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Evaluation of two-loop EW box diagrams for $e^+e^- \to ZH$

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8 November, Tuesday

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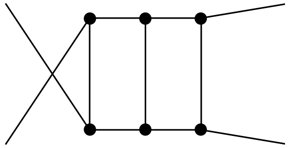
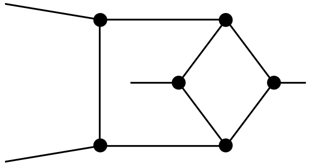
- Evaluation method: planar box diagram

  non-planar box diagram





- Numerical result
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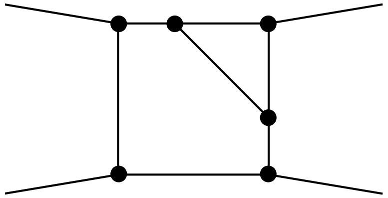
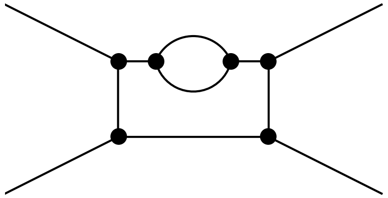


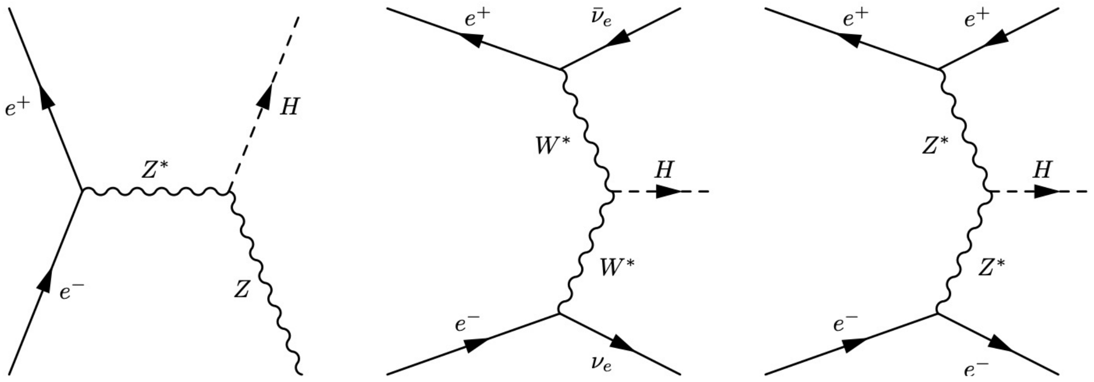


1. Introduction

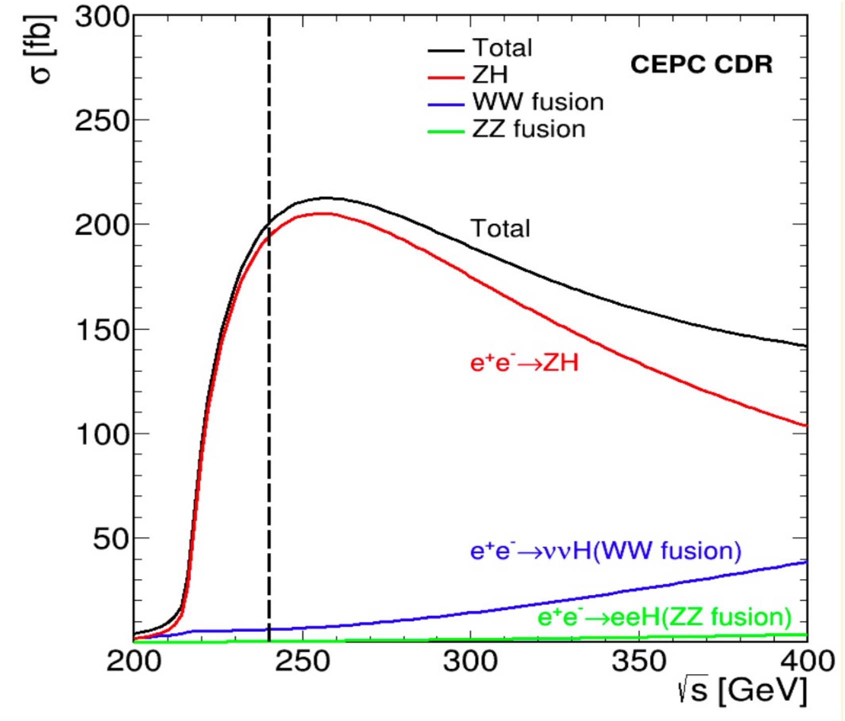
- Discovery of Higgs boson(2012,LHC): last fundamental particle in SM
- Experiments at the ATLAS and CMS: agrees with the result SM predicted
- Problems not solved: electroweak symmetry breaking, Higgs coupling to SM particles/DM, hierarchy problem... Require new physics beyond SM
- One promising way probing new physics: precision measurements of the properties of H
- LHC is difficult to reach very high precision due to complicated background

1. Introduction

- FCC-ee, CEPC, ILC: e+e- collider, large statistics, high luminosity, clean environment, measure H properties with very high precision ($\sqrt{s}$=240-250GeV)
- ILC: σ_{ZH}~1.2%, 250fb-1 (H. Baer et al. [arXiv:1306.6352 [hep-ph]])
- FCC-ee: σ_{ZH}~ 0.4%, 5ab-1(A.Abada et al[FCC Collaboration])
- CEPC: σ_{ZH}~ 0.5%, 5.6ab-1(arXiv:1811.10545)



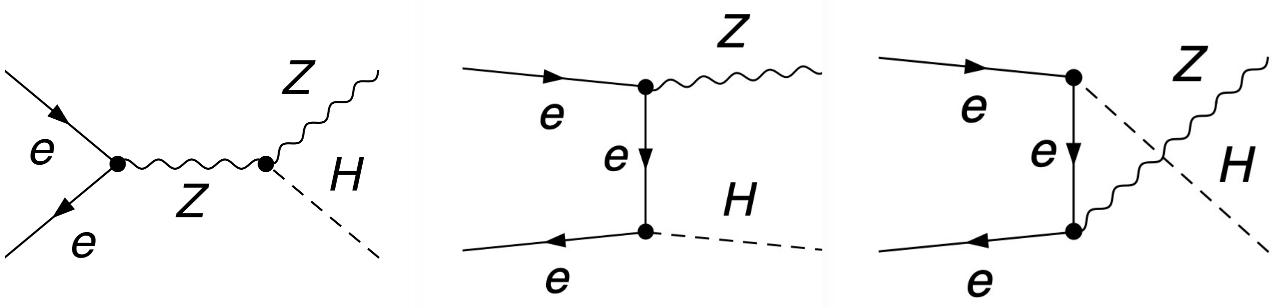
arXiv:1810.09037[hep-ph]



$\sim \frac{1}{s}$

$\sim ln(s)$

1. Introduction



- LO on $\sigma(e^+e^- \to ZH)$:
  only consider s channel
  t,u channel amplitude is zero due to small Yukawa coupling
- NLO on $\sigma(e^+e^- \to ZH)$:
  unpolarized beam: 5-10%;
  (A. Denner et al,Phys. C 56, 261(1992))
  polarized beam: 10-20%;
  (S.Bondarenko, Phys. Rev. D 100,073002(2019))

$$\sigma(P_{e^-}, P_{e^+}) = \frac{1}{4}\sum_{\chi_1,\chi_2}(1+\chi_1 P_{e^+})(1+\chi_2 P_{e^-})\sigma_{\chi_1\chi_2},$$

TABLE I. Hard ($E_\gamma > 1$ GeV), Born, and one-loop cross sections in fb and relative corrections δ in % for the c.m. energy $\sqrt{s} = 250$ GeV and various polarization degrees of the initial particles.

P_{e^-}	P_{e^+}	σ^{hard}, fb	σ^{Born}, fb	$\sigma^{\text{one-loop}}$, fb	δ, %
0	0	82.0(1)	225.59(1)	206.77(1)	−8.3(1)
−0.8	0	96.7(1)	266.05(1)	223.33(2)	−16.1(1)
−0.8	−0.6	46.3(1)	127.42(1)	111.67(2)	−12.4(1)
−0.8	0.6	147.1(1)	404.69(1)	334.99(1)	−17.2(1)

1. Introduction

- NNLO:(s= 240-250GeV)

EW+QCD:0.4-1.3% ($\alpha(0), \alpha(M_z), G_\mu$)

(Q.F.Sun, Phys.Rev.D 96,051301(2017))

EW+QCD:1.3% ($\overline{MS}, \alpha(M_z)$)

(Q.F.Sun, Phys.Rev.D 96,051301(2017))

$\sqrt{s}$	schemes	σ_{LO} (fb)	σ_{NLO} (fb)	σ_{NNLO} (fb)
	$\alpha(0)$	223.14 ± 0.47	229.78 ± 0.77	$232.21^{+0.75+0.10}_{-0.75-0.21}$
240	$\alpha(M_Z)$	252.03 ± 0.60	$228.36^{+0.82}_{-0.81}$	$231.28^{+0.80+0.12}_{-0.79-0.25}$
	G_μ	239.64 ± 0.06	$232.46^{+0.07}_{-0.07}$	$233.29^{+0.07+0.03}_{-0.06-0.07}$
	$\alpha(0)$	223.12 ± 0.47	229.20 ± 0.77	$231.63^{+0.75+0.12}_{-0.75-0.21}$
250	$\alpha(M_Z)$	252.01 ± 0.60	$227.67^{+0.82}_{-0.81}$	$230.58^{+0.80+0.14}_{-0.79-0.25}$
	G_μ	239.62 ± 0.06	231.82 ± 0.07	$232.65^{+0.07+0.04}_{-0.07-0.07}$

TABLE II. Total cross sections at various collider energies in the $\alpha(m_Z)$ scheme.

$\sqrt{s}$ (GeV)	σ_{LO} (fb)	σ_{NLO} (fb)	σ_{NNLO} (fb)	σ_{NNLO}^{exp} (fb)
240	252.0	228.6	231.5	231.5
250	252.0	227.9	230.8	230.8
300	190.0	170.7	172.9	172.9
350	135.6	122.5	124.2	124.0
500	60.12	54.03	54.42	54.81

1. Introduction

- EW+QCD:0.4-1.3% ($\alpha(0), \alpha(M_z), G_\mu$) (Q.F.Sun, Phys.Rev.D 96,051301(2017))

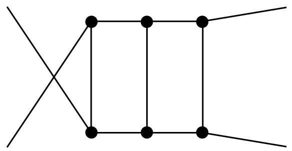
  EW+QCD:1.3% ($\overline{MS}, \alpha(M_z)$) (Q.F.Sun, Phys.Rev.D 96,051301(2017))
- EW+EW: ~1% (arXiv:1906.05379) (25377 diagrams(arXiv:2102.15213))

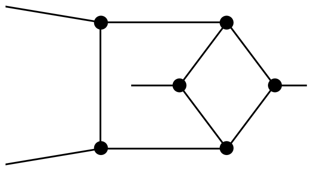
  challenging type: 2250 diagrams with 7 denominators, 4 independent mass scale, 2 independent energy scale

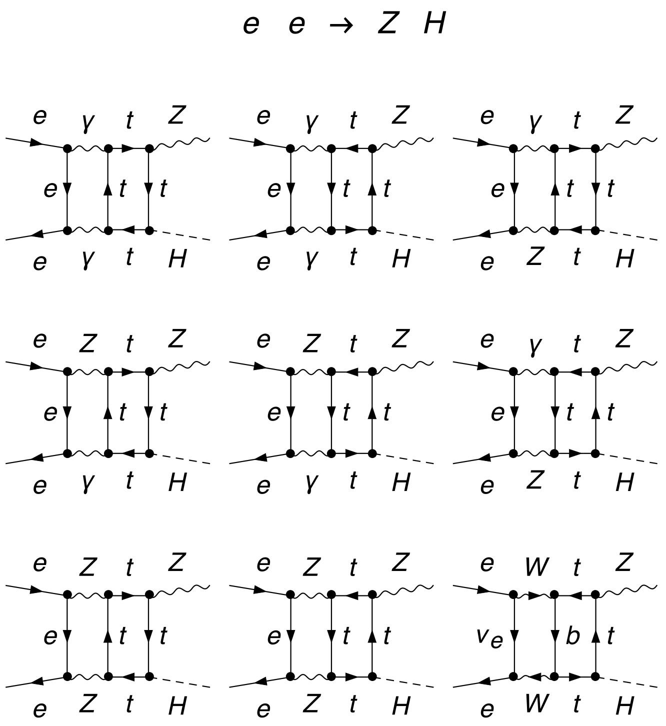
  diagrams with closed fermion loop dominant due to large top-quark Yukawa coupling and large number of fermions in SM

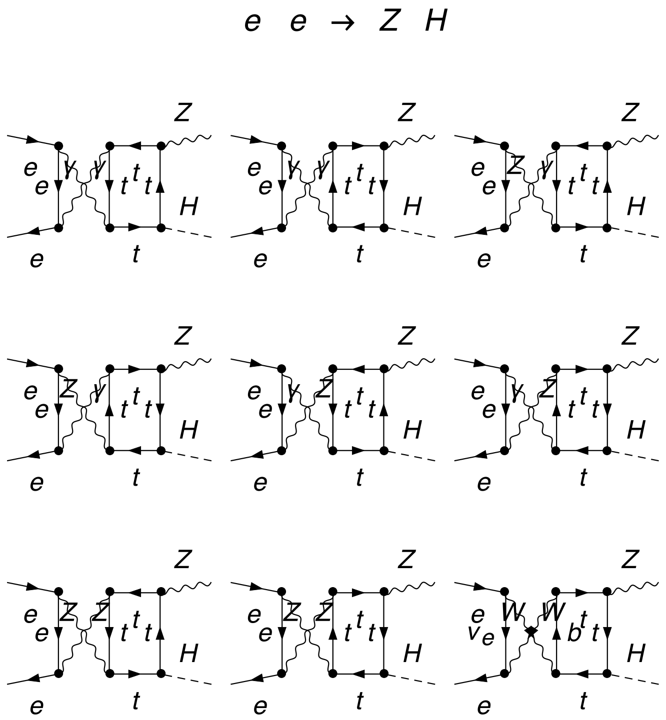
  → planar & Non-planar diagrams with closed top-quark loop (18+9)

1. Introduction

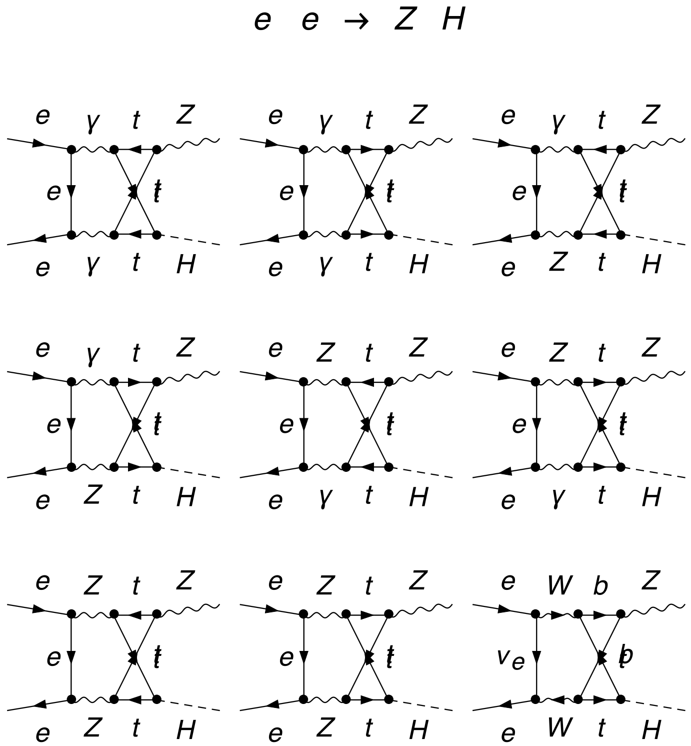








Planar double-box diagrams



Non-planar double-box diagrams

1. Introduction

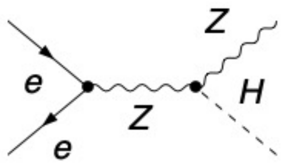
- Analytical calculation: can be done for 1-loop, but difficult in 2-loop: require more knowledge about special functions(harmonic polylogarithmic functions, iterated elliptic integrals)
- Numerical calculation: use Feynman parametrization. Box diagram is equal to integration over 6 Feynman parameters. It requires large computing resources and takes few days because the integrand converges slowly

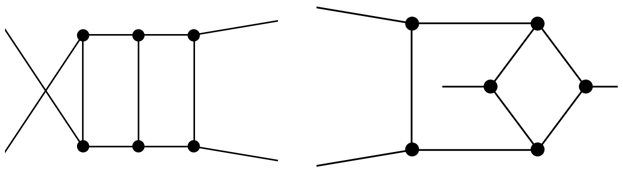
(F. Yuasa et al; Comput. Phys. Commun. 183, 2136-2144 (2012))

$$I_{planar} = -\int_0^1 d\rho \int_0^1 d\xi \int_0^1 du_1 \int_0^{1-u_1} du_2 \int_0^1 du_3 \int_0^{1-u3} du_4 \, \frac{\mathcal{C}}{(\mathcal{D} - i\epsilon\mathcal{C})^3} \rho^3 \xi^2 (1-\xi)^2,$$

- Our method: simplify the integrand with Feynman parametrization and dispersion relation. The box diagram is reduced to 3-fold integration, which takes few minutes to calculate.

1. Introduction





- Feynman diagrams → FeynArts (T. Hahn, Comput. Phys. Commun. 140, 418 (2001). [hep-ph/0012260])
- Square amplitude → FeynCalc (UV finite,dim=4)

(V. Shtabovenko, R. Mertig and F. Orellana, "FeynCalc 9.3: New features and improvements", arXiv:2001.04407.)

$$M_0 M_2^* = \iiint dx\,dy\,d\sigma\,(\ldots)$$

- (…) → dispersion relation and Feynman parameterization(Mathematica)
- Numerical calculation → C++, LoopTools, Gauss-Kronrod quadrature In Boost package

(Comput.Phys.Commun.118(1999)153)

(https://www.boost.org/doc/libs/master/libs/math/doc/html/index.html)

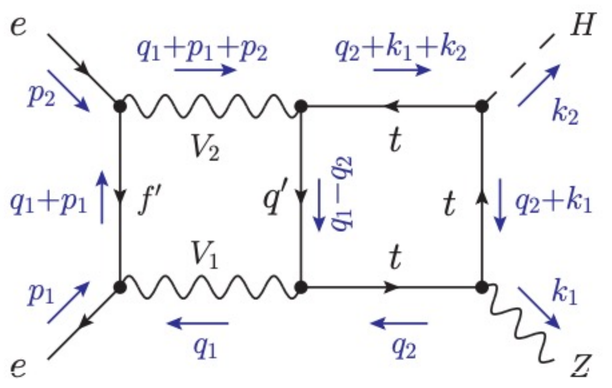
2. Evaluation Method – planar diagram

According to Feynman rules, the amplitude for planar diagram can be written as I_{plan}.
Use Feynman parametrization to simplify the denominators only involve q2

$$I_{plan} = \int d^D_{q_1} d^D_{q_2} \frac{1}{(q_1^2 - m_{V_1}^2)((q_1+p_1)^2 - m_{f'}^2)((q_1+p_1+p_2)^2 - m_{V_2}^2)(q_1-q_2)^2 - m_{q'}^2}$$

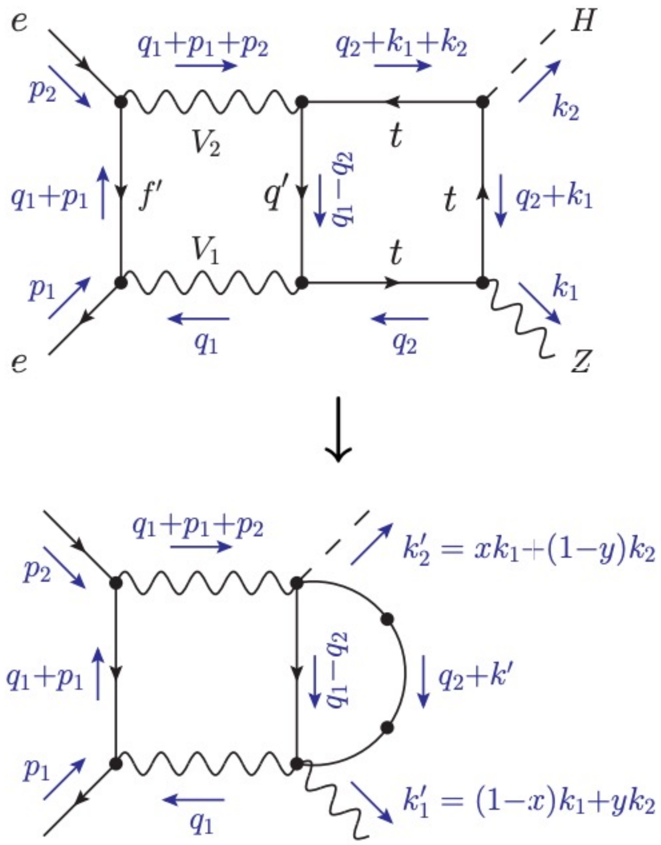
$$\underbrace{\frac{1}{(q_2^2 - m_t^2)((q_2+k_1)^2 - m_t^2)((q_2+k_1+k_2)^2 - m_t^2)}}_{\int_0^1 dx \int_0^{1-x} dy \frac{1}{((q_2+k')^2 - m'^2)^3} = \int_0^1 dx \int_0^{1-x} dy \partial^2_{m'^2} \frac{1}{(q_2+k')^2 - m'^2}}$$

$$\text{Feynman parametrizaiton:} \frac{1}{abc} = \int_0^1 dx \int_0^{1-x} dy \frac{1}{(ax+by+c(1-x-y))^3}$$



2. Evaluation Method – planar diagram

$$I_{plan} = \int_0^1 dx \int_0^{1-x} dy \partial^2_{m'^2} \int d^D_{q_1} d^D_{q_2} \frac{1}{(q_1^2 - m_{V_1}^2)((q_1+p_1)^2 - m_{f'}^2)((q_1+p_1+p_2)^2 - m_{V_2}^2)}$$
$$\frac{1}{((q_1-q_2)^2 - m_{q'}^2)} \frac{1}{(q_2+k')^2 - m'^2}$$
$$= \int_0^1 dx \int_0^{1-x} dy \partial^2_{m'^2} \int d^D_{q_1} \frac{B_0((q_1+k')^2, m_{q'}^2, m'^2)}{(q_1^2 - m_{V_1}^2)((q_1+p_1)^2 - m_{f'}^2)((q_1+p_1+p_2)^2 - m_{V_2}^2)}$$



Loop momentum q1 appears in B0 functions, so cannot integrate over q1.
→ use dispersion relation to put q1 outside B0 function

$$B_0(p_1, m_0, m_1) = \frac{(2\pi\mu)^{4-D}}{i\pi^2} \int d^D q \frac{1}{q^2 - m_0^2 + i\epsilon} \frac{1}{(q+p_1)^2 - m_1^2 + i\epsilon}$$

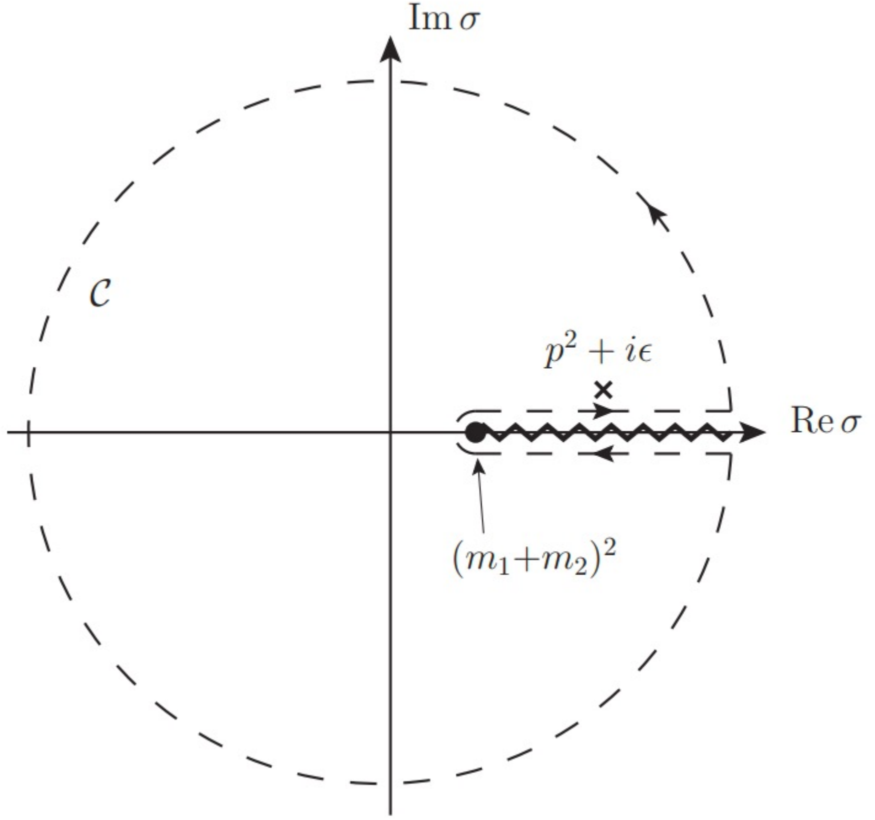
2. Evaluation Method – planar diagram

Residue theorem: $\oint f(z)dz = 2\pi i \sum_{k=1}^{n} Res(f, a_k)$

dispersion relation

$$B_0(p^2, m_1^2, m_2^2) = \frac{1}{\pi}\int_{\sigma_0}^{\infty} d\sigma \frac{ImB_0(\sigma, m_1^2, m_2^2)}{\sigma - p^2 - i\epsilon}$$

$$\begin{aligned}
B_0(p^2, m_1^2, m_2^2) &= \frac{1}{2\pi i}\oint_C d\sigma \frac{B_0(\sigma, m_1^2, m_2^2)}{\sigma - p^2 - i\epsilon} \\
&= \frac{1}{2\pi i}\left(\int_{\sigma_0}^{\infty} + \int_{c_1} + \int_{c_2} + \int_{\infty}^{\sigma_0}\right) d\sigma \frac{B_0(\sigma, m_1^2, m_2^2)}{\sigma - p^2 - i\epsilon} \\
&= \frac{1}{2\pi i}\int_{\sigma_0}^{\infty} d\sigma \frac{B_0(\sigma + i\delta, m_1^2, m_2^2)}{\sigma - p^2 - i\epsilon} + \int_{\infty}^{\sigma_0} d\sigma \frac{B_0(\sigma - i\delta, m_1^2, m_2^2)}{\sigma - p^2 - i\epsilon} \\
&= \frac{1}{2\pi i}\int_{\sigma_0}^{\infty} d\sigma \frac{B_0(z, m_1^2, m_2^2)}{\sigma - p^2 - i\epsilon} + \int_{\infty}^{\sigma_0} d\sigma \frac{B_0(z^*, m_1^2, m_2^2)}{\sigma - p^2 - i\epsilon} \\
&= \frac{1}{2\pi i}\int_{\sigma_0}^{\infty} d\sigma \frac{B_0(z, m_1^2, m_2^2) - B_0^*(z, m_1^2, m_2^2)}{\sigma - p^2 - i\epsilon} \\
&= \frac{1}{2\pi i}\int_{\sigma_0}^{\infty} d\sigma \frac{2iImB_0(z, m_1^2, m_2^2)}{\sigma - p^2 - i\epsilon} \\
&= \frac{1}{\pi}\int_{\sigma_0}^{\infty} d\sigma \frac{ImB_0(\sigma, m_1^2, m_2^2)}{\sigma - p^2 - i\epsilon}
\end{aligned}$$



S. Bauberger, F. A. Berends, M. B¨ohm and M. Buza, Nucl. Phys. B434, 383 (1995)[hep-ph/9409388]

2. Evaluation Method – planar diagram

Integrating over q1 gets the D0 function.
Use Leibiniz's rule to put the derivative inside the integral: ΔB_0 is divergent at the lower bound, it can be fixed by subtracting one term to make the integrand become 0 at the lower bound.

$$I_{plan} = \int_0^1 dx \int_0^{1-x} dy \partial^2_{m'^2} \int_{(m'+m_{q'})^2}^{\infty} d\sigma \int d^D_{q_1} \Delta B_0(s, m'^2, m^2_{q'})$$
$$\frac{1}{(q_1^2 - m^2_{V_1})((q_1+p_1)^2 - m^2_{f'})((q_1+p_1+p_2)^2 - m^2_{V_2})(s-(q_1+k')^2)}$$
$$= -\int_0^1 dx \int_0^{1-x} \partial^2_{m'^2} \int_{(m'+m_{q'})^2}^{\infty} d\sigma \Delta B_0(\sigma, m'^2, m^2_{q'}) D_0(p_1^2, p_2^2, k'^2_2, k'^2_1, s, t, m^2_{V_1}, m^2_{f'}, m^2_{V_2}, \sigma)$$

FeynCalc packge;
https://feyncalc.github.io/FeynCalcBook/guide/FeynCalc.html
TID function;
Tensor Integral Decomposition

Leibiniz's rule:

$$\frac{d}{dx}\left(\int_{a(x)}^{b(x)} f(x,t)dt\right) = \int_{a(x)}^{b(x)} \frac{\partial}{\partial x} f(x,t)dt + f(x,b(x))\frac{db(x)}{dx} - f(x,a(x))\frac{da(x)}{dx}$$

2. Evaluation Method – planar diagram

$$\partial^2_{m'^2}\int_{(m'+m_{q'})^2}^{\infty} d\sigma \Delta B_0(\sigma, m'^2, m^2_{q'})\left(D_0(...,\sigma) - \frac{\sigma_0}{\sigma}D_0(...,\sigma_0) + \frac{\sigma_0}{\sigma}D_0(...,\sigma_0)\right)$$

$$= \partial^2_{m'^2}\int_{(m'+m_{q'})^2}^{\infty} d\sigma \Delta B_0(\sigma, m'^2, m^2_{q'})\left(D_0(...,\sigma) - \frac{\sigma_0}{\sigma}D_0(...,\sigma_0)\right)$$

→ 0 at the lower bound, so derivative van be put inside the integral

$$+ \partial^2_{m'^2}\int_{(m'+m_{q'})^2}^{\infty} d\sigma \Delta B_0(\sigma, m'^2, m^2_{q'})\frac{\sigma_0}{\sigma}D_0(...,\sigma_0)$$

→ integrate over σ gives $B_0(0, m'^2, m^2_{q'})$ (dispersion relation)

$$I_{\text{plan}} = \int_0^1 dx \int_0^{1-x} dy \partial^2_{m'^2}\int_{(m'+m_{q'})^2}^{\infty} d\sigma \Delta B_0(s, m'^2, m^2_{q'}) D_0(p_1^2, p_2^2, k'^2_2, k'^2_1, s, t, m^2_{V_1}, m^2_{f'}, m^2_{V_2}, \sigma)$$

$$= \int_0^1 dx \int_0^{1-x} dy \int_{(m'+m_{q'})^2}^{\infty} d\sigma \partial^2_{m'^2} \Delta B_0(s, m'^2, m^2_{q'})\left(D_0(...,\sigma) - \frac{\sigma_0}{\sigma}D_0(...,\sigma_0)\right)$$

$$+ \int_0^1 dx \int_0^{1-x} dy \sigma_0 D_0(...,\sigma_0)\partial^2_{m'^2} B_0(0, m'^2, m^2_{q'})$$

2. Evaluation Method – planar diagram

If the numerator is not equal to 1, integrating over q2 gets B1,B00,B11 functions. They have same dispersion relation as B0.

For example, num = $p_1 \cdot q_2$

$$\text{num} = p_1 \cdot q_2, (p_1 \cdot q_2)(k_1 \cdot q_2)... \neq 1$$

$$\int d^D q_2 \frac{p_1 \cdot q_2}{(q_2^2 - m_{q'}^2)(q_2 + q_1 + k')^2 - m'^2} = p_{1\mu} \int d^D q_2 \frac{q_2^\mu}{(q_2^2 - m_{q'}^2)(q_2 + q_1 + k')^2 - m'^2}$$

$$= p_{1\mu} B_\mu((q_1 + k')^2, m'^2, m_{q'}^2)$$

$$= \underbrace{p_{1\mu}(p_1 + k')_\mu}_{p_1 \cdot (p_1 + k')} B_1((q_1 + k')^2, m'^2, m_{q'}^2) \Rightarrow \frac{p_1 \cdot (p_1 + k')}{\sigma - (q_1 + k')^2} \int d\sigma \Delta B_1$$

similarly,

$$\int d^D q_2 \frac{q_2^\mu q_2^\nu}{(q_2^2 - m_{q'}^2)(q_2 + q_1 + k')^2 - m'^2} \quad \Rightarrow B_{00}, B_{11} \Rightarrow \int d\sigma \Delta B_{00}, \int d\sigma \Delta B_{11}$$

$$\int d^D q_2 \frac{q_2^\mu q_2^\nu, q_2^\rho}{(q_2^2 - m_{q'}^2)(q_2 + q_1 + k')^2 - m'^2} \quad \Rightarrow B_{001}, B_{111} \Rightarrow \int d\sigma \Delta B_{001}, \int d\sigma \Delta B_{111}$$

2. Evaluation Method – non-planar diagram

Similarly, use Feynman parametrization to simplify the denominators including q2 and integrating loop momentum q2 gives B0 function

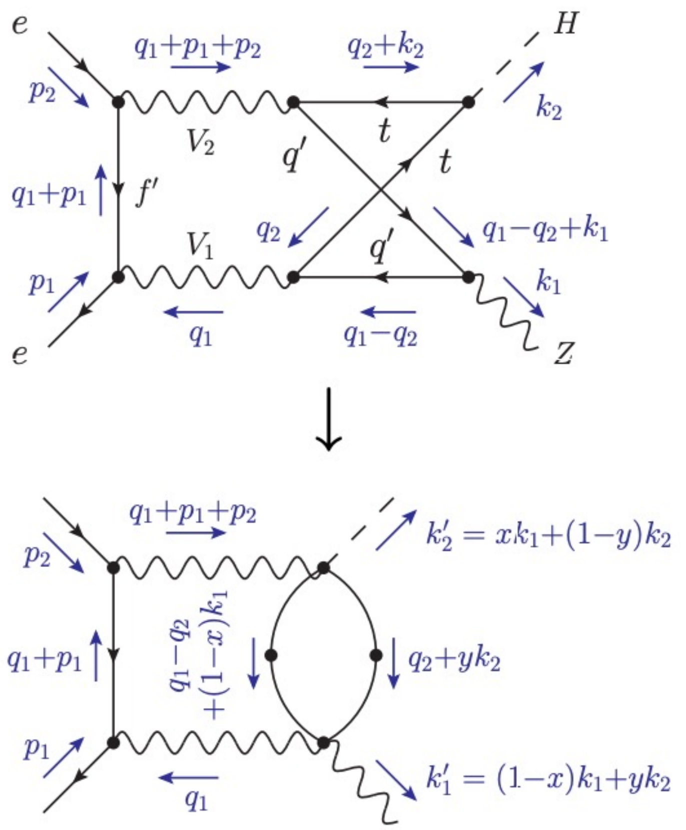
$$I_{NP} = \int d^D_{q_1} d^D_{q_2} \frac{1}{(q_1^2 - m_{V_1}^2)((q_1+p_1)^2 - m_{f'}^2)((q_1+p_1+p_2)^2 - m_{V_2}^2)}$$

$$\frac{1}{\underbrace{((q_1-q_2)^2 - m_{q'}^2)((q_1-q_2+k_1)^2 - m_{q'}^2)}_{\int_0^1 dx \partial_{m'^2_1} \frac{1}{(q_1-q_2+(1-x)k_1)^2 - m'^2_1}} \underbrace{(q_2^2 - m_t^2)((q_2+k_2)^2 - m_t^2)}_{\int_0^1 dy \partial_{m'^2_2} \frac{1}{(q_2+yk_2)^2 - m'^2_2}}}$$

$$= \int_0^1 dx \int_0^1 dy \partial_{m'^2_1} \partial_{m'^2_2} \int d^D_{q_1} B_0((q1 + (1-x)k_1 + yk_2)^2, m'^2_1, m'^2_2)$$

$$\frac{1}{(q_1^2 - m_{V_1}^2)((q_1+p_1)^2 - m_{f'}^2)((q_1+p_1+p_2)^2 - m_{V_2}^2)}$$

$$\frac{1}{ab} = \int_0^1 dx \frac{1}{(xa + (1-x)b)^2}$$

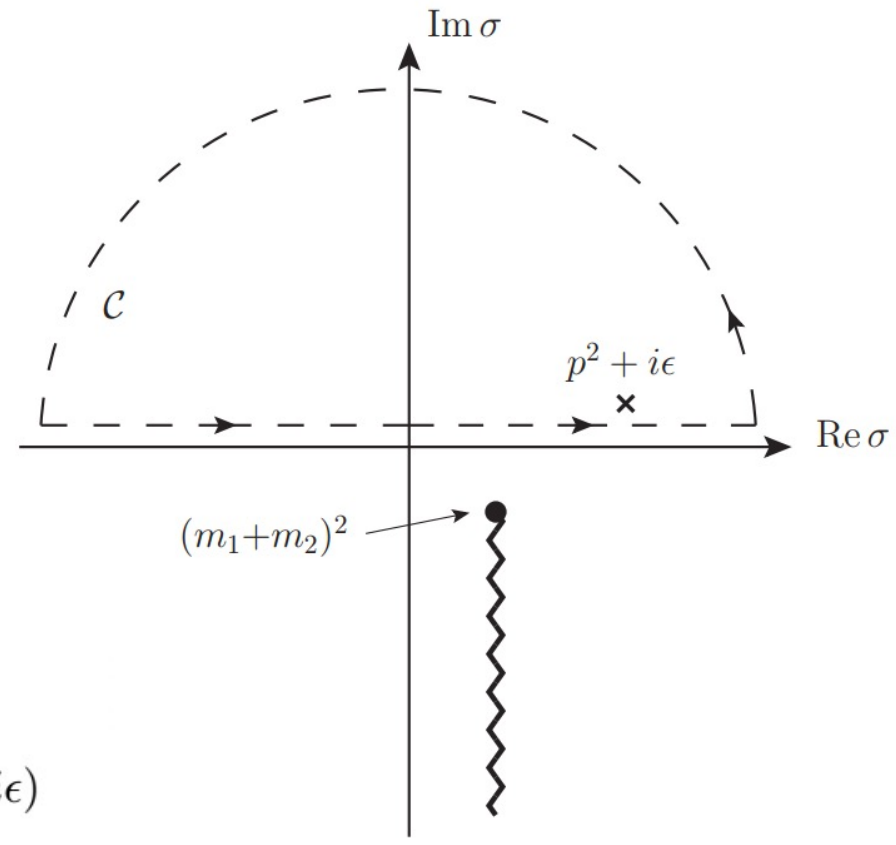


2. Evaluation Method – non-planar diagram

- For non-planar double box including $\gamma\gamma, \gamma Z, ZZ$, use the same dispersion relation as planar diagram $m_1'^2 = m_t^2 - x(1-x)m_Z^2 > 0$
- For non-planar double-box including WW:
  $m_1'^2 = m_b^2 - x(1-x)m_Z^2 < 0$
  Branch cut changes , we use a new dispersion relation

$$B_0(p^2, {m'}_1^2, {m'}_2^2) = \frac{1}{2\pi i}\oint_C d\sigma \frac{B_0(\sigma, {m'}_1^2, {m'}_2^2)}{\sigma - p^2 - i\varepsilon}$$

$$= \frac{1}{2\pi i}\int_{-\infty}^{\infty} d\sigma \frac{B_0(\sigma, {m'}_1^2, {m'}_2^2)}{\sigma - p^2 - i\epsilon}$$



$$I_{NP-WW} = \frac{-1}{2\pi i}\int_0^1 dx \int_0^1 dy \int_{-\infty}^{\infty} d\sigma \partial_{{m'}_1^2}\partial_{{m'}_2^2} B_0(\sigma, {m'}_1^2, {m'}_2^2) D0(..., \sigma - i\epsilon)$$

$B_1, B_{00}, B_{11}, B_{001}, B_{111}$

2. Evaluation Method

Feynman parametrization → $\int dx \int dy$; Dispersion relation → $\int d\sigma$

q_2 $\qquad$ q_1

$$I = \underbrace{\int dx \int dy \int d\sigma}_{\text{Gauss-kronrod quadrature(Boost)}} \underbrace{B_0(\sigma, m_1^2, m_2^2) \text{or} \Delta B_0(\sigma, m_1^2, m_2^2)}_{\text{analytical expression is known}} \times \underbrace{(c_A A_0 + c_B B_0 + c_C C_0 ...)}_{\text{LoopTools package}}$$

- Programming using C++
- Running time: few minutes to half an hour(non-planar WW)
- Advantages: low requirement of computer,

  short running time
- Precision: 4-digit, the precision is confined by the Looptools(double-precision)
- Stability: integrand is smooth, except 1) upper, lower bound of σ

  2) x = y for non-planar diagram

2. Evaluation Method

- Upper and lower bound of the integrand, $\delta\sim 10^{-3}, \Lambda\sim 10^{8}$
  $$\int_{\sigma_0}^{\infty} f(\sigma) = \left(\int_{\sigma_0}^{\sigma_0(1+\delta)} + \int_{\sigma_0(1+\delta)}^{\Lambda} + \int_{\Lambda}^{\infty} d\sigma\right) f(\sigma) \qquad \lim_{\sigma\approx\sigma_0} f \sim (\sigma-\sigma_0)^{-1/2}$$
  $$= \int_{\sigma_0(1+\delta)}^{\Lambda} f(\sigma) + 2\sigma_0\delta f(\sigma_0\delta) + \Lambda f(\Lambda) \qquad \lim_{\sigma\approx\infty} f \sim \sigma^{-2}$$
- For non-planar diagram, the Gram determinants(tensor decomposition arXiv:0812.2134[hep-ph])for some Passarino-Veltman tensor functions vanish when x is equal to y, and Looptools is not able to give a number.
  a) separate the integration region of x: (0,0.5) (0.5,1)
  b) separate the integration region of y: (0,x- δ),(x- δ,x+δ),(x+ δ,1) $\delta = 10^{-2,-3,\ldots}$
- For non-planar diagram with W bosons, $\sigma - i\epsilon, \epsilon\sim 10^{-9}|\sigma|$ or $\epsilon\sim 10^{-5}$

3. Result

Parameter	Value
M_Z	91.1876 GeV
M_W	80.379 GeV
M_H	125.1 GeV
m_t	172.76 GeV
α	$1/137$
E_{CM}	240 GeV
m_γ	10^{-6} GeV
θ	$\pi/2$

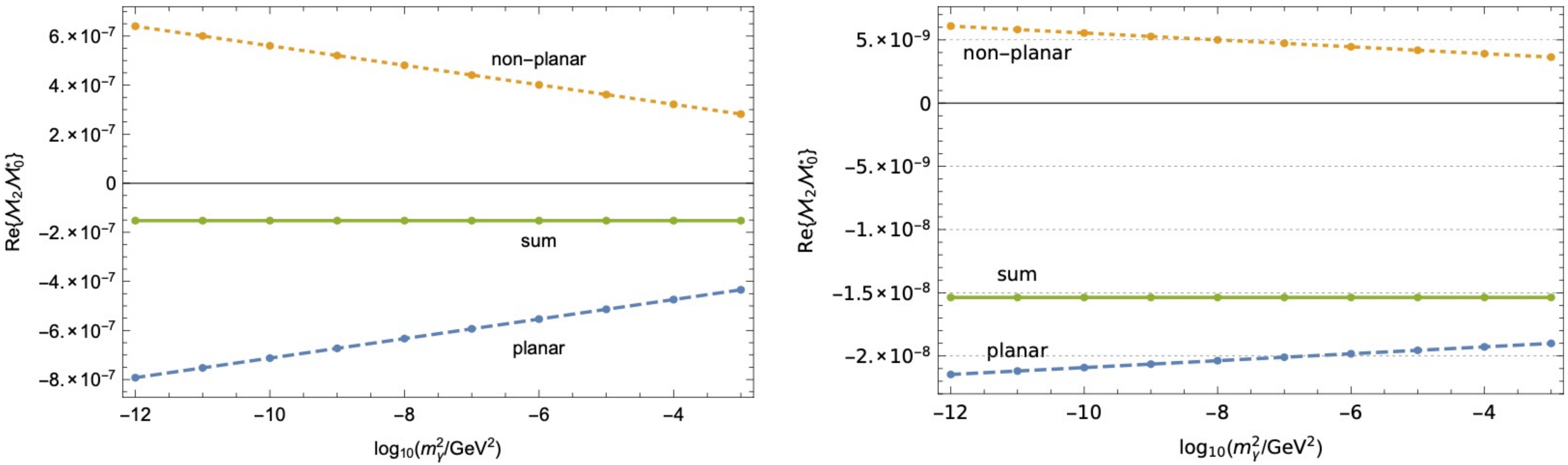
regulate the IR divergence,
no UV divergence

few minutes

V_1V_2 diagr. class	$\mathrm{Re}\{\mathcal{M}_2\mathcal{M}_0^*\}$
$\gamma\gamma$	$-1.524(1)\times10^{-7}$
γZ	$-1.537(1)\times10^{-8}$
ZZ planar	$-4.402(4)\times10^{-8}$
ZZ non-planar	$1.724(2)\times10^{-8}$
WW planar	$-1.1392(8)\times10^{-6}$
WW non-planar	$-5.577(5)\times10^{-7}$

~ 30 minutes

3. Result



Dependence of the $\gamma\gamma$(left) and γZ(right) two-loop boxes on the photon mass m_γ

3. Result

few minutes

Parameter	Value
M_Z	91.1876 GeV
M_W	80.379 GeV
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~ 30 minutes

regulate the IR divergence,
no UV divergence

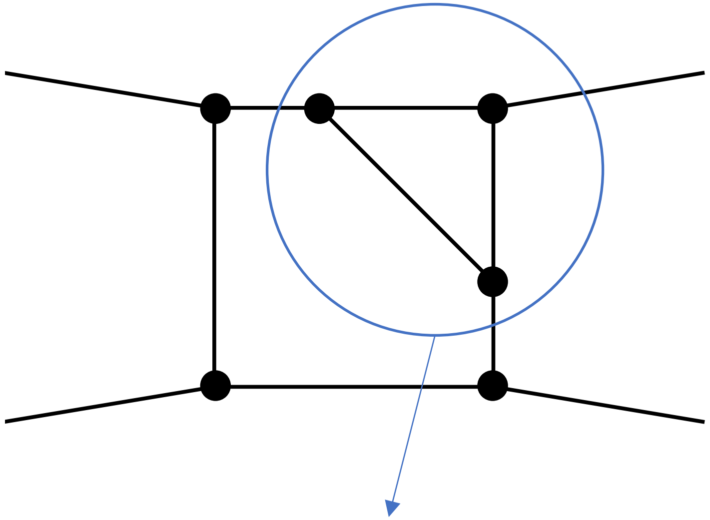
4. UV divergence

fermion propagator: $\frac{\gamma\cdot(q_2-p)+m_f}{((q_2-p)^2-m_f^2)}$

$\lim_{s\to\infty}\partial_{m_1^2} Im B_{001}(s;m_1,m_2)=const$ ← $\sim\int d^4q_2\frac{q_2^3}{q_2^6}=\int dq_2 1=\infty$

$\lim_{s\to\infty}\partial_{m_1^2} Im B_{00}(s;m_1,m_2)=const$ ← $\sim\int d^4q_2\frac{q_2^2}{q_2^6}=\int dq_2\frac{1}{q_2}=Ln(\infty)$

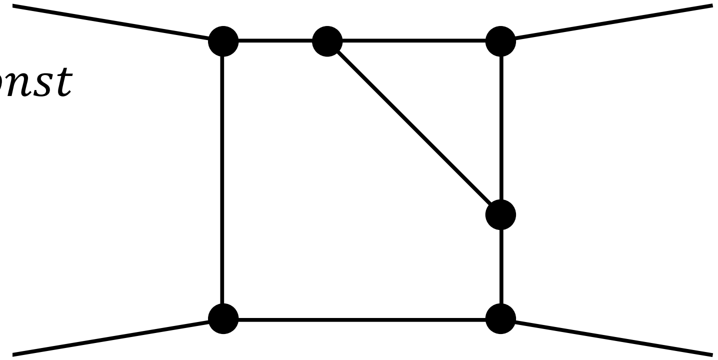
$$\int d^Dq_2\frac{q_2^\mu q_2^\nu}{(q_2^2-m_1^2)((q_2+p)^2-m_2^2)}\Rightarrow B_{00},B_{11}$$
$$\int d^Dq_2\frac{q_2^\mu q_2^\nu q_2^\rho}{(q_2^2-m_1^2)((q_2+p)^2-m_2^2)}\Rightarrow B_{001},B_{111}$$



Fermionic loop

4. UV divergence

$$\lim_{s\to\infty} \partial_{m_1^2} ImB_{00}(s; m_1, m_2) = const$$



$$T = \int_0^1 dx DM_1 B_{00}((q_1+p)^2, m_1^2, m_2^2) \frac{1}{q_1^2((q_1+p1)^2 - m_{V_1}^2)((q_1-p2)^2 - m_{V_2}^2)}$$

$$= \int_0^1 dx \int_{s0}^{\infty} ds \frac{-1}{\pi} \frac{ImDM_1B_{00}(s, m_1^2, m_2^2)}{(q_1+p)^2 - s} \frac{1}{q_1^2((q_1+p1)^2 - m_{V_1}^2)((q_1-p2)^2 - m_{V_2}^2)}$$

$$= \int_0^1 dx \int_{s0}^{\infty} ds \frac{-1}{\pi} ImDM_1B_{00}(s, m_1^2, m_2^2)\left(\frac{1}{(q_1+p)^2 - s} - \frac{1}{s} + \frac{1}{s}\right) \frac{1}{q_1^2((q_1+p1)^2 - m_{V_1}^2)((q_1-p2)^2 - m_{V_2}^2)}$$

$$= \int_0^1 dx \int_{s0}^{\infty} ds \frac{-1}{\pi} ImDM_1B_{00}(s, m_1^2, m_2^2)\left(\frac{1}{(q_1+p)^2 - s} + \frac{1}{s}\right) \frac{1}{q_1^2((q_1+p1)^2 - m_{V_1}^2)((q_1-p2)^2 - m_{V_2}^2)} \quad \rightarrow \quad \frac{1}{s^2}$$

$$+ \int_0^1 dx \int_{s0}^{\infty} ds \frac{-1}{\pi} ImDM_1B_{00}(s, m_1^2, m_2^2)\left(\frac{-1}{s}\right) \frac{1}{q_1^2((q_1+p1)^2 - m_{V_1}^2)((q_1-p2)^2 - m_{V_2}^2)}$$

$$\Rightarrow \int_0^1 dx DM_1 B_{00}(0, m_1^2, m_2^2)(C0(...))$$

$$= \int_0^1 dx DM_1 B_{00}(0, m_1^2, m_2^2)|_{finite}(C0(...)) + \int_0^1 dx DM_1 B_{00}(0, m_1^2, m_2^2)|_{div}(C0(...))$$

→ cancel with the CT

4. UV divergence

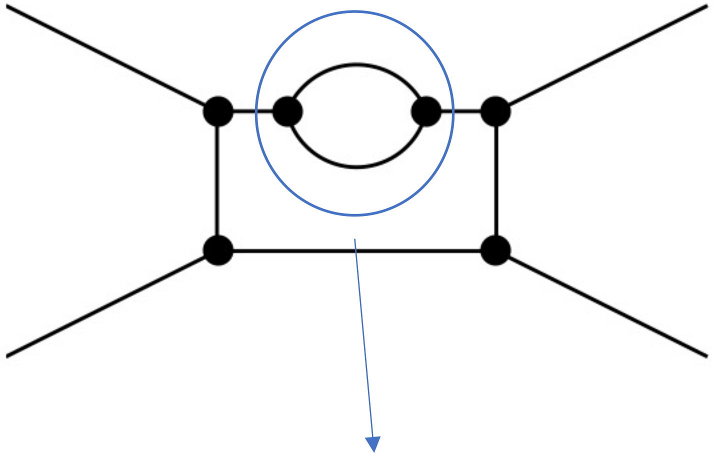
fermion propagator: $\frac{\gamma \cdot (q_2 - p) + m_f}{((q_2 - p)^2 - m_f^2)}$

$$\lim_{s \to \infty} ImB_{00}(s; m_1, m_2) = s \quad \leftarrow \quad \sim \int d^4 q_2 \frac{q_2^2}{q_2^4} = \int dq_2 q_2 = \infty$$

$$\lim_{s \to \infty} ImB_0(s; m_1, m_2) = const \quad \leftarrow \quad \sim \int d^4 q_2 \frac{q_2^1}{q_2^4} = \int dq_2 1 = \infty$$

$$\int d^D q_2 \frac{q_2^\mu}{(q_2^2 - m_1^2)((q_2 + p)^2 - m_2^2)} \Rightarrow B_0, B_1$$

$$\int d^D q_2 \frac{q_2^\mu q_2^\nu}{(q_2^2 - m_1^2)((q_2 + p)^2 - m_2^2)} \Rightarrow B_{00}, B_{11}$$



Fermionic loop

4. UV divergence

$$T = \int_0^1 dx B_{00}((q_1+p)^2, m_1^2, m_2^2) \frac{1}{q_1^2((q_1+p1)^2 - m_{V_1}^2)((q_1-p2)^2 - m_{V_2}^2)}$$

$$= \int_0^1 dx \int_{s0}^{\infty} ds \frac{-1}{\pi} \frac{ImB_{00}(s, m_1^2, m_2^2)}{(q_1+p)^2 - s} \frac{1}{q_1^2((q_1+p1)^2 - m_{V_1}^2)((q_1-p2)^2 - m_{V_2}^2)}$$

$$= \int_0^1 dx \int_{s0}^{\infty} ds \frac{-1}{\pi} ImB_{00}(s, m_1^2, m_2^2) (\frac{1}{(q_1+p)^2 - s} - \frac{1}{s - m_{V_1}^2} + \frac{1}{s - m_{V_1}^2} - \frac{(q_1+p)^2}{(s - m_{V_1}^2)^2} + \frac{(q_1-p)^2}{(s - m_{V_1}^2)^2})$$

$$\frac{1}{q_1^2((q_1+p1)^2 - m_{V_1}^2)((q_1-p2)^2 - m_{V_2}^2)}$$

$$= \int_0^1 dx \int_{s0}^{\infty} ds \frac{-1}{\pi} ImB_{00}(s, m_1^2, m_2^2) (\frac{1}{(q_1+p)^2 - s} + \frac{1}{s - m_{V_1}^2} + \frac{(q_1+p)^2}{(s - m_{V_1}^2)^2}) \longrightarrow \frac{1}{s^2}$$

$$\frac{1}{q_1^2((q_1+p1)^2 - m_{V_1}^2)((q_1-p2)^2 - m_{V_2}^2)}$$

$$+ \int_0^1 dx \int_{s0}^{\infty} ds \frac{-1}{\pi} ImB_{00}(s, m_1^2, m_2^2) (-\frac{1}{s - m_{V_1}^2} - \frac{(q_1+p)^2}{(s - m_{V_1}^2)^2}) \frac{1}{q_1^2((q_1+p1)^2 - m_{V_1}^2)((q_1-p2)^2 - m_{V_2}^2)}$$

4. UV divergence

$$\Rightarrow \int_0^1 dx B_{00}(m_{V_1}^2, m_1^2, m_2^2)(C0(...))$$

$$= \int_0^1 dx B_{00}(m_{V_1}^2, m_1^2, m_2^2)|_{finite}(C0(...)) + \int_0^1 dx DM_1 B_{00}(m_{V_1}^2, m_1^2, m_2^2)|_{div}(C0(...))$$

$$\Rightarrow \int_0^1 dx \int_{s0}^{\infty} ds \frac{1}{\pi} Im B_{00}(s, m_1^2, m_2^2)(\frac{d}{dm^2}\frac{1}{s-m^2})|_{m^2=m_{V_1}^2} \frac{(q_1+p)^2}{q_1^2((q_1+p1)^2 - m_{V_1}^2)((q_1-p2)^2 - m_{V_2}^2)}$$

$$= \int_0^1 dx (\frac{d}{dm^2} B_{00}(m^2, m_1^2, m_2^2))|_{m^2=m_{V_1}^2} \frac{(q_1+p)^2}{q_1^2((q_1+p1)^2 - m_{V_1}^2)((q_1-p2)^2 - m_{V_2}^2)}$$

$$= \int_0^1 DMB_{00}(m^2, m_1^2, m_2^2))|_{m^2=m_{V_1}^2} (b * B0(...) + c * C0(...) + ...)$$

$$= \int_0^1 DMB_{00}(m^2, m_1^2, m_2^2))|_{m^2=m_{V_1}^2}^{finite} (b * B0(...) + c * C0(...) + ...)$$

$$+ \int_0^1 DMB_{00}(m^2, m_1^2, m_2^2))|_{m^2=m_{V_1}^2}^{div} (b * B0(...) + c * C0(...) + ...)$$

cancel with the CT

5. Summary

- Double-box diagrams can be efficiently evaluated by Feynman parametrization and dispersion relation (For non-planar diagrams with 2 W bosons, dispersion relation is different from other diagrams)
- Takes few minutes for numerical calculation. For non-planar diagrams with 2 W bosons, takes half an hour.
- IR divergence is controlled by giving photon a small mass without loss of numerical precision.
- The evaluation method can also be applied for the calculation of electroweak corrections to other $2 \to 2$ process, such as $e^+e^- \to W^+W^-$

Thank you!