Note of `TwoLoopSunriseFeynmanIntegrals.jl`

Wen-Di Li*

School of Fundamental Physics and Mathematical Sciences,
Hangzhou Institute for Advanced Study,
University of Chinese Academy of Sciences,
Hangzhou 310024, CHINA

Quan-feng WU†

Institute of High Energy Physics,
Chinese Academy of Sciences,
Beijing 100049, CHINA

March 12, 2025‡

Abstract

TBA.

Contents

*E-mail: TBD

†E-mail: wuquanfeng@ihep.ac.cn

1 Introduction

We provide a JULIA[1] package `TwoLoopSunriseFeynmanIntegrals.jl`[2] for two-loop sunrise Feynman integrals[3], which reads [2, Eq. (2.56)][4]

$$I_{\rm TSI}^{(\nu_1,\nu_2,\nu_3)}(d,m_1,m_2,m_3) := \int \frac{\widetilde{\mathrm{d}q_1}\,\widetilde{\mathrm{d}q_2}}{(-q_1^2+m_1^2)^{\nu_1}(-q_2^2+m_2^2)^{\nu_2}(-q_{12}^2+m_3^2)^{\nu_3}}, \tag{1}$$

where $d = 4-2\varepsilon$ is the spacetime dimension, m_i's are the masses, ν_i's are the exponents, and q_i are the loop momenta ($q_{12} \equiv q_1+q_2$). In this note, we take the loop momentum measure as

$$\widetilde{\mathrm{d}q} := \frac{\mathrm{d}^d q}{\mathrm{i}\pi^{d/2}}. \tag{2}$$

One can easily verify that that this integral is invariant under the permutation of (m_1,ν_1), (m_2,ν_2), and (m_3,ν_3), *e.g.*,

$$I_{\rm TSI}^{(\nu_1\nu_2\nu_3)}(d,m_1,m_2,m_3) \equiv I_{\rm TSI}^{(\nu_2\nu_3\nu_1)}(d,m_2,m_3,m_1). \tag{3}$$

If all masses vanish, the integral vanishes as

$$I_{\rm TSI}^{(\nu_1\nu_2\nu_3)}(d,0,0,0) \equiv 0 \tag{4}$$

since the definition of the Feynman integral in the dimensional regularization [2, Sec. 2.4.2].

This note is organized as follows: In Sec. 2, we reduce the two-loop sunrise Feynman integrals to the master integrals (MIs) via integration-by-part (IBP) techniques. In Sec. 3, the MIs are evaluated and expanded into ε-series. In Sec. 4, we introduce the implementation of the package. Finally, we conclude in Sec. 5.

2 Integration-by-Part Reduction

In this section, we consider the integration-by-part (IBP) reduction for the two-loop sunrise Feynman integrals. The IBP reduction starts from the fact that [2, Eq. (6.2)]

$$\int \widetilde{\mathrm{d}q}\,\frac{\partial}{\partial q^\mu}[k^\mu\cdots] \equiv 0, \tag{5}$$

where k is an arbitrary momentum. We also have

$$\frac{\partial}{\partial q^\mu}\frac{1}{(-q^2+m^2)^\nu} = \frac{2\nu q_\mu}{(-q^2+m^2)^{\nu+1}}, \tag{6}$$

$$\frac{\partial}{\partial q_1^\mu}\frac{1}{(-q_{12}^2+m_3^2)^{\nu_3}} = \frac{2\nu_3(q_{12})_\mu}{(-q_{12}^2+m_3^2)^{\nu_3+1}}. \tag{7}$$

Therefore,

$$\begin{aligned} 0 = {} & \int \widetilde{\mathrm{d}q_1}\,\widetilde{\mathrm{d}q_2}\,\frac{\partial}{\partial q_1^\mu}\frac{q_1^\mu}{(-q_1^2+m_1^2)^{\nu_1}(-q_2^2+m_2^2)^{\nu_2}(-q_{12}^2+m_3^2)^{\nu_3}} \\ = {} & (d-2\nu_1-\nu_3)I_{\rm TSI}^{(\nu_1\nu_2\nu_3)} + 2\nu_1 m_1^2 I_{\rm TSI}^{(\nu_1+1,\nu_2,\nu_3)} - \nu_3\Big(I_{\rm TSI}^{(\nu_1-1,\nu_2,\nu_3+1)} - I_{\rm TSI}^{(\nu_1,\nu_2-1,\nu_3+1)}\Big) \\ & + \nu_3\big(m_1^2-m_2^2+m_3^2\big)I_{\rm TSI}^{(\nu_1,\nu_2,\nu_3+1)}. \end{aligned} \tag{8}$$

Or equivalently,

$$\begin{aligned} -2\nu_1 m_1^2 I_{\rm TSI}^{(\nu_1+1,\nu_2,\nu_3)} - \nu_3\big(m_1^2-m_2^2+m_3^2\big)I_{\rm TSI}^{(\nu_1,\nu_2,\nu_3+1)} = {} & (d-2\nu_1-\nu_3)I_{\rm TSI}^{(\nu_1\nu_2\nu_3)} \\ & - \nu_3\Big(I_{\rm TSI}^{(\nu_1-1,\nu_2,\nu_3+1)} - I_{\rm TSI}^{(\nu_1,\nu_2-1,\nu_3+1)}\Big). \end{aligned} \tag{9}$$

Similarly, we have

$$\begin{aligned} -2\nu_2 m_2^2 I_{\rm TSI}^{(\nu_1,\nu_2+1,\nu_3)} - \nu_3\big(m_2^2-m_1^2+m_3^2\big)I_{\rm TSI}^{(\nu_1,\nu_2,\nu_3+1)} = {} & (d-2\nu_2-\nu_3)I_{\rm TSI}^{(\nu_1\nu_2\nu_3)} \\ & - \nu_3\Big(I_{\rm TSI}^{(\nu_1,\nu_2-1,\nu_3+1)} - I_{\rm TSI}^{(\nu_1-1,\nu_2,\nu_3+1)}\Big). \end{aligned} \tag{10}$$

[1] https://julialang.org
[2] https://github.com/Fenyutanchan/TwoLoopSunriseFeynmanIntegrals.jl.git
[3] We suggest Refs. [1, 2] for pedagogical introduction to Feynman integrals.
[4] For simplicity, the prefactor $\mathrm{e}^{2\varepsilon\gamma_{\rm E}}(\mu^2)^{\nu-d}$ with $\nu \equiv \nu_1+\nu_2+\nu_3$ for the *modified minimal subtraction scheme* is omitted here.

Now consider

$$
\begin{aligned}
0 = & \int \widetilde{\mathrm{d}q_1}\, \widetilde{\mathrm{d}q_2}\, \frac{\partial}{\partial q_2^\mu} \frac{q_1^\mu}{(-q_1^2+m_1^2)^{\nu_1}(-q_2^2+m_2^2)^{\nu_2}(-q_{12}^2+m_3^2)^{\nu_3}} \\
= & (\nu_2-\nu_3) I_{\mathrm{TSI}}^{(\nu_1\nu_2\nu_3)} + \nu_2 I_{\mathrm{TSI}}^{(\nu_1-1,\nu_2+1,\nu_3)} - \nu_2 I_{\mathrm{TSI}}^{(\nu_1,\nu_2+1,\nu_3-1)} + \nu_2\big(-m_1^2-m_2^2+m_3^2\big) I_{\mathrm{TSI}}^{(\nu_1,\nu_2+1,\nu_3)} \\
& + \nu_3 I_{\mathrm{TSI}}^{(\nu_1,\nu_2-1,\nu_3+1)} - \nu_3 I_{\mathrm{TSI}}^{(\nu_1-1,\nu_2,\nu_3+1)} + \nu_3\big(m_1^2-m_2^2+m_3^2\big) I_{\mathrm{TSI}}^{(\nu_1,\nu_2,\nu_3+1)},
\end{aligned}
\tag{11}
$$

or equivalently,

$$
\begin{aligned}
& \nu_2\big(m_1^2+m_2^2-m_3^2\big) I_{\mathrm{TSI}}^{(\nu_1,\nu_2+1,\nu_3)} - \nu_3\big(m_1^2-m_2^2+m_3^2\big) I_{\mathrm{TSI}}^{(\nu_1,\nu_2,\nu_3+1)} \\
= \; & (\nu_2-\nu_3) I_{\mathrm{TSI}}^{(\nu_1\nu_2\nu_3)} + \nu_2\Big(I_{\mathrm{TSI}}^{(\nu_1-1,\nu_2+1,\nu_3)} - I_{\mathrm{TSI}}^{(\nu_1,\nu_2+1,\nu_3-1)}\Big) + \nu_3\Big(I_{\mathrm{TSI}}^{(\nu_1,\nu_2-1,\nu_3+1)} - I_{\mathrm{TSI}}^{(\nu_1-1,\nu_2,\nu_3+1)}\Big).
\end{aligned}
\tag{12}
$$

Combining Eqs. (9), (10), and (12), we have

$$
\begin{aligned}
& \begin{pmatrix} -2\nu_1 m_1^2 & 0 & -\nu_3\big(m_1^2-m_2^2+m_3^2\big) \\ 0 & -2\nu_2 m_2^2 & -\nu_3\big(m_2^2-m_1^2+m_3^2\big) \\ 0 & \nu_2\big(m_1^2+m_2^2-m_3^2\big) & -\nu_3\big(m_1^2-m_2^2+m_3^2\big) \end{pmatrix} \begin{pmatrix} I_{\mathrm{TSI}}^{(\nu_1+1,\nu_2,\nu_3)} \\ I_{\mathrm{TSI}}^{(\nu_1,\nu_2+1,\nu_3)} \\ I_{\mathrm{TSI}}^{(\nu_1,\nu_2,\nu_3+1)} \end{pmatrix} \\
= & \begin{pmatrix} d-2\nu_1-\nu_3 & 0 & \nu_3 & 0 & -\nu_3 \\ d-2\nu_2-\nu_3 & 0 & -\nu_3 & 0 & \nu_3 \\ \nu_2-\nu_3 & -\nu_2 & \nu_3 & \nu_2 & -\nu_3 \end{pmatrix} \begin{pmatrix} I_{\mathrm{TSI}}^{(\nu_1\nu_2\nu_3)} \\ I_{\mathrm{TSI}}^{(\nu_1,\nu_2+1,\nu_3-1)} \\ I_{\mathrm{TSI}}^{(\nu_1,\nu_2-1,\nu_3+1)} \\ I_{\mathrm{TSI}}^{(\nu_1-1,\nu_2+1,\nu_3)} \\ I_{\mathrm{TSI}}^{(\nu_1-1,\nu_2,\nu_3+1)} \end{pmatrix}.
\end{aligned}
\tag{13}
$$

Defining the matrices $\mathbf{A}$ and $\mathbf{B}$ as

$$
\mathbf{A} := \begin{pmatrix} -2\nu_1 m_1^2 & 0 & -\nu_3\big(m_1^2-m_2^2+m_3^2\big) \\ 0 & -2\nu_2 m_2^2 & -\nu_3\big(m_2^2-m_1^2+m_3^2\big) \\ 0 & \nu_2\big(m_1^2+m_2^2-m_3^2\big) & -\nu_3\big(m_1^2-m_2^2+m_3^2\big) \end{pmatrix}, \tag{14}
$$

$$
\mathbf{B} := \begin{pmatrix} d-2\nu_1-\nu_3 & 0 & \nu_3 & 0 & -\nu_3 \\ d-2\nu_2-\nu_3 & 0 & -\nu_3 & 0 & \nu_3 \\ \nu_2-\nu_3 & -\nu_2 & \nu_3 & \nu_2 & -\nu_3 \end{pmatrix}, \tag{15}
$$

the solution is given by

$$
\begin{pmatrix} I_{\mathrm{TSI}}^{(\nu_1+1,\nu_2,\nu_3)} \\ I_{\mathrm{TSI}}^{(\nu_1,\nu_2+1,\nu_3)} \\ I_{\mathrm{TSI}}^{(\nu_1,\nu_2,\nu_3+1)} \end{pmatrix} = \mathbf{A}^{-1}\mathbf{B} \begin{pmatrix} I_{\mathrm{TSI}}^{(\nu_1\nu_2\nu_3)} \\ I_{\mathrm{TSI}}^{(\nu_1,\nu_2+1,\nu_3-1)} \\ I_{\mathrm{TSI}}^{(\nu_1,\nu_2-1,\nu_3+1)} \\ I_{\mathrm{TSI}}^{(\nu_1-1,\nu_2+1,\nu_3)} \\ I_{\mathrm{TSI}}^{(\nu_1-1,\nu_2,\nu_3+1)} \end{pmatrix} \tag{16}
$$

if $\det \mathbf{A} \neq 0$. Notice that the determinant of $\mathbf{A}$ is given by

$$
\det \mathbf{A} = 2\nu_1\nu_2\nu_3 m_1^2 \lambda\big(m_1^2, m_2^2, m_3^2\big), \tag{17}
$$

where $\lambda(x,y,z)$ is the Källén triangle function [3, Eq. (6.3)–(6.7)]

$$
\begin{aligned}
\lambda(x,y,z) &:= x^2+y^2+z^2-2xy-2yz-2zx \\
&= \big(\sqrt{x}+\sqrt{y}+\sqrt{z}\big)\big(\sqrt{x}+\sqrt{y}-\sqrt{z}\big)\big(\sqrt{x}-\sqrt{y}+\sqrt{z}\big)\big(-\sqrt{x}+\sqrt{y}+\sqrt{z}\big).
\end{aligned}
\tag{18}
$$

Hence, there are two cases — non-collinear and collinear — to be considered.

2.1 Non-Collinear Case

In the non-collinear case, the solution in Eq. (16) is valid, which can be used to eliminate the sum of ν_i's by one from the left-hand-side (LHS) to the right-hand-side (RHS) of Eq. (16), which is the key to reduce the two-loop sunrise Feynman integrals to the master integrals (MIs). The expression of $\mathbf{A}^{-1}\mathbf{B}$ is too lengthy to be presented here, but it could be reproduced by the Wolfram Mathematica[5] notebook `note/Mathematica_notebooks/IBP_NC.nb`. The generated expressions are stored in the directory `ext/ibp_nc/` for further use.

[5] https://www.wolfram.com/mathematica

As Eq. (17) shows,

$$\begin{aligned} &\det \mathbf{A} = 0 \\ \Leftrightarrow\quad & \nu_1 = 0 \vee \nu_2 = 0 \vee \nu_3 = 0 \vee \lambda\left(m_1^2, m_2^2, m_3^2\right) = 0. \end{aligned} \tag{19}$$

with $m_1 > 0$[6], $m_2 \geq 0$, and $m_3 \geq 0$. The part of $\lambda\left(m_1^2, m_2^2, m_3^2\right) = 0$ is so-called collinear condition since it can be factorized as [Eq. (18)]

$$\lambda\left(m_1^2, m_2^2, m_3^2\right) = (m_1 + m_2 + m_3)(m_1 + m_2 - m_3)(m_1 - m_2 + m_3)(-m_1 + m_2 + m_3). \tag{20}$$

For the part of $\nu_1 = 0 \vee \nu_2 = 0 \vee \nu_3 = 0$, there are several cases to be considered.

$\boldsymbol{\nu_1 = \nu_2 = \nu_3 = 0.}$ The integrals are trivial as

$$I_{\text{TSI}}^{(000)}(d, m_1, m_2, m_3) = \int \widetilde{\mathrm{d}q_1}\, \widetilde{\mathrm{d}q_2} \equiv 0. \tag{21}$$

$\boldsymbol{\nu_2 = \nu_3 = 0.}$ The integrals are also trivial as

$$I_{\text{TSI}}^{(00\nu_3)} = \int \frac{\widetilde{\mathrm{d}q_1}\, \widetilde{\mathrm{d}q_2}}{\left(-q_1^2 + m_1^2\right)^{\nu_1}} = \int \widetilde{\mathrm{d}q_2} \int \frac{\widetilde{\mathrm{d}q_1}}{\left(-q_1^2 + m_1^2\right)^{\nu_1}} \equiv 0. \tag{22}$$

For the cases of $\nu_3 = \nu_1 = 0$ or $\nu_1 = \nu_2 = 0$, the permutation of (m_1, ν_1), (m_2, ν_2), and (m_3, ν_3) can be applied to obtain the same results.

$\boldsymbol{\nu_3 = 0.}$ The integrals are factorized as

$$\begin{aligned} I_{\text{TSI}}^{(\nu_1\nu_2 0)} = \int \frac{\widetilde{\mathrm{d}q_1}\, \widetilde{\mathrm{d}q_2}}{\left(-q_1^2 + m_1^2\right)^{\nu_1}\left(-q_2^2 + m_2^2\right)^{\nu_2}} &= \int \frac{\widetilde{\mathrm{d}q_1}}{\left(-q_1^2 + m_1^2\right)^{\nu_1}} \int \frac{\widetilde{\mathrm{d}q_2}}{\left(-q_2^2 + m_2^2\right)^{\nu_2}} \\ &\equiv I_1^{(\nu_1)}(d, m_1) I_1^{(\nu_2)}(d, m_2), \end{aligned} \tag{23}$$

where $I_1^{(\nu)}(d, m)$ is evaluateed to [1, Eq. (10.1)]

$$I_1^{(\nu)}(d, m) = \frac{\Gamma\left(\nu - \frac{d}{2}\right)}{\Gamma(\nu)} \left(m^2\right)^{\frac{d}{2} - \nu}. \tag{24}$$

For the cases of $\nu_1 = 0$ or $\nu_2 = 0$, the permutation of (m_1, ν_1), (m_2, ν_2), and (m_3, ν_3) can be applied to obtain the same results.

The integrals with $\nu_1 = 0 \vee \nu_2 = 0 \vee \nu_3 = 0$ are called the boundary cases. For every integral with $\nu_1 \geq 0 \wedge \nu_2 \geq 0 \wedge \nu_3 \geq 0$, the IBP reduction can be applied to reduce the integrals to the boundary cases and $I_{\text{TSI}}^{(111)}$. Actually, there are only two MIs in the non-collinear case — $I_{\text{TSI}}^{(111)}$ and $I_{\text{TSI}}^{(110)}$. However, the boundary cases are easy to evaluate as Eq. (24) shows, so we do not reduce $I_{\text{TSI}}^{(\nu_1\nu_2 0)}$ to $I_{\text{TSI}}^{(110)}$ in practice.

2.2 Collinear Case

If $\lambda\left(m_1^2, m_2^2, m_3^2\right) = 0$, we cannot apply Eq. (16) to reduce the integrals since $\mathbf{A}$ is singular, *i.e.*, $\mathbf{A}^{-1}$ does not exist. Notice that

$$\lambda(m_1^2, m_2^2, m_3^2) = 0 \quad \Longleftrightarrow \quad m_1 + m_2 + m_3 = 0 \vee m_1 = m_2 + m_3 \vee m_2 = m_1 + m_3 \vee m_3 = m_1 + m_2. \tag{25}$$

Since $m_i \geq 0$ and $I_{\text{TSI}}^{(\nu_1\nu_2\nu_3)}(d, 0, 0, 0)$ vanishes as Eq. (4) shows, the first condition is excluded. The other three conditions are called the collinear cases. Without loss of generality, the permutation of (m_1, ν_1), (m_2, ν_2), and (m_3, ν_3) can be applied to obtain the case $m_1 = m_2 + m_3$.

From Eq. (2.4) of Ref. [4], we have

$$I_{\text{TSI}}^{(\nu_1,\nu_2,\nu_3)}(d, m_1, m_2, m_3) = \frac{1}{2(d + 3 - 2\nu) m_1 m_2 m_3} \left\{ \begin{aligned} &[m_1(d + 2 - \nu) - m_2\nu_3 - m_3\nu_2] I_{\text{TSI}}^{(\nu_1 - 1,\nu_2,\nu_3)} \\ +\, &[m_1\nu_3 - m_2(d + 2 - \nu) - m_3\nu_1] I_{\text{TSI}}^{(\nu_1,\nu_2 - 1,\nu_3)} \\ +\, &[m_1\nu_2 - m_2\nu_1 - m_3(d + 2 - \nu)] I_{\text{TSI}}^{(\nu_1,\nu_2,\nu_3 - 1)} \end{aligned} \right\}, \tag{26}$$

[6] If $m_1 = 0$, we can just apply the permutation of (m_1, ν_1), (m_2, ν_2), and (m_3, ν_3) to satisfy the condition except for the case of $m_1 = m_2 = m_3 = 0$. However the case of $m_1 = m_2 = m_3 = 0$ is evaluated to 0 as Eq. (4) shows.

where $m_1 = m_2 + m_3$ and $\nu = \nu_1 + \nu_2 + \nu_3$. We can apply this formula to reduce the collinear cases to the boundary cases, *i.e.*, $\nu_i = 0$ for any $i = 1, 2, 3$. The boundary cases of any $\nu_i = 0$ are the same as Eqs. (21), (22), and (23). We also perform the ε-expansion in `note/Mathematica_notebooks/IBP_CL.nb`, and the results are stored in the directory `ext/ibp_cl/` for further use.

Different from the non-collinear case, $I^{(111)}_{\text{TSI}}$ is no longer the boundary case (or MIs) that needs to be evaluated independently. Instead, we have [4, Eq. (2.14)]

$$I^{(111)}_{\text{TSI}}(d, m_1, m_2, m_3) = \frac{d-2}{2(d-3)}\left(\frac{I^{(011)}_{\text{TSI}}}{m_2 m_3} - \frac{I^{(101)}_{\text{TSI}}}{m_3 m_1} - \frac{I^{(110)}_{\text{TSI}}}{m_1 m_2}\right) \tag{27}$$

for $m_1 = m_2 + m_3$.

3 Master Integrals

In this section, we evaluate the MIs and expand them into ε-series.

3.1 Factorization as Products of One-Loop Integrals

As Eq. (23) shows, the factorization of $I^{(\nu_1\nu_2 0)}_{\text{TSI}} = I^{(\nu_1)}_1 I^{(\nu_2)}_1$ makes the evaluation of $I^{(\nu_1\nu_2 0)}_{\text{TSI}}$ easier. The expansion of $I^{(\nu)}_1(d, m)$ into ε-series is easily obtained as

$$I^{(1)}_1(d, m) = -\frac{m^2}{\varepsilon} - m^2\left(1 - \gamma_{\text{E}} - \ln m^2\right) + \mathcal{O}\left(\varepsilon^1\right), \tag{28}$$

$$I^{(2)}_1(d, m) = \frac{1}{\varepsilon} - \left(\gamma_{\text{E}} + \ln m^2\right) + \mathcal{O}\left(\varepsilon^1\right), \tag{29}$$

$$I^{(\nu>2)}_1(d, m) = \frac{\left(m^2\right)^{2-\nu}}{(\nu-1)(\nu-2)} + \mathcal{O}\left(\varepsilon^1\right). \tag{30}$$

These expansions are evaluated in `note/Mathematica_notebooks/I_1-loop.nb` and stored in the directory `ext/one_loop/` for further use.

3.2 Non-Collinear $I^{(111)}_{\text{TSI}}$

For the master integral $I^{(111)}_{\text{TSI}}$, Eq. (4.9) of Ref. [5] shows

$$I^{(111)}_{\text{TSI}}(d, m_1, m_2, m_3) = \frac{1}{2}\left(m_1^2\right)^{1-2\varepsilon} A(\varepsilon)\left[-\frac{1}{\varepsilon^2}(1+x+y) + \frac{2}{\varepsilon}(x\ln x + y\ln y) - x\ln^2 x - y\ln^2 y \right.$$
$$\left. + (1-x-y)\ln x\ln y - \lambda(1,x,y)\Phi(x,y)\right] \tag{31}$$

for

$$\lambda(1,x,y) > 0 \quad \text{and} \quad 0 < x, y < 1, \tag{32}$$

where

$$x := \frac{m_2^2}{m_1^2}, \quad y := \frac{m_3^2}{m_1^2}, \tag{33}$$

and

$$A(\varepsilon) := \frac{\Gamma^2(1+\varepsilon)}{(1-\varepsilon)(1-2\varepsilon)},$$
$$\Phi(x,y) := \frac{1}{\sqrt{\lambda(1,x,y)}}\left[\begin{aligned} & 2\ln\left(\frac{1+x-y-\sqrt{\lambda(1,x,y)}}{2}\right)\ln\left(\frac{1-x+y-\sqrt{\lambda(1,x,y)}}{2}\right) - \ln x\ln y \\ & - 2\text{Li}_2\left(\frac{1-x+y-\sqrt{\lambda(1,x,y)}}{2}\right) - 2\text{Li}_2\left(\frac{1+x-y-\sqrt{\lambda(1,x,y)}}{2}\right) + \frac{\pi^2}{3}\end{aligned}\right]. \tag{34}$$

For $\lambda(1,x,y) < 0$ and $0 < x, y < 1$, Eq. (4.12) of Ref. [5] shows

$$I^{(111)}_{\text{TSI}}(d, m_1, m_2, m_3) = \left(m_1^2\right)^{1-2\varepsilon}\frac{A(\varepsilon)}{2\varepsilon^2}\left[\begin{aligned} & x^{-\varepsilon}y^{-\varepsilon}(1-x-y)\;{}_2F_1\left(\left.\begin{matrix}\varepsilon,\ 1\\ \frac{1}{2}+\varepsilon\end{matrix}\right| -\frac{\lambda(1,\ x,\ y)}{4xy}\right) \\ & - x^{-\varepsilon}(1+x-y)\;{}_2F_1\left(\left.\begin{matrix}\varepsilon,\ 1\\ \frac{1}{2}+\varepsilon\end{matrix}\right| -\frac{\lambda(1,\ x,\ y)}{4x}\right) \\ & - y^{-\varepsilon}(1-x+y)\;{}_2F_1\left(\left.\begin{matrix}\varepsilon,\ 1\\ \frac{1}{2}+\varepsilon\end{matrix}\right| -\frac{\lambda(1,\ x,\ y)}{4y}\right)\end{aligned}\right]. \tag{35}$$

The ε-series expansions of $I_{\mathrm{TSI}}^{(111)}$ are evaluated in `note/Mathematica_notebooks/TSI111_NC.nb` and stored in the directory `ext/TSI111_nc/` for further use.

4 Implementation

5 Conclusion

References

[1] Vladimir A. Smirnov. *Analytic tools for Feynman integrals*. Vol. 250. 2012. DOI: 10.1007/978-3-642-34886-0.

[2] Stefan Weinzierl. *Feynman Integrals. A Comprehensive Treatment for Students and Researchers*. UNITEXT for Physics. Springer, 2022. ISBN: 978-3-030-99557-7, 978-3-030-99560-7, 978-3-030-99558-4. DOI: 10.1007/978-3-030-99558-4. arXiv: 2201.03593 [hep-th].

[3] E. Byckling and K. Kajantie. *Particle Kinematics*. London: John Wiley & Sons Ltd, 1973.

[4] Andrei I. Davydychev and York Schröder. "Recursion-free solution for two-loop vacuum integrals with "collinear" masses". In: *JHEP* 12 (2022), p. 047. DOI: 10.1007/JHEP12(2022)047. arXiv: 2210.10593 [hep-ph].

[5] Andrei I. Davydychev and J. B. Tausk. "Two loop selfenergy diagrams with different masses and the momentum expansion". In: *Nucl. Phys. B* 397 (1993), pp. 123–142. DOI: 10.1016/0550-3213(93)90338-P.