \tag{54}
$$

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

$$
\begin{aligned}
\zeta_1\zeta_1 &= ({\alpha_1}^2 - 2y\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q}) + y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})^2) \\
\zeta_1\lambda_1 &= (y\alpha_1\beta_1 - y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})) \\
\zeta_1\zeta_q &= (\alpha_1\beta_1 - y({\alpha_1}^2+{\beta_1}^2)(\frac{Q^2}{2p_i\cdot Q}) + y^2\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q})^2) \\
\zeta_1\lambda_q &= (y{\alpha_1}^2 - y^2\beta_1\alpha_1(\frac{Q^2}{2p_i\cdot Q})) \\
\zeta_q\zeta_q &= ({\beta_1}^2 - 2y\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q}) + y^2{\alpha_1}^2(\frac{Q^2}{2p_i\cdot Q})^2) \\
\zeta_q\lambda_1 &= (y{\beta_1}^2 - y^2\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q})) \\
\zeta_q\zeta_1 &= (\beta_1\alpha_1 - y({\beta_1}^2+{\alpha_1}^2)(\frac{Q^2}{2p_i\cdot Q}) + y^2\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q})^2) \\
\zeta_q\lambda_q &= (y\beta_1\alpha_1 - y^2{\alpha_1}^2(\frac{Q^2}{2p_i\cdot Q})) \\
\lambda_1\lambda_1 &= y^2{\beta_1}^2 \\
\lambda_1\zeta_q &= (y{\beta_1}^2 - y^2\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q})) \\
\lambda_1\lambda_q &= y^2\beta_1\alpha_1 \\
\lambda_1\zeta_1 &= (y\beta_1\alpha_1 - y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})) \\
\lambda_q\lambda_q &= y^2{\alpha_1}^2 \\
\lambda_q\lambda_1 &= y^2\alpha_1\beta_1 \\
\lambda_q\zeta_q &= (y\alpha_1\beta_1 - y^2{\alpha_1}^2(\frac{Q^2}{2p_i\cdot Q})) \\
\lambda_q\zeta_1 &= (y{\alpha_1}^2 - y^2\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q}))
\end{aligned} \tag{55}
$$

0.14 Common scalar products

$$
\begin{aligned}
k_1\cdot q_i &= (\zeta_1\lambda_q + \lambda_1\zeta_q)p_i\cdot Q + \lambda_1\lambda_q Q^2 - y\alpha_1\beta_1 {n^2}_{\perp,1} \\
&= [(\alpha_1 - y\beta_1(\frac{Q^2}{2p_i\cdot Q}))y\alpha_1 + y\beta_1(\beta_1 - \alpha_1 y(\frac{Q^2}{2p_i\cdot Q}))]\, p_i\cdot Q \\
&\quad y^2\beta_1\alpha_1\, Q^2 + 2y\alpha_1\beta_1\, p_iQ
\end{aligned} \tag{56}
$$

$$
\begin{aligned}
\Rightarrow k_1\cdot q_i &= [y{\alpha_1}^2 - y^2\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q}) + y{\beta_1}^2 - y^2\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q})]\, p_i\cdot Q \\
&\quad y^2\beta_1\alpha_1\, Q^2 + 2y\alpha_1\beta_1\, p_iQ
\end{aligned}
$$

$$
\boxed{k_1\cdot q_i = y(\alpha_1+\beta_1)^2\, p_i\cdot Q = y\, p_i\cdot Q} \tag{57}
$$

$$
\begin{aligned}
k_1 \cdot q_k &= (\zeta_1 A_2 + \lambda_1 A_1) p_i \cdot Q + \zeta_1 \sqrt{1-y}\, p_i \cdot p_k + \lambda_1 A_2\, Q^2 + \lambda_1 \sqrt{1-y}\, Q \cdot p_k \\
&\quad + \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1} \\
&\quad = \{[(\alpha_1 - y\beta_1(\frac{Q^2}{2p_i \cdot Q}))\frac{(y^2 - y - y\sqrt{1-y})(p_i \cdot p_k)}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})}] \\
&\quad + y\beta_1[\frac{-y^2 Q^2 (p_i \cdot p_k)}{4(p_i \cdot Q)^2(1+\sqrt{1-y}-\frac{y}{2})} + \frac{y(1+\sqrt{1-y})(Q \cdot p_k)}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})}]\}\, p_i \cdot Q \\
&\quad + (\alpha_1 - y\beta_1(\frac{Q^2}{2p_i \cdot Q}))\sqrt{1-y}\, p_i \cdot p_k + y\beta_1 \frac{(y^2 - y - y\sqrt{1-y})(p_i \cdot p_k)}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})} Q^2 \\
&\quad + y\beta_1 \sqrt{1-y} Q \cdot p_k + \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{58}
$$

$$
\begin{aligned}
k_1 \cdot q_k &= \alpha_1 \frac{(y^2 - y - y\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})}(p_i \cdot p_k) - y\beta_1(\frac{Q^2}{2p_i \cdot Q})\frac{(y^2 - y - y\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})}(p_i \cdot p_k) \\
&\quad + y\beta_1 \frac{-y^2 Q^2}{4(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})}(p_i \cdot p_k) + y\beta_1 \frac{y(1+\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})}\, Q \cdot p_k \\
&\quad + \alpha_1 \sqrt{1-y}\, p_i \cdot p_k - y\beta_1(\frac{Q^2}{2p_i \cdot Q})\sqrt{1-y}\, p_i \cdot p_k \\
&\quad + y\beta_1(\frac{Q^2}{2p_i \cdot Q})\frac{(y^2 - y - y\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})}(p_i \cdot p_k) + y\beta_1 \sqrt{1-y}(Q \cdot p_k) \\
&\quad + \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{59}
$$

$$
\begin{aligned}
k_1 \cdot q_k &= [\alpha_1 \frac{(y^2 - y - y\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})} + y\beta_1 \frac{-y^2 Q^2}{4(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})} + \alpha_1 \sqrt{1-y} \\
&\quad - y\beta_1(\frac{Q^2}{2p_i \cdot Q})\sqrt{1-y}]\, p_i \cdot p_k + [y\beta_1 \frac{y(1+\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})} + y\beta_1 \sqrt{1-y}](Q \cdot p_k) \\
&\quad + \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{60}
$$

$$
\begin{aligned}
k_1 \cdot q_k &= \{\alpha_1 [\frac{(y^2 - y - y\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})} + \sqrt{1-y}] \\
&\quad + y\beta_1(\frac{Q^2}{p_i \cdot Q})[\frac{-y^2}{4(1+\sqrt{1-y}-\frac{y}{2})} - \sqrt{1-y}]\}\, p_i \cdot p_k \\
&\quad + y\beta_1[\frac{y(1+\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})} + \sqrt{1-y}](Q \cdot p_k) \\
&\quad + \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{61}
$$

$$
\boxed{k_1 \cdot q_k = [\alpha_1(1-y) + y\beta_1(\tfrac{Q^2}{2p_i \cdot Q})]\, p_i \cdot p_k + y\beta_1\, Q \cdot p_k + \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}} \tag{62}
$$

$$
\begin{aligned}
q_i \cdot q_k = &(\zeta_q A_2 + \lambda_q A_1) p_i \cdot Q + \zeta_q \sqrt{1-y}\, p_i \cdot p_k + \lambda_q A_2\, Q^2 + \lambda_q \sqrt{1-y}\, Q \cdot p_k \\
&- \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1} \\
&= \{[(\beta_1 - y\alpha_1(\frac{Q^2}{2p_i \cdot Q}))\frac{(y^2 - y - y\sqrt{1-y})(p_i \cdot p_k)}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})}] \\
&+ y\alpha_1[\frac{-y^2 Q^2 (p_i \cdot p_k)}{4(p_i \cdot Q)^2(1+\sqrt{1-y}-\frac{y}{2})} + \frac{y(1+\sqrt{1-y})(Q \cdot p_k)}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})}]\}\, p_i \cdot Q \\
&+ (\beta_1 - y\alpha_1(\frac{Q^2}{2p_i \cdot Q}))\sqrt{1-y}\, p_i \cdot p_k + y\alpha_1 \frac{(y^2 - y - y\sqrt{1-y})(p_i \cdot p_k)}{2(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})} Q^2 \\
&+ y\alpha_1 \sqrt{1-y} Q \cdot p_k - \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{63}
$$

$$
\begin{aligned}
q_i \cdot q_k = &\beta_1 \frac{(y^2 - y - y\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})}(p_i \cdot p_k) - y\alpha_1(\frac{Q^2}{2p_i \cdot Q})\frac{(y^2 - y - y\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})}(p_i \cdot p_k) \\
&+ y\alpha_1 \frac{-y^2 Q^2}{4(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})}(p_i \cdot p_k) + y\alpha_1 \frac{y(1+\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})}\, Q \cdot p_k \\
&+ \beta_1 \sqrt{1-y}\, p_i \cdot p_k - y\alpha_1(\frac{Q^2}{2p_i \cdot Q})\sqrt{1-y}\, p_i \cdot p_k \\
&+ y\alpha_1(\frac{Q^2}{2p_i \cdot Q})\frac{(y^2 - y - y\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})}(p_i \cdot p_k) + y\alpha_1 \sqrt{1-y}(Q \cdot p_k) \\
&- \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{64}
$$

$$
\begin{aligned}
q_i \cdot q_k = &[\beta_1 \frac{(y^2 - y - y\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})} + y\alpha_1 \frac{-y^2 Q^2}{4(p_i \cdot Q)(1+\sqrt{1-y}-\frac{y}{2})} + \beta_1 \sqrt{1-y} \\
&- y\alpha_1(\frac{Q^2}{2p_i \cdot Q})\sqrt{1-y}]\, p_i \cdot p_k + [y\alpha_1 \frac{y(1+\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})} + y\alpha_1 \sqrt{1-y}](Q \cdot p_k) \\
&- \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{65}
$$

$$
\begin{aligned}
k_1 \cdot q_k = &\{\beta_1[\frac{(y^2 - y - y\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})} + \sqrt{1-y}] \\
&+ y\alpha_1(\frac{Q^2}{p_i \cdot Q})[\frac{-y^2}{4(1+\sqrt{1-y}-\frac{y}{2})} - \sqrt{1-y}]\}\, p_i \cdot p_k \\
&+ y\alpha_1[\frac{y(1+\sqrt{1-y})}{2(1+\sqrt{1-y}-\frac{y}{2})} + \sqrt{1-y}](Q \cdot p_k) \\
&- \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{66}
$$

$$
\boxed{q_i \cdot q_k = [\beta_1(1-y) + y\alpha_1(\tfrac{Q^2}{2p_i \cdot Q})]\, p_i \cdot p_k + y\alpha_1\, Q \cdot p_k - \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}} \tag{67}
$$

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

$$\boxed{(k_1 \cdot q_i)(k_1 \cdot q_k) \approx y(1-\beta_1)(1-y)\,(p_i \cdot p_k)(p_i \cdot Q)} \tag{68}$$

$$\begin{aligned}
{k_1}^\eta {k_1}^{\eta'} &= [(1-\beta_1)^2 - y^2{\beta_1}^2(\frac{Q^2}{2p_i \cdot Q})^2]{p_i}^\eta {p_i}^{\eta'} - y^2{\beta_1}^2(\frac{Q^2}{2p_i \cdot Q}){p_i}^\eta Q^{\eta'} - y^2{\beta_1}^2(\frac{Q^2}{2p_i \cdot Q})Q^\eta {p_i}^{\eta'} \\
{k_1}^\eta {q_i}^{\eta'} &= [\beta_1(1-\beta_1) - y{\beta_1}^2(\frac{Q^2}{2p_i \cdot Q})]{p_i}^\eta {p_i}^{\eta'} + y{\beta_1}^2 Q^\eta {p_i}^{\eta'} \\
{q_i}^\eta {k_1}^{\eta'} &= [\beta_1(1-\beta_1) - y{\beta_1}^2(\frac{Q^2}{2p_i \cdot Q})]{p_i}^\eta {p_i}^{\eta'} + y{\beta_1}^2 {p_i}^\eta Q^{\eta'} \\
{q_i}^\eta {q_i}^{\eta'} &= {\beta_1}^2 {p_i}^\eta {p_i}^{\eta'} \\
{k_1}^\eta {q_k}^{\eta'} &= [(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i \cdot Q})]\sqrt{1-y}{p_i}^\eta {p_k}^{\eta'} - y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_1\, {p_i}^\eta {p_i}^{\eta'} - y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_2\, {p_i}^\eta Q^{\eta'} \\
&\quad + y\beta_1 A_1\, Q^\eta {p_i}^{\eta'} + y\beta_1 A_2\, Q^\eta Q^{\eta'} + y\beta_1\sqrt{1-y}Q^\eta {p_k}^{\eta'} \\
{q_i}^\eta {q_k}^{\eta'} &= A_1\beta_1 {p_i}^\eta {p_i}^{\eta'} + A_2\beta_1 {p_i}^\eta Q^{\eta'} + \beta_1\sqrt{1-y}{p_i}^\eta {p_k}^{\eta'} \\
{q_k}^\eta {k_1}^{\eta'} &= [(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i \cdot Q})]\sqrt{1-y}{p_k}^\eta {p_i}^{\eta'} - y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_1\, {p_i}^\eta {p_i}^{\eta'} - y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_2\, Q^\eta {p_i}^{\eta'} \\
&\quad + y\beta_1 A_1\, {p_i}^\eta Q^{\eta'} + y\beta_1 A_2\, Q^\eta Q^{\eta'} + y\beta_1\sqrt{1-y}{p_k}^\eta Q^{\eta'} \\
{q_k}^\eta {q_i}^{\eta'} &= A_1\beta_1 {p_i}^\eta {p_i}^{\eta'} + A_2\beta_1 Q^\eta {p_i}^{\eta'} + \beta_1\sqrt{1-y}{p_k}^\eta {p_i}^{\eta'}
\end{aligned} \tag{69}$$

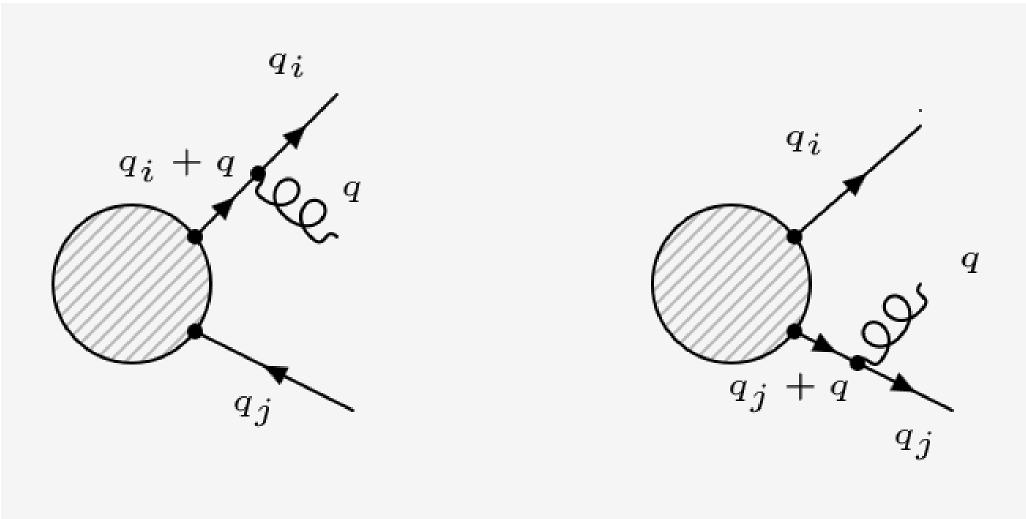
0.16 Parametrization in terms of $(k_1 \cdot q_i)(k_1 \cdot q_i)$

$$\boxed{(k_1 \cdot q_i)(k_1 \cdot q_i) = y^2(p_i \cdot Q)(p_i \cdot Q)} \tag{70}$$

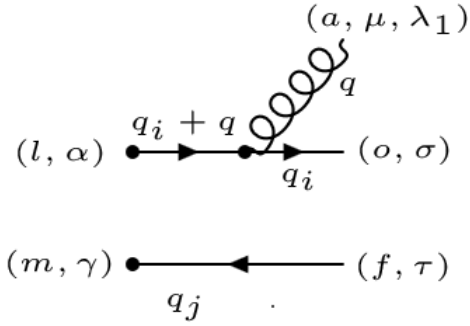
$$\begin{aligned}
{k_1}^\eta {k_1}^{\eta'} &= [(1-\beta_1)^2 - 2y\beta_1(\frac{Q^2}{2p_i \cdot Q})]{p_i}^\eta {p_i}^{\eta'} + y\beta_1(1-\beta_1)(\frac{Q^2}{2p_i \cdot Q}){p_i}^\eta Q^{\eta'} + y\beta_1(1-\beta_1)(\frac{Q^2}{2p_i \cdot Q})Q^\eta {p_i}^{\eta} \\
{k_1}^\eta {q_i}^{\eta'} &= [\beta_1(1-\beta_1) - y(1-\beta_1)^2(\frac{Q^2}{2p_i \cdot Q}) - y{\beta_1}^2(\frac{Q^2}{2p_i \cdot Q})]{p_i}^\eta {p_i}^{\eta'} + y(1-\beta_1)^2 Q^\eta {p_i}^{\eta'} \\
{q_i}^\eta {k_1}^{\eta'} &= [\beta_1(1-\beta_1) - y(1-\beta_1)^2(\frac{Q^2}{2p_i \cdot Q}) - y{\beta_1}^2(\frac{Q^2}{2p_i \cdot Q})]{p_i}^\eta {p_i}^{\eta'} + y(1-\beta_1)^2 {p_i}^\eta Q^{\eta'} \\
{q_i}^\eta {q_i}^{\eta'} &= [{\beta_1}^2 - 2y\beta_1(1-\beta_1)(\frac{Q^2}{2p_i \cdot Q})]{p_i}^\eta {p_i}^{\eta'} + y\beta_1(1-\beta_1)(\frac{Q^2}{2p_i \cdot Q}){p_i}^\eta Q^{\eta'} + y\beta_1(1-\beta_1)(\frac{Q^2}{2p_i \cdot Q})Q^{\eta} \\
{k_1}^\eta {q_k}^{\eta'} &= (1-\beta_1)A_1 {p_i}^\eta {p_i}^{\eta'} + (1-\beta_1)A_2 {p_i}^\eta Q^{\eta'} + (1-\beta_1)\sqrt{1-y}{p_i}^\eta {p_k}^{\eta'} \\
{q_i}^\eta {q_k}^{\eta'} &= A_1\beta_1 {p_i}^\eta {p_i}^{\eta'} + A_2\beta_1 {p_i}^\eta Q^{\eta'} + \beta_1\sqrt{1-y}{p_i}^\eta {p_k}^{\eta'} \\
{q_k}^\eta {k_1}^{\eta'} &= (1-\beta_1)A_1 {p_i}^\eta {p_i}^{\eta'} + (1-\beta_1)A_2 Q^\eta {p_i}^{\eta'} + (1-\beta_1)\sqrt{1-y}{p_k}^\eta {p_i}^{\eta'} \\
{q_k}^\eta {q_i}^{\eta'} &= A_1\beta_1 {p_i}^\eta {p_i}^{\eta'} + A_2\beta_1 Q^\eta {p_i}^{\eta'} + \beta_1\sqrt{1-y}{p_k}^\eta {p_i}^{\eta'}
\end{aligned} \tag{71}$$

Chapter 1

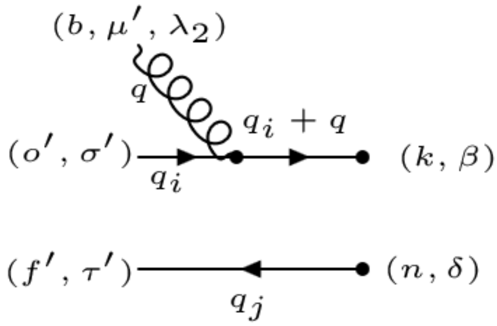
Quark antiquark gluon emission kernel



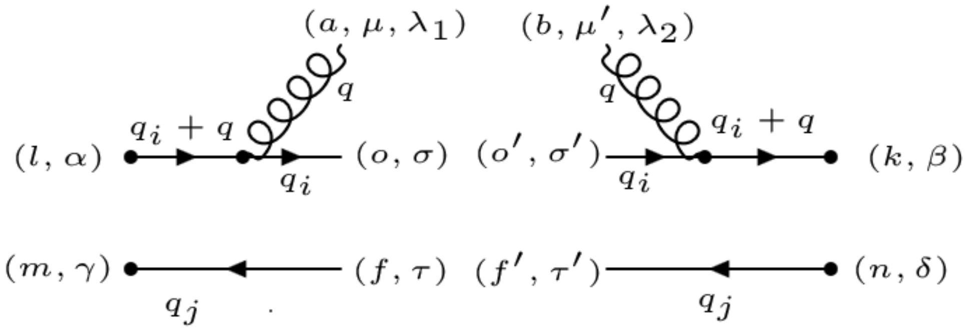
1.1 qg-$\bar{q}$



$$M_1 = [\bar{u}_\sigma(q_i)(-ig_s\gamma^\mu \times [T^a]_o{}^l)\frac{i(\not{q}_i + \not{q})}{(q_i+q)^2}\varepsilon^{\lambda_1}{}_\mu(q)]\,[v_\tau(q_j)] \tag{1.1}$$



$$M_1{}^\dagger = [\frac{-i(\not{q}_i + \not{q})}{(q_i+q)^2}\,(ig_s\gamma^{\mu'} \times [T^b]_{o'}{}^k)\,u_{\sigma'}(q_i)\,\varepsilon^{\lambda_2}{}_{\mu'}(q)][\bar{v}_{\tau'}(q_j)] \tag{1.2}$$



$$
\begin{aligned}
|M_1|^2 = M_1\, M_1{}^{\dagger} = [\bar{u}_\sigma(q_i)\,(-ig_s\gamma^\mu \times [T^a]_o{}^l)\,\frac{i(\not{q}_i + \not{q})}{(q_i+q)^2}\,\varepsilon^{\lambda_1}{}_\mu(q)][v_\tau(q_j)] \\
[\frac{-i(\not{q}_i + \not{q})}{(q_i+q)^2}\,(ig_s\gamma^{\mu'} \times [T^b]_{o'}{}^k)\,u_{\sigma'}(q_i)\,\varepsilon^{\lambda_2}{}_{\mu'}{}^*(q)][\bar{v}_{\tau'}(q_j)]
\end{aligned}
\tag{1.3}
$$

$$
\begin{aligned}
|M_1|^2 = [\frac{-i(\not{q}_i + \not{q})}{(q_i+q)^2}\,(ig_s\gamma^{\mu'} \times [T^b]_{o'}{}^k)\,\bar{u}_\sigma(q_i)\,u_{\sigma'}(q_i)\,\varepsilon^{\lambda_2 *}{}_{\mu'}(q)\varepsilon^{\lambda_1}{}_\mu(q) \\
\times(-ig_s\gamma^\mu \times [T^a]_o{}^l)\,\frac{i(\not{q}_i + \not{q})}{(q_i+q)^2}][\bar{v}_{\tau'}(q_j)v_\tau(q_j)]
\end{aligned}
\tag{1.4}
$$

and after sum over the lorenz index (σ, σ') and (τ, τ') and unsing the spin addition relation:

$$
\begin{aligned}
\sum_{\sigma,\sigma'} \bar{u}_\sigma(q_i)\,u_{\sigma'}(q_i) = \not{q}_i\delta^{oo'}, \\
\sum_{\tau,\tau'} \bar{v}_\tau(q_j)\,v_{\tau'}(q_j) = \not{q}_j\delta^{ff'}
\end{aligned}
\tag{1.5}
$$

and sum over polarization index (λ_1, λ_2) :

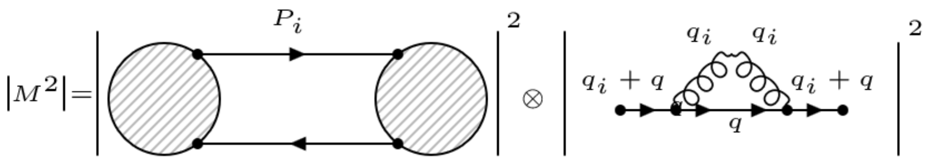
$$
\sum_{\mu,\mu'} \varepsilon^{\lambda_2 *}{}_{\mu'}(q)\varepsilon^{\lambda_1}{}_\mu(q) = -g_{\mu\mu'}\delta^{ab} \tag{1.6}
$$

$$
|M_1|^2 = \frac{-g_s^2[T^a]_o{}^k\,[T^a]_o{}^l}{(q_i+q)^2(q_i+q)^2}[(\not{q}_i + \not{q})\;\gamma^{\mu'}\;\;\not{q}_i\,g_{\mu'\mu}\gamma^\mu\,(\not{q}_i+q)][\not{q}_j] \tag{1.7}
$$

from here and after contraction between all indices we can actually make statements about the last result.

$$
|M_1|^2 = \frac{-g_s^2[T^a]_o{}^k\,[T^a]_o{}^l}{(q_i+q)^2(q_i+q)^2}[(\not{q}_i + \not{q})\;\gamma^{\mu'}\;\;\not{q}_i\,\gamma_{\mu'}\,(\not{q}_i+q)][\not{q}_j] \tag{1.8}
$$

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



$$|M_1|^2 = \frac{-g_s^2 {[T^a]_o}^k \, {[T^a]_o}^l}{(q_i+q)^2(q_i+q)^2} [\not{P}_i][\not{P}_j] \otimes \text{(a complex number)} \tag{1.9}$$

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

$$\begin{aligned} N =: \gamma^{\mu'} \not{q}_i \gamma_{\mu'} &= q_{i\sigma} \gamma^{\mu'} \gamma^{\sigma} \gamma_{\mu'} \\ &= q_{i\sigma} (\{\gamma^{\mu'}, \gamma^{\sigma}\} - \gamma^{\sigma}\gamma^{\mu'})\gamma_{\mu'} \\ &= q_{i\sigma} 2 g^{\mu'\sigma} \gamma_{\mu'} - d\, \gamma^{\sigma} \\ &= (2-d) \not{q}_i \end{aligned} \tag{1.10}$$

$$|M_1|^2 = -(2-d) \frac{g_s^2 {[T^a]_o}^k \, {[T^a]_o}^l}{(q_i+q)^2(q_i+q)^2} [(\not{q}_i + \not{q}) \not{q}_i (\not{q}_i + q)][\not{q}_j] \tag{1.11}$$

$$|M_1|^2 = -(2-d) \frac{g_s^2 {[T^a]_o}^k \, {[T^a]_o}^l}{(q_i+q)^2(q_i+q)^2} [\not{q}_i \not{q}_i \not{q}_i + \not{q}_i \not{q}_i \not{q} + \not{q} \not{q}_i \not{q}_i + \not{q} \not{q}_i \not{q}][\not{q}_j] \tag{1.12}$$

For the momenta are on-shell which means:

$$\begin{aligned} \not{q}_i \not{q}_i &= {q_i}^2 = {m_i}^2 \\ \not{q} \not{q} &= q^2 = m^2 \\ \not{q}_j \not{q}_j &= {q_j}^2 = {m_j}^2 \end{aligned} \tag{1.13}$$

we can first neglect the mass of patrons and ignore each term with $\not{q}_i \not{q}_i$ and $\not{q} \not{q}$ as well.

$$|M_1|^2 = -(2-d) \frac{g_s^2 {[T^a]_o}^k \, {[T^a]_o}^l}{(2q_i q)(2q_i q)} [\not{q} \not{q}_i \not{q}][\not{q}_j] \tag{1.14}$$

$$
\begin{aligned}
L = \not{q}\ \not{q}_i\ \not{q} &= \not{q}[q_{i\sigma} q_\mu\left(\{\gamma^\mu,\gamma^\sigma\} - \gamma^\sigma\gamma^\mu\right)] \\
&\not{q}[2{q_i}^\mu q_\mu - q_{i\sigma} q_\mu \gamma^\mu\gamma^\sigma \\
&= \not{q}(2q_i q) - q_\mu q_{i\sigma} q_\mu[\gamma^\mu\gamma^\mu\gamma^\sigma] \\
&= \not{q}(2q_i q) - q_\mu q_{i\sigma} q_\mu[\frac{\gamma^\mu\gamma^\mu}{2} + \frac{\gamma^\mu\gamma^\mu}{2}]\gamma^\sigma \\
&= \not{q}(2q_i q) - q_\mu q_{i\sigma} q_\mu[g^{\mu\mu}]\gamma^\sigma \\
&= \not{q}(2q_i q) - q_\mu q_{i\sigma} q^\mu\gamma^\sigma \\
&= \not{q}(2q_i q) - q^2\ \not{q}_i \\
&= \not{q}(2q_i q)
\end{aligned}
\tag{1.15}
$$

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

$$
|M_1|^2 = -(2-d)\,\frac{g_s^2 {[T^a]_o}^k\, {[T^a]_o}^l}{2y(1-2z+2z^2)(p_i\cdot p_j)}[\not{q}][\not{q}_j] \tag{1.16}
$$

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.

$$
|M_1|^2 = (d-2)\,\frac{g_s^2 {[T^a]_o}^k\, {[T^a]_o}^l}{2y(1-2z+2z^2)(p_i\cdot p_j)}[(1-z)\ \not{p}_i + zy\ \not{p}_j - \sqrt{zy(1-z)}\ \not{m}_\perp][(1-y)\ \not{p}_j] \tag{1.17}
$$

Multiplying the both sides

$$
\begin{aligned}
|M_1|^2 = (d-2)\,\frac{g_s^2 {[T^a]_o}^k\, {[T^a]_o}^l}{2y(1-2z+2z^2)(p_i\cdot p_j)}&[(1-z)(1-y)\ \not{p}_i\ \not{p}_j \\
&+zy(1-y)\ \not{p}_j\ \not{p}_j + (1-y)\sqrt{zy(1-z)}\ \not{m}_\perp\ \not{p}_j]
\end{aligned}
\tag{1.18}
$$

and 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.

$$
|M_1|^2 = (d-2)(1-z)(1-y)\,\frac{g_s^2 {[T^a]_o}^k\, {[T^a]_o}^l}{2y(1-2z+2z^2)(p_i\cdot p_j)}[\not{p}_i][\not{p}_j] \tag{1.19}
$$

with the new parametrisation

$$|M_1|^2 = (d-2)\,\frac{g_s^2 C_F}{(2k_1\cdot q_i)}[\not{k}_1][\not{q}_k] \tag{1.20}$$

$$\begin{aligned}|M_1|^2 = (d-2)\,&\frac{g_s^2\,C_F}{2y\,p_i\cdot Q}[(\alpha_1 - y\beta_1(\frac{Q^2}{2p_i\cdot Q}))\ \not{p}_i + y\beta_1\ \not{Q} + \sqrt{y\alpha_1\beta_1}\ \not{n}_{\perp,1}]\\ &[A_1\ \not{p}_i + A_2\ \not{Q} + \sqrt{1-y}\ \not{p}_k]\end{aligned} \tag{1.21}$$

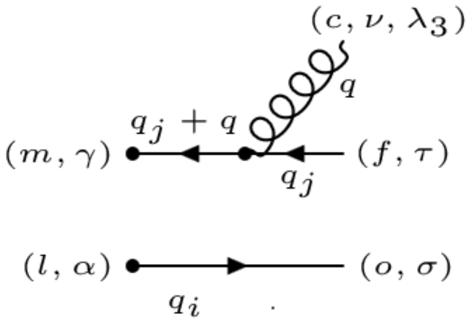
$$\begin{aligned}|M_1|^2 = (d-2)\,&\frac{g_s^2\,C_F}{2y\,p_i\cdot Q}[(A_2(\alpha_1 - y\beta_1(\frac{Q^2}{2p_i\cdot Q})) + A_1 y\beta_1)p_i\cdot Q\\ &+ (\alpha_1 - y\beta_1(\frac{Q^2}{2p_i\cdot Q}))\sqrt{1-y}p_i\cdot p_k + A_2 y\beta_1 Q^2 + \sqrt{1-y}\sqrt{y\alpha_1\beta_1}n_{\perp,1}\cdot p_k]\end{aligned} \tag{1.22}$$

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

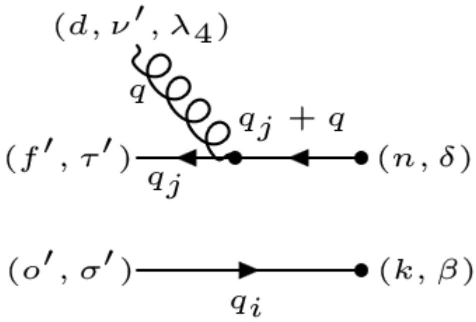
$$\begin{aligned}|M_1|^2 = (d-2)\,&\frac{g_s^2\,C_F}{2y\,p_i\cdot Q}[(A_2(\alpha_1 - y\beta_1(\frac{Q^2}{2p_i\cdot Q})) + A_1 y\beta_1)\ \not{p}_i\ \not{Q}\\ &+ (\alpha_1 - y\beta_1(\frac{Q^2}{2p_i\cdot Q}))\sqrt{1-y}\ \not{p}_i\ \not{p}_k + A_2 y\beta_1 Q^2 + \sqrt{1-y}\sqrt{y\alpha_1\beta_1}\ \not{n}_{\perp,1}\ \not{p}_k]\end{aligned} \tag{1.23}$$

$$|M_1|^2 = (d-2)(1-\beta_1)\sqrt{1-y}\ \frac{g_s^2\,C_F}{2y\,p_i\cdot Q}[\not{p}_i\ \not{p}_k] \tag{1.24}$$

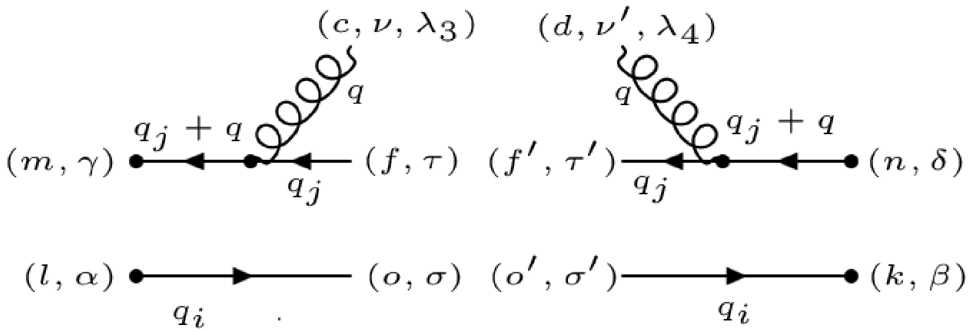
1.2 $\bar{q}$g-q



$$M_2 = [\frac{i(\not{q}_j + \not{q})}{(q_j+q)^2}(-ig_s\gamma^{\nu} \times [T^c]_f{}^m)\, v_\tau(q_j)\, \varepsilon^{\lambda_3}{}_\nu(q)]\, [u_\sigma(q_i)] \tag{1.25}$$



$$M_2^\dagger = [\bar{v}_{\tau'}(q_j)\, (ig_s\gamma^{\nu'} \times [T^d]_{f'}{}^n)\, \frac{-i(\not{q}_j + \not{q})}{(q_j+q)^2}\, \varepsilon^{\lambda_4}{}_{\nu'}(q)]\, [\bar{u}_{\sigma'}(q_i)] \tag{1.26}$$



$$|M_2|^2 = M_2\, {M_2}^\dagger = [\frac{i(\not{q}_j + \not{q})}{(q_j+q)^2}(-ig_s\gamma^{\nu} \times [T^c]_f{}^m)\, v_\tau(q_j)\, \varepsilon^{\lambda_3}{}_\nu(q)]\, [u_\sigma(q_i)]$$
$$[\bar{v}_{\tau'}(q_j)\, (ig_s\gamma^{\nu'} \times [T^d]_{f'}{}^n)\, \frac{-i(\not{q}_j + \not{q})}{(q_j+q)^2}\, \varepsilon^{\lambda_4}{}_{\nu'}(q)]\, [\bar{u}_{\sigma'}(q_i)] \tag{1.27}$$

$$|M_2|^2 = \frac{g_s^2\,[T^c]_f{}^m\,[T^d]_{f'}{}^n}{(q_j+q)^2(q_j+q)^2}[(\not{q}_j + \not{q})\gamma^\nu\, v_\tau(q_j)\bar{v}_{\tau'}(q_j)\,\varepsilon^{\lambda_3}{}_\nu(q)\varepsilon^{\lambda_4}{}_{\nu'}(q)\gamma^{\nu'}(\not{q}_j + \not{q})] \\ [u_\sigma(q_i)]\,[\bar{u}_{\sigma'}(q_i)] \tag{1.28}$$

and after sum over the lorenz index (σ, σ') and (τ, τ') and unsing the spin addition relation:

$$\sum_{\sigma,\sigma'} \bar{u}_\sigma(q_i)\,u_{\sigma'}(q_i) = \not{q}_i\delta^{oo'}, \\ \sum_{\tau,\tau'} \bar{v}_\tau(q_j)\,v_{\tau'}(q_j) = \not{q}_j\delta^{ff'} \tag{1.29}$$

and sum over polarization index (λ_3, λ_4) :

$$\sum_{\nu,\nu'} \varepsilon^{\lambda_4}{}^*_{\nu'}(q)\varepsilon^{\lambda_3}{}_\nu(q) = -g_{\nu\nu'}\delta^{cd} \tag{1.30}$$

$$|M_2|^2 = \frac{g_s^2\,[T^c]_f{}^m\,[T^c]_f{}^n}{(q_j+q)^2(q_j+q)^2}[(\not{q}_j + \not{q})\gamma^\nu\ \ \not{q}_j\,(-g_{\nu\nu'})\gamma^{\nu'}(\not{q}_j + \not{q})]\,[\not{q}_i] \tag{1.31}$$

After the same calculation from the last part, we'll get:

$$|M_2|^2 = (d-2)\frac{g_s^2\,[T^c]_f{}^m\,[T^c]_f{}^n}{(2qq_j)}[\not{q}]\,[\not{q}_i] \tag{1.32}$$

finally:

$$|M_2|^2 = -(d-2)yz^2\,\frac{g_s^2\,[T^c]_f{}^m\,[T^c]_f{}^n}{2(1-z)(1-y)(p_i\cdot p_j)}[\not{p}_i][\not{p}_j] \tag{1.33}$$

with the new kinematic

$$|M_2|^2 = (d-2)\frac{g_s^2\,{[T^c]_f}^m\,{[T^c]_f}^n}{2k_1\cdot q_k}[\not{k}_1]\,[\not{q}_i] \tag{1.34}$$

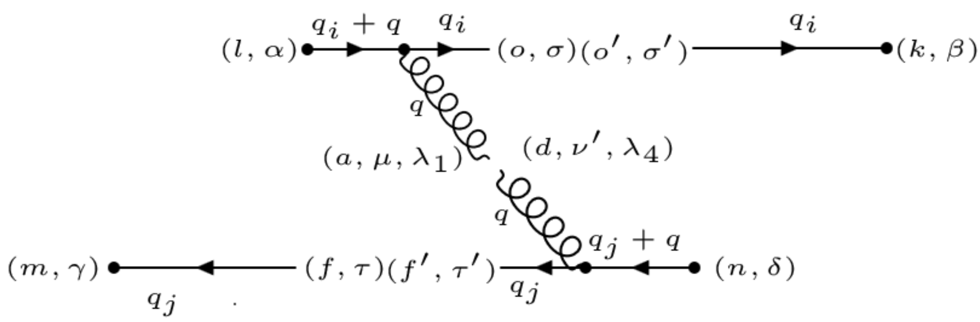
$$\begin{aligned}|M_2|^2 = (d-2)\frac{g_s^2\,C_F}{2k_1\cdot q_k}&[(\alpha_1 - y\beta_1(\frac{Q^2}{2p_i\cdot Q}))\ \not{p}_i + y\beta_1\ \not{Q} + \sqrt{y\alpha_1\beta_1}\ \not{n}_{\perp,1}]\\ &[(\beta_1 - \alpha_1 y(\frac{Q^2}{2p_i\cdot Q}))\ \not{p}_i + y\alpha_1\ \not{Q} - \sqrt{y\alpha_1\beta_1}\ \not{n}_{\perp,l}]\end{aligned} \tag{1.35}$$

$$\begin{aligned}|M_2|^2 = (d-2)\frac{g_s^2\,C_F}{2k_1\cdot q_k}&[y\alpha_1(\alpha_1 - y\beta_1(\frac{Q^2}{2p_i\cdot Q}))\ \not{p}_i\ \not{Q} + y\beta_1(\beta_1 - \alpha_1 y(\frac{Q^2}{2p_i\cdot Q}))]\ \not{Q}\ \not{p}_i\\ &+ y^2\alpha_1\beta_1 Q^2 - y\beta_1\sqrt{y\alpha_1\beta_1}\ \not{Q}\ \not{n}_{\perp,1} + y\beta_1\sqrt{y\alpha_1\beta_1}\ \not{n}_{\perp,1}\ \not{Q} - y\alpha_1\beta_1\, {n_{\perp,l}}^2\\ &+ (\beta_1 - \alpha_1 y(\frac{Q^2}{2p_i\cdot Q}))\sqrt{y\alpha_1\beta_1}\ \not{n}_{\perp,1}\ \not{p}_i - (\alpha_1 - \alpha_1 y(\frac{Q^2}{2p_i\cdot Q}))\sqrt{y\alpha_1\beta_1}\ \not{p}_i\ \not{n}_{\perp,1}]\end{aligned} \tag{1.36}$$

Which means:

$$\begin{aligned}|M_2|^2 &\sim (d-2)\frac{g_s^2\,C_F}{2k_1\cdot q_k}y[...]\\ |M_2|^2 &\to 0 \quad \text{for} \quad y\to 0\end{aligned} \tag{1.37}$$

1.3 $M_1 {M_2}^{\dagger}$



$$M_1 \, {M_2}^{\dagger} = [\bar{u}_{\sigma}(q_i)\,(-ig_s\gamma^{\mu} \times [T^a]_o{}^l)\,\frac{i(\not{q}_i + \not{q})}{(q_i+q)^2}\,\varepsilon^{\lambda_1}{}_{\mu}(q)][v_{\tau}(q_j)]$$
$$[\bar{v}_{\tau'}(q_j)\,(ig_s\gamma^{\nu'} \times [T^d]_{f'}{}^n)\,\frac{-i(\not{q}_j + \not{q})}{(q_j+q)^2}\,\varepsilon^{\lambda_4}{}_{\nu'}(q)]\,[u_{\sigma'}(q_i)] \tag{1.38}$$

$$M_1 \, {M_2}^{\dagger} = \frac{g_s^2 [T^a]_o{}^l \, [T^d]_{f'}{}^n}{(2q_i q)(2q_j q)} [\not{q}_i \, \gamma^{\mu} \, (\not{q}_i + \not{q})\,] \varepsilon^{\lambda_1}{}_{\mu}(q)\, \varepsilon^{\lambda_4}{}_{\nu'}(q)$$
$$[\not{q}_j \, \gamma^{\nu'} \, (\not{q}_j + \not{q})] \tag{1.39}$$

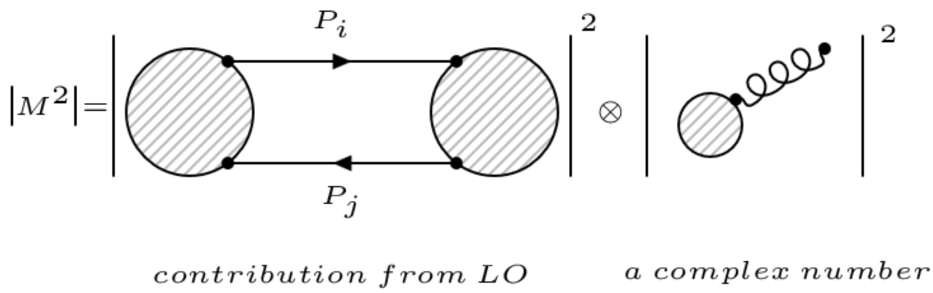
$$M_1 \, {M_2}^{\dagger} = \frac{g_s^2 [T^a]_o{}^l \, [T^a]_{f'}{}^n}{(2q_i q)(2q_j q)} [\not{q}_i \, \gamma^{\mu} \, (\not{q}_i + \not{q})\,] - g_{\mu\nu'}$$
$$[\not{q}_j \, \gamma^{\nu'} \, (\not{q}_j + \not{q})] \tag{1.40}$$

$$M_1 \, {M_2}^{\dagger} = \frac{-g_s^2 [T^a]_o{}^l \, [T^a]_{f'}{}^n}{(2q_i q)(2q_j q)} [\not{q}_i \, \gamma^{\mu} \, (\not{q}_i + \not{q})\,]\,[\not{q}_j \, \gamma_{\mu} \, (\not{q}_j + \not{q})] \tag{1.41}$$

Expectation:

$$M_1 \, {M_2}^{\dagger} = \frac{-g_s^2 [T^a]_o{}^l \, [T^a]_{f'}{}^n}{(2q_i q)(2q_j q)} [(\not{q}_i + \not{q})\,\gamma^{\mu} \;\; \not{q}_i\,]\,[(\not{q}_j + \not{q})\,\gamma_{\mu} \;\; \not{q}_j] \tag{1.42}$$

$$M_1 \, {M_2}^{\dagger} = \frac{-g_s^2 [T^a]_o{}^l \, [T^a]_{f'}{}^n}{(2q_i q)(2q_j q)} [-(\not{q}_i + \not{q}) \;\; \not{q}_i \, \gamma^{\mu} \; + 2(\not{q}_i + \not{q})\, q_i{}^{\mu}]$$
$$[-(\not{q}_j + \not{q}) \;\; \not{q}_j \, \gamma_{\mu} \; + 2(\not{q}_j + \not{q}) q_{j\mu}] \tag{1.43}$$



$$
\begin{aligned}
M_1\, M_2{}^\dagger = & \frac{-g_s^2[T^a]_o{}^l\,[T^a]_{f'}{}^n}{(2q_iq)(2q_jq)}[(\not{q}_i+\not{q})\ \not{q}_i\,\gamma^\mu]\,[(\not{q}_j+\not{q})\ \not{q}_j\gamma_\mu] \\
& -2[(\not{q}_i+\not{q})\ \not{q}_i\,\gamma^\mu]\,[(\not{q}_j+\not{q})q_{j\mu}]-2[(\not{q}_i+\not{q})\,q_i{}^\mu][(\not{q}_j+\not{q})\ \not{q}_j\,\gamma_\mu] \\
& +4[(\not{q}_i+\not{q})\,q_i{}^\mu][(\not{q}_j+\not{q})q_{j\mu}]
\end{aligned}
\tag{1.44}
$$

$$
\begin{aligned}
M_1\, M_2{}^\dagger = & \frac{-g_s^2[T^a]_o{}^l\,[T^a]_{f'}{}^n}{(2q_iq)(2q_jq)}[(\not{q}_i+\not{q})\ \not{q}_i\,\gamma^\mu]\,[(\not{q}_j+\not{q})\ \not{q}_j\gamma_\mu] \\
& -2[(\not{q}_i+\not{q})\ \not{q}_i\ \not{q}_j]\,[\not{q}_j+\not{q}]-2[\not{q}_i+\not{q}\,][(\not{q}_j+\not{q})\ \not{q}_j\ \not{q}_i] \\
& +4[(\not{q}_i+\not{q})\,q_i{}^\mu][(\not{q}_j+\not{q})q_{j\mu}]
\end{aligned}
\tag{1.45}
$$

$$
\begin{aligned}
M_1\, M_2{}^\dagger = & \frac{-g_s^2[T^a]_o{}^l\,[T^a]_{f'}{}^n}{(2q_iq)(2q_jq)}[(\not{q}_i+\not{q})\ \not{q}_i\,\gamma^\mu]\,[(\not{q}_j+\not{q})\ \not{q}_j\gamma_\mu] \\
& +4[(\not{q}_i+\not{q})\,q_i{}^\mu][(\not{q}_j+\not{q})q_{j\mu}]
\end{aligned}
\tag{1.46}
$$

$$
\begin{aligned}
M_1\, M_2{}^\dagger = & \frac{-g_s^2\ [T^a]_o{}^l\,[T^a]_{f'}{}^n}{4(1-z)(1-y)y(1-2z+2z^2)(p_i\cdot p_j)(p_i\cdot p_j)} \\
& [y(1-2z+2z^2)\ \not{p}_i\ \ \not{p}_j\,\gamma^\mu]\,[(1-z)(1-y)\ \not{p}_i\ \not{p}_j\gamma_\mu] \\
& +4(q_i{}^\mu\cdot q_{j\mu})[(\not{q}_i+\not{q})][(\not{q}_j+\not{q})]
\end{aligned}
\tag{1.47}
$$

$$
\begin{aligned}
M_1\, M_2{}^\dagger = & \frac{-g_s^2\ [T^a]_o{}^l\,[T^a]_{f'}{}^n}{4(1-z)(1-y)y(1-2z+2z^2)(p_i\cdot p_j)(p_i\cdot p_j)} \\
& [y(1-2z+2z^2)\ \not{p}_i\ \ \not{p}_j\,\gamma^\mu]\,[(1-z)(1-y)\ \not{p}_i\ \not{p}_j\gamma_\mu] \\
& +4(p_i\cdot p_j)[(\not{p}_i+y\ \not{p}_j)][(1-z)\ \not{p}_i+(1+yz-y)\ \not{p}_j-\sqrt{zy(1-z)}\ \not{m}]
\end{aligned}
\tag{1.48}
$$

$$
M_1\, M_2{}^\dagger = \frac{-g_s^2\ [T^a]_o{}^l\,[T^a]_{f'}{}^n}{(1-z)(1-y)y(1-2z+2z^2)(p_i\cdot p_j)}z(1-y)[\not{p}_i][\not{p}_j]
\tag{1.49}
$$

$$
M_1\, M_2{}^\dagger = \frac{-g_s^2\ [T^a]_o{}^l\,[T^a]_{f'}{}^n}{(1-z)y(1-2z+2z^2)(p_i\cdot p_j)}z[\not{p}_i][\not{p}_j]
\tag{1.50}
$$

With the new kinematic

$$M_1\, {M_2}^\dagger = \frac{-g_s^2 [T^a]_o{}^l\, [T^a]_{f'}{}^n}{(2q_ik_1)(2q_kk_1)} [(\not{q}_i + \not{k}_1)\ \not{q}_i\, \gamma^\mu]\, [(\not{q}_k + \not{k}_1)\ \not{q}_k \gamma_\mu] \\ + 4[(\not{q}_i + \not{k}_1)\, {q_i}^\mu][(\not{q}_k + \not{k}_1) q_{k\mu}] \tag{1.51}$$

$$M_1\, {M_2}^\dagger = \frac{-g_s^2\, C_F}{4y(1-\beta_1)(1-y)\, (p_i \cdot p_k)(p_i \cdot Q)} \\ [(\not{q}_i\ \not{q}_i + \not{k}_1\ \not{q}_i)\, \gamma^\mu][(\not{q}_k\ \not{q}_k + \not{k}_1\ \not{q}_k)\gamma_\mu] + 4({q_i}^\mu q_{k\mu})[\not{q}_i + \not{k}_1\,][\not{q}_k + \not{k}_1] \tag{1.52}$$

$$M_1\, {M_2}^\dagger = \frac{-g_s^2\, C_F}{4y(1-\beta_1)(1-y)\, (p_i \cdot p_k)(p_i \cdot Q)} \\ [\not{k}_1\ \not{q}_i\, \gamma^\mu][\not{k}_1\ \not{q}_k \gamma_\mu] + 4(q_i \cdot q_k)[\not{q}_i\ \not{q}_k + \not{k}_1\ \not{q}_k + \not{q}_i\ \not{k}_1] \tag{1.53}$$

$$M_1\, {M_2}^\dagger = \frac{-g_s^2\, C_F}{4y(1-\beta_1)(1-y)\, (p_i \cdot p_k)(p_i \cdot Q)} \\ 4(A_1\beta_1 p_i \cdot p_i + A_2\beta_1 p_i \cdot Q + \beta_1\sqrt{1-y} p_i \cdot p_k) \\ [A_1\beta_1\ \not{p}_i\ \not{p}_i + A_2\beta_1\ \not{p}_i\ \not{Q} + \beta_1\sqrt{1-y}\ \not{p}_i\ \not{p}_k \\ + [(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i \cdot Q})]\sqrt{1-y}\ \not{p}_i\ \not{p}_k - y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_1\ \ \not{p}_i\ \not{p}_i \\ - y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_2\ \ \not{p}_i\ \not{Q} + y\beta_1 A_1\ \ \not{Q}\ \not{p}_i + y\beta_1 A_2\ \ \not{Q}\ \not{Q} + y\beta_1\sqrt{1-y}\ \not{Q}\ \not{p}_k \\ + [\beta_1(1-\beta_1) - y{\beta_1}^2(\frac{Q^2}{2p_i \cdot Q})]\ \not{p}_i\ \not{p}_i + y{\beta_1}^2\ \not{p}_i\ \not{Q}] \tag{1.54}$$

$$M_1\, {M_2}^\dagger = \frac{-g_s^2\, C_F}{4y(1-\beta_1)(1-y)\, (p_i \cdot p_k)(p_i \cdot Q)} \\ 4(A_2\beta_1 p_i \cdot Q + \beta_1\sqrt{1-y} p_i \cdot p_k)[A_2\beta_1\ \not{p}_i\ \not{Q} + \beta_1\sqrt{1-y}\ \not{p}_i\ \not{p}_k \\ + [(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i \cdot Q})]\sqrt{1-y}\ \not{p}_i\ \not{p}_k - y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_2\ \ \not{p}_i\ \not{Q} \\ + y\beta_1 A_1\ \ \not{Q}\ \not{p}_i + y\beta_1 A_2\ \ \not{Q}\ \not{Q} + y\beta_1\sqrt{1-y}\ \not{Q}\ \not{p}_k + y{\beta_1}^2\ \not{p}_i\ \not{Q}] \tag{1.55}$$

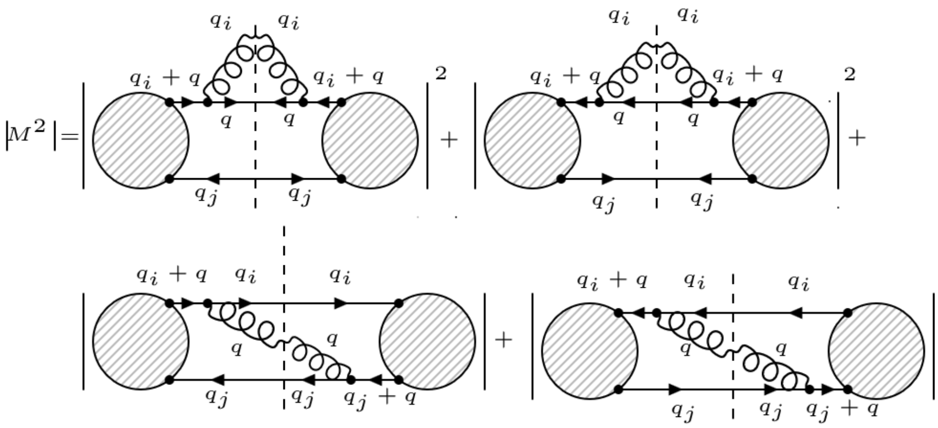
$$M_1\, {M_2}^\dagger = \frac{-g_s^2\, C_F}{4y(1-\beta_1)(1-y)\, (p_i \cdot p_k)(p_i \cdot Q)} \\ 4(\beta_1\sqrt{1-y} p_i \cdot p_k)[\beta_1\sqrt{1-y}\ \not{p}_i\ \not{p}_k + (1-\beta_1)\sqrt{1-y}\ \not{p}_i\ \not{p}_k] \tag{1.56}$$

$$M_1\, {M_2}^\dagger = \frac{-g_s^2\, C_F}{y(1-\beta_1)\, (p_i \cdot p_k)(p_i \cdot Q)} \beta_1 (p_i \cdot p_k)[\beta_1\ \not{p}_i\ \not{p}_k + (1-\beta_1)\ \not{p}_i\ \not{p}_k] \tag{1.57}$$

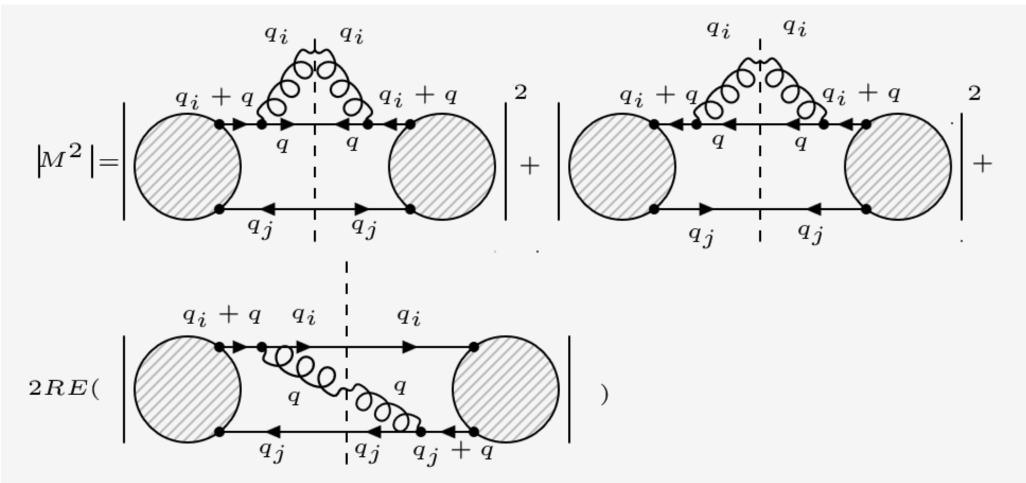
$$M_1\, {M_2}^\dagger = \frac{\beta_1}{(1-\beta_1)}\, \frac{-g_s^2\, C_F}{y\, (p_i \cdot Q)} [\not{p}_i\ \not{p}_k] \tag{1.58}$$

1.4 $|M^2|$

$$| M|^2 = | M_1|^2 + | M_2|^2 + M_1\, {M_2}^{\dagger} + {M_1}^{\dagger} M_2 \tag{1.59}$$



$$| M|^2 = | M_1|^2 + | M_2|^2 + 2RE(M_1\, {M_2}^{\dagger}) \tag{1.60}$$



$$\begin{aligned} | M|^2 = (d-2)(1-z)(1-y)\, &\frac{g_s^2 [T^a]_o{}^k\, [T^a]_o{}^l}{2y(1-2z+2z^2)(p_i \cdot p_j)} [\not{p}_i][\not{p}_j] \\ -(d-2)yz^2\, &\frac{g_s^2\, [T^c]_f{}^m\, [T^c]_f{}^n}{2(1-z)(1-y)(p_i \cdot p_j)} [\not{p}_i][\not{p}_j] \\ +2RE\left(\left(\frac{-2z}{z-1}\right) \right.&\left.\frac{g_s^2\;\, [T^a]_o{}^l\, [T^a]_f{}^n}{2y(1-2z+2z^2)(p_i \cdot p_j)} [\not{p}_i][\not{p}_j]\right) \end{aligned} \tag{1.61}$$

$$T^a{}_{o\,k}\, T^a{}_{l\,o} = \frac{1}{2}(\delta_{oo}\delta_{lk} - \frac{1}{N}\delta_{ok}\delta_{lo}) = \frac{1}{2}(N\delta_{lk} - \frac{1}{N}\delta_{lk}) = C_F \delta_{lk} \tag{1.62}$$

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

$$T^a{}_{o\,k}\,T^a{}_{l\,o} = C_F\delta_{lk} = \frac{1}{N}\sum_{l=1}^{N}\delta_{lk}C_F = C_F \tag{1.63}$$

The same calculation for $T^c{}_{m\,f}\,T^c{}_{f\,n}$ and $T^a{}_{o\,l}\,T^a{}_{f\,n}$ 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:

$$y \longrightarrow 0 \tag{1.64}$$

$$\begin{aligned} |\,M|^2 = (d-2)(1-z)(1-y)\,&\frac{g_s^2 C_F}{2y(1-2z+2z^2)(p_i\cdot p_j)}[\not{p}_i][\not{p}_j] \\ -(d-2)yz^2\,&\frac{g_s^2\,C_F}{2(1-z)(1-y)(p_i\cdot p_j)}[\not{p}_i][\not{p}_j] \\ +2RE((\frac{-2z}{z-1})&\frac{g_s^2 C_F}{2y(1-2z+2z^2)(p_i\cdot p_j)}[\not{p}_i][\not{p}_j] \end{aligned} \tag{1.65}$$

$$|\,M|^2 = C_F((d-2)(1-z) - \frac{4z}{z-1})\,\frac{g_s^2}{2y(1-2z+2z^2)(p_i\cdot p_j)}[\not{p}_i][\not{p}_j] \tag{1.66}$$

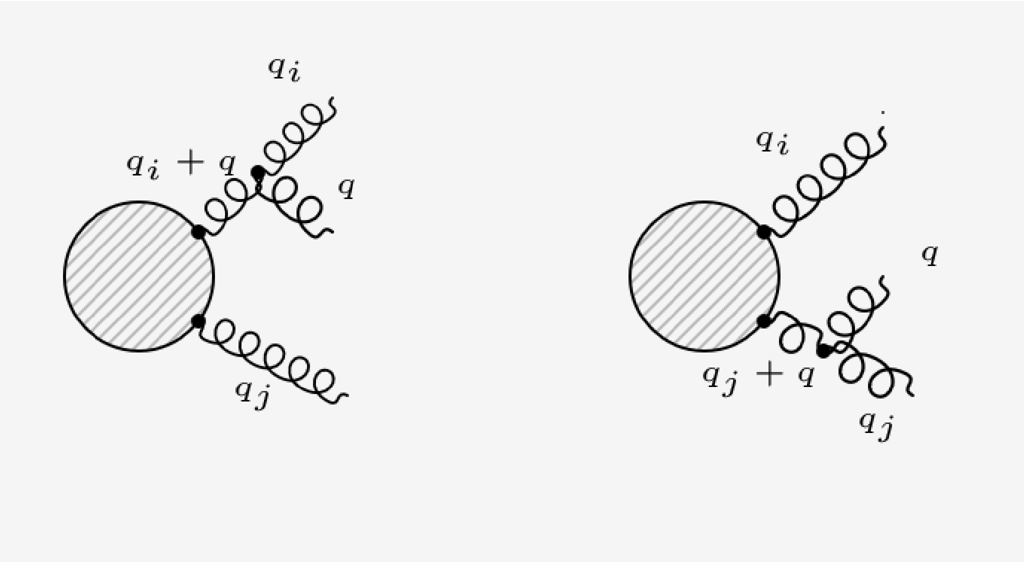
for

$$d = 4-2\epsilon \tag{1.67}$$

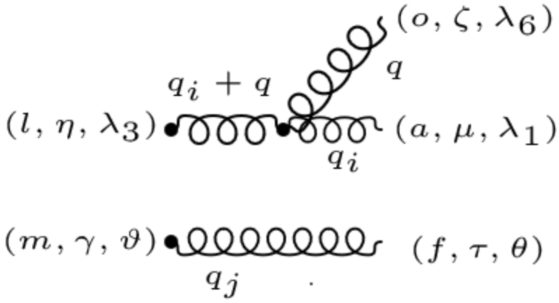
$$\begin{aligned} |\,M|^2 &= C_F((4-2\epsilon-2)(1-z) + \frac{4z}{1-z})\,\frac{g_s^2}{2y(1-2z+2z^2)(p_i\cdot p_j)}[\not{p}_i][\not{p}_j] \\ &= C_F(\frac{2(1-\epsilon)(1-z)^2+4z}{1-z})\,\frac{g_s^2}{2y(1-2z+2z^2)(p_i\cdot p_j)}[\not{p}_i][\not{p}_j] \\ &C_F(\frac{2-4z+2z^2-\epsilon(1-z)^2+4z}{1-z})\,\frac{g_s^2}{2y(1-2z+2z^2)(p_i\cdot p_j)}[\not{p}_i][\not{p}_j] \\ &= C_F(\frac{(1+z^2)}{1-z} - \epsilon(1-z))\,\frac{g_s^2}{y(1-2z+2z^2)(p_i\cdot p_j)}[\not{p}_i][\not{p}_j] \\ &= \langle\,\hat{P}_{qq}\rangle\,\frac{g_s^2}{q_i\cdot q}[\not{p}_i][\not{p}_j] \end{aligned} \tag{1.68}$$

Chapter 2

Gluon gluon gluon emission kernel

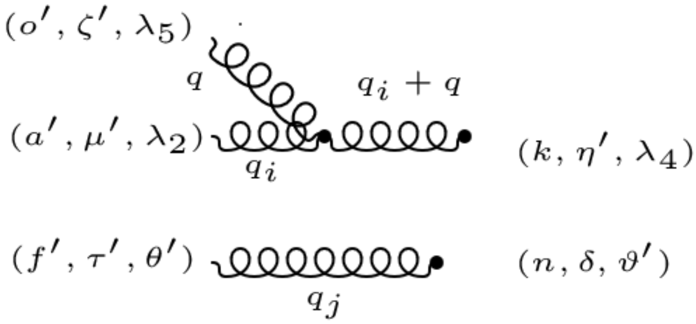


2.1 Gluon-Emitter Bubble



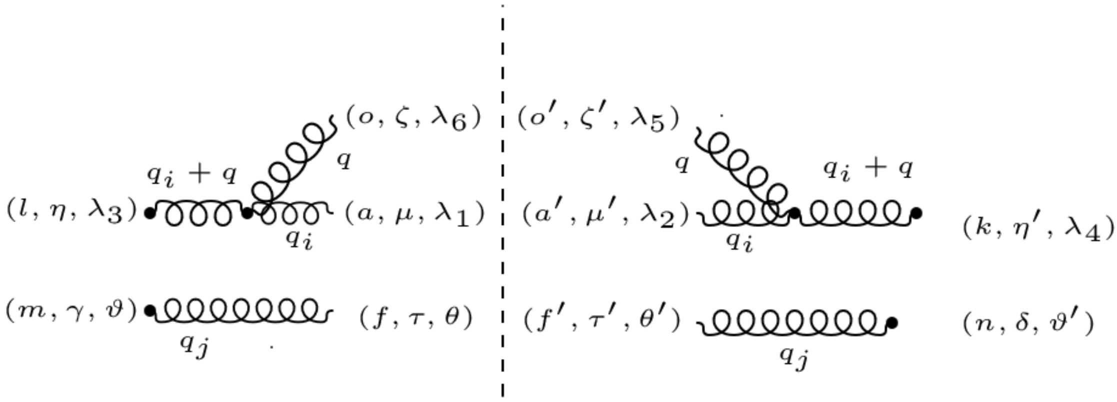
$$M_1 = [\frac{-i}{(q+q_i)^2}(-g_s f^{\,a\,o\,l}(g^{\mu\zeta}(q-q_i)^{\eta} + g^{\zeta\eta}(-q-(q+q_i))^{\mu} + g^{\eta\mu}(q_i+q_i+q)^{\zeta}) \\ \varepsilon^{\lambda_1}{}_{\mu}(q)\varepsilon^{\lambda_6}{}_{\zeta}(q)][\varepsilon^{\theta}{}_{\tau'}(q_j)] \tag{2.1}$$

$$M_1 = [\frac{-i}{(q_i+q)^2}(-g_s f^{\,a\,o\,l}(g^{\mu\zeta}(q-q_i)^{\eta} - g^{\zeta\eta}(2q+q_i)^{\mu} + g^{\eta\mu}(2q_i+q)^{\zeta}) \\ \varepsilon^{\lambda_1}{}_{\mu}(q_i)\varepsilon^{\lambda_6}{}_{\zeta}(q)][\varepsilon^{\theta}{}_{\tau'}(q_j)] \tag{2.2}$$



$$M_1{}^{\dagger} = [\frac{i}{(q_i+q)^2}(-g_s f^{\,a'\,k\,o'}(-g^{\mu'\eta'}(2q_i+q)^{\zeta'} + g^{\eta'\zeta'}(2q+q_i)^{\mu'} + g^{\zeta'\mu'}(q_i-q)^{\eta'}) \\ \varepsilon^{\lambda_2}{}_{\mu'}{}^{*}(q_i)\varepsilon^{\lambda_5}{}_{\zeta'}{}^{*}(q)][\varepsilon^{\theta'}{}_{\tau'}{}^{*}(q_j)] \tag{2.3}$$

$$|M_1|^2 = [\frac{-i}{(q_i+q)^2}(-g_s f^{\,a\,o\,l}(g^{\mu\zeta}(q-q_i)^{\eta} - g^{\zeta\eta}(2q+q_i)^{\mu} + g^{\eta\mu}(2q_i+q)^{\zeta}) \\ \varepsilon^{\lambda_1}{}_{\mu}(q_i)\,\varepsilon^{\lambda_2}{}_{\mu'}{}^{*}(q_i)\varepsilon^{\lambda_6}{}_{\zeta}(q)\,\varepsilon^{\lambda_5}{}_{\zeta'}{}^{*}(q) \\ (-g_s f^{\,a'\,k\,o'}(-g^{\mu'\eta'}(2q_i+q)^{\zeta'} + g^{\eta'\zeta'}(2q+q_i)^{\mu'} + g^{\zeta'\mu'}(q_i-q)^{\eta'})\frac{i}{(q_i+q)^2}][g^{\gamma\delta}] \tag{2.4}$$



$$\begin{aligned} N \equiv g_{\mu\mu'} g_{\zeta\zeta'} [&-g^{\mu\zeta} g^{\mu'\eta'} (q-q_i)^{\eta} (2q_i+q)^{\zeta'} + g^{\mu\zeta} g^{\eta'\zeta'} (q-q_i)^{\eta} (2q+q_i)^{\mu'} \\ &+g^{\mu\zeta} g^{\zeta'\mu'} (q-q_i)^{\eta} (q_i-q)^{\eta'} + g^{\zeta\eta} g^{\mu'\zeta'} (2q+q_i)^{\mu} (2q_i+q)^{\zeta'} \\ &-g^{\zeta\eta} g^{\eta'\zeta'} (2q+q_i)^{\mu} (2q+q_i)^{\mu'} - g^{\zeta\eta} g^{\zeta'\mu'} (2q+q_i)^{\mu} (q_i-q)^{\eta'} \\ &-g^{\eta\mu} g^{\mu'\eta'} (2q_i+q)^{\zeta} (2q_i+q)^{\zeta'} + g^{\eta\mu} g^{\eta'\zeta'} (2q_i+q)^{\zeta} (2q+q_i)^{\mu'} \\ &+g^{\eta\mu} g^{\zeta'\mu'} (2q_i+q)^{\zeta} (q_i-q)^{\eta'}][g^{\gamma\delta}] \end{aligned} \tag{2.5}$$

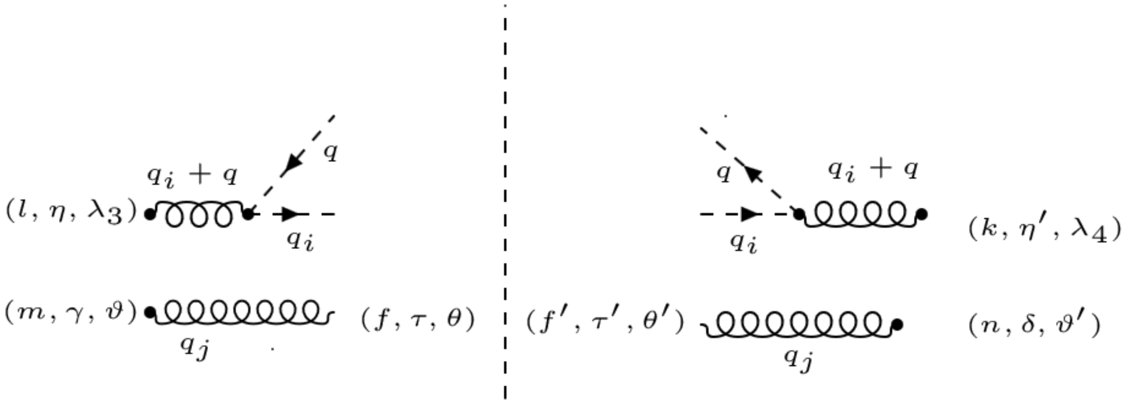
$$\begin{aligned} N \equiv [&-(q-q_i)^{\eta} (2q_i+q)^{\eta'} + (q-q_i)^{\eta} (2q+q_i)^{\eta'} + d(q-q_i)^{\eta} (q_i-q)^{\eta'} \\ &+(2q+q_i)^{\eta'} (2q_i+q)^{\eta} - g^{\eta\eta'} (2q+q_i)^{\mu} (2q+q_i)_{\mu} - (2q+q_i)^{\eta} (q_i-q)^{\eta'} \\ &-g^{\eta\eta'} (2q_i+q)^{\zeta} (2q_i+q)_{\zeta} + (2q_i+q)^{\eta'} (2q+q_i)^{\eta} + (2q_i+q)^{\eta} (q_i-q)^{\eta'}][g^{\gamma\delta}] \end{aligned} \tag{2.6}$$

$$\begin{aligned} N \equiv [&-(q^{\eta} q^{\eta'} + 2q^{\eta} {q_i}^{\eta'} - {q_i}^{\eta} q^{\eta'} - 2{q_i}^{\eta} {q_i}^{\eta'}) + (2q^{\eta} q^{\eta'} + q^{\eta} {q_i}^{\eta'} - 2{q_i}^{\eta} q^{\eta'} - {q_i}^{\eta} {q_i}^{\eta'}) \\ &+(dq^{\eta} {q_i}^{\eta'} - dq^{\eta} q^{\eta'} - d{q_i}^{\eta} {q_i}^{\eta'} + d{q_i}^{\eta} q^{\eta'}) + (4q^{\eta'} {q_i}^{\eta} + 2q^{\eta'} q^{\eta} + 2{q_i}^{\eta'} {q_i}^{\eta} + {q_i}^{\eta'} q^{\eta}) \\ &-(-2q^{\eta} q^{\eta'} + 2q^{\eta} {q_i}^{\eta'} - {q_i}^{\eta} q^{\eta'} + {q_i}^{\eta} {q_i}^{\eta'}) + (2q^{\eta'} q^{\eta} + q^{\eta'} {q_i}^{\eta} + 4{q_i}^{\eta'} q^{\eta} + 2{q_i}^{\eta'} {q_i}^{\eta}) \\ &+(-q^{\eta} q^{\eta'} + q^{\eta} {q_i}^{\eta'} - 2{q_i}^{\eta} q^{\eta'} + 2{q_i}^{\eta} {q_i}^{\eta'}) - g^{\eta\eta'} (5q^2 + 5{q_i}^2 + 8qq_i)][g^{\gamma\delta}] \end{aligned} \tag{2.7}$$

$$\begin{aligned} N \equiv [&(6-d) q^{\eta} q^{\eta'} + (d+3) q^{\eta} {q_i}^{\eta'} + (d+3) {q_i}^{\eta} q^{\eta'} + (6-d) {q_i}^{\eta} {q_i}^{\eta'} \\ &-g^{\eta\eta'} (5q^2 + 5{q_i}^2 + 8qq_i)][g^{\gamma\delta}] \end{aligned} \tag{2.8}$$

$$\begin{aligned} |M_1|^2 = \frac{g_s^2 \, f^{\,a\,o\,l} \, f^{\,a\,k\,o}}{(q_i+q)^2 (q_i+q)^2} [&(6-d) q^{\eta} q^{\eta'} + (d+3) q^{\eta} {q_i}^{\eta'} + (d+3) {q_i}^{\eta} q^{\eta'} + (6-d) {q_i}^{\eta} {q_i}^{\eta'} \\ &-g^{\eta\eta'} (5q^2 + 5{q_i}^2 + 8qq_i)][g^{\gamma\delta}] \end{aligned} \tag{2.9}$$

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



$$|M_1|^2_{Ghost\ loop} = \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{(q_i+q)^2(q_i+q)^2}[-{q_i}^{\eta}q^{\eta'} - q^{\eta}{q_i}^{\eta'}][g^{\gamma\delta}] \tag{2.10}$$

$$\begin{aligned} |M_1'|^2 &= |M_1|^2 + |M_1|^2_{Ghost\ loop} \\ &= \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{(q_i+q)^2(q_i+q)^2}[(6-d)q^{\eta}q^{\eta'} + (d+3)q^{\eta}{q_i}^{\eta'} \\ &+(d+3){q_i}^{\eta}q^{\eta'} + (6-d){q_i}^{\eta}{q_i}^{\eta'} - g^{\eta\eta'}(5q^2+5{q_i}^2+8qq_i) - {q_i}^{\eta}q^{\eta'} - q^{\eta}{q_i}^{\eta'}][g^{\gamma\delta}] \end{aligned} \tag{2.11}$$

$$\begin{aligned} |M_1'|^2 = \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{(q_i+q)^2(q_i+q)^2}&[(6-d)q^{\eta}q^{\eta'} + (d+2)q^{\eta}{q_i}^{\eta'} \\ &+(d+2){q_i}^{\eta}q^{\eta'} + (6-d){q_i}^{\eta}{q_i}^{\eta'} - g^{\eta\eta'}(8qq_i)][g^{\gamma\delta}] \end{aligned} \tag{2.12}$$

$$\begin{aligned} |M_1'|^2 &= \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{4y^2(\alpha_1+\beta_1)^2\,(p_i\cdot Q)\,(p_i\cdot Q)} \\ &[(6-d)(\zeta_1{p_i}^{\eta} + \lambda_1 Q^{\eta} + \sqrt{y\alpha_1\beta_1}n^{\eta}{}_{\perp,1})(\zeta_1{p_i}^{\eta'} + \lambda_1 Q^{\eta'} + \sqrt{y\alpha_1\beta_1}n^{\eta'}{}_{\perp,1}) \\ &+(d+2)(\zeta_1{p_i}^{\eta} + \lambda_1 Q^{\eta} + \sqrt{y\alpha_1\beta_1}n^{\eta}{}_{\perp,1})(\zeta_q{p_i}^{\eta'} + \lambda_q Q^{\eta'} - \sqrt{y\alpha_1\beta_1}n^{\eta'}{}_{\perp,1}) \\ &+(d+2)(\zeta_q{p_i}^{\eta} + \lambda_q Q^{\eta} - \sqrt{y\alpha_1\beta_1}n^{\eta}{}_{\perp,1})(\zeta_1{p_i}^{\eta'} + \lambda_1 Q^{\eta'} + \sqrt{y\alpha_1\beta_1}n^{\eta'}{}_{\perp,1}) \\ &+(6-d)(\zeta_q{p_i}^{\eta} + \lambda_q Q^{\eta} - \sqrt{y\alpha_1\beta_1}n^{\eta}{}_{\perp,1})(\zeta_q{p_i}^{\eta'} + \lambda_q Q^{\eta'} - \sqrt{y\alpha_1\beta_1}n^{\eta'}{}_{\perp,1}) \\ &-8g^{\eta\eta'}[({\alpha_1}^2+{\beta_1}^2)p_i\cdot Q - (\beta_1(1-\beta_1))n_{\perp,1}\cdot n_{\perp,1}]][g^{\gamma\delta}] \end{aligned} \tag{2.13}$$

$$
\begin{aligned}
|M_1'|^2 = \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{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{2.14}
$$

$$
\begin{aligned}
|M_1'|^2 = {} & \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{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})+y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})^2){p_i}^{\eta}{p_i}^{\eta'} \\
& +(y\alpha_1\beta_1-y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})){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-y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q}))Q^{\eta}{p_i}^{\eta'}+y^2{\beta_1}^2Q^{\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)[(\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){p_i}^{\eta}{p_i}^{\eta'} \\
& +(y{\alpha_1}^2-y^2\beta_1\alpha_1(\frac{Q^2}{2p_i\cdot Q})){p_i}^{\eta}Q^{\eta'}-\zeta_1\sqrt{y\alpha_1\beta_1}{p_i}^{\eta}{n^{\eta'}}_{\perp,1} \\
& +(y{\beta_1}^2-y^2\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q}))Q^{\eta}{p_i}^{\eta'}+y^2\beta_1\alpha_1Q^{\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)[(\beta_1\alpha_1-y({\beta_1}^2+{\alpha_1}^2)(\frac{Q^2}{2p_i\cdot Q})+y^2\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q})^2){p_i}^{\eta}{p_i}^{\eta'} \\
& +(y{\beta_1}^2-y^2\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q})){p_i}^{\eta}Q^{\eta'}+\zeta_q\sqrt{y\alpha_1\beta_1}{p_i}^{\eta}{n^{\eta'}}_{\perp,1} \\
& +(y{\alpha_1}^2-y^2\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q}))Q^{\eta}{p_i}^{\eta'}+y^2\alpha_1\beta_1Q^{\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)[({\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){p_i}^{\eta}{p_i}^{\eta'} \\
& +(y\beta_1\alpha_1-y^2{\alpha_1}^2(\frac{Q^2}{2p_i\cdot Q})){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-y^2{\alpha_1}^2(\frac{Q^2}{2p_i\cdot Q}))Q^{\eta}{p_i}^{\eta'}+y^2{\alpha_1}^2Q^{\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{2.15}
$$

$$
\begin{aligned}
|M_1'|^2 &= \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{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{2.16}
$$

$$
\begin{aligned}
|M_1'|^2 &= \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k}}{4y^2\,(p_i\cdot Q)\,(p_i} \\
&[(6-d)\{({\alpha_1}^2 - 2y\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q}))p_i{}^{\eta} p_i{}^{\eta'} + y\alpha_1\beta_1 p_i{}^{\eta} Q^{\eta'} + y\beta_1\alpha_1 Q \\
&+y\alpha_1\beta_1 n^{\eta}{}_{\perp,1} n^{\eta'} \\
&+(d+2)\{(\alpha_1\beta_1 - y({\alpha_1}^2 + {\beta_1}^2)(\frac{Q^2}{2p_i\cdot Q}))p_i{}^{\eta} p_i{}^{\eta'} + y{\alpha_1}^2 p_i{}^{\eta} Q^{\eta'} + y{\beta_1}^2 Q \\
&-y\alpha_1\beta_1 n^{\eta}{}_{\perp,1} n^{\eta'}{}_{\perp,1}\} + (d+2)\{(\beta_1\alpha_1 - y({\beta_1}^2 + {\alpha_1}^2)(\frac{Q^2}{2p_i\cdot Q}))p_i{}^{\eta} p_i{}^{\eta'} + y{\beta_1}^2 p_i \\
&+y{\alpha_1}^2 Q^{\eta} p_i{}^{\eta'} - y\alpha_1\beta_1 n^{\eta}{}_{\perp,1} n^{\eta'}{}_{\perp,1}\} + (6-d)\{({\beta_1}^2 - 2y\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q}))p_i \\
&+y\beta_1\alpha_1 p_i{}^{\eta} Q^{\eta'} + y\alpha_1\beta_1 Q^{\eta} p_i{}^{\eta'} + y\alpha_1\beta_1 n^{\eta}{}_{\perp,1} n^{\eta'}{}_{\perp,1}\} - 8g^{\eta\eta'}[({\alpha_1}^2 + {\beta_1}^2)p_i\cdot Q - (\beta_1(1-\beta_1))n_{\perp,1}\cdot n_{\perp,1}]]
\end{aligned}
\tag{2.17}
$$

$$|M_1'|^2 = \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{4y^2\,(p_i\cdot Q)\,(p_i\cdot Q)}$$
$$[(6-d)(\alpha_1{}^2 - 2y\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q})) + 2(d+2)(\alpha_1\beta_1 - y(\alpha_1{}^2+\beta_1{}^2)(\frac{Q^2}{2p_i\cdot Q}))$$
$$+(6-d)(\beta_1{}^2 - 2y\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q}))]p_i{}^\eta p_i{}^{\eta'}$$
$$+[2(6-d)y\alpha_1\beta_1 + (d+2)y(\alpha_1{}^2+\beta_1{}^2)]p_i{}^\eta Q^{\eta'}$$
$$+[2(6-d)y\beta_1\alpha_1 + (d+2)y(\alpha_1{}^2+\beta_1{}^2)]Q^\eta p_i{}^{\eta'}$$
$$+[2(6-d)-2(d+2)]y\alpha_1\beta_1 n^\eta{}_{\perp,1}n^{\eta'}{}_{\perp,1} - 8g^{\eta\eta'}[(\alpha_1{}^2+\beta_1{}^2)p_i\cdot Q - (\beta_1(1-\beta_1))n_{\perp,1}\cdot n_{\perp,1}][g^{\gamma\delta}]] \tag{2.18}$$

$$|M_1'|^2 = \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{4y^2\,(p_i\cdot Q)\,(p_i\cdot Q)}$$
$$[(6-d)(\alpha_1{}^2 - 2y\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q})) + 2(d+2)(\alpha_1\beta_1 - y(\alpha_1{}^2+\beta_1{}^2)(\frac{Q^2}{2p_i\cdot Q}))$$
$$+(6-d)(\beta_1{}^2 - 2y\alpha_1\beta_1(\frac{Q^2}{2p_i\cdot Q}))]p_i{}^\eta p_i{}^{\eta'}$$
$$+y[(4d-8)\alpha_1{}^2 + (8-4d)\alpha_1 + (d+2)]p_i{}^\eta Q^{\eta'}$$
$$+y[(4d-8)\alpha_1{}^2 + (8-4d)\alpha_1 + (d+2)]Q^\eta p_i{}^{\eta'}$$
$$+y[8-4d](\alpha_1-\alpha_1{}^2)n^\eta{}_{\perp,1}n^{\eta'}{}_{\perp,1} - 8g^{\eta\eta'}[(\alpha_1{}^2+\beta_1{}^2)p_i\cdot Q - (\beta_1(1-\beta_1))n_{\perp,1}\cdot n_{\perp,1}][g^{\gamma\delta}]] \tag{2.19}$$

$$|M_1'|^2 = \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{4y\,(p_i\cdot Q)\,(p_i\cdot Q)}$$
$$[[8-4d]\beta_1(1-\beta_1)n^\eta{}_{\perp,1}n^{\eta'}{}_{\perp,1} - 8g^{\eta\eta'}[(\alpha_1{}^2+\beta_1{}^2)p_i\cdot Q - (\beta_1(1-\beta_1))n_{\perp,1}\cdot n_{\perp,1}][g^{\gamma\delta}]] \tag{2.20}$$

$$|M_1'|^2 = \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{4y\,(p_i\cdot Q)\,(p_i\cdot Q)}$$
$$[8[\epsilon-1]\beta_1(1-\beta_1)n^\eta{}_{\perp,1}n^{\eta'}{}_{\perp,1} - 8g^{\eta\eta'}[(\alpha_1{}^2+\beta_1{}^2)p_i\cdot Q - (\beta_1(1-\beta_1))(-2p_i\cdot Q)][g^{\gamma\delta}]] \tag{2.21}$$

$$|M_1'|^2 = \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{4y\,(p_i\cdot Q)\,(p_i\cdot Q)} \tag{2.22}$$
$$[8[\epsilon-1]\beta_1(1-\beta_1)n^\eta{}_{\perp,1}n^{\eta'}{}_{\perp,1} - 8g^{\eta\eta'}[(\alpha_1{}^2+\beta_1{}^2)p_i\cdot Q + 2\alpha_1\beta_1 p_i\cdot Q)][g^{\gamma\delta}]]$$

$$|M_1'|^2 = \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{4y\,(p_i\cdot Q)\,(p_i\cdot Q)} \tag{2.23}$$
$$[8[\epsilon-1]\beta_1(1-\beta_1)n^\eta{}_{\perp,1}n^{\eta'}{}_{\perp,1} - 8g^{\eta\eta'}[(\alpha_1+\beta_1)^2 p_i\cdot Q)][g^{\gamma\delta}]]$$

$$|M_1'|^2 = \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{y\,(p_i \cdot Q)}[2[\epsilon-1]\beta_1(1-\beta_1)n^{\eta}{}_{\perp,1}n^{\eta'}{}_{\perp,1} - 2g^{\eta\eta'}][g^{\gamma\delta}]] \tag{2.24}$$

Another way:

$$
\begin{aligned}
{k_1}^{\eta}{k_1}^{\eta'} &= ({\alpha_1}^2 - 2\alpha_1\beta_1 y(\frac{Q^2}{2p_i\cdot Q})){p_i}^{\eta}{p_i}^{\eta'} + y\alpha_1\beta_1{p_i}^{\eta}Q^{\eta'} + y\alpha_1\beta_1 Q^{\eta}{p_i}^{\eta'} + y\alpha_1\beta_1 n^{\eta}_{\perp,1}n^{\eta'}_{\perp,1}\\
{k_1}^{\eta}{q_i}^{\eta'} &= (\alpha_1\beta_1 - y({\alpha_1}^2+{\beta_1}^2)(\frac{Q^2}{2p_i\cdot Q})){p_i}^{\eta}{p_i}^{\eta'} + y{\alpha_1}^2{p_i}^{\eta}Q^{\eta'} + y{\beta_1}^2 Q^{\eta}{p_i}^{\eta'} - y\alpha_1\beta_1 n^{\eta}_{\perp,1}n^{\eta'}_{\perp,1}\\
{q_i}^{\eta}{k_1}^{\eta'} &= (\alpha_1\beta_1 - y({\alpha_1}^2+{\beta_1}^2)(\frac{Q^2}{2p_i\cdot Q})){p_i}^{\eta}{p_i}^{\eta'} + y{\beta_1}^2{p_i}^{\eta}Q^{\eta'} + y{\alpha_1}^2 Q^{\eta}{p_i}^{\eta'} - y\alpha_1\beta_1 n^{\eta}_{\perp,1}n^{\eta'}_{\perp,1}\\
{q_i}^{\eta}{q_i}^{\eta'} &= ({\beta_1}^2 - 2\alpha_1\beta_1 y(\frac{Q^2}{2p_i\cdot Q})){p_i}^{\eta}{p_i}^{\eta'} + y\alpha_1\beta_1{p_i}^{\eta}Q^{\eta'} + y\alpha_1\beta_1 Q^{\eta}{p_i}^{\eta'} + y\alpha_1\beta_1 n^{\eta}_{\perp,1}n^{\eta'}_{\perp,1}
\end{aligned}
\tag{2.25}
$$

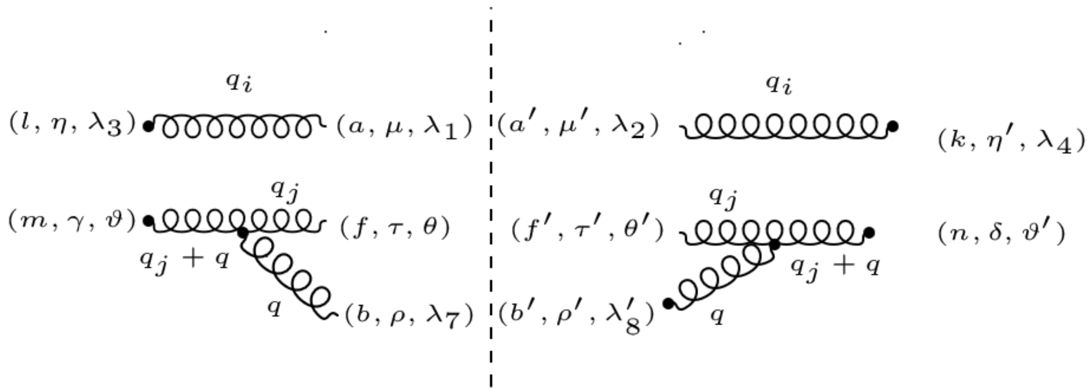
$$
\begin{aligned}
N \equiv &(6-d)({\alpha_1}^2 - 2\alpha_1\beta_1 y(\frac{Q^2}{2p_i\cdot Q})){p_i}^{\eta}{p_i}^{\eta'} + y\alpha_1\beta_1{p_i}^{\eta}Q^{\eta'} + y\alpha_1\beta_1 Q^{\eta}{p_i}^{\eta'} + y\alpha_1\beta_1 n^{\eta}_{\perp,1}n^{\eta'}_{\perp,1}\\
&+ (d+2)(\alpha_1\beta_1 - y({\alpha_1}^2+{\beta_1}^2)(\frac{Q^2}{2p_i\cdot Q})){p_i}^{\eta}{p_i}^{\eta'} + y{\alpha_1}^2{p_i}^{\eta}Q^{\eta'} + y{\beta_1}^2 Q^{\eta}{p_i}^{\eta'} - y\alpha_1\beta_1 n^{\eta}_{\perp,1}n^{\eta'}_{\perp,1}\\
&+ (d+2)(\alpha_1\beta_1 - y({\alpha_1}^2+{\beta_1}^2)(\frac{Q^2}{2p_i\cdot Q})){p_i}^{\eta}{p_i}^{\eta'} + y{\beta_1}^2{p_i}^{\eta}Q^{\eta'} + y{\alpha_1}^2 Q^{\eta}{p_i}^{\eta'} - y\alpha_1\beta_1 n^{\eta}_{\perp,1}n^{\eta'}_{\perp,1}\\
&+ (6-d)({\beta_1}^2 - 2\alpha_1\beta_1 y(\frac{Q^2}{2p_i\cdot Q})){p_i}^{\eta}{p_i}^{\eta'} + y\alpha_1\beta_1{p_i}^{\eta}Q^{\eta'} + y\alpha_1\beta_1 Q^{\eta}{p_i}^{\eta'} + y\alpha_1\beta_1 n^{\eta}_{\perp,1}n^{\eta'}_{\perp,1}\\
&- 8g^{\eta\eta'}[({\alpha_1}^2+{\beta_1}^2)p_i\cdot Q - (\beta_1(1-\beta_1))n_{\perp,1}\cdot n_{\perp,1}]
\end{aligned}
\tag{2.26}
$$

$$
\begin{aligned}
N \equiv &[(6-d)({\alpha_1}^2 - 2\alpha_1\beta_1 y(\frac{Q^2}{2p_i\cdot Q})) + (d+2)(\alpha_1\beta_1 - y({\alpha_1}^2+{\beta_1}^2)(\frac{Q^2}{2p_i\cdot Q}))\\
&+ (d+2)(\alpha_1\beta_1 - y({\alpha_1}^2+{\beta_1}^2)(\frac{Q^2}{2p_i\cdot Q})) + (6-d)({\beta_1}^2 - 2\alpha_1\beta_1 y(\frac{Q^2}{2p_i\cdot Q}))]{p_i}^{\eta}{p_i}^{\eta'}\\
&+ [(6-d)y\alpha_1\beta_1 + (d+2)y{\alpha_1}^2 + (d+2)y{\beta_1}^2 + (6-d)y\alpha_1\beta_1]{p_i}^{\eta}Q^{\eta'}\\
&+ [(6-d)y\alpha_1\beta_1 + (d+2)y{\beta_1}^2 + (d+2)y{\alpha_1}^2 + (6-d)y\alpha_1\beta_1]Q^{\eta}{p_i}^{\eta'}\\
&+ [(6-d)y\alpha_1\beta_1 - (d+2)y\alpha_1\beta_1 - (d+2)y\alpha_1\beta_1 + (6-d)y\alpha_1\beta_1]n^{\eta}_{\perp,1}n^{\eta'}_{\perp,1}\\
&- 8g^{\eta\eta'}[({\alpha_1}^2+{\beta_1}^2)p_i\cdot Q - (\beta_1(1-\beta_1))n_{\perp,1}\cdot n_{\perp,1}]
\end{aligned}
\tag{2.27}
$$

$$
\begin{aligned}
&|M_1'|^2 = \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{4y\,(p_i\cdot Q)^2}[(12-2d)y\alpha_1\beta_1 - 2(d+2)y\alpha_1\beta_1]n^{\eta}_{\perp,1}n^{\eta'}_{\perp,1} - 8yg^{\eta\eta'}p_i\cdot Q][g_{\gamma\delta}]\\
&\Rightarrow |M_1'|^2 = \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{4y\,(p_i\cdot Q)^2}[(12-2d)\alpha_1\beta_1 - 2(d+2)\alpha_1\beta_1]n^{\eta}_{\perp,1}n^{\eta'}_{\perp,1} - 8g^{\eta\eta'}({\alpha_1}^2+{\beta_1}^2)p_i\cdot Q][g_{\gamma\delta}]\\
&|M_1'|^2 = \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{4y\,(p_i\cdot Q)\,(p_i\cdot Q)}\\
&[8[\epsilon-1]\beta_1(1-\beta_1){n^{\eta}}_{\perp,1}{n^{\eta'}}_{\perp,1} - 8g^{\eta\eta'}[({\alpha_1}^2+{\beta_1}^2)p_i\cdot Q - \beta_1\alpha_1(-2p_i\cdot Q)]][g_{\gamma\delta}]
\end{aligned}
\tag{2.28}
$$

$$|M_1'|^2 = \frac{g_s^2\, f^{\,a\,o\,l}\, f^{\,a\,k\,o}}{y\,(p_i \cdot Q)}[2[\epsilon - 1]\beta_1(1-\beta_1)n^{\eta}{}_{\perp,1}n^{\eta'}{}_{\perp,1} - 2g^{\eta\eta'}][g^{\gamma\delta}] \tag{2.29}$$

2.2 Gluon-Spectator Bubble



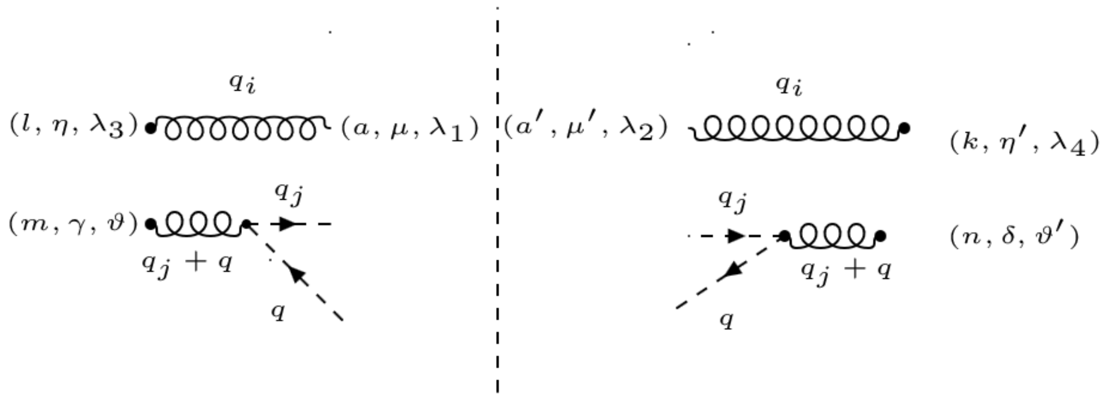
$$|M_2|^2 = [\frac{-i}{(q_j+q)^2}(-g_s f^{\,b\,f\,m}(g^{\tau\gamma}(-2q_j-q)^\rho + g^{\gamma\rho}(2q+q_j)^\tau + g^{\rho\tau}(q_j-q)^\gamma)$$
$$g_{\tau\tau'}g_{\rho\rho'}(-g_s f^{\,b'\,n\,f'}(g^{\rho'\delta}(-2q-q_j)^{\tau'} + g^{\delta\tau'}(2q_j+q)^{\rho'} + g^{\tau'\rho'}(q-q_j)^\delta)\frac{i}{(q_j+q)^2}][g^{\eta\eta'}] \tag{2.30}$$

$$|M_2|^2 = \frac{g_s^2\, f^{\,b\,f\,m} f^{\,b'\,n\,f'}\delta^{aa'}\delta^{ff'}\delta^{bb'}}{(q_j+q)^2(q_j+q)^2}[g_{\tau\tau'}g_{\rho\rho'}(g^{\tau\gamma}(2q_j+q)^\rho g^{\rho'\delta}(2q+q_j)^{\tau'}$$
$$-g^{\tau\gamma}(2q_j+q)^\rho g^{\delta\tau'}(2q_j+q)^{\rho'} - g^{\tau\gamma}(2q_j+q)^\rho g^{\tau'\rho'}(q-q_j)^\delta - g^{\gamma\rho}(2q+q_j)^\tau g^{\rho'\delta}(2q+q_j)^{\tau'}$$
$$+g^{\gamma\rho}(2q+q_j)^\tau g^{\delta\tau'}(2q_j+q)^{\rho'} + g^{\gamma\rho}(2q+q_j)^\tau g^{\tau'\rho'}(q-q_j)^\delta - g^{\rho\tau}(q_j-q)^\gamma g^{\rho'\delta}(2q+q_j)^{\tau'}$$
$$+g^{\rho\tau}(q_j-q)^\gamma g^{\delta\tau'}(2q_j+q)^{\rho'} + g^{\rho\tau}(q_j-q)^\gamma g^{\tau'\rho'}(q-q_j)^\delta][g^{\eta\eta'}] \tag{2.31}$$

$$\begin{aligned} |M_2|^2 = \frac{g_s^2\, f^{\,b\,f\,m} f^{\,b\,n\,f}}{(q_j+q)^2(q_j+q)^2}&[(2q+q_j)^\gamma(2q_j+q)^\delta \\ -g^{\delta\gamma}(2q_j+q)^\rho(2q_j+q)_\rho - (2q_j+q)^\gamma(q-q_j)^\delta &- g^{\delta\gamma}(2q+q_j)^\tau(2q+q_j)_\tau \\ +(2q_j+q)^\gamma(2q+q_j)^\delta + (2q+q_j)^\gamma(q-q_j)^\delta &- (q_j-q)^\gamma(2q+q_j)^\delta \\ +(q_j-q)^\gamma(2q_j+q)^\delta &+ d(q_j-q)^\gamma(q-q_j)^\delta][g^{\eta\eta'}] \end{aligned} \tag{2.32}$$

$$\begin{aligned} |M_2|^2 = \frac{g_s^2\, f^{\,b\,f\,m} f^{\,b\,n\,f}}{(q_j+q)^2(q_j+q)^2}&[(3+d)q^\gamma {q_j}^\delta + (6-d)q^\gamma q^\delta \\ +(6-d){q_j}^\gamma {q_j}^\delta + (3+d){q_j}^\gamma q^\delta &- g^{\delta\gamma}(5{q_j}^2 + 5q^2 + 8qq_j) \\ &][g^{\eta\eta'}] \end{aligned} \tag{2.33}$$

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



$$|M_2|^2_{Ghost\,loop} = \frac{g_s^2\, f^{\,b\,f\,m} f^{\,b\,n\,f}}{(q_j+q)^2(q_j+q)^2}[-{q_j}^{\gamma} q^{\delta} - q^{\delta} {q_j}^{\gamma}][g^{\eta\eta'}] \tag{2.34}$$

$$\begin{aligned} |M_2'|^2 = &\frac{g_s^2\, f^{\,b\,f\,m} f^{\,b\,n\,f}}{(q_j+q)^2(q_j+q)^2}[(2+d)q^{\gamma}{q_j}^{\delta} + (6-d)q^{\gamma}q^{\delta} \\ &+(6-d){q_j}^{\gamma}{q_j}^{\delta} + (2+d){q_j}^{\gamma}q^{\delta} - g^{\delta\gamma}(8qq_j)][g^{\eta\eta'}] \end{aligned} \tag{2.35}$$

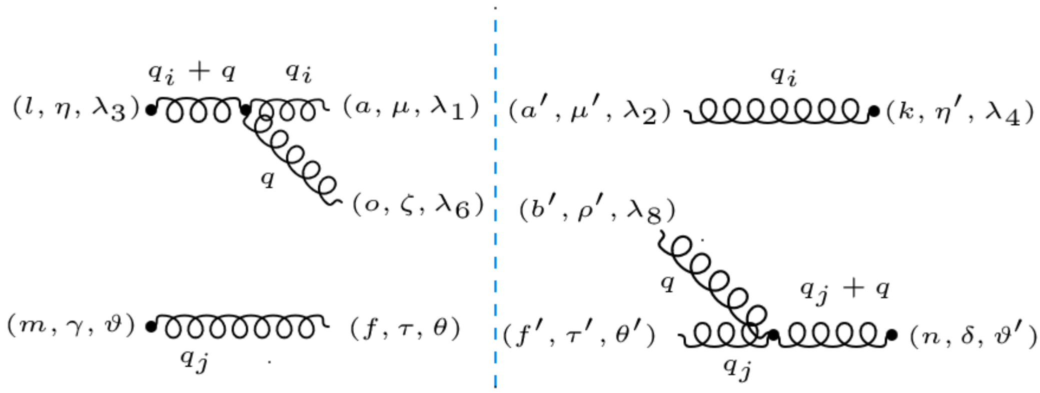
$$|M_2'|^2 = \frac{g_s^2\, f^{\,b\,f\,m} f^{\,b\,n\,f}}{4(q_j\cdot q)(q_j\cdot q)}[-8g^{\delta\gamma}(q\cdot q_j)][g^{\eta\eta'}] \tag{2.36}$$

$$|M_2'|^2 = \frac{g_s^2\, f^{\,b\,f\,m} f^{\,b\,n\,f}}{(q_j\cdot q)}[-2g^{\delta\gamma}][g^{\eta\eta'}] \tag{2.37}$$

$$|M_2'|^2 = \frac{g_s^2\, f^{\,b\,f\,m} f^{\,b\,n\,f}}{(1-\beta_1)(1-y)\,(p_i\cdot p_k)}[-2g^{\delta\gamma}][g^{\eta\eta'}] \tag{2.38}$$

2.3 Interference term $M_1 {M_2}^{\dagger}$

$$\begin{aligned} &M_1 {M_2}^{\dagger} = [\frac{-i}{(q_i+q)^2}(-g_s f^{\,l\,a\,o}(g^{\eta\mu}(2q_i+q)^{\zeta} + g^{\mu\zeta}(q-q_i)^{\eta} - g^{\zeta\eta}(2q+q_i)^{\mu})\varepsilon^{\lambda_1}{}_{\mu}(q_i)\varepsilon^{\lambda_6}{}_{\zeta}(q)] \\ &[\varepsilon^{\theta}{}_{\tau}{}^{*}(q_j)] \\ &[\frac{i}{(q+q_j)^2}(-g_s f^{\,f'\,b'\,n}(g^{\tau'\rho'}(q_j-q)^{\delta} + g^{\rho'\delta}(2q+q_j)^{\tau'} - g^{\delta\tau'}(2q_j+q)^{\rho'})\varepsilon^{\theta'}{}_{\tau'}{}^{*}(q_j)\varepsilon^{\lambda_8}{}_{\rho'}{}^{*}(q)] \\ &[\varepsilon^{\lambda_2}{}_{\mu'}{}^{*}(q_i)] \end{aligned} \tag{2.39}$$



$$M_1 M_2{}^\dagger = \frac{g_s^2 f^{\,l\,a\,o} f^{\,f'\,b'\,n} \delta^{aa'} \delta^{ob'} \delta^{ff'}}{(q_i+q)^2 (q_j+q)^2} [g_\mu{}^{\eta'} g_{\tau\tau'} (g^{\eta\mu}(2q_i+q)^\zeta + g^{\mu\zeta}(q-q_i)^\eta - g^{\zeta\eta}(2q+q_i)^\mu)$$
$$g_{\zeta\rho'}(g^{\tau'\rho'}(q_j-q)^\delta + g^{\rho'\delta}(2q+q_j)^{\tau'} - g^{\delta\tau'}(2q_j+q)^{\rho'}] \tag{2.40}$$

$$\begin{aligned} M_1 M_2{}^\dagger = {} & \frac{g_s^2 f^{\,l\,a\,o} f^{\,f'\,b'\,n} \delta^{aa'} \delta^{ob'} \delta^{ff'}}{(q_i+q)^2 (q_j+q)^2} \\ & [g^{\eta\eta'}(2q_i+q)^\gamma (q_j-q)^\delta + g^{\eta\eta'}(2q+q_j)^\gamma (2q_i+q)^\delta - g^{\eta\eta'} g^{\gamma\delta}(2q_i+q)\cdot(2q_j+q) \\ & + g^{\gamma\eta'}(q-q_i)^\eta (q_j-q)^\delta + g^{\eta'\delta}(q-q_i)^\eta (2q+q_j)^\gamma - g^{\gamma\delta}(q-q_i)^\eta (2q_j+q)^{\eta'} \\ & - g^{\gamma\eta}(2q+q_i)^{\eta'}(q_j-q)^\delta - g^{\eta\delta}(2q+q_i)^{\eta'}(2q+q_j)^\gamma + g^{\gamma\delta}(2q_j+q)^\eta (2q+q_i)^{\eta'}] \end{aligned} \tag{2.41}$$

$$\begin{aligned} M_1 M_2{}^\dagger = {} & \frac{g_s^2 f^{\,l\,a\,o} f^{\,f\,o\,n}}{4(q\cdot q_i)(q\cdot q_j)} \\ & \{g^{\eta\eta'}[2q_i{}^\gamma q_j{}^\delta + 2q_i{}^\gamma q^\delta + q^\gamma q_j{}^\delta + q^\gamma q^\delta + 4q^\gamma q_i{}^\delta + 2q^\gamma q^\delta + 2q_j{}^\gamma q_i{}^\delta + q_j{}^\gamma q^\delta] \\ & - g^{\eta\eta'} g^{\gamma\delta}(2q\cdot q_j + q\cdot q + 4q_i\cdot q_j + 2q_i\cdot q) + g^{\gamma\eta'}[q^\eta q_j{}^\delta - q^\eta q^\delta - q_i{}^\eta q_j{}^\delta + q_i{}^\eta q^\delta] \\ & + g^{\eta'\delta}[2q^\eta q^\gamma + q^\eta q_j{}^\gamma + q_i{}^\eta q^\gamma + q_i{}^\eta q_j{}^\gamma] - g^{\gamma\delta}[2q^\eta q_j{}^{\eta'} + q^\eta q^{\eta'} - 2q_i{}^\eta q_j{}^{\eta'} - q_i{}^\eta q^{\eta'}] \\ & - g^{\gamma\eta}[2q^{\eta'} q_j{}^\delta - 2q^{\eta'} q^\delta + q_i{}^{\eta'} q_j{}^\delta - q_i{}^{\eta'} q^\delta] - g^{\eta\delta}[4q^{\eta'} q^\gamma + 2q^{\eta'} q_j{}^\gamma + 2q_i{}^{\eta'} q^\gamma + q_i{}^{\eta'} q_j{}^\gamma] \\ & + g^{\gamma\delta}[4q_j{}^\eta q^{\eta'} + 2q_j{}^\eta q_i{}^{\eta'} + q^\eta q^{\eta'} + q^\eta q_i{}^{\eta'}]\} \end{aligned} \tag{2.42}$$

$$
\begin{aligned}
{k_1}^\eta {k_1}^{\eta'} &= [(1-\beta_1)^2 - y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})^2]{p_i}^\eta {p_i}^{\eta'} - y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q}){p_i}^\eta Q^{\eta'} - y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})Q^\eta {p_i}^{\eta'}\\
{k_1}^\eta {q_i}^{\eta'} &= [\beta_1(1-\beta_1) - y{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})]{p_i}^\eta {p_i}^{\eta'} + y{\beta_1}^2 Q^\eta {p_i}^{\eta'}\\
{q_i}^\eta {k_1}^{\eta'} &= [\beta_1(1-\beta_1) - y{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})]{p_i}^\eta {p_i}^{\eta'} + y{\beta_1}^2 {p_i}^\eta Q^{\eta'}\\
{q_i}^\eta {q_i}^{\eta'} &= {\beta_1}^2 {p_i}^\eta {p_i}^{\eta'}\\
{k_1}^\eta {q_k}^{\eta'} &= [(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i\cdot Q})]\sqrt{1-y}{p_i}^\eta {p_k}^{\eta'} - y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_1\,{p_i}^\eta {p_i}^{\eta'} - y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_2\,{p_i}^\eta Q^{\eta'}\\
&\quad + y\beta_1 A_1\,Q^\eta {p_i}^{\eta'} + y\beta_1 A_2\,Q^\eta Q^{\eta'} + y\beta_1\sqrt{1-y}Q^\eta {p_k}^{\eta'}\\
{q_i}^\eta {q_k}^{\eta'} &= A_1\beta_1 {p_i}^\eta {p_i}^{\eta'} + A_2\beta_1 {p_i}^\eta Q^{\eta'} + \beta_1\sqrt{1-y}{p_i}^\eta {p_k}^{\eta'}\\
{q_k}^\eta {k_1}^{\eta'} &= [(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i\cdot Q})]\sqrt{1-y}{p_k}^\eta {p_i}^{\eta'} - y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_1\,{p_i}^\eta {p_i}^{\eta'} - y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_2\,Q^\eta {p_i}^{\eta'}\\
&\quad + y\beta_1 A_1\,{p_i}^\eta Q^{\eta'} + y\beta_1 A_2\,Q^\eta Q^{\eta'} + y\beta_1\sqrt{1-y}{p_k}^\eta Q^{\eta'}\\
{q_k}^\eta {q_i}^{\eta'} &= A_1\beta_1 {p_i}^\eta {p_i}^{\eta'} + A_2\beta_1 Q^\eta {p_i}^{\eta'} + \beta_1\sqrt{1-y}{p_k}^\eta {p_i}^{\eta'}
\end{aligned}
\tag{2.43}
$$

Calculation of the first Term

$$
\begin{aligned}
& g^{\eta\eta'}[2\{A_1\beta_1 {p_i}^\gamma {p_i}^\delta + A_2\beta_1 {p_i}^\gamma Q^\delta + \beta_1\sqrt{1-y}{p_i}^\gamma {p_k}^\delta\}\\
& + 2\{[\beta_1(1-\beta_1) - y{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})]{p_i}^\gamma {p_i}^\delta + y{\beta_1}^2 {p_i}^\gamma Q^\delta\}\\
& + \{[(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i\cdot Q})]\sqrt{1-y}{p_i}^\gamma {p_k}^\delta - y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_1\,{p_i}^\gamma {p_i}^\delta - y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_2\,{p_i}^\gamma Q^\delta\\
& + y\beta_1 A_1\,Q^\gamma {p_i}^\delta + y\beta_1 A_2\,Q^\gamma Q^\delta + y\beta_1\sqrt{1-y}Q^\gamma {p_k}^\delta\}\\
& + 3\{[(1-\beta_1)^2 - y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})^2]{p_i}^\gamma {p_i}^\delta - y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q}){p_i}^\gamma Q^\delta - y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})Q^\gamma {p_i}^\delta\}\\
& + 4\{[\beta_1(1-\beta_1) - y{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})]{p_i}^\gamma {p_i}^\delta + y{\beta_1}^2 Q^\gamma {p_i}^\delta\}\\
& + 2\{A_1\beta_1 {p_i}^\gamma {p_i}^\delta + A_2\beta_1 Q^\gamma {p_i}^\delta + \beta_1\sqrt{1-y}{p_k}^\gamma {p_i}^\delta\}\\
& + \{[(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i\cdot Q})]\sqrt{1-y}{p_k}^\gamma {p_i}^\delta - y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_1\,{p_i}^\gamma {p_i}^\delta - y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_2\,Q^\gamma {p_i}^\delta\\
& + y\beta_1 A_1\,{p_i}^\gamma Q^\delta + y\beta_1 A_2\,Q^\gamma Q^\delta + y\beta_1\sqrt{1-y}{p_k}^\gamma Q^\delta\}]
\end{aligned}
\tag{2.44}
$$

$$
\begin{aligned}
&g^{\eta\eta'}\{[2A_1\beta_1 + 2[\beta_1(1-\beta_1) - y{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})] \\
&+ 4[\beta_1(1-\beta_1) - y{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})] + 3[(1-\beta_1)^2 - y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})^2] \\
&+ 2A_1\beta_1 - y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_1 \; - y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_1\,]{p_i}^\gamma{p_i}^\delta \\
&+ [2A_2\beta_1 + 2y{\beta_1}^2 - y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_2 \; - 3y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q}) + y\beta_1A_1]{p_i}^\gamma Q^\delta \\
&+ [2\beta_1 + [(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i\cdot Q})]]\sqrt{1-y}{p_i}^\gamma{p_k}^\delta \\
&+ [y\beta_1A_1 + 4y{\beta_1}^2 + 2A_2\beta_1 - 3y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q}) - y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_2\,]\,Q^\gamma{p_i}^\delta \\
&+ [y\beta_1A_2 + y\beta_1A_2]\,Q^\gamma Q^\delta + y\beta_1\sqrt{1-y}Q^\gamma{p_k}^\delta \\
&+ [2\beta_1 + [(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i\cdot Q})]]\sqrt{1-y}{p_k}^\gamma{p_i}^\delta + y\beta_1\sqrt{1-y}{p_k}^\gamma Q^\delta\}
\end{aligned}
\tag{2.45}
$$

Calculation of the second term

$$
-g^{\eta\eta'}g^{\gamma\delta}(2q\cdot q_j + q\cdot q + 4q_i\cdot q_j + 2q_i\cdot q) \tag{2.46}
$$

$$
\begin{aligned}
&-g^{\eta\eta'}g^{\gamma\delta}[2([\alpha_1(1-y) + y\beta_1(\frac{Q^2}{2p_i\cdot Q})]\,p_i\cdot p_k + y\beta_1\,Q\cdot p_k + \sqrt{\alpha_1\beta_1 y(1-y)}p_k\cdot n_{\perp,1}) \\
&4([\beta_1(1-y) + y\alpha_1(\frac{Q^2}{2p_i\cdot Q})]\,p_i\cdot p_k + y\alpha_1\,Q\cdot p_k - \sqrt{\alpha_1\beta_1 y(1-y)}p_k\cdot n_{\perp,1}) \\
&+ 2(y\,p_i\cdot Q)]
\end{aligned}
\tag{2.47}
$$

Calculation of the third term

$$
\begin{aligned}
&+ g^{\gamma\eta'}\{[(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i\cdot Q})]\sqrt{1-y}{p_i}^\eta{p_k}^\delta - y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_1\,{p_i}^\eta{p_i}^\delta - y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_2\,{p_i}^\eta Q^{\eta'} \\
&+ y\beta_1A_1\,Q^\eta{p_i}^\delta + y\beta_1A_2\,Q^\eta Q^\delta + y\beta_1\sqrt{1-y}Q^\eta{p_k}^\delta \\
&- [[(1-\beta_1)^2 - y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})^2]{p_i}^\eta{p_i}^\delta - y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q}){p_i}^\eta Q^\delta - y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})Q^\eta{p_i}^\delta] \\
&- [A_1\beta_1{p_i}^\eta{p_i}^\delta + A_2\beta_1{p_i}^\eta Q^\delta + \beta_1\sqrt{1-y}{p_i}^\eta{p_k}^\delta] \\
&+ [\beta_1(1-\beta_1) - y{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})]{p_i}^\eta{p_i}^{\eta'} + y{\beta_1}^2{p_i}^\eta Q^{\eta'}\}
\end{aligned}
\tag{2.48}
$$

Calculation of the fourth term

$$
\begin{aligned}
&+ g^{\eta'\delta}\{[(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i \cdot Q}) - \beta_1]\sqrt{1-y}p_i{}^{\eta}p_k{}^{\gamma} \\
&+ [2[(1-\beta_1)^2 - y^2\beta_1{}^2(\frac{Q^2}{2p_i \cdot Q})^2] - y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_1 + A_1\beta_1 + \\
&[\beta_1(1-\beta_1) - y\beta_1{}^2(\frac{Q^2}{2p_i \cdot Q})]]p_i{}^{\eta}p_i{}^{\gamma} \\
&+ [-2y^2\beta_1{}^2(\frac{Q^2}{2p_i \cdot Q}) - y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_2 \ + A_2\beta_1 + y\beta_1{}^2]p_i{}^{\eta}Q^{\gamma} \\
&+ [y\beta_1 A_1 \ + 2y^2\beta_1{}^2(\frac{Q^2}{2p_i \cdot Q})]Q^{\eta}p_i{}^{\gamma} + y\beta_1 A_2\, Q^{\eta}Q^{\gamma} + y\beta_1\sqrt{1-y}Q^{\eta}p_k{}^{\gamma}\}
\end{aligned} \tag{2.49}
$$

Calculation of the fifth term

$$
\begin{aligned}
&- g^{\gamma\delta}\{[2[(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i \cdot Q})] - 2\beta_1]\sqrt{1-y}p_i{}^{\eta}p_k{}^{\eta'} \\
&[-2y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_1 + [(1-\beta_1)^2 - y^2\beta_1{}^2(\frac{Q^2}{2p_i \cdot Q})^2] - 2A_1\beta_1 \\
&- [\beta_1(1-\beta_1) - y\beta_1{}^2(\frac{Q^2}{2p_i \cdot Q})]]\ p_i{}^{\eta}p_i{}^{\eta'} \\
&[-2y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_2 \ - y^2\beta_1{}^2(\frac{Q^2}{2p_i \cdot Q}) - y\beta_1{}^2 - 2A_2\beta_1]p_i{}^{\eta}Q^{\eta'} \\
&+ [2y\beta_1 A_1 - y^2\beta_1{}^2(\frac{Q^2}{2p_i \cdot Q})]\ Q^{\eta}p_i{}^{\eta'} + 2y\beta_1 A_2\, Q^{\eta}Q^{\eta'} + 2y\beta_1\sqrt{1-y}Q^{\eta}p_k{}^{\eta'}\}
\end{aligned} \tag{2.50}
$$

Calculation of the sixth term

$$
\begin{aligned}
&- g^{\gamma\eta}\{[2[(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i \cdot Q})] + \beta_1]\sqrt{1-y}p_i{}^{\eta'}p_k{}^{\delta} \\
&[-2y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_1 - 2[(1-\beta_1)^2 - y^2\beta_1{}^2(\frac{Q^2}{2p_i \cdot Q})^2] \\
&- [\beta_1(1-\beta_1) - y\beta_1{}^2(\frac{Q^2}{2p_i \cdot Q})] + A_1\beta_1]\ p_i{}^{\eta'}p_i{}^{\delta} \\
&[-2y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_2 \ + 2y^2\beta_1{}^2(\frac{Q^2}{2p_i \cdot Q}) + A_2\beta_1 - y\beta_1{}^2]p_i{}^{\eta'}Q^{\delta} \\
&+ [2y\beta_1 A_1 + 2y^2\beta_1{}^2(\frac{Q^2}{2p_i \cdot Q})]\ Q^{\eta'}p_i{}^{\delta} + 2y\beta_1 A_2\, Q^{\eta'}Q^{\delta} + 2y\beta_1\sqrt{1-y}Q^{\eta'}p_k{}^{\delta}\}
\end{aligned} \tag{2.51}
$$

Calculation of the seventh term

$$
\begin{aligned}
&-g^{\eta\delta}\{[2[(1-\beta_1)-y\beta_1(\frac{Q^2}{2p_i\cdot Q})]+\beta_1]\sqrt{1-y}{p_i}^{\eta'}{p_k}^{\gamma} \\
&[4[(1-\beta_1)^2-y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})^2]-2y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_1+A_1\beta_1 \\
&+2[\beta_1(1-\beta_1)-y{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})]]{p_i}^{\eta'}{p_i}^{\gamma} \\
&+[-4y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})-2y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_2\ +2y{\beta_1}^2+A_2\beta_1]{p_i}^{\eta'}Q^{\gamma} \\
&+[-4y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})+2y\beta_1A_1]Q^{\eta}{p_i}^{\eta'}+2y\beta_1A_2\,Q^{\eta}Q^{\eta'}+2y\beta_1\sqrt{1-y}Q^{\eta'}{p_k}^{\gamma}\}
\end{aligned}
\tag{2.52}
$$

Calculation of the eighth term

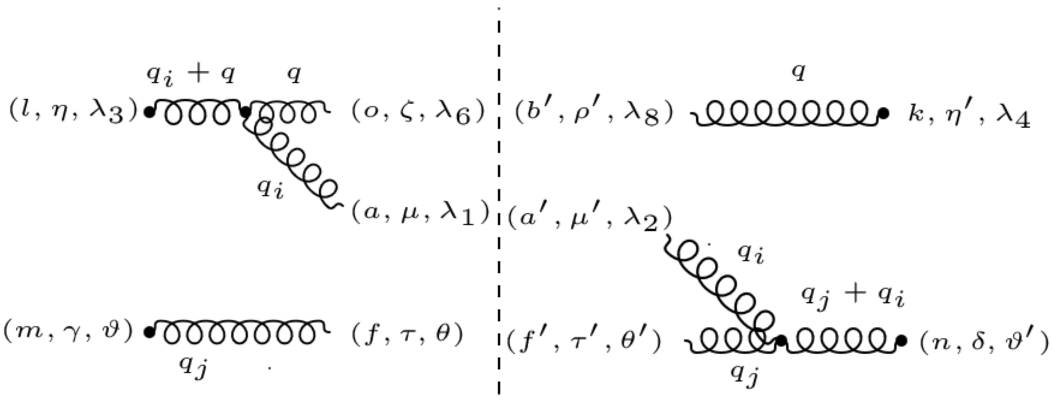
$$
\begin{aligned}
&+g^{\gamma\delta}\{[4[(1-\beta_1)-y\beta_1(\frac{Q^2}{2p_i\cdot Q})]+2\beta_1]\sqrt{1-y}{p_k}^{\eta}{p_i}^{\eta'} \\
&+[-4y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_1+2A_1\beta_1+[\beta_1(1-\beta_1)-y{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})] \\
&+[(1-\beta_1)^2-y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})^2]]\ {p_i}^{\eta}{p_i}^{\eta'} \\
&+[4y\beta_1A_1-y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})]\ {p_i}^{\eta}Q^{\eta'}+4y\beta_1A_2\,Q^{\eta}Q^{\eta'}+4y\beta_1\sqrt{1-y}{p_k}^{\eta}Q^{\eta'} \\
&+[2A_2\beta_1-4y\beta_1(\frac{Q^2}{2p_i\cdot Q})A_2\ -y^2{\beta_1}^2(\frac{Q^2}{2p_i\cdot Q})+y{\beta_1}^2]Q^{\eta}{p_i}^{\eta'}\}
\end{aligned}
\tag{2.53}
$$

Final result

$$
\begin{aligned}
&M_1{M_2}^{\dagger}=\frac{g_s^2C_A}{4y(1-\beta_1)(1-y)\ (p_i\cdot p_k)(p_i\cdot Q)}g^{\eta\eta'}g^{\gamma\delta} \\
&[2([\alpha_1(1-y)+y\beta_1(\frac{Q^2}{2p_i\cdot Q})]\ p_i\cdot p_k+y\beta_1\,Q\cdot p_k+\sqrt{\alpha_1\beta_1y(1-y)}p_k\cdot n_{\perp,1}) \\
&4([\beta_1(1-y)+y\alpha_1(\frac{Q^2}{2p_i\cdot Q})]\ p_i\cdot p_k+y\alpha_1\,Q\cdot p_k-\sqrt{\alpha_1\beta_1y(1-y)}p_k\cdot n_{\perp,1}) \\
&+2(y\,p_i\cdot Q)]
\end{aligned}
\tag{2.54}
$$

$$
\begin{aligned}
M_1{M_2}^{\dagger}=&\ g_s^2\,C_A\,g^{\eta\eta'}g^{\gamma\delta}[\frac{1}{2y(p_i\cdot Q)}+\frac{\beta_1(\frac{Q^2}{2p_i\cdot Q})}{2y(1-\beta_1)(1-y)\ (p_i\cdot Q)} \\
&+\frac{\beta_1\,Q\cdot p_k}{2y(1-\beta_1)(1-y)\ (p_i\cdot p_k)(p_i\cdot Q)}+\frac{\beta_1}{y(1-\beta_1)(p_i\cdot Q)}+\frac{1}{2(1-\beta_1)(1-y)(p_i\cdot p_k)}]
\end{aligned}
\tag{2.55}
$$

2.4 Interference term of inverse $M_1 M_2^{\dagger'}$



$$M_1 M_2^\dagger = \frac{g_s^2 f^{\,l\,o\,a} f^{\,f'\,a'\,n} \delta^{aa'} \delta^{ob'} \delta^{ff'}}{(q_i+q)^2 (q_j+q_i)^2} [g_\zeta{}^{\eta'} g^\gamma{}_{\tau'} (g^{\eta\zeta}(2q+q_i)^\mu + g^{\zeta\mu}(q_i-q)^\eta - g^{\mu\eta}(2q_i+q)^\zeta)$$
$$g_{\mu\mu'}(g^{\tau'\mu'}(q_j-q_i)^\delta + g^{\mu'\delta}(2q_i+q_j)^{\tau'} - g^{\delta\tau'}(2q_j+q_i)^{\mu'}] \tag{2.56}$$

$$\begin{aligned} M_1 M_2^\dagger &= \frac{g_s^2 f^{\,l\,o\,a} f^{\,f\,a\,n}}{4(q\cdot q_i)(q_i \cdot q_j)} \\ &[g^{\eta\eta'}(2q+q_i)^\gamma (q_j-q_i)^\delta + g^{\eta\eta'}(2q_i+q_j)^\gamma (2q+q_i)^\delta - g^{\eta\eta'} g^{\gamma\delta}(2q+q_i)\cdot(2q_j+q_i) \\ &+ g^{\gamma\eta'}(q_i-q)^\eta (q_j+q_i)^\delta + g^{\eta'\delta}(q_i-q)^\eta (2q_i+q_j)^\gamma - g^{\gamma\delta}(q_i-q)^\eta (2q_j+q_i)^{\eta'} \\ &- g^{\gamma\eta}(2q_i+q)^{\eta'}(q_j-q_i)^\delta - g^{\eta\delta}(2q_i+q)^{\eta'}(2q_i+q_j)^\gamma + g^{\gamma\delta}(2q_j+q_i)^\eta (2q_i+q)^{\eta'}] \end{aligned} \tag{2.57}$$

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

$$\boxed{(k_1\cdot q_i)(k_1\cdot q_k) \approx y\beta_1(1-y)\,(p_i\cdot Q)(p_i\cdot Q)} \tag{2.58}$$

Calculation of the third term

$$-g^{\eta\eta'} g^{\gamma\delta}\{4k_1\cdot q_j + 2k_1\cdot q_i + 2q_i\cdot q_k\} \tag{2.59}$$

$$\begin{aligned} M_1 M_2^\dagger &= \frac{g_s^2 C_A}{4y\beta_1(1-y)\,(p_i\cdot p_k)(p_i\cdot Q)} g^{\eta\eta'} g^{\gamma\delta} \\ &[4([\alpha_1(1-y) + y\beta_1(\frac{Q^2}{2p_i\cdot Q})]\,p_i\cdot p_k + y\beta_1\,Q\cdot p_k + \sqrt{\alpha_1\beta_1 y(1-y)}p_k\cdot n_{\perp,1}) \\ &2([\beta_1(1-y) + y\alpha_1(\frac{Q^2}{2p_i\cdot Q})]\,p_i\cdot p_k + y\alpha_1\,Q\cdot p_k - \sqrt{\alpha_1\beta_1 y(1-y)}p_k\cdot n_{\perp,1}) \\ &+ 2(y\,p_i\cdot Q)] \end{aligned} \tag{2.60}$$

$$
\begin{aligned}
&-g^{\eta\eta'}g^{\gamma\delta}[4([\alpha_1(1-y)+y\beta_1(\frac{Q^2}{2p_i\cdot Q})]\,p_i\cdot p_k+y\beta_1\,Q\cdot p_k+\sqrt{\alpha_1\beta_1 y(1-y)}p_k\cdot n_{\perp,1})\\
&2([\beta_1(1-y)+y\alpha_1(\frac{Q^2}{2p_i\cdot Q})]\,p_i\cdot p_k+y\alpha_1\,Q\cdot p_k-\sqrt{\alpha_1\beta_1 y(1-y)}p_k\cdot n_{\perp,1})\\
&+2(y\,p_i\cdot Q)]
\end{aligned}
\tag{2.61}
$$

$$
\begin{aligned}
M_1{M_2}^\dagger = g_s^2\,C_A\,g^{\eta\eta'}g^{\gamma\delta}[\frac{1-\beta_1}{y\beta_1(p_i\cdot Q)}+\frac{1}{2y(p_i\cdot Q)}+\frac{(1-\beta_1)(\frac{Q^2}{2p_i\cdot Q})}{2y\beta_1(1-y)\,(p_i\cdot Q)}\\
+\frac{(1-\beta_1)\,Q\cdot p_k}{2y\beta_1(1-y)\,(p_i\cdot p_k)(p_i\cdot Q)}+\frac{1}{2(1-\beta_1)(1-y)(p_i\cdot p_k)}]
\end{aligned}
\tag{2.62}
$$

2.6 $|M^2|$

$$
\begin{aligned}
&|M|^2=|M'_2|^2+|M'_1|^2+2RE(M_1{M_2}^\dagger+M_1{M_2}^{\dagger\prime})\\
&|M|^2=\frac{g_s^2\,C_A}{y\,(p_i\cdot Q)}[2[\epsilon-1]\beta_1(1-\beta_1)n^\eta{}_{\perp,1}n^{\eta'}{}_{\perp,1}-2g^{\eta\eta'}][g^{\gamma\delta}]\\
&+\frac{g_s^2\,C_A}{(1-\beta_1)(1-y)\,(p_i\cdot p_k)}[-2g^{\delta\gamma}][g^{\eta\eta'}]\\
&+2Re(g_s^2\,C_A\,g^{\eta\eta'}g^{\gamma\delta}[\frac{1}{2y(p_i\cdot Q)}+\frac{\beta_1(\frac{Q^2}{2p_i\cdot Q})}{2y(1-\beta_1)(1-y)\,(p_i\cdot Q)}\\
&+\frac{\beta_1\,Q\cdot p_k}{2y(1-\beta_1)(1-y)\,(p_i\cdot p_k)(p_i\cdot Q)}+\frac{\beta_1}{y(1-\beta_1)(p_i\cdot Q)}+\frac{1}{2(1-\beta_1)(1-y)(p_i\cdot p_k)}]\\
&+g_s^2\,C_A\,g^{\eta\eta'}g^{\gamma\delta}[\frac{1-\beta_1}{y\beta_1(p_i\cdot Q)}+\frac{1}{2y(p_i\cdot Q)}+\frac{(1-\beta_1)(\frac{Q^2}{2p_i\cdot Q})}{2y\beta_1(1-y)\,(p_i\cdot Q)}\\
&+\frac{(1-\beta_1)\,Q\cdot p_k}{2y\beta_1(1-y)\,(p_i\cdot p_k)(p_i\cdot Q)}+\frac{1}{2(1-\beta_1)(1-y)(p_i\cdot p_k)}])
\end{aligned}
\tag{2.63}
$$

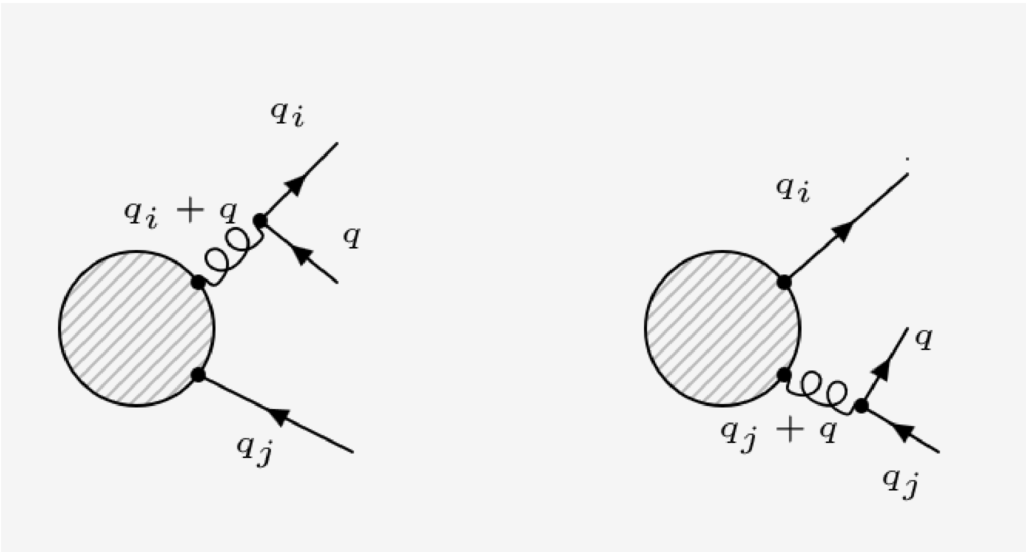
$$
\begin{aligned}
&|M|^2=|M'_2|^2+|M'_1|^2+2RE(M_1{M_2}^\dagger+M_1{M_2}^{\dagger\prime})\\
&|M|^2=g_s^2\,C_A\,g^{\eta\eta'}g^{\gamma\delta}[2[\epsilon-1]\beta_1(1-\beta_1)n^\eta{}_{\perp,1}n^{\eta'}{}_{\perp,1}+\frac{\beta_1(\frac{Q^2}{2p_i\cdot Q})}{y(1-\beta_1)(1-y)\,(p_i\cdot Q)}\\
&+\frac{\beta_1\,Q\cdot p_k}{y(1-\beta_1)(1-y)\,(p_i\cdot p_k)(p_i\cdot Q)}+\frac{2\beta_1}{y(1-\beta_1)(p_i\cdot Q)}\\
&+\frac{2(1-\beta_1)}{y\beta_1(p_i\cdot Q)}+\frac{(1-\beta_1)(\frac{Q^2}{2p_i\cdot Q})}{y\beta_1(1-y)\,(p_i\cdot Q)}+\frac{(1-\beta_1)\,Q\cdot p_k}{y\beta_1(1-y)\,(p_i\cdot p_k)(p_i\cdot Q)}]
\end{aligned}
\tag{2.64}
$$

$$|M|^2 = g_s^2\, C_A\, g^{\eta\eta'} g^{\gamma\delta}[2\beta_1(1-\beta_1) + \frac{2\beta_1}{y(1-\beta_1)(p_i\cdot Q)} + \frac{2(1-\beta_1)}{y\beta_1(p_i\cdot Q)} + \frac{(\frac{Q^2}{2p_i\cdot Q})}{y\beta_1(1-y)\,(p_i\cdot Q)} + \frac{Q\cdot p_k}{y\beta_1(1-y)\,(p_i\cdot p_k)(p_i\cdot Q)}] \tag{2.65}$$

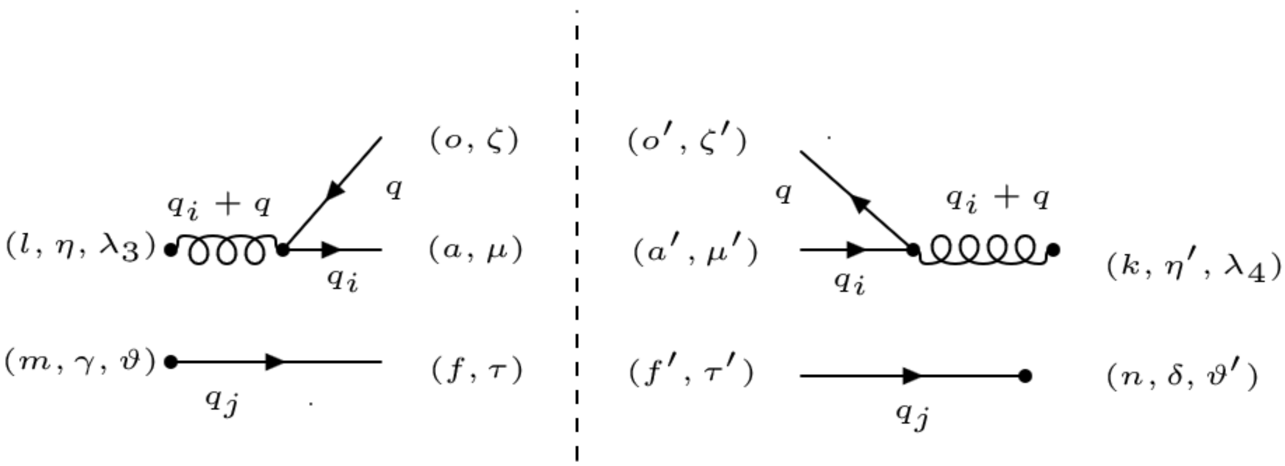
$$|M|^2 = 2\frac{g_s^2\, C_A}{y(p_i\cdot Q)}\, g^{\eta\eta'} g^{\gamma\delta}[\beta_1(1-\beta_1) + \frac{\beta_1}{1-\beta_1} + \frac{1-\beta_1}{\beta_1}] \tag{2.66}$$

Chapter 3

Quark gluon quark emission kernel



3.1 Quark loop



$$|M_1|^2 = [\frac{-i}{(q_i+q)^2} \not{q}_i(-ig_s\gamma^\eta \times [T^l]_a{}^o) \not{q}(ig_s\gamma^{\eta'} \times [T^k]_{o'}{}^{a'})\frac{i}{(q_i+q)^2}][\not{q}_j] \tag{3.1}$$

$$|M_1|^2 = \frac{{g_s}^2[T^l]_a{}^o[T^k]_{o'}{}^{a'}}{4(k_1\cdot q_i)(k_1\cdot q_i)}[\not{q}_i\gamma^\eta \not{k}_1 \gamma^{\eta'}][\not{q}_k] \tag{3.2}$$

$$|M_1|^2 = -\frac{{g_s}^2[T^l]_a{}^o[T^k]_{o'}{}^{a'}}{4y^2(p_i\cdot Q)(p_i\cdot Q)}[\not{q}_i \not{k}_1 \gamma^\eta\gamma^{\eta'}][\not{q}_k] \tag{3.3}$$

$$\begin{aligned}
&|M_1|^2 = -\frac{{g_s}^2[T^l]_a{}^o[T^k]_{o'}{}^{a'}}{4y^2(p_i\cdot Q)(p_i\cdot Q)}\\
&[((\beta_1 - \alpha_1 y(\frac{Q^2}{2p_i\cdot Q})) \not{p}_i + y\alpha_1 \not{Q} - \sqrt{y\alpha_1\beta_1} \not{n}_{\perp,l})\\
&((\alpha_1 - y\beta_1(\frac{Q^2}{2p_i\cdot Q})) \not{p}_i + y\beta_1 \not{Q} + \sqrt{y\alpha_1\beta_1} \not{n}_{\perp,1})\ \gamma^\eta\gamma^{\eta'}]\\
&[A_1 \not{p}_i + A_2 \not{Q} + \sqrt{1-y} \not{p}_k]
\end{aligned} \tag{3.4}$$

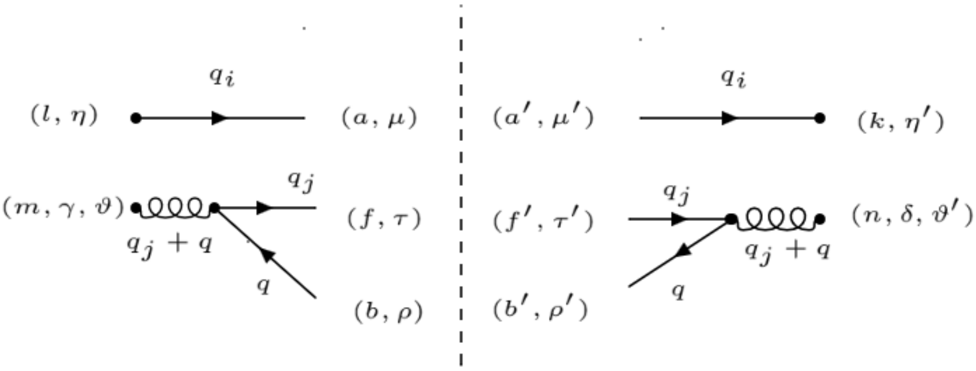
$$\begin{aligned}
&|M_1|^2 = -\frac{{g_s}^2[T^l]_a{}^o[T^k]_{o'}{}^{a'}}{4y^2(p_i\cdot Q)(p_i\cdot Q)}\\
&[(y\beta_1(\beta_1 - \alpha_1 y(\frac{Q^2}{2p_i\cdot Q})) \not{p}_i \not{Q} + y\alpha_1(\alpha_1 - y\beta_1(\frac{Q^2}{2p_i\cdot Q})) \not{p}_i \not{Q} + y^2\alpha_1\beta_1 \not{Q} \not{Q})g^{\eta\eta'}]\\
&[A_1 \not{p}_i + A_2 \not{Q} + \sqrt{1-y} \not{p}_k]
\end{aligned} \tag{3.5}$$

$$|M_1|^2 = -\frac{{g_s}^2 [T^l]_a{}^o [T^k]_{o'}{}^{a'}}{4y^2 (p_i \cdot Q)(p_i \cdot Q)} [(y{\beta_1}^2 \not{p}_i \not{Q} + y{\alpha_1}^2 \not{Q} \not{p}_i) g^{\eta\eta'}][A_1 \not{p}_i + A_2 \not{Q} + \sqrt{1-y} \not{p}_k] \tag{3.6}$$

$$|M_1|^2 = -\frac{{g_s}^2 [T^l]_a{}^o [T^k]_{o'}{}^{a'}}{4y^2 (p_i \cdot Q)(p_i \cdot Q)} [y({\beta_1}^2 - {\alpha_1}^2) \not{p}_i \not{Q} g^{\eta\eta'}][A_1 \not{p}_i + A_2 \not{Q} + \sqrt{1-y} \not{p}_k] \tag{3.7}$$

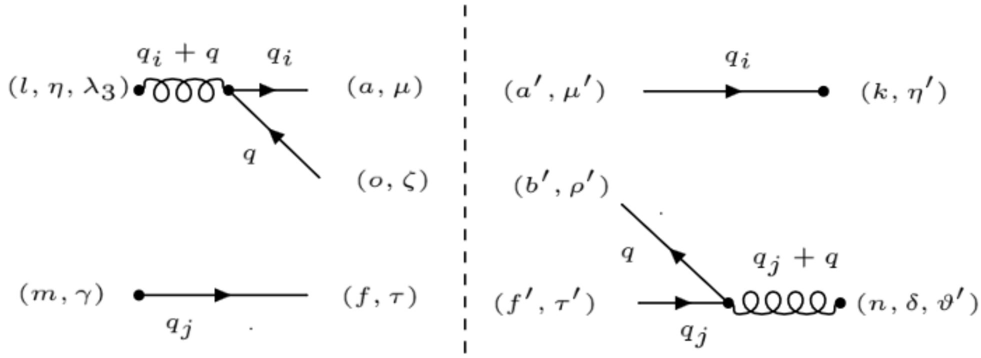
$$|M_1|^2 = -\frac{{g_s}^2 [T^l]_a{}^o [T^k]_{o'}{}^{a'}}{4y (p_i \cdot Q)(p_i \cdot Q)} [g^{\eta\eta'}][\sqrt{1-y}({\beta_1}^2 - {\alpha_1}^2) \not{p}_i \not{Q} \not{p}_k] \tag{3.8}$$

3.2 Spectator Quark loop



$$|M_2|^2 = \frac{{g_s}^2 [T^m]_f{}^b [T^n]_f{}^b}{4(k_1 \cdot q_k)(k_1 \cdot q_k)} [\not{q}_k \gamma^\gamma \not{k}_1 \gamma^\delta][\not{q}_i] \tag{3.9}$$

3.3 Interference term



$$M_1\, {M_2}^\dagger = \frac{{g_s}^2 [T^l]_a{}^o [T^n]_f{}^o}{4(qq_i)(qq_j)} [\not{q}_i \gamma^\eta \not{q}\ \gamma^\delta \not{q}_j] \tag{3.10}$$

$$M_1\, {M_2}^\dagger = -\frac{{g_s}^2 [T^l]_a{}^o [T^n]_f{}^o}{4(k_1 \cdot q_i)(k_1 \cdot q_k)} [\not{q}_i\ \not{k}_1\ \ \not{q}_k][g^{\eta\delta}] \tag{3.11}$$

$$\begin{aligned} M_1\, {M_2}^\dagger &= -\frac{{g_s}^2 [T^l]_a{}^o [T^n]_f{}^o}{4y(1-\beta_1)(1-y)\,(p_i \cdot p_k)(p_i \cdot Q)} [g^{\eta\delta}] \\ &[((\beta_1 - \alpha_1 y (\frac{Q^2}{2p_i \cdot Q}))\ \not{p}_i + y\alpha_1\ \not{Q} - \sqrt{y\alpha_1\beta_1}\ \not{n}_{\perp,l}) \\ &((\alpha_1 - y\beta_1 (\frac{Q^2}{2p_i \cdot Q}))\ \not{p}_i + y\beta_1\ \not{Q} + \sqrt{y\alpha_1\beta_1}\ \not{n}_{\perp,1}) \\ &(A_1\ \not{p}_i + A_2\ \not{Q} + \sqrt{1-y}\ \not{p}_k)] \end{aligned} \tag{3.12}$$

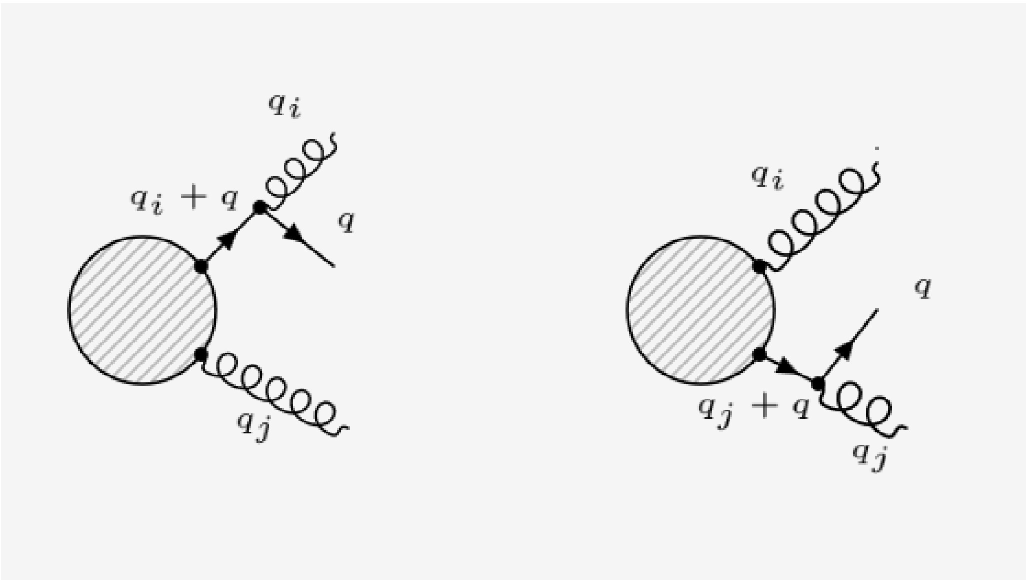
$$M_1\, {M_2}^\dagger = -\frac{{g_s}^2 [T^l]_a{}^o [T^n]_f{}^o}{4y(1-\beta_1)(1-y)\,(p_i \cdot p_k)(p_i \cdot Q)} [g^{\eta\delta}][\beta_1 \sqrt{1-y}\ \not{p}_i\ \not{Q}\ \not{p}_k] \tag{3.13}$$

3.4 $|M^2|$

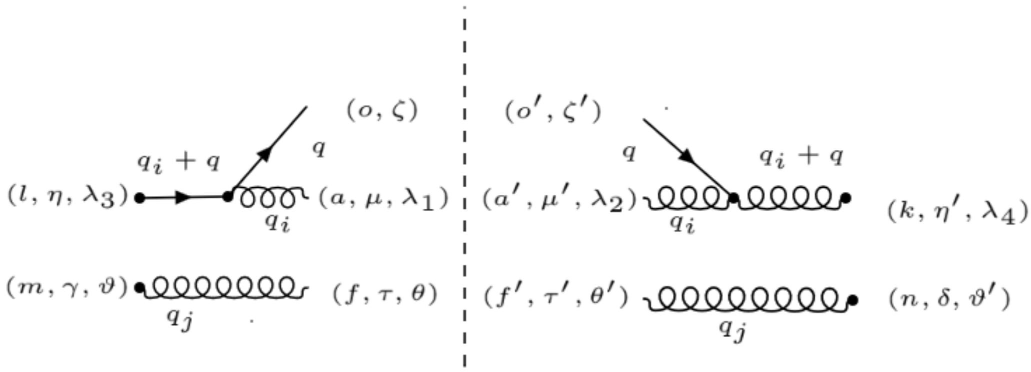
$$\begin{aligned} &|M|^2 = |M_2|^2 + |M_1|^2 + 2RE(M_1 {M_2}^\dagger) \\ &- \frac{{g_s}^2 [T^l]_a{}^o [T^k]_{o'}{}^{a'}}{4y(p_i \cdot Q)(p_i \cdot Q)} [g^{\eta\eta'}][\sqrt{1-y}({\beta_1}^2 - {\alpha_1}^2)\ \not{p}_i\ \not{Q}\ \not{p}_k] \\ &+ 2RE(-\frac{{g_s}^2 [T^l]_a{}^o [T^n]_f{}^o}{4y(1-\beta_1)(1-y)\,(p_i \cdot p_k)(p_i \cdot Q)} [g^{\eta\delta}][\beta_1 \sqrt{1-y}\ \not{p}_i\ \not{Q}\ \not{p}_k]) \end{aligned} \tag{3.14}$$

Chapter 4

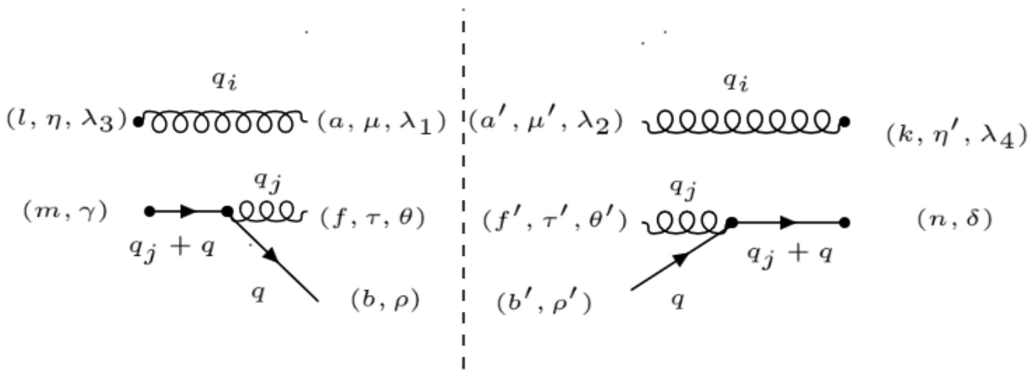
Gluon quark quark emission kernel



4.1 M_1


(o, ζ)
(o', ζ')
$q_i + q$
q
q
$q_i + q$
(l, η, λ_3)
(a, μ, λ_1)
q_i
(a', μ', λ_2)
q_i
(k, η', λ_4)
(m, γ, ϑ)
(f, τ, θ)
q_j
(f', τ', θ')
(n, δ, ϑ')
q_j

4.2 M_2


q_i
(l, η, λ_3)
(a, μ, λ_1)
(a', μ', λ_2)
q_i
(k, η', λ_4)
q_j
(m, γ)
(f, τ, θ)
(f', τ', θ')
q_j
(n, δ)
$q_j + q$
$q_j + q$
q
(b, ρ)
(b', ρ')
q

4.3 $M1M_2^\dagger$