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Diphoton Production in pp Collision at NLO: Signal Analysis

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Outline:

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  - **Standard Model**
  - **Beyond Standard Model**
  - **Motivation behind studying diphoton channel**
- **Signal Analysis of the diphoton production:**
  - **Leading Order Calculations:**

    Higgs sub-production process

    Higgs decay sub-process

    Differential cross section of gg→H→ γγ
  - **Next to Leading order Calculations:**

    Effective vertices

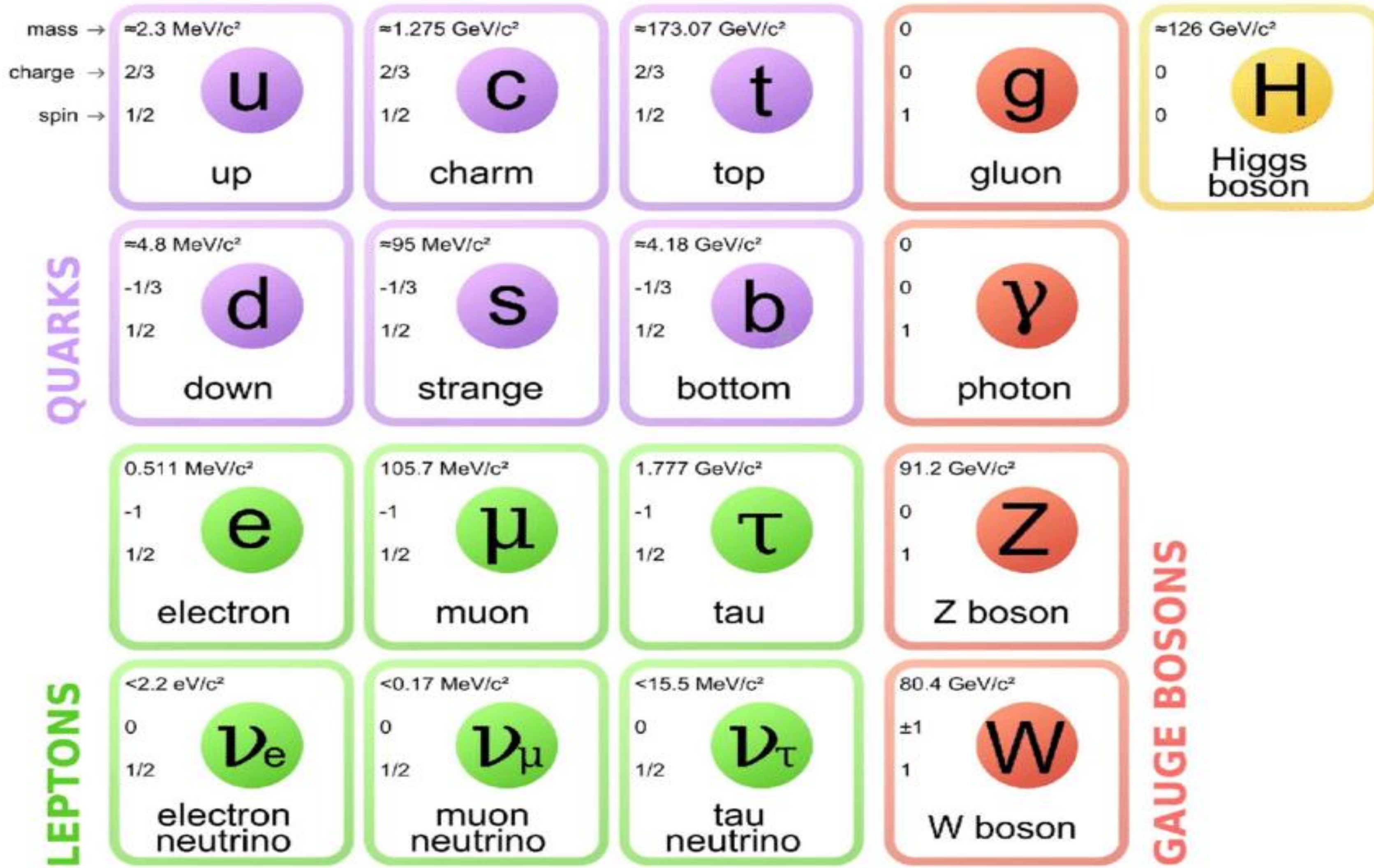
    Virtual Contributions

    Real Emission Contributions

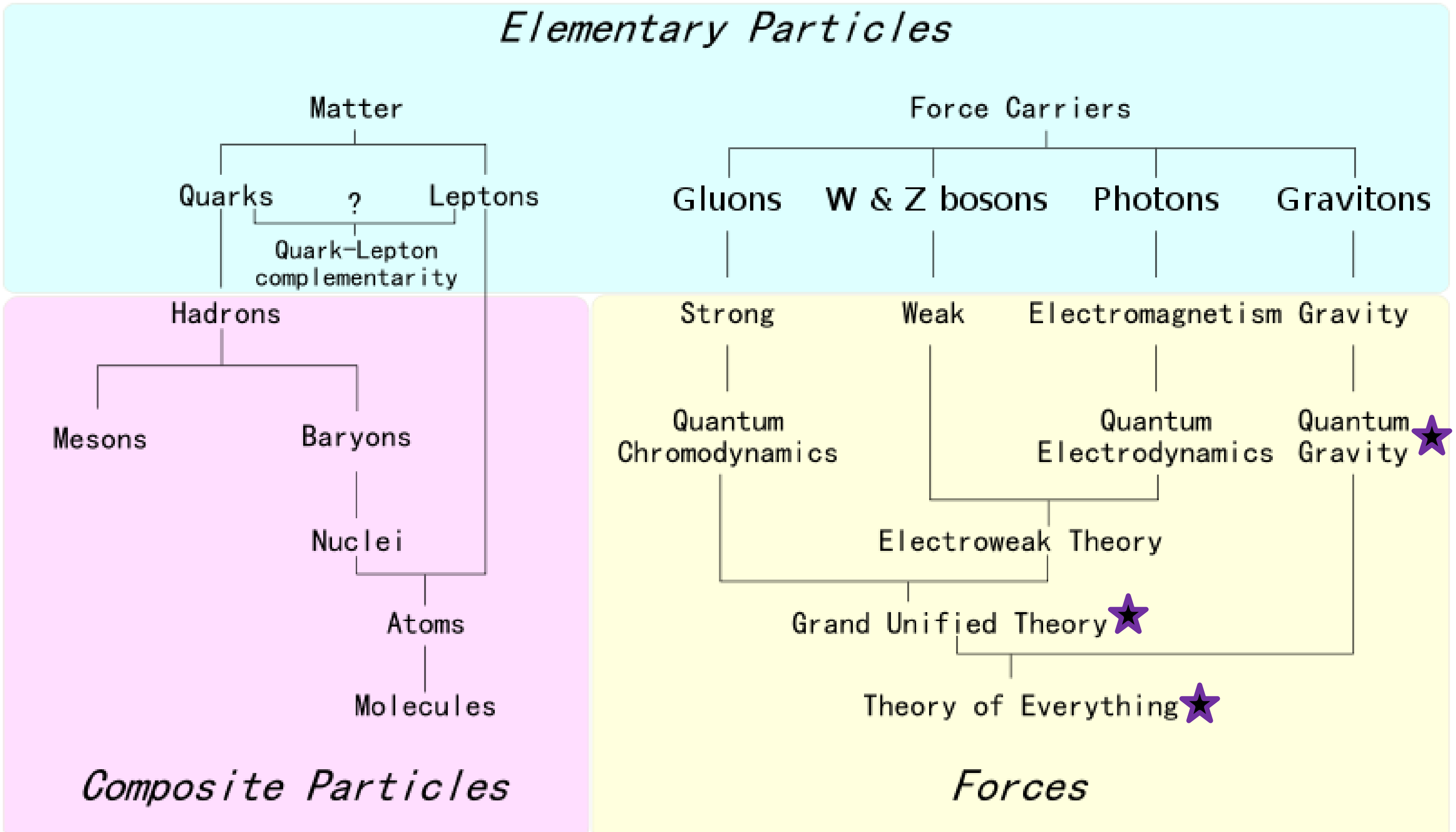
    NLO differential cross section
- **Conclusion**

Introduction:

Standard Model of Elementary Particles



Beyond Standard Model:



Experimental issues:

Dark Matter

Neutrino masses

Baryon Asymmetry

Cosmic Acceleration

Theoretical issues:

Unification

Quantum Gravity Inflation

Electroweak Scale

Vacuum energy...

What do we have in the future:

The Optimistic Scenario:

- ❑ **The Higgs (-Like) boson ≠ SM Higgs,**
- ❑ **Direct production of SUSY particles,**
- ❑ **Detection of Dark Matter, in the sky, underground and at the LHC..**

Motivation for studying diphoton final state:

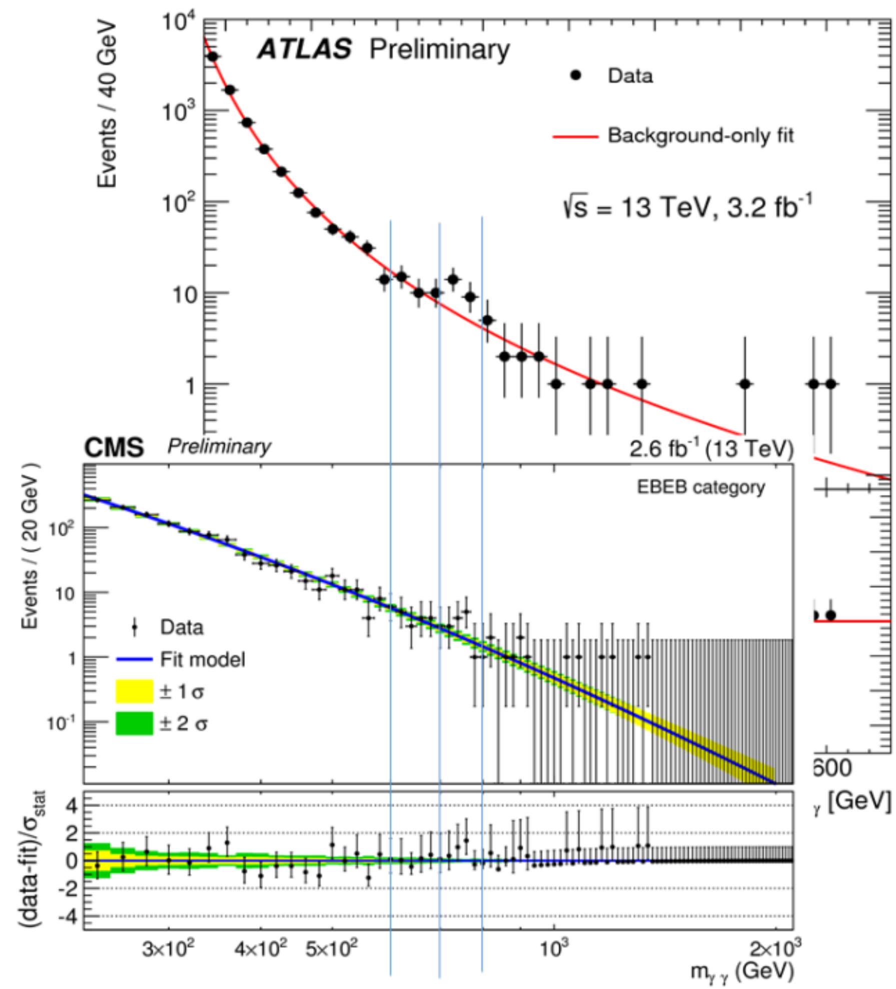
It is one of the important channels to study the physics beyond the Standard Model.

Plays a crucial role in the discovery of:

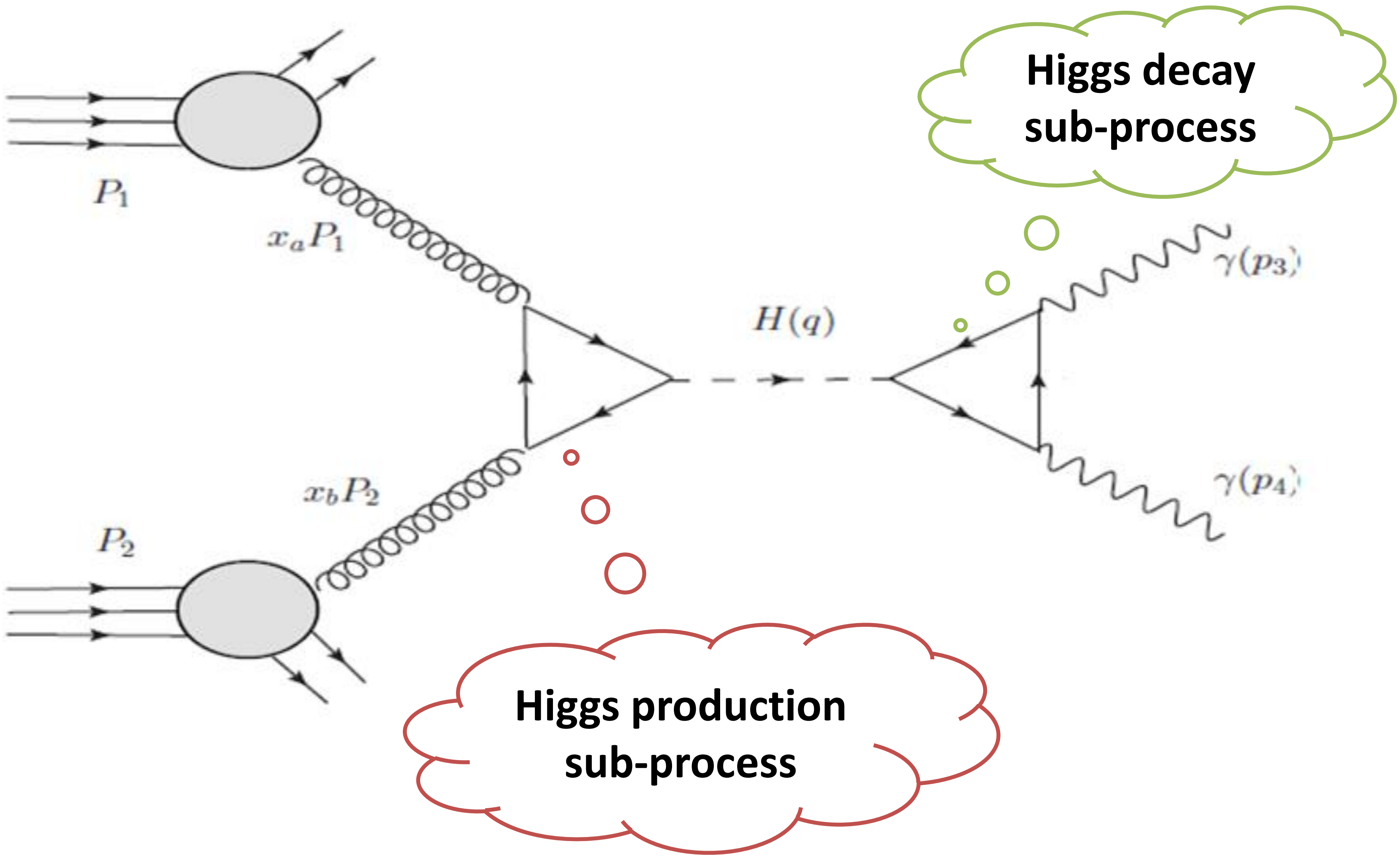
- **new bosons at the LHC,**
- **Heavy new particles and**
- **Searches for extra dimensions, etc.…**

In spring 2016 CMS and ATLAS recorded a new resonance in the diphoton spectrum with an invariant mass of 750 GeV.

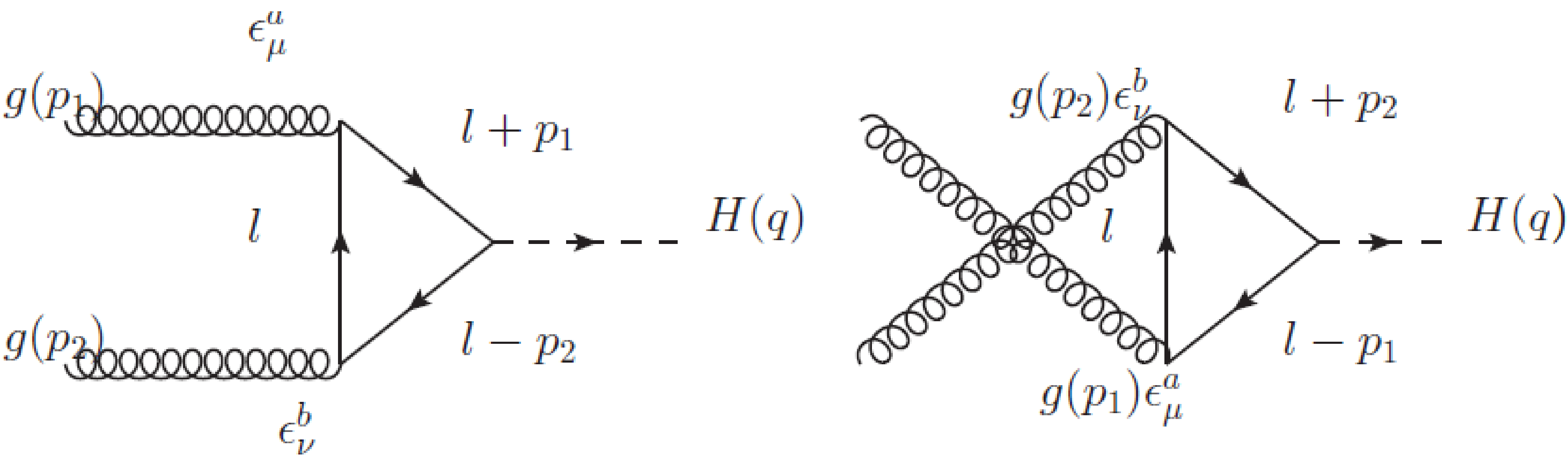
Higgs like particle



Lowest Order Calculations:



Higgs production sub-process:



$$M^{\mu\nu}_{ab} = g_s^2\left(\frac{m_q}{v}\right)\mu^\varepsilon Tr[T^aT^b]\int \frac{d^nl}{(2\pi)^n}\, Tr\left[\frac{\gamma^\mu(\not l+\not p_1+m_q)(\not l-\not p_2+m_q)\gamma^\nu(\not l+m_q)}{((l+p_1)^2-m_q^2+i\varepsilon)((l-p_2)^2-m_q^2+i\varepsilon)((l^2-m^2+i\varepsilon)}\right]$$
$$\times\, \epsilon^a_\mu(p_1)\epsilon^b_\nu(p_2), \qquad (3.1)$$

High momentum limits → **Ultra violet divergences**

↓

Dimensional Regularization

$$M_{ab}^{\mu\nu} = ig_s^2\mu^\varepsilon \frac{4}{(4\pi)^2}\frac{m_q^2}{v}\frac{\delta_{ab}}{2}\Big(g^{\mu\nu} - \frac{2p_1^\nu p_2^\mu}{M_H^2}\Big)\frac{M_H^2}{2m_q^2}\Big[2\frac{m_q^2}{M_H^2} + (1 - 4\frac{m_q^2}{M_H^2}J(\frac{m_q^2}{M_H^2})\Big]\epsilon_a^\mu\epsilon_b^\nu$$

$$= g_s^2\frac{i}{(4\pi)^2}\frac{gm_q^2}{M_w}\delta_{ab}\epsilon_a^\mu\epsilon_b^\nu\Big(g^{\mu\nu} - \frac{2p_1^\nu p_2^\mu}{M_H^2}\Big)\frac{M_H^2}{2m_q^2} \times \sum_q F(z).$$

Eq. 1

with $F(z) = 2z + (1 - 4z)J(z),$

where $J(z) = -\frac{z}{2}\log^2(1 - \frac{1}{x_1}).$

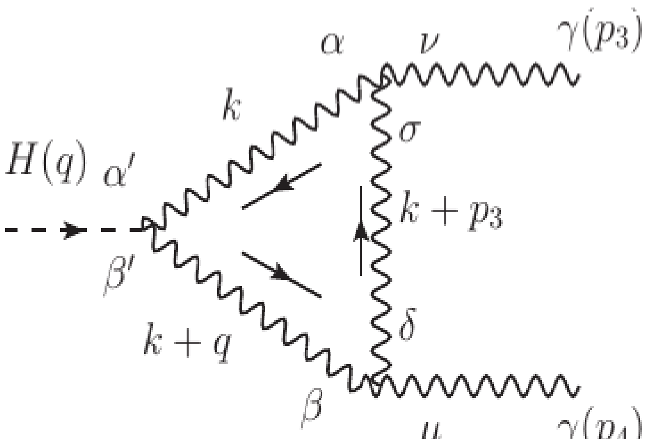
and $g = 2\frac{M_w}{v}$ where M_w is the W boson mass.

Finally, we defined the effective vertex of the process gg → H considering only a top quark loop as:

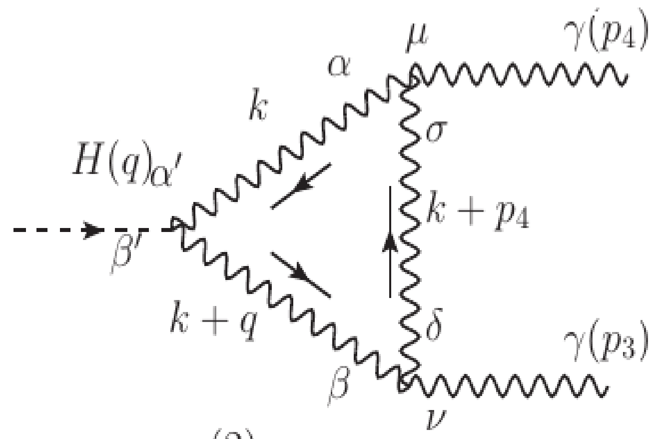
$$\boxed{V_{ab}^{\mu\nu} = \frac{g}{2\pi}\frac{M_H^2}{M_w}\Big(g^{\mu\nu} - \frac{2p_1^\nu p_2^\mu}{M_H^2}\Big)\alpha_s\frac{i\delta_{ab}}{2}F(\frac{m_t^2}{M_H^2}).}$$

Eq. 2

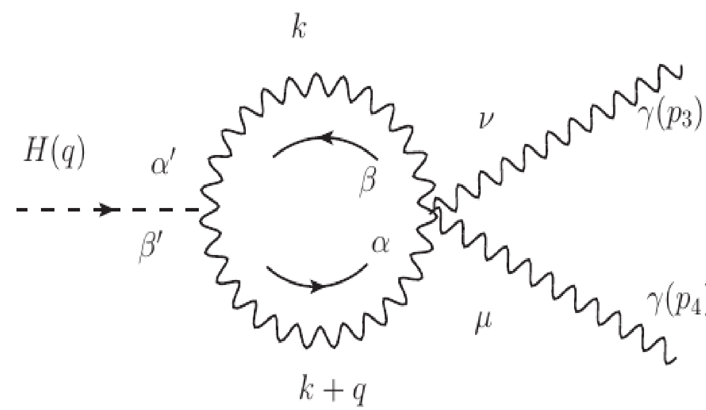
Higgs decay sub-process:



(1)



(2)



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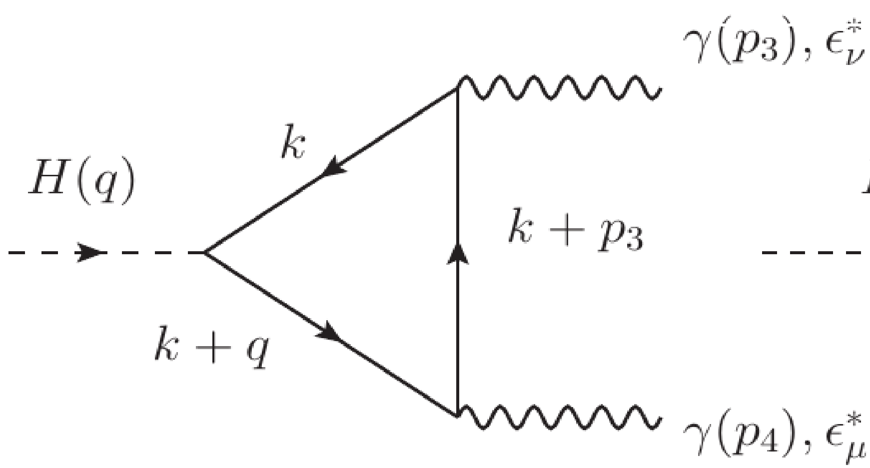
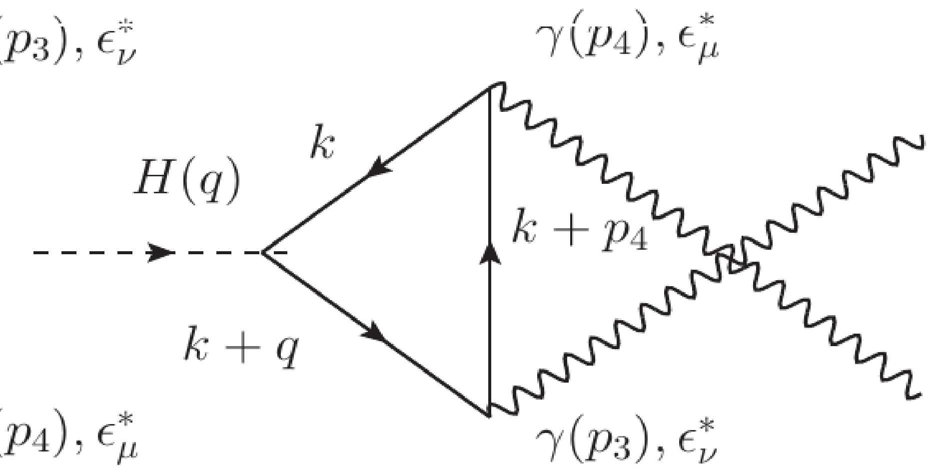




Higgs decay via W boson loop:

$$T = i\frac{M_H^2}{M_w}\frac{g}{2\pi}\alpha\left(g^{\mu\nu} - \frac{2p_3^\mu p_4^\nu}{M_H^2}\right)\frac{1}{2}G(z_w)\epsilon_\mu^*(p_4)\epsilon_\nu^*(p_3),$$

Eq.3

Taking $g = \frac{2M_w}{v}$ and $\alpha = \frac{e^2}{(4\pi)}$; $z_w = \frac{M_w^2}{M_H^2}$ and $G(z_w) = 1 + 6z_w + 6(1 - 2z_w)J(z_w)$.

Higgs decay via fermion loop:

$$T_f = \frac{g}{2\pi}\frac{M_H^2}{M_w}\left(g^{\mu\nu} - \frac{2p_4^\nu p_3^\mu}{M_H^2}\right)i\alpha\epsilon_\mu^*(p_4)\epsilon_\nu^*(p_3)\left(N_c\sum_q Q_q^2 F(\frac{m_q^2}{M_H^2}) + \sum_l Q_l^2 F(\frac{m_l^2}{M_H^2})\right),$$

Eq. 4

Total amplitude of Higgs decay into two photons:

$$\boxed{V^{\mu\nu} = i\frac{g}{2\pi}\frac{M_H^2}{M_w}\left(g^{\mu\nu} - \frac{2p_4^\nu p_3^\mu}{M_H^2}\right)\alpha \times \left[N_c\sum_q Q_q^2 F(\frac{m_q^2}{M_H^2}) + \sum_l Q_l^2 F(\frac{m_l^2}{M_H^2}) + \frac{1}{2}G(\frac{m_w^2}{M_H^2})\right].}$$

Eq. 5

Differential cross section of the diphoton production process:

$$M = \Big[\frac{g}{2\pi}\frac{M_H^2}{M_w}\Big(g^{\alpha\beta} - \frac{2p_4^\alpha p_3^\beta}{M_H^2}\Big)\alpha i[N_c\sum_q Q_q^2 F(z_q) + \sum_l Q_l^2 F(z_l) + \frac{1}{2}G(z_w)]\Big]$$
$$\Big[\frac{i}{(q^2 - M_H^2 + i\Gamma_H M_H)}\Big]\Big[\frac{g}{2\pi}\frac{M_H^2}{M_w}\Big(g^{\mu\nu} - \frac{2p_1^\nu p_2^\mu}{M_H^2}\Big)\alpha_s i\frac{\delta_{ab}}{2}[N_c\sum_q F(z_q)]\Big]$$
$$\times\ \epsilon^\mu_{a,\lambda_1}(p_1)\epsilon^\nu_{b,\lambda_2}(p_2)\epsilon^{*\alpha}_{\lambda_3}(p_3)\epsilon^{*\beta}_{\lambda_4}(p_4).$$

$$\overline{|M|}^2 = \frac{1}{2^2}\frac{1}{(N_c^2-1)^2}\sum_{pol.}^{2}\sum_{a,b}^{N_c^2-1} M^2.$$

$$\overline{|M|}^2 = \frac{1}{16\pi^2(N_c^2-1)}\frac{\alpha^4\alpha_s^2}{\sin^4(\theta_w)}\frac{\hat{s}^4}{M_w^4}\frac{1}{((\hat{s}-M_H^2)^2+\Gamma_H^2 M_H^2)^2}$$
$$|(\hat{s}^2 - M_H^2 - i\Gamma_H M_H)F(z_q)\Big(2N_c\sum_q Q_q^2 F(z_q) + 2\sum_l Q_l^2 F(z_l) + G(z_w)\Big)|^2.$$

Eq. 6

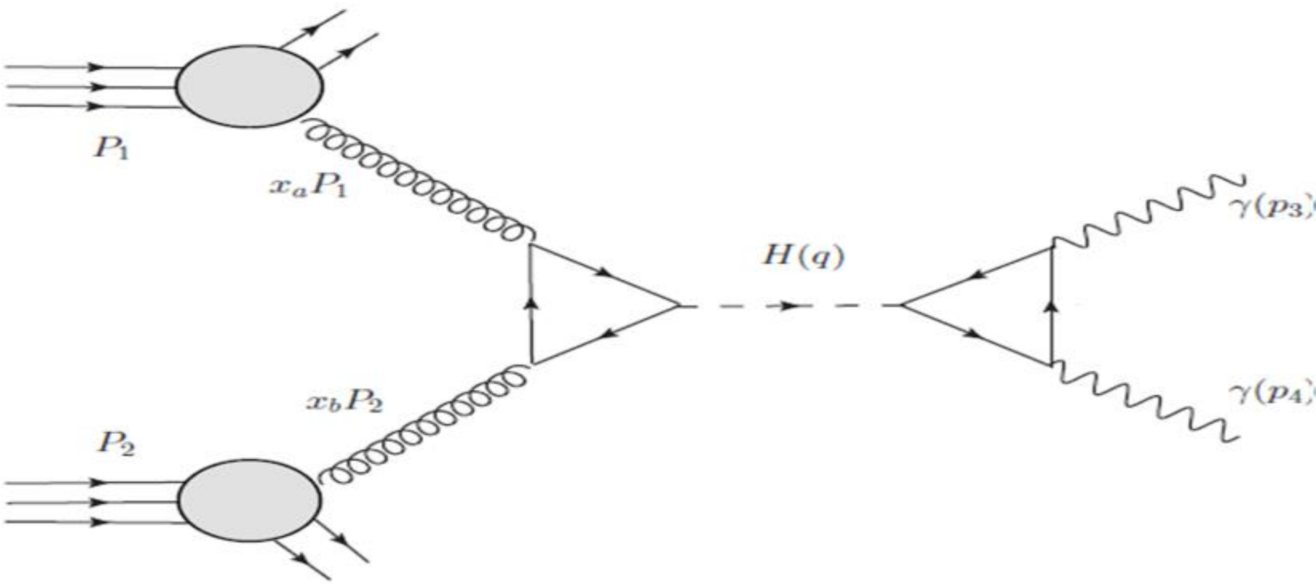
Then the partonic differential cross section as a function of the diphoton invariant mass reads:

$$\frac{d\hat{\sigma}}{dM_{\gamma\gamma}^2} = \frac{1}{4p_1.p_2}\frac{1}{(2\pi)^2}\int\frac{d^3\vec{p_3}}{2E_3}\frac{d^3\vec{p_4}}{2E_4}\delta^4(p_1+p_2-p_3-p_4)\delta(\hat{s}-M_{\gamma\gamma}^2)\overline{|M|}^2$$
$$= \frac{1}{2\hat{s}}\frac{1}{(2\pi)^2}\int\frac{d^3\vec{p_3}}{2E_3}\delta^+((p_1+p_2-p_3)^2)\delta(\hat{s}-M_{\gamma\gamma}^2)\overline{|M|}^2$$
$$= \frac{1}{2\hat{s}}\frac{1}{(2\pi)^2}\int\frac{d^3\vec{p_3}}{2E_3}\delta^+(\hat{s}-2[(E_1+E_2)E_3-(p_{1_L}+p_{2_L})p_{3_L}])\delta(\hat{s}-M_{\gamma\gamma}^2)\overline{|M|}^2.$$

Eq. 7

Hadronic differential cross section:

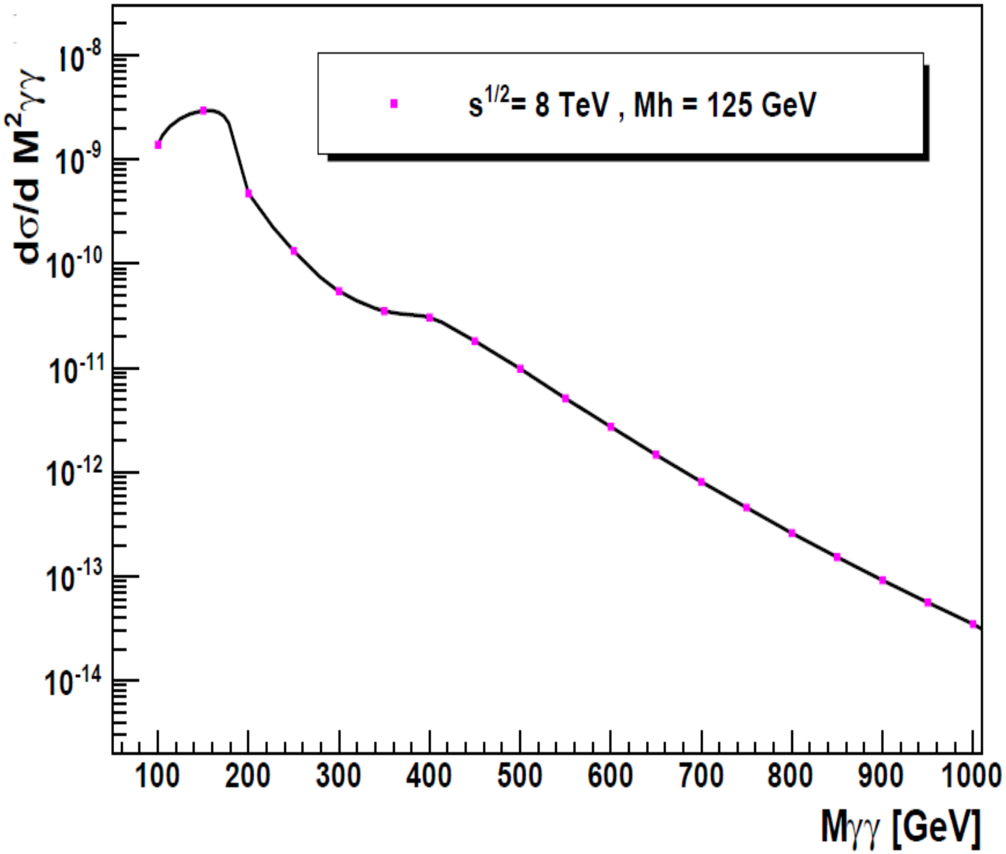
$$d\sigma_{had} = \int dx_a \int dx_b f(x_a) f(x_b) d\hat{\sigma}_{part},$$

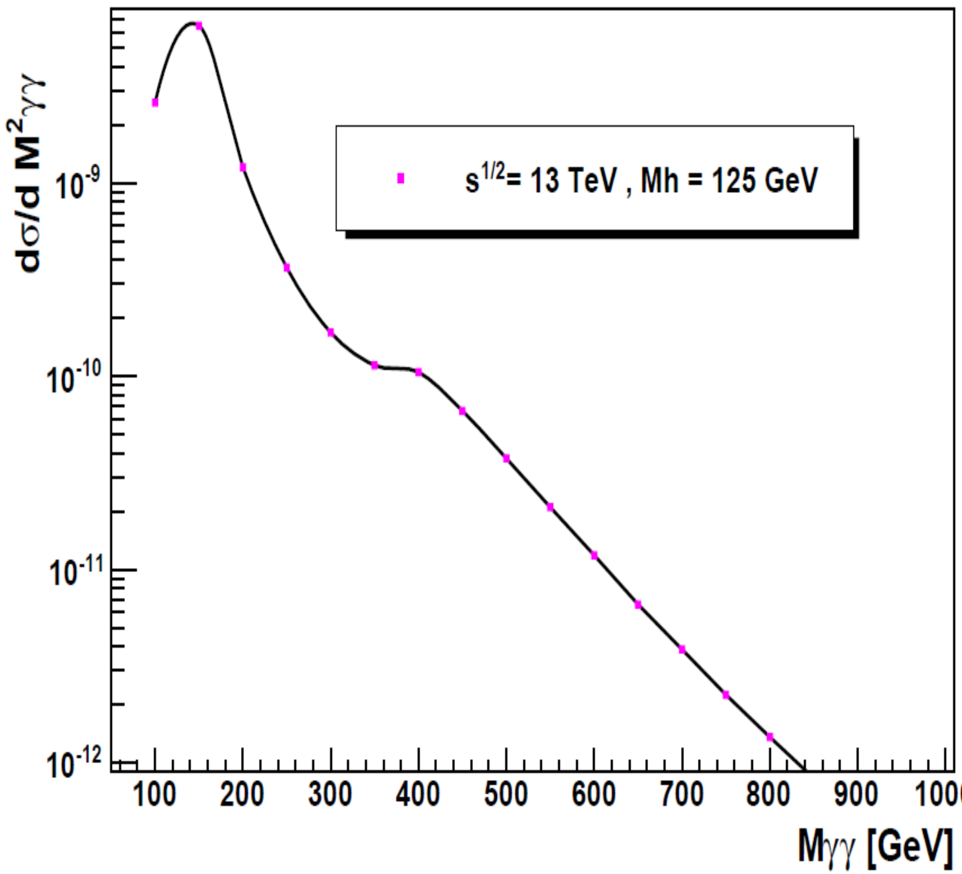


$$\frac{d\sigma}{dM^2_{\gamma\gamma}} = \frac{s^2}{128\pi^3(N_c^2-1)} \frac{\alpha^4\alpha_s^2}{\sin^4(\theta_w)} \frac{|Z|^2}{M_w^4}$$
$$\sum_{a,b} \int dy_3 du_1 f_{g_a}(x_a, M^2) f_{g_b}(x_b, M^2) \frac{1}{(x_a^2 e^{-2y_3} + x_b^2 e^{2y_3} + 2\tau) x_a} \frac{\tau^4}{((\tau * s - M_H^2)^2 + \Gamma_H^2 M_H^2)^2}.$$

Eq. 8

$$Z = (\tau * s - M_H^2 - i\Gamma_H M_H) \sum_q F(z_q)(2N_c \sum_q Q_q^2 F(z_q) + 2\sum_l Q_l^2 F(z_l) + G(z_w))$$


$d\sigma/d\,M^2\gamma\gamma$
$s^{1/2}$= 8 TeV , Mh = 125 GeV
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
100 200 300 400 500 600 700 800 900 1000
$M\gamma\gamma$ [GeV]

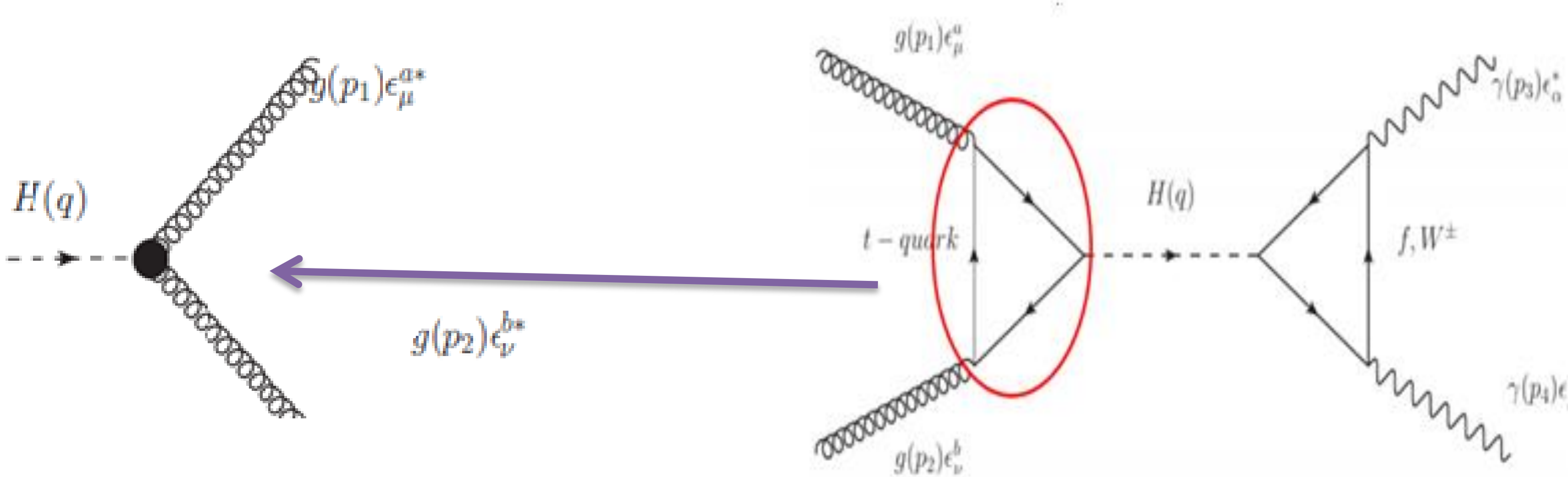

$d\sigma/d\,M^2\gamma\gamma$
$s^{1/2}$= 13 TeV , Mh = 125 GeV
10^{-9}
10^{-10}
10^{-11}
10^{-12}
100 200 300 400 500 600 700 800 900 1000
$M\gamma\gamma$ [GeV]

Heavy top quark limits:

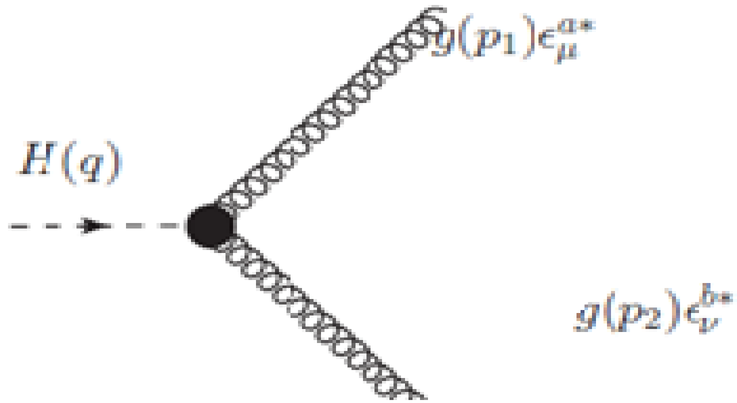
In the limit where $m_t >> M_H$ → the fermion loop effectively becomes a point interaction,

Interactions of Higgs boson with 2,3,&4 gluons will be encoded in the effective Lagrangian.

ggH effective vertex: $$V_{ab}^{\mu\nu} = -\frac{\alpha_s}{3\pi v}\left(p_1 . p_2 g^{\mu\nu} - p_2^{\mu} p_1^{\nu}\right)\delta^{ab}.$$



LO of Higgs production sub-process in ET:



$$\overline{|M_0|}^2 = \frac{1}{(n-2)}\frac{1}{(N_c^2-1)}\frac{\alpha_s^2}{9\pi^2 v^2}\left(\frac{4\pi}{m_t^2}\right)^\varepsilon \Gamma(1+\varepsilon)$$
$$= \frac{\alpha_s^2}{576\pi^2 v^2} M_H^4 \left(\frac{4\pi}{m_t^2}\right)^\varepsilon \Gamma(1+\varepsilon)(1+\varepsilon)$$

Eq. 9

LO differential cross section: $d\sigma_0 = \frac{1}{2s}\overline{|M_0|}^2 \frac{d^{n-1}q}{(2\pi)^{n-1}2E_H}(2\pi)^n \delta^n(p_1+p_2-q).$

Eq. 10

LO cross section of Higgs production sub-process in the infinite top quark mass limit: $\sigma_0 = \frac{1}{2s}\overline{|M^0_{H\to\gamma\gamma}|}^2 2\pi\delta(\hat{s}-M_H^2)$

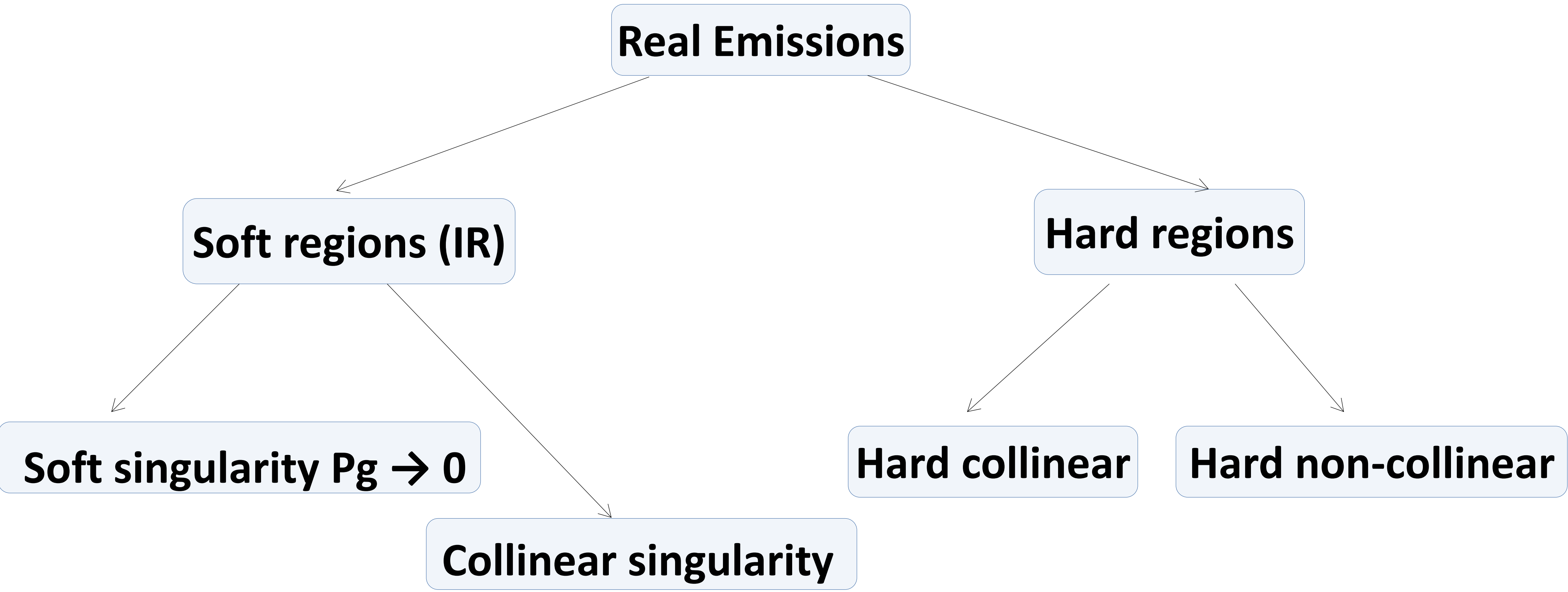
$$= \frac{\alpha_s^2}{576\pi^2 v^2} M_H^2 \left(\frac{4\pi}{m_t^2}\right)^\varepsilon \Gamma(1+\varepsilon)(1+\varepsilon)\delta(\hat{s}-M_H^2).$$

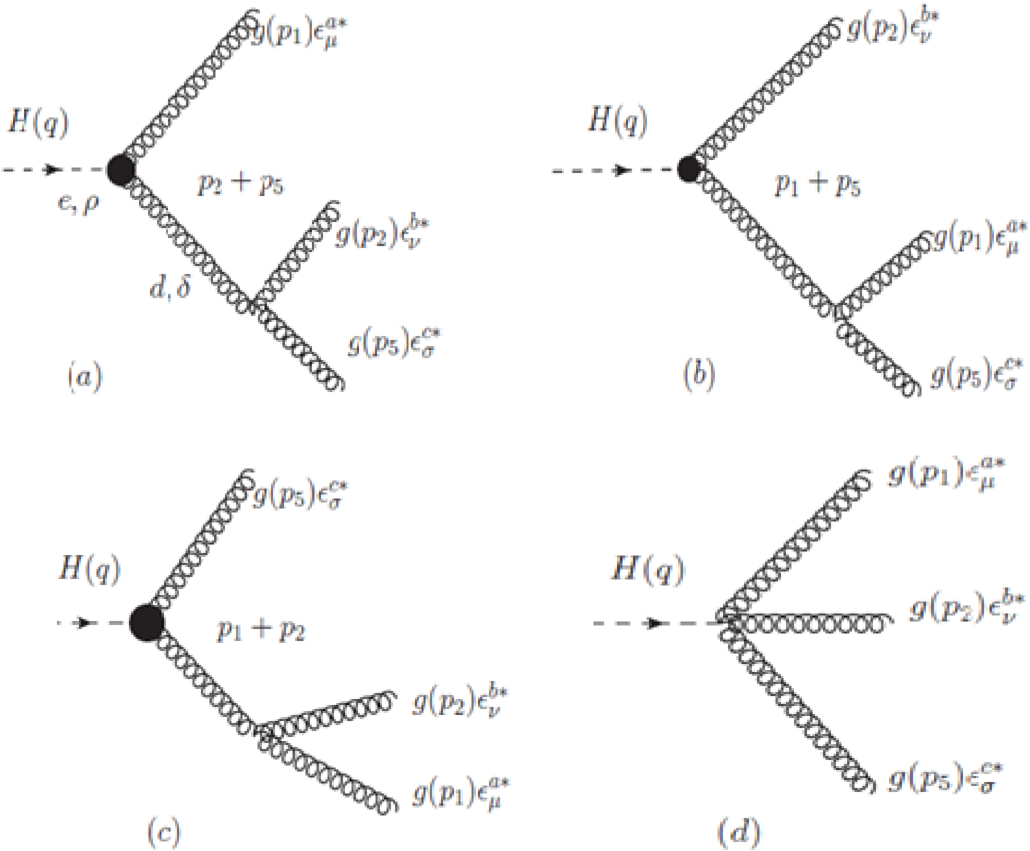
Eq. 11

Next to Leading Calculations:

Real Contributions:

Corrections from real gluon emission:





To simplify our calculations, we computed first the total amplitude of the process:

$$H \to g^a(p_1^\mu) + g^b(p_2^\nu) + g^c(p_5^\sigma),$$

then at the end we will use crossing to obtain the amplitude for gg → gH.

Hggg coupling:

$$Hggg = i\frac{\alpha_s}{3\pi v} g_s f^{abc}\Big[g^{\mu\nu}(p_2 - p_1)^\sigma + g^{\nu\sigma}(p_5 - p_2)^\mu + g^{\sigma\mu}(p_1 - p_5)^\nu\Big].$$

The averaged total matrix element squared of gg → gH which is:

$$\boxed{\overline{|M(gg \to H)|}^2 = \frac{\alpha_s^3}{24\pi v^2}\frac{1}{(1-\varepsilon)^2}\Big[\Big(\frac{M_H^8 + s^2 + u^4 + t^4}{stu}\Big)(1-2\varepsilon) + \frac{\varepsilon}{2}\Big(\frac{(M_H^4 + s^2 + t^2 + u^2)^2}{stu}\Big)\Big].}$$

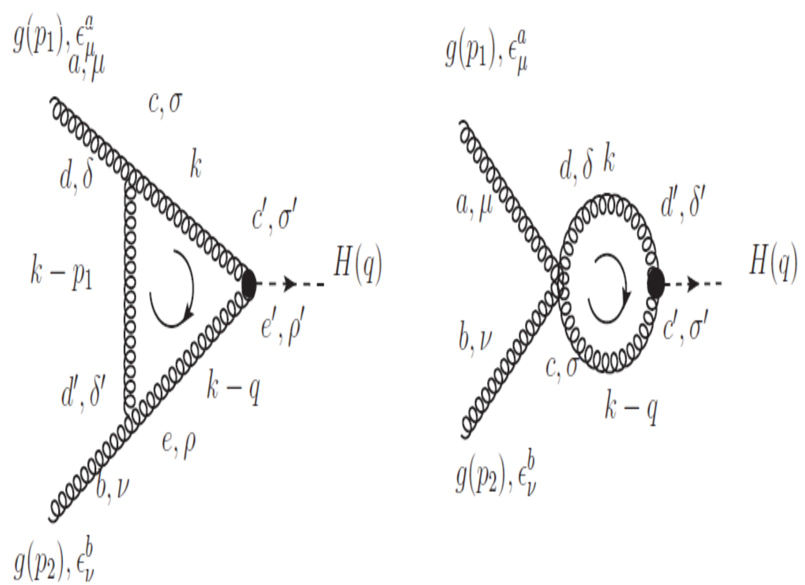
Eq. 12

Virtual Contributions (virtual gluon exchange):

Divergences to be solved:

- ❑ **Infrared divergences**
  - **Soft singularity : Pg → 0**
  - **Collinear singularity: Pg || P1 or Pg || P2**
- ❑ **Ultraviolet divergences Pg → ∞**

$$d\hat{\sigma}_{virt} = dPS\overline{\sum} 2\Re(M_{virt}M_0^*),$$



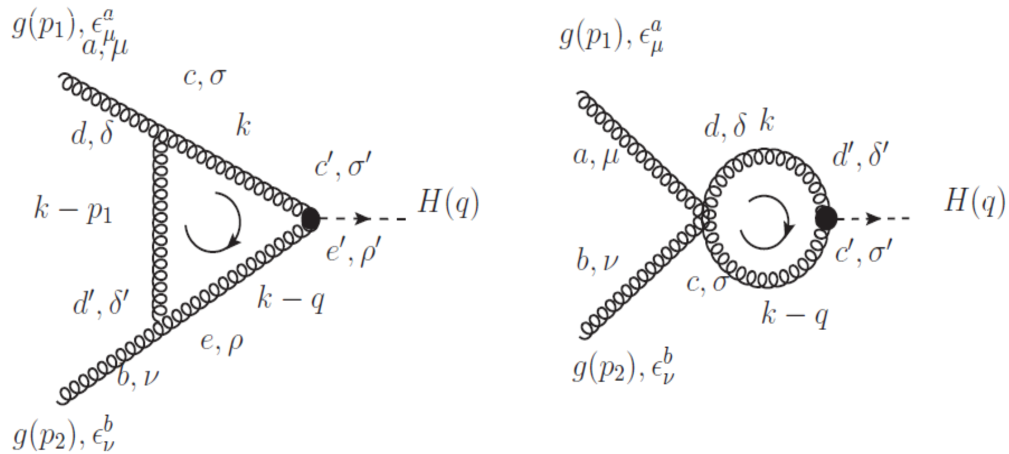
$$\overline{|M_1^{virt}M_B^*|} = -i\frac{1}{n-2}\frac{N_c}{(N_c^2-1)}\frac{\alpha_s^2 g^2}{9\pi^2 v^2} g_{\sigma\sigma'}g_{\rho\rho'}g_{\delta\delta'}$$
$$\left[g^{\mu\sigma}(p_1+k)^\delta + g^{\sigma\delta}(-2k+p_1)^\mu + g^{\delta\mu}(k-2p_1)^\sigma\right]$$
$$\left[g^{\nu\rho}(p_2-k+q)^{\delta'} + g^{\rho\delta'}(2k-p_1-q)^\nu + g^{\delta'\nu}(-k+p_1-p_2)^\rho\right]$$
$$(k.(k-q)g^{\sigma'\delta'} - k^{\sigma'}(k-q)^{\delta'})$$
$$\frac{1}{(k^2+i\varepsilon)((k-q)^2+i\varepsilon)((k-p_1)^2+i\varepsilon)},$$

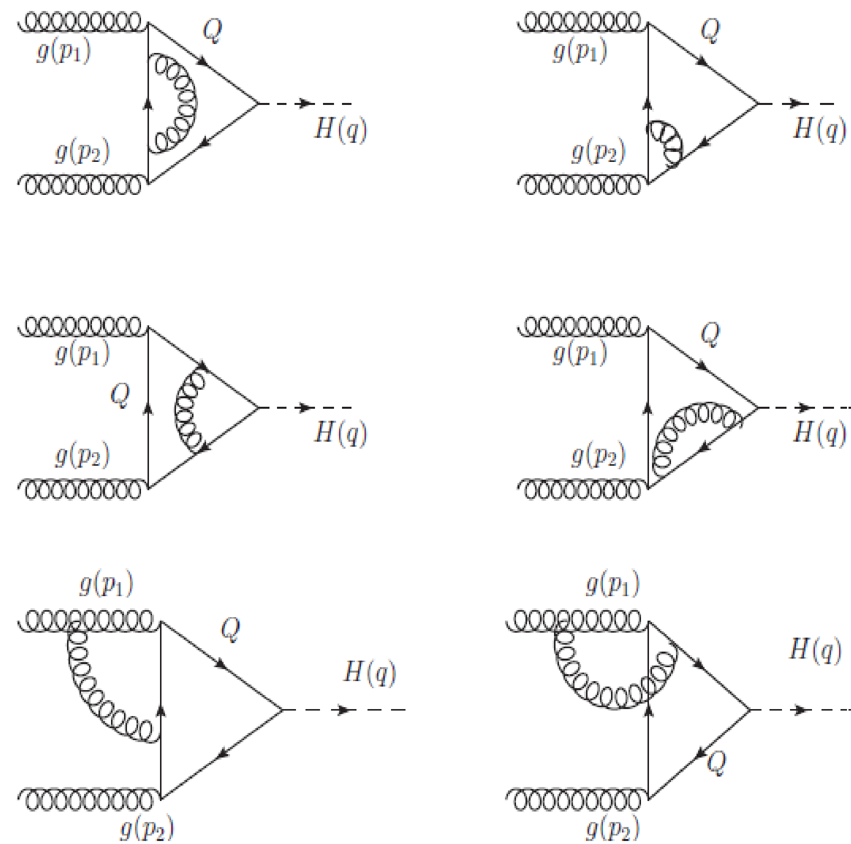
Eq. 13

$$\overline{|M_2^{virt}M_B^*|} = i\frac{1}{n-2}\frac{N_c}{(N_c^2-1)}\frac{\alpha_s^2 g^2}{9\pi^2 v^2}(p_1.p_2 g_{\mu\nu} - p_{1\nu}p_{2\mu})$$
$$(g^{\mu\sigma'}g^{\nu\delta'} + g^{\mu\delta'}g^{\nu\sigma'} - 2g^{\mu\nu}g^{\delta'\sigma'})(k.(k-q)g^{\sigma'\delta'} - k^{\sigma'}(k-q)^{\delta'})$$
$$\frac{1}{(k^2+i\varepsilon)((k-q)^2+i\varepsilon)}.$$

Eq. 14

QCD radiative corrections to the quark loop of gg → H sub-process:





Can be parametrized as:

$$M_Q = M_Q^{LO}\left(1 + \frac{\alpha_s}{\pi}\frac{11}{4}\right),$$

The final expression of the virtual cross section is:

$$\boxed{d\sigma_{virt} = \frac{1}{1-\varepsilon}\frac{\alpha_s^2}{v^2}\frac{s^2}{36\pi^2(N_c^2-1)}\frac{\alpha_s}{2\pi}\left(\frac{4\pi\mu^2}{Q^2}\right)^{\varepsilon} d\phi_2 r_\Gamma\left[\frac{-N_c}{\varepsilon^2} + \frac{N_c}{\varepsilon}\log\left(\frac{s^2}{Q^2}\right) - \frac{1}{\varepsilon}b_{gg}\delta(1-z) + \frac{N_c\pi^2}{2}\right].}$$

Eq. 15

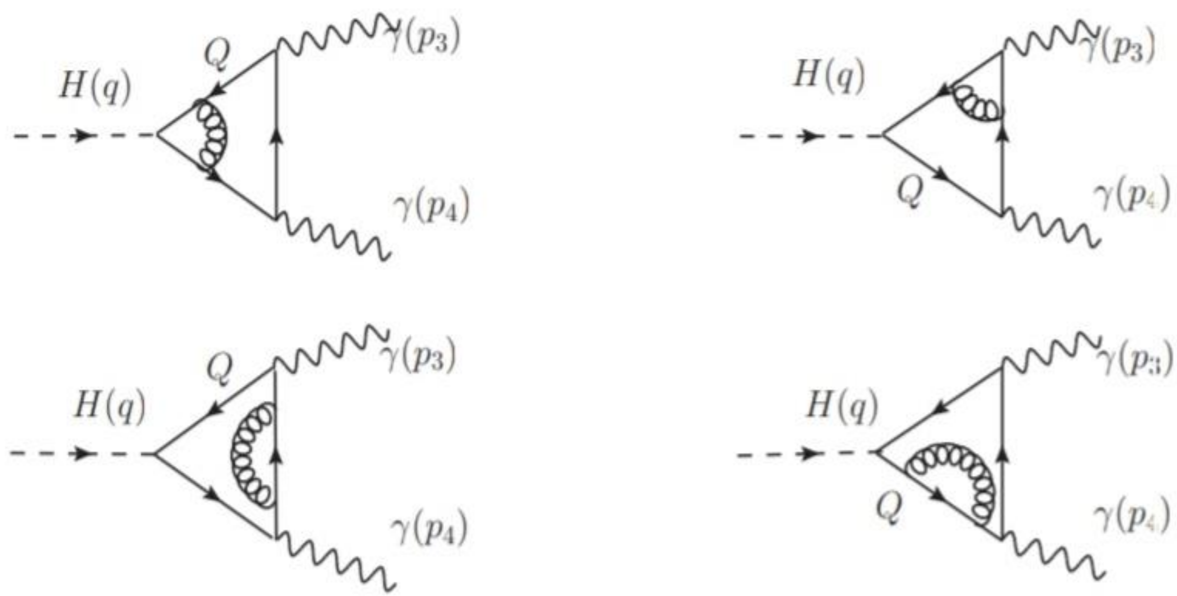
Where $r_\Gamma = \frac{\Gamma(1+\varepsilon)\Gamma^2(1-\varepsilon)}{\Gamma(1-2\varepsilon)}, b_{gg} = \frac{11N_c - 2N_f}{6}$ with N_f being the number of the light quarks.

Higgs decay sub-process:

LO cross section in ET:

$$\sigma^0_{H\to\gamma\gamma} = \frac{1}{64\pi(1-\varepsilon)}\frac{\alpha^2}{v^2}M_H^2|A|^2\delta(\hat{s}-M_H^2).$$

QCD radiative corrections to the quark loop:



QCD correction factor of the quark contribution to the Hγγ coupling [arXiv:hep-ph/9504378v1]:

$$1-\frac{\alpha_s}{\pi}.$$

The virtual cross section of Higgs decay sub-process:

$$\sigma_{H\to\gamma\gamma} = \frac{1}{64\pi(1-\varepsilon)}\frac{\alpha^2}{v^2}z\delta(1-z)|A|^2\left[1-\frac{\alpha_s}{\pi}\right] \quad \boxed{\textbf{Eq. 16}}$$

where $z \equiv \frac{M_H^2}{\hat{s}}$.

Virtual differential cross section:

$$d\sigma_{virt} = \frac{1}{1-\varepsilon}\frac{\alpha_s^2}{v^2}\frac{s^2}{36\pi^2(N_c^2-1)}\frac{\alpha_s}{2\pi}\left(\frac{4\pi\mu^2}{Q^2}\right)^{\varepsilon} d\phi_2 r_\Gamma\left[\cancel{\frac{-N_c}{\varepsilon^2}} + \cancel{\frac{N_c}{\varepsilon}\log\left(\frac{s^2}{Q^2}\right)} - \frac{1}{\varepsilon}b_{gg}\delta(1-z) + \frac{N_c\pi^2}{2}\right]$$

Eq. 17

Soft part:

$$\zeta_s = \frac{\alpha_s}{2\pi}\frac{\alpha_s^2}{v^2}\frac{s^2}{36\pi^2(N_c^2-1)}\left(\frac{4\pi\mu^2}{Q^2}\right)^{\varepsilon}\frac{\Gamma(1+\varepsilon)\Gamma^2(1-\varepsilon)}{\Gamma(1-2\varepsilon)}d\Phi_2$$
$$\times\frac{1}{1-\varepsilon}\left[\frac{N_c}{\varepsilon^2} - \frac{N_c}{\varepsilon}\log\left(\frac{\xi_c^2 s}{Q^2}\right) + \frac{N_c}{2}\log^2\left(\frac{\xi_c^2 s}{Q^2}\right) - \frac{\pi^2}{6}\right].$$

Eq. 18

$$\log\left(\frac{\xi_c^2 s}{Q^2}\right) = \log(\xi_c^2) + \log\left(\frac{s}{Q^2}\right).$$

Virtual + soft:

$$d\sigma_{virt} + \zeta_s = \frac{\alpha_s}{2\pi}\frac{\alpha_s^2}{v^2}\frac{s^2}{36\pi^2(N_c^2-1)}\left(\frac{4\pi\mu^2}{Q^2}\right)^{\varepsilon}\frac{\Gamma(1+\varepsilon)\Gamma^2(1-\varepsilon)}{\Gamma(1-2\varepsilon)}d\Phi_2$$
$$\times\frac{1}{1-\varepsilon}\left[-\frac{1}{\varepsilon}b_{gg}\delta(1-z) - \frac{N_c}{\varepsilon}\log(\xi_c) + \frac{N_c}{2}\log^2\left(\frac{\xi_c^2 s}{Q^2}\right) + 4\frac{\pi^2}{3}\right]$$

Eq. 19

Collinear parts:

P1 collinear with p5:

$$\sigma^{(1)} = \frac{1}{2s}\frac{1}{2s}\frac{\alpha_s}{2\pi}\left(\frac{4\pi\mu^2}{Q^2}\right)^{\varepsilon}\frac{1}{\Gamma(1-\varepsilon)}\int_0^1 dx_1\int_0^1 dx_2 \frac{F_2(x_2^0)}{x_2^0}(2\pi)^n\delta^n(z_1p_1+p_2-p_3-p_4)\frac{d^{n-1}p_3}{(2\pi)^{n-1}2E_3}$$

$$\times\frac{d^{n-1}p_4}{(2\pi)^{n-1}2E_4}\overline{|T|^2}\int_{x_1}^1\frac{dz_1}{z_1}\frac{F_1\left(\frac{x_1}{z_1}\right)}{x_1}a_{gg}\Big[-\frac{1}{\varepsilon}\frac{1}{(1-z_1)_+}+\frac{1}{\varepsilon}\log(\xi_c)\delta(1-z_1) \leftarrow \cancel{\frac{N_c}{\varepsilon}\log(\xi_c)},$$

$$+\frac{1}{(1-z_1)_+}\log\left(\frac{s\delta_I}{2Q^2}\right)-log\left(\frac{s\delta_I}{2Q^2}\right)\log(\xi_c)\delta(1-z_1)+2\frac{\log(1-z_1)}{(1-z_1)_+}-\log^2(\xi_c)\delta(1-z_1)\Big]$$

Eq. 20

P2 collinear with p5:

$$\sigma^{(2)} = \frac{1}{2s}\frac{1}{2s}\frac{\alpha_s}{2\pi}\left(\frac{4\pi\mu^2}{Q^2}\right)^{\varepsilon}\frac{1}{\Gamma(1-\varepsilon)}\int_0^1 dx_1\int_0^1 dx_2 \frac{F_1(x_1^0)}{x_1^0}(2\pi)^n\delta^n(p_1+z_2p_2-p_3-p_4)\frac{d^{n-1}p_3}{(2\pi)^{n-1}2E_3}$$

$$\times\frac{d^{n-1}p_4}{(2\pi)^{n-1}2E_4}\overline{|T|^2}\int_{x_2}^1\frac{dz_2}{z_2}\frac{F_2\left(\frac{x_2}{z_2}\right)}{x_2}a_{gg}\Big[-\frac{1}{\varepsilon}\frac{1}{(1-z_2)_+}+\frac{1}{\varepsilon}\log(\xi_c)\delta(1-z_2) \leftarrow \cancel{\frac{N_c}{\varepsilon}\log(\xi_c)},$$

$$+\frac{1}{(1-z_2)_+}\log\left(\frac{s\delta_I}{2Q^2}\right)-log\left(\frac{s\delta_I}{2Q^2}\right)\log(\xi_c)\delta(1-z_2)+2\frac{\log(1-z_2)}{(1-z_2)_+}-\log^2(\xi_c)\delta(1-z_2)\Big].$$

Eq. 21

Virtual + soft:

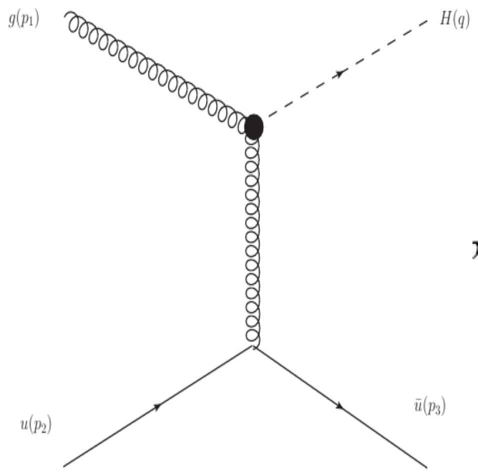
$$\sigma_{virt}+\zeta_s = \frac{\alpha_s}{2\pi}\left(\frac{4\pi\mu^2}{Q^2}\right)^{\varepsilon}\frac{\Gamma(1+\varepsilon)\Gamma^2(1-\varepsilon)}{\Gamma(1-2\varepsilon)}d\Phi_2\overline{|T|}^2$$

$$2\Big[-\frac{1}{\varepsilon}b_{gg}\delta(1-z)-\cancel{\frac{N_c}{\varepsilon}\log(\xi_c)}+\frac{N_c}{2}\log^2\left(\frac{\xi_c^2 s}{Q^2}\right)-\frac{\pi^2}{6}\Big],$$

Eq. 22

Other Higgs production channels:

g + q → q +H



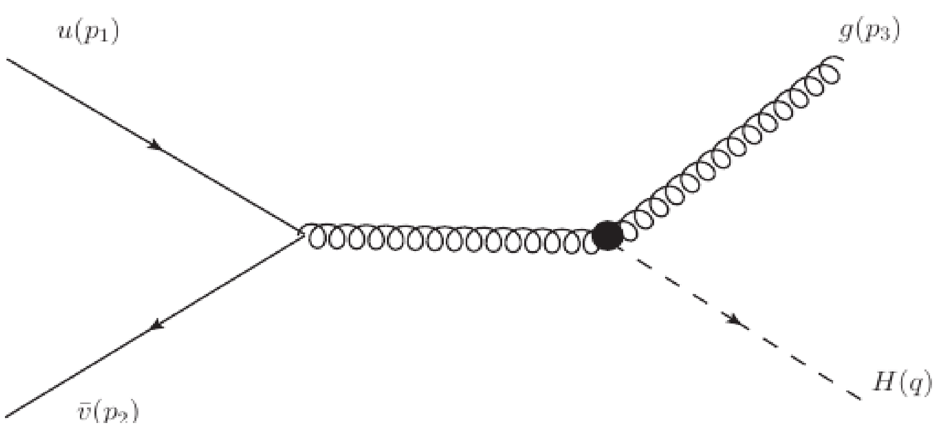
No virtual gluon exchange in this sub-process, so all we have to do is to study the existence of soft and collinear divergences:

$$r^{(1)}_{gq\to qH} = \frac{\alpha_s}{2\pi}\frac{1}{2s}\overline{|T|}^2\frac{1}{\Gamma(1-\varepsilon)}\int_0^1 dx_1\int_0^1 dx_2^0\frac{F_2(x_2^0)}{x_2^0}(2\pi)^n\delta^n(\tilde{p}_1+p_2-\sum_{i=3}^{4}p_i)\prod_{l=3}^{4}\frac{d^{n-1}p_l}{(2\pi)^{n-1}2E_l}\overline{|T|}^2$$

$$\times\int_{x_1}^1\frac{dz_1}{z_1}\frac{F_1\left(\frac{x_1}{z_1}\right)}{x_1}a_{gq}^{(n)}\Big[-\frac{1}{\varepsilon}\frac{1}{(1-z_1)_+}+\log\left(\frac{s\delta_I}{2Q^2}\right)\frac{1}{(1-z_1)_+}-\log\left(\frac{s\delta_I}{2Q^2}\right)\log(\xi_c)\delta(1-z_1)$$
$$+2\frac{\log(1-z_1)}{(1-z_1)_+}-\log^2(\xi_c)\delta(1-z_1)\Big].$$

Eq. 23

q + q → g + H



$$\sigma(q\bar{q}\to gH) = \frac{1}{486\pi^2}\frac{\alpha_s^3}{v^2}\left(1-\frac{M_H^2}{s}\right)^3$$

Eq. 24

Finally, one can easily find the NLO cross section of gg → γγ:

σ NLO = σ virt + σ soft + σ hc + σ hnc

Eq. 25

Remarks:

1. **NLO calculations are very important since it provides an accurate QCD predictions and reliable error estimates.**

2. The calculation of the NLO corrections using EFT simplifies the calculations by integrating the quark loops and hence reducing the scale uncertainties.

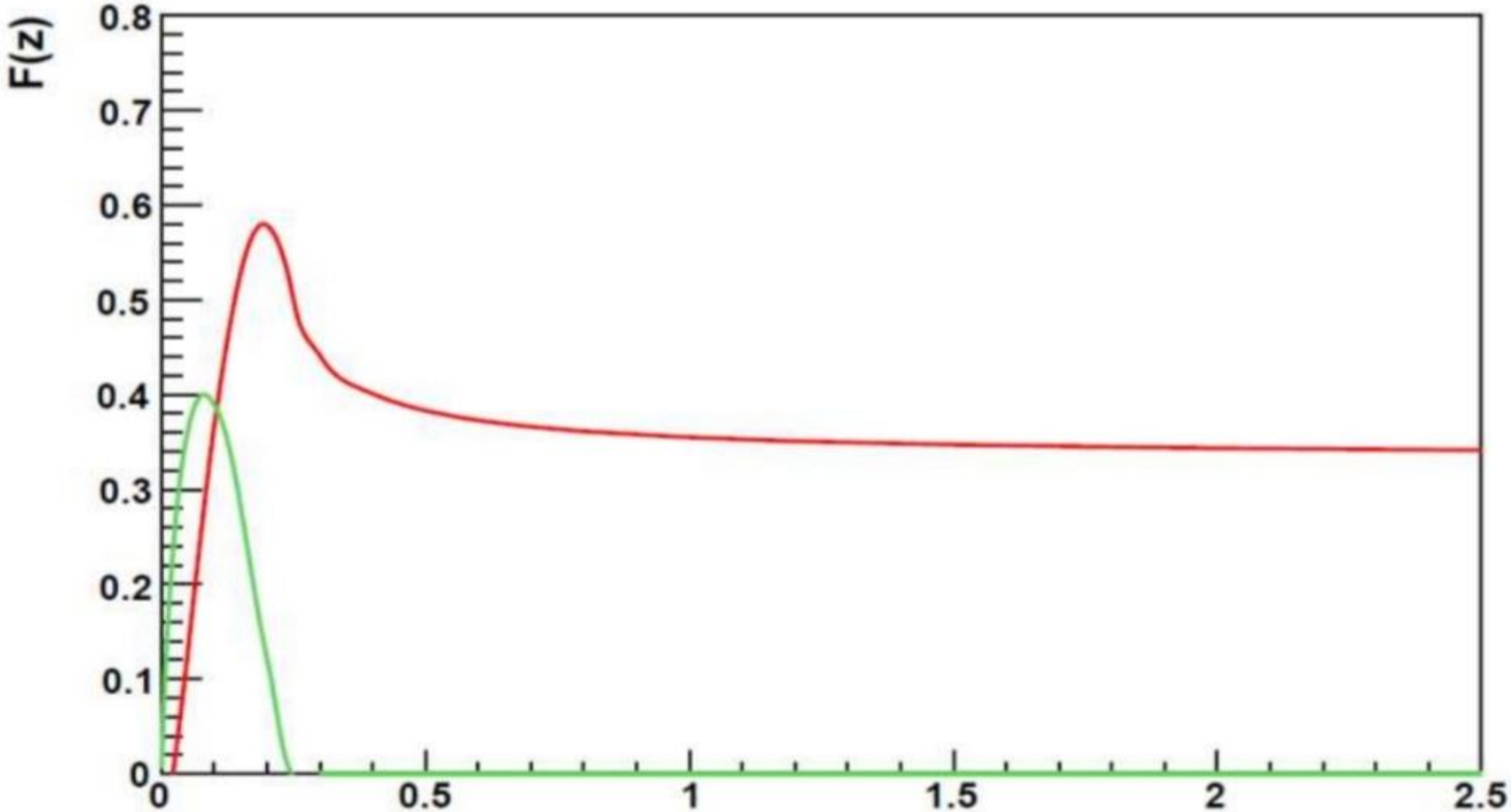
3. The extra partonic channels appear at NLO can have a significant impact on differential distributions.

4. This method can be used for any new scalar resonance that may appear in the diphoton channel.

Thank you!

Backup

Verification of the validity of infinite top quark mass limit which shows that it agrees perfectly wit effective field theory of Higgs Boson



The variation of the real(red) and imaginary (green) parts of F(z) as a function of different quark masses.

$$M_{ab}^{\mu\nu} = g_s^2\left(\frac{m_q}{v}\right)\mu^{\varepsilon} Tr[T^aT^b]\int \frac{d^n l}{(2\pi)^n}\, Tr\left[\frac{\gamma^{\mu}(\not{l}+\not{p}_1+m_q)(\not{l}-\not{p}_2+m_q)\gamma^{\nu}(\not{l}+m_q)}{((l+p_1)^2-m_q^2+i\varepsilon)((l-p_2)^2-m_q^2+i\varepsilon)((l^2-m^2+i\varepsilon)}\right]$$
$$\times\, \epsilon_{\mu}^{a}(p_1)\epsilon_{\nu}^{b}(p_2),$$

Eq. 26

$$Tr[T^aT^b] = \frac{1}{2}\delta^{ab}.$$

$$\begin{aligned}Tr[\gamma^{\mu}(\not{l}+\not{p}_1+m_q)(\not{l}-\not{p}_2+m_q)\gamma^{\nu}(\not{l}+m_q)] &= 4m_q\left[4l^{\mu}l^{\nu}+2l^{\nu}p_1^{\mu}-2l^{\mu}p_2^{\nu}+p_1^{\nu}p_2^{\mu}-\right.\\ &\quad \left. p_1^{\mu}p_2^{\nu}+g^{\mu\nu}(m_q^2-p_1.p_2)-g^{\mu\nu}l^2\right]\\ &= 4m_qN^{\mu\nu}.\end{aligned}$$

Eq. 27

$$\frac{1}{ABC} = \int_0^1 dy\int_0^1 dx\frac{2}{(Axy+B(1-x)y+C(1-y))^3}$$

$$M_{ab}^{\mu\nu} = ig_s^2\mu^{\varepsilon}\frac{4}{(4\pi)^2}\frac{m_q^2}{v}\frac{\delta_{ab}}{2}\left(g^{\mu\nu}-\frac{2p_1^{\nu}p_2^{\mu}}{M_H^2}\right)\int_0^1 dy\,y\int_0^1 dx\left[2+\frac{M_H^2}{2}\left(1-\frac{4m_q^2}{M_H^2}\right)\frac{1}{m_q^2-y^2x(1-x)M_H^2-i\varepsilon}\right]\epsilon_a^{\mu}\epsilon_b^{\nu},$$

Eq. 28

Partonic model of the gluon-gluon scattering process where the emitted real gluon is collinear to g (p1)