Code generation (automatized programming) of symbolic formulae for helicity amplitudes

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Abstract

We propose a project for automatic representation and evaluation of helicity amplitudes we started to develop and explain it’s main functioning principles.

Introduction

In the field of modern High Energy Computational Physics (well-known computational packages Comphep [1], Grace [2], FeynArts/FeynCalc[3], MADGRAPH [4], O’Mega [5]) a great attention is payed to the evaluation of squared matrix elements of Feynman diagrams as a contribution to the study of cross-section type observables.

In [6] we presented a newly modified method for symbolic calculation of Feynman amplitudes. The initial idea of the method rises to early 80th see [7], [8]. We choose a way to represent these helicity amplitudes in a form, that can be used as a computer input and in the same way it is readable (comprehensible) by humans. As a programming tool we did use an object-oriented programming language standard C++ [10]. The idea of using helicity amplitudes and C++ language for generation matrix elements for study multi-paricle production in high energy particles collisions independently applied by authors of [11].

There are three main aims of algorithmization: 1) acceleration rapidity of calculations; 2) reducing an amount of auxiliary information, which requires to obtain results, but does not contribute to them itself; 3) algorithmization in accordance with applicability for investigation concrete observables and possibility to determine them in an experiment.

We did make a program code to obtain symbolic formulae for helicity amplitudes, that uses as an input data source the Comphep data for Feynman diagrams and produces as an output REDUCE program that contains helicity amplitudes in a form of mathematical traces — so-called fermion strings in High Energy Physics terminology [9].

The essence of the algorithm to built helicity amplitudes expressions is the following. For each diagram and for each polarization we have to obtain an expression that is a product of $n \ (n \geq 1)$ fermion strings. The notion of fermion strings was defined in [9] (expr.(1)). As described in [6] one can assign basis spinor $\xi_+$ or $\xi_-$ to any fermion. Plus or minus will be standing depending on the polarization ($\lambda = \pm 1$) and the type of the spinor ($u, v, \bar{u}, \bar{v}, u^c, v^c, \bar{u}^c, \bar{v}^c$). So we regard spinor pairs as entities to form a short or long (double) fermion strings. Our algorithm of fermion strings formation gives tree level helicity amplitudes each of those contain not more than two polarization vectors ($\eta$ and $k$ or $\eta^*$ and $k$ in one amplitude, not

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\(\eta\) and \(\eta^*\) together). To achieve this form for helicity amplitudes one do not need to apply any symbolic formulae substitutions (cf. [9]), but to use traces building technic.

On the contrary, using algorithm of [9] one makes symbolic transformations of helicity amplitudes expressions and obtains polarization vector dependence proportional either to \(\eta\) and \(\eta^*\).

**The realization of the algorithm to build helicity amplitudes**

On the step of forming fermion strings we restricted our algorithm by a number of external particles equal 6. This includes most interesting processes, that can be evaluated, and fit for practical purposes. Further generalization is straightforward, but analysis of results of output will be more cumbersome because of big number of amplitudes and a length of symbolic expressions, that will expire a lot of computer memory, and can be done later. The algorithm to form fermion strings under above restrictions is the following:

1. First, one searches for a spinor pairs that can form short fermion string, i.e., string, that contain only one pair of spinors (fermion and anti-fermion) of the same chirality.

2. Then one searches if there exists a possibility to form a double (long) fermion string, i.e., trace that contain four spinors (two spinor pairs each of them consists of fermion and anti-fermion).

3. Finally, one should check if there any spinor pairs that need to be united into a fermion string yet, if needed short fermion strings arise.

What are the criteria to unify a pair of spinors into short or long fermion string? We define fermion string as double if it contains two spinor pairs so, that for each basis spinor in one pair it corresponds the basis spinor of opposite chirality in the other pair. In each spinor pair that comprise double fermion string the chiralities of basis spinors are opposite.

After defining all fermion strings in the amplitude a task reduces itself to automatize a process of writing down fermion strings in a form of traces and further their multiplication to obtain amplitudes themselves.

But, what is the inner structure of a fermion string and how one can find it from Feynman diagram? How one can establish a sequence of fermion strings?

The last question has a simple answer: sequence of fermion strings does not strictly fixed, at least, if we have \(g_{\mu\nu} = g_{\nu\mu}\) symmetric metric tensor in plain Minkowski space, i.e., changing an order of fermion strings does not change result of evaluation, as each fermion string is a trace. Trace is a scalar value, or it does contain Lorentz indices, that can be contracted with ones from the other fermion string in the amplitude (more precisely, with metric tensors of the numerator of boson particles propagators for Feynman gauge). All indices should be contracted inside helicity amplitude. We fix a sequence of fermion strings from the algorithm.

The algorithm of formation inner structure of fermion string is done without strong limitation on the number of external particles (it can be changed), structure of propagators and vertices (new structures can be added). First we restricted vertex structure types by QED vertex structure and propagator structure types by QED propagator in Feynman gauge for simplicity. Let us consider electron-positron scattering \(ee^+ \rightarrow ee^+\mu\mu^+\) (see diagr.1 below). There are three spinor pairs in each whole helicity amplitude that related to this scattering process. Certainly, for polarized particles a fermion string structure of amplitude depends on a set of polarizations of external particles. E.g., if one puts all polarizations equal \(-1/2\) one will
have three short fermion strings in this helicity amplitude:

\[ A(\lambda_i = -1/2) \propto A_1 \ast A_2 \ast A_3, \quad i = 1, \ldots, 6, \quad A_1 = \bar{v}_{e+}(p_2) \gamma_{\mu_1} v_{e+}(p_4), \]

\[ A_2 = \bar{u}_{\mu}(p_5) \gamma_{\mu_2} v_{\mu+}(p_6), \quad A_3 = \bar{u}_e(p_3) \gamma_{\mu_3} \text{prop}(p_8) \gamma_{\mu_4} u_e(p_1), \]

where \( p_8 \) momentum of virtual electron, \( \text{prop}(p_8) \) propagator of the virtual electron with momentum \( p_8 \). In our considerations we take into account only numerator of particles propagators as denominators could be included to the numerical factor, which is common for each helicity amplitude in the diagram. One can found from the results of symbolic evaluation that any helicity amplitude of diagr.1 that contain long fermion string nullify itself. It can be easily shown using trace mathematics [12], it occurs due to the chiral symmetry of the part of each spinor product that depends on polarization. In this diagram only helicity amplitudes containing short fermion strings will contribute. Moreover, amplitude constructions those contain more than one \( \eta \) (\( \eta^* \)) contribution in one term also nullify itself. It is a significant simplification one can observe.

For the Standard Model our code can process diagrams with fermion and anti-fermion external particles, virtual photons and bosons in Feynman gauge (excluding diagrams with Higgs excluding also diagrams with many-gluon vertices if the QCD-sector of the Standard Model is involved). Recently we did work on diagrams with external photons (bosons) and planned to include also scalar particles, such as Higgs.

Comparing results obtained through summation over all helicities for squared helicity amplitudes and non-polarized squared matrix elements for each diagram in a given process (excluding cross terms), we did check numerically correctness of evaluation of helicity amplitudes using the algorithm to form fermion strings on an examples of processes those comprise of tree level diagrams.

1 First, for \( 2 \rightarrow 2 \) scattering for the Standard Model process \( ee^+ \rightarrow ee^+ \) in the limit of massless electrons (positrons). No contradictions are found.

2 In [9] we did describe processes \( ee^+ \rightarrow t\bar{t} \) in the Standard Model and \( ee^+ \rightarrow \) neutralino pair in SUSY (MSSM) with massive quarks in final states, the second process with heavy neutralinos, and massless limit for electron and positron mass(es) and tried investigation of symbolic structure of helicity amplitudes on these simple examples. Numerical calculations give no contradictions.

3 We tried the Standard Model diagrams (with \( \gamma_\mu \) vertices) \( ee^+ \rightarrow ee^+ \mu\mu^+ \) process (assigning mass to muons and excluding diagrams with Higgs particles) (see diagr.1). The numerical results of summation over polarized squared helicity amplitudes coincide with ones obtained for non-polarized squared matrix elements, but one can put a question on the degree of confidence to machine calculated output. It is still remains difficulty to check a correctness of symbolic formulae and numerical calculation for such a big symbolic output.

4 We checked \( e\gamma \rightarrow e\gamma \) (Compton scattering) very preliminarily, i.e., we did check results numerically in the limit of massless electrons (positrons).

Namely, we did treat numerically Lorentz covariant symbolic expressions for helicity amplitudes, obtained after evaluation traces (output of REDUCE code) of symbolic code for helicity
amplitudes generated from our initial C++ program. We tend to call this our new computational project as CG-project (CG means CODE GENERATION). Briefly, one can characterize CG-project as a sequence of steps:

1 code on C++. Input: Comphep Feynman diagrams data. Output: REDUCE program (formulae for helicity amplitudes).

2 REDUCE program. Input: trace structures. Output: Lorentz covariant symbolic expressions.

**CG-project realization**

The realized part of work on creation CG-programming code could be formulated as an annex list of accomplished tasks.

1) Using REDUCE package a set of test programs was created and an applicability of helicity amplitudes method for the evaluation of helicity amplitudes and squared matrix elements on the examples of simplest tree-level process $2 \rightarrow 2$ was tested (modification of helicity basis):
   a) numerical testing is applied;
   b) symbolic testing is applied;
   c) results’ analysis is applied.

2) A way to optimize helicity amplitudes evaluation was found.
   a) It was created a set of programs allowing to test helicity amplitudes optimization process and to compare results for helicity amplitudes in either numeric and symbolic form.
   b) Possibilities to optimize symbolic formulae for helicity amplitudes were investigated on the examples of chosen diagrams of QED, SUSY (MSSM), Standard Model. It was foreseeing a possibility to use C-conjugate spinors. A possibilities to optimize symbolic formulae using C-conjugation and changing spinor pairs’ conjunctions were taken into account.
   c) Analysis of the results of optimization of symbolic expressions for helicity amplitudes was realized.
   d) The comparison for non-polarized squared matrix elements with Comphep package was realized in numeric and symbolic form.

3) There were investigated ways to automatize helicity amplitudes evaluation for the case of multiple diagrams and processes that includes $\leq 6$ particles:
   a) initial code realized on programming language Standard C++ was created with minimal user interface. A testing is applied, an analysis of possibilities of optimization of the code is applied.
   b) Using object-oriented C++ features it was created a code that operates with minimal test database (that is a set of objects of a definite class) and generates file of symbolic results (in the form of traces that one able to evaluate using REDUCE) for helicity amplitudes. It was realized an analysis of the results of code functioning.
   c) The complarison of numerical values of non-polarized squared matrix elements, those obtained by sum over polarizations of squared numerical values for helicity amplitudes, with numerical values of non-polarized squared matrix elements formulae was executed.
   d) The code for generation tree-level processes (which include up to 6 particles in the initial and final states and have vertices of the type boson-fermion-antifermion) helicity amplitudes’ symbolic formulae was created. Applyed an algorithm of optimization by changing spinor pair conjunction.
   e) An interface of our program, that generates trace symbolic formulae for helicity amplitudes, with Comphep symbolic tables allowing to do automatical generation of symbolic formulae for helicity amplitudes for mentioned above types of scattering processes’ diagrams.
f) It was applied the testing on functioning of the code and the interface with Comphep on the examples of selected process’ diagrams and the comparison of numerical values of non-polarized squared matrix elements of selected diagrams with results of summed over polarizations squared numerical values of symbolic formulae for helicity amplitudes.

g) It was created and tried out the test program’s interface: debugger that functions on the first step of CG (see above) and translator for representation symbolic formulae for helicity amplitudes in the form of traces into LaTeX format (see Appendix: symbolic representation of helicity amplitudes for selected diagram of the process $ee^+ \rightarrow ee^+\mu\mu^+$). Translator can function when the first CG step is completed.

Conclusions
We described an algorithm to build helicity amplitudes and a way we started to realize it.
It is not an accidental choice that we use C++ and REDUCE languages in our project. We built a code that is, on one hand, in close connection with Comphep project, on the other hand, C++ is the modest object-oriented language allowing more advanced interfaces and structuring.

Our project on helicity amplitudes is at the beginning. It could be expanded to wider types of processes. It could be discussed a possibility of application of its results to numerical computation of phenomenology of some High Energy or DIS processes.

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Appendix

We give symbolic formulae for helicity amplitudes $A$ for diagram 1 (see an applied list of diagrams generated by Comphep) for the process $ee^+ \rightarrow ee^+\mu\mu^+$. Here $m_0$ is the electron and positron mass, $q$ symbolizes the virtual electron momentum, $M_m$ – the mass of muon and corresponding anti-particle. One can find $A$ dependence of initial and final states particles polarizations in round brackets (positive or negative signs of polarizations $\lambda_i$): $A(\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6)$.

\[ A(-, -, -, -, -, -) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)] \]
\[ Tr [\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)] \]
\[ Tr [\hat{\mu}_2(-\hat{p}_6 + M_m)(1 - \gamma_5)\hat{\eta}^*\hat{k}(\hat{p}_5 + M_m)]; \]
\[ A(-, -, -, -, +, -) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 - \gamma_5)\hat{k}(\hat{p}_2 + m_0)] \]
\[ Tr [\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)] \]
\[ Tr [\hat{\mu}_2(-\hat{p}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{p}_5 + M_m)]; \]
\[ A(-, -, -, +, +, -) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)] \]
\[ Tr [\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)] \]
\[ Tr [\hat{\mu}_2(-\hat{p}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{p}_5 + M_m)]; \]
\[ A(-, -, -, +, -, -) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)] \]
\[ Tr [\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)] \]
\[ Tr [\hat{\mu}_2(-\hat{p}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{p}_5 + M_m)]; \]
\[ A(-, -, -, +, +, +) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 - \gamma_5)\hat{k}(\hat{p}_2 + m_0)] \]
\[ Tr [\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)] \]
\[ Tr [\hat{\mu}_2(-\hat{p}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{p}_5 + M_m)]; \]
\[ A(-, -, +, +, +, -) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)] \]
\[ Tr [\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)] \]
\[ Tr [\hat{\mu}_2(-\hat{p}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{p}_5 + M_m)]; \]
\[ A(-, -, +, -, -) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)] \]
\[\text{Tr}[\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_5 + M_m)]\]

\[\hat{\mu}_2(-\hat{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\hat{p}_3 + m_0);\]

\[A(-, - , + , - , +) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]\]

\[\text{Tr}[\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(\hat{p}_3 + m_0)]\]

\[\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{p}_5 + M_m)];\]

\[A(-, - , + , - , +) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]\]

\[\text{Tr}[\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(\hat{p}_3 + m_0)]\]

\[\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\hat{p}_5 + M_m)];\]

\[A(-, - , + , - , +) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]\]

\[\text{Tr}[\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(\hat{p}_3 + m_0)]\]

\[\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\hat{p}_5 + M_m)];\]

\[A(-, + , + , + , -) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]\]

\[\text{Tr}[\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(-1)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)]\]

\[\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\hat{p}_5 + M_m)];\]

\[A(-, + , + , + , +) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]\]

\[\text{Tr}[\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(\hat{p}_3 + m_0)]\]

\[\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{p}_5 + M_m)];\]

\[A(-, + , - , - , -) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_5 + M_m)]\]

\[\hat{\mu}_2(-\hat{p}_6 + M_m)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0);\]

\[A(-, + , - , - , +) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(-\hat{p}_2 + m_0)]\]

\[\text{Tr}[\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 + \gamma_5)\hat{\eta}\hat{k}(\hat{p}_3 + m_0)]\]

\[\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{p}_5 + M_m)];\]

\[A(-, + , - , - , +) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(-\hat{p}_2 + m_0)]\]

\[\text{Tr}[\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)]\]

\[\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\hat{p}_5 + M_m)];\]

\[A(-, + , - , - , +) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(-\hat{p}_2 + m_0)]\]
\[
\begin{align*}
\text{Tr}[\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)]
\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(\hat{p}_5 + M_m)]
\end{align*}
\]
A(−, +, −, +, −, −) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)]
\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]
\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(1 - \gamma_5)\hat{\eta}\hat{k}(\hat{p}_5 + M_m)]
A(−, +, −, +, −, +) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)]
\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]
\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{p}_5 + M_m)]
A(−, +, −, +, +, −) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)]
\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]
\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{p}_5 + M_m)]
A(−, +, +, −, +, +) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)]
\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]
\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{p}_5 + M_m)]
\]
\[
\text{Tr}[\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(\hat{p}_3 + m_0)]
\text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(-\hat{p}_2 + m_0)]
\end{align*}
\]
A(−, +, +, −, −, −) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_5 + M_m)]
\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]
\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\hat{p}_5 + M_m)]
A(−, +, +, −, +, +) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)]
\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]
\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(\hat{p}_5 + M_m)]
\]
\[
\text{Tr}[\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(\hat{p}_3 + m_0)]
\text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(-\hat{p}_2 + m_0)]
\end{align*}
\]
A(−, +, +, −, +, +) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)]
\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(\hat{p}_3 + m_0)]
\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(\hat{p}_5 + M_m)]
\]
\[
\text{Tr}[\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 - \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]
\text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 - \gamma_5)\hat{k}(\hat{p}_5 + M_m)]
\end{align*}
\]
A(−, +, +, −, +, +) = \text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\hat{p}_3 + m_0)]
\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(-1)(1 + \gamma_5)\hat{\eta}\hat{k}(\hat{p}_3 + m_0)]
\text{Tr}[\hat{\mu}_2(-\hat{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\hat{p}_5 + M_m)]
\]
\[
\text{Tr}[\hat{\mu}_2(-\hat{q} + m_0)\hat{\mu}_1(\hat{p}_1 + m_0)(1 - \gamma_5)\hat{k}(\hat{p}_3 + m_0)]
\text{Tr}[\hat{\mu}_1(-\hat{p}_4 + m_0)(1 - \gamma_5)\hat{k}(\hat{p}_5 + M_m)]
\end{align*}
\]
\[ \text{Tr} [\hat{\mu}_2 (-\hat{\varphi} + m_0) \hat{\mu}_1 (\hat{p}_1 + m_0) (1 - \gamma_5) \hat{k} (\hat{p}_3 + m_0)] \]
\[ \text{Tr} [\hat{\mu}_2 (-\hat{p}_6 + M_m) (1 - \gamma_5) \hat{k} (\hat{p}_5 + M_m)]; \]
\[ A(-, +, +, +, +) = \text{Tr} [\hat{\mu}_1 (-\hat{p}_4 + m_0) (-1)(1 + \gamma_5) \hat{\eta} \hat{k} (-\hat{p}_2 + m_0)] \]
\[ \text{Tr} [\hat{\mu}_2 (-\hat{\varphi} + m_0) \hat{\mu}_1 (\hat{p}_1 + m_0) (1 - \gamma_5) \hat{k} (\hat{p}_3 + m_0)] \]
\[ \text{Tr} [\hat{\mu}_2 (-\hat{p}_6 + M_m) (1 - \gamma_5) \hat{\eta} \hat{k} (\hat{p}_5 + M_m)]; \]
\[ A(+, -,-,-, -) = \text{Tr} [\hat{\mu}_1 (-\hat{p}_4 + m_0) (1 - \gamma_5) \hat{\eta} \hat{k} (-\hat{p}_2 + m_0)] \]
\[ \text{Tr} [\hat{\mu}_2 (-\hat{\varphi} + m_0) \hat{\mu}_1 (\hat{p}_1 + m_0) (1 + \gamma_5) \hat{k} (\hat{p}_3 + m_0)] \]
\[ \text{Tr} [\hat{\mu}_2 (-\hat{p}_6 + M_m) (1 + \gamma_5) \hat{k} (\hat{p}_5 + M_m)]; \]
\[ A(+, -,-,-, -) = \text{Tr} [\hat{\mu}_1 (-\hat{p}_4 + m_0) (1 - \gamma_5) \hat{\eta} \hat{k} (-\hat{p}_2 + m_0)] \]
\[ \text{Tr} [\hat{\mu}_2 (-\hat{\varphi} + m_0) \hat{\mu}_1 (\hat{p}_1 + m_0) (1 + \gamma_5) \hat{k} (\hat{p}_3 + m_0)] \]
\[ \text{Tr} [\hat{\mu}_2 (-\hat{p}_6 + M_m) (1 - \gamma_5) \hat{k} (\hat{p}_5 + M_m)]; \]
\[ A(+, -,-,-, -) = \text{Tr} [\hat{\mu}_1 (-\hat{p}_4 + m_0) (1 - \gamma_5) \hat{\eta} \hat{k} (-\hat{p}_2 + m_0)] \]
\[ \text{Tr} [\hat{\mu}_2 (-\hat{\varphi} + m_0) \hat{\mu}_1 (\hat{p}_1 + m_0) (1 + \gamma_5) \hat{k} (\hat{p}_3 + m_0)] \]
\[ \text{Tr} [\hat{\mu}_2 (-\hat{p}_6 + M_m) (1 + \gamma_5) \hat{k} (\hat{p}_5 + M_m)]; \]
\[ A(+, -,-,-, -) = \text{Tr} [\hat{\mu}_1 (-\hat{p}_4 + m_0) (1 - \gamma_5) \hat{\eta} \hat{k} (-\hat{p}_2 + m_0)] \]
\[ \text{Tr} [\hat{\mu}_2 (-\hat{\varphi} + m_0) \hat{\mu}_1 (\hat{p}_1 + m_0) (1 + \gamma_5) \hat{k} (\hat{p}_3 + m_0)] \]
\[ \text{Tr} [\hat{\mu}_2 (-\hat{p}_6 + M_m) (1 - \gamma_5) \hat{k} (\hat{p}_5 + M_m)]; \]
\[ A(+, -,-,-, -) = \text{Tr} [\hat{\mu}_1 (-\hat{p}_4 + m_0) (1 - \gamma_5) \hat{\eta} \hat{k} (-\hat{p}_2 + m_0)] \]
\[ \text{Tr} [\hat{\mu}_2 (-\hat{\varphi} + m_0) \hat{\mu}_1 (\hat{p}_1 + m_0) (1 + \gamma_5) \hat{k} (\hat{p}_3 + m_0)] \]
\[ \text{Tr} [\hat{\mu}_2 (-\hat{p}_6 + M_m) (1 + \gamma_5) \hat{k} (\hat{p}_5 + M_m)]; \]
\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 + \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, -, +, +, +) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 - \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, +, +, +, -) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 - \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, -, +, +, +) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 - \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, -, +, +, +) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 - \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 + \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, +, -, +, +) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 + \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, +, -, +, +) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 + \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, +, -, +, +) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, +, -, +, +) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(-1)(1 + \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, +, -, +, +) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, +, -, +, +) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, +, -, +, +) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, +, -, +, +) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, +, -, +, +) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, +, -, +, +) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, +, -, +, +) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]

\[A(+, +, -, +, +) = Tr [\dot{\mu}_1(-\dot{p}_4 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_3 + m_0)\]

\[\dot{\mu}_2(-\dot{q} + m_0)\dot{\mu}_1(\dot{p}_1 + m_0)(1 + \gamma_5)\hat{k}(\dot{p}_2 + m_0)\]

\[Tr [\dot{\mu}_2(-\dot{p}_6 + M_m)(1 - \gamma_5)\hat{k}(\dot{p}_5 + M_m)];\]
$$Tr [\hat{\mu}_2\hat{a}(-\hat{q} + m_0)\hat{\mu}_1(\hat{\rho}_1 + m_0)(1 - \gamma_5)\eta^*\hat{k}(\hat{\rho}_3 + m_0)]$$

$$Tr [\hat{\mu}_2(-\hat{\rho}_6 + M_m)(1 - \gamma_5)\eta^*\hat{k}(\hat{\rho}_5 + M_m)]$$

$$A(+, +, -, +, +, +) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]$$

$$Tr [\hat{\mu}_1(\hat{p}_1 + m_0)(1 - \gamma_5)\eta^*\hat{k}(\hat{p}_3 + m_0)]$$

$$Tr [\hat{\mu}_2(-\hat{\rho}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{\rho}_5 + M_m)]$$

$$A(+, +, +, +, +, +) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]$$

$$Tr [\hat{\mu}_2(-\hat{\rho}_6 + M_m)(1 - \gamma_5)\hat{k}(\hat{\rho}_5 + M_m)]$$

$$A(+, +, +, -, +, +) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]$$

$$Tr [\hat{\mu}_2(-\hat{\rho}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{\rho}_5 + M_m)]$$

$$A(+, +, +, +, +, +) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]$$

$$Tr [\hat{\mu}_2(-\hat{\rho}_6 + M_m)(1 - \gamma_5)\hat{k}(\hat{\rho}_5 + M_m)]$$

$$A(+, +, +, +, +, +) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]$$

$$Tr [\hat{\mu}_2(-\hat{\rho}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{\rho}_5 + M_m)]$$

$$A(+, +, +, +, +, +) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]$$

$$Tr [\hat{\mu}_2(-\hat{\rho}_6 + M_m)(1 - \gamma_5)\hat{k}(\hat{\rho}_5 + M_m)]$$

$$A(+, +, +, +, +, +) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]$$

$$Tr [\hat{\mu}_2(-\hat{\rho}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{\rho}_5 + M_m)]$$

$$A(+, +, +, +, +, +) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]$$

$$Tr [\hat{\mu}_2(-\hat{\rho}_6 + M_m)(1 - \gamma_5)\hat{k}(\hat{\rho}_5 + M_m)]$$

$$A(+, +, +, +, +, +) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]$$

$$Tr [\hat{\mu}_2(-\hat{\rho}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{\rho}_5 + M_m)]$$

$$A(+, +, +, +, +, +) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]$$

$$Tr [\hat{\mu}_2(-\hat{\rho}_6 + M_m)(1 - \gamma_5)\hat{k}(\hat{\rho}_5 + M_m)]$$

$$A(+, +, +, +, +, +) = Tr [\hat{\mu}_1(-\hat{p}_4 + m_0)(1 + \gamma_5)\hat{k}(-\hat{p}_2 + m_0)]$$

$$Tr [\hat{\mu}_2(-\hat{\rho}_6 + M_m)(1 + \gamma_5)\hat{k}(\hat{\rho}_5 + M_m)]$$
$$Tr [\hat{\mu}_2 (-\hat{q} + m_0) \hat{\mu}_1 (\hat{p}_1 + m_0) (1 - \gamma_5) \hat{k} (\hat{p}_3 + m_0)]$$
$$Tr [\hat{\mu}_2 (-\hat{p}_6 + M_m)(-1) (1 + \gamma_5) \hat{k} (\hat{p}_5 + M_m)].$$
