# Higgs production in e and real gamma collision

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# Outline

1. Introduction and motivations
2. Higgs production in e and real $\gamma$ collision in SM
3. Two-photon and Z-photon fusion diagrams
4. W-related and Z-related diagrams
5. Numerical analysis
6. Summary

# 1. Introduction and motivations

- A Higgs particle was found at the LHC

  Is it the SM Higgs boson , a SUSY Higgs boson,

  a Higgs boson of a different model?

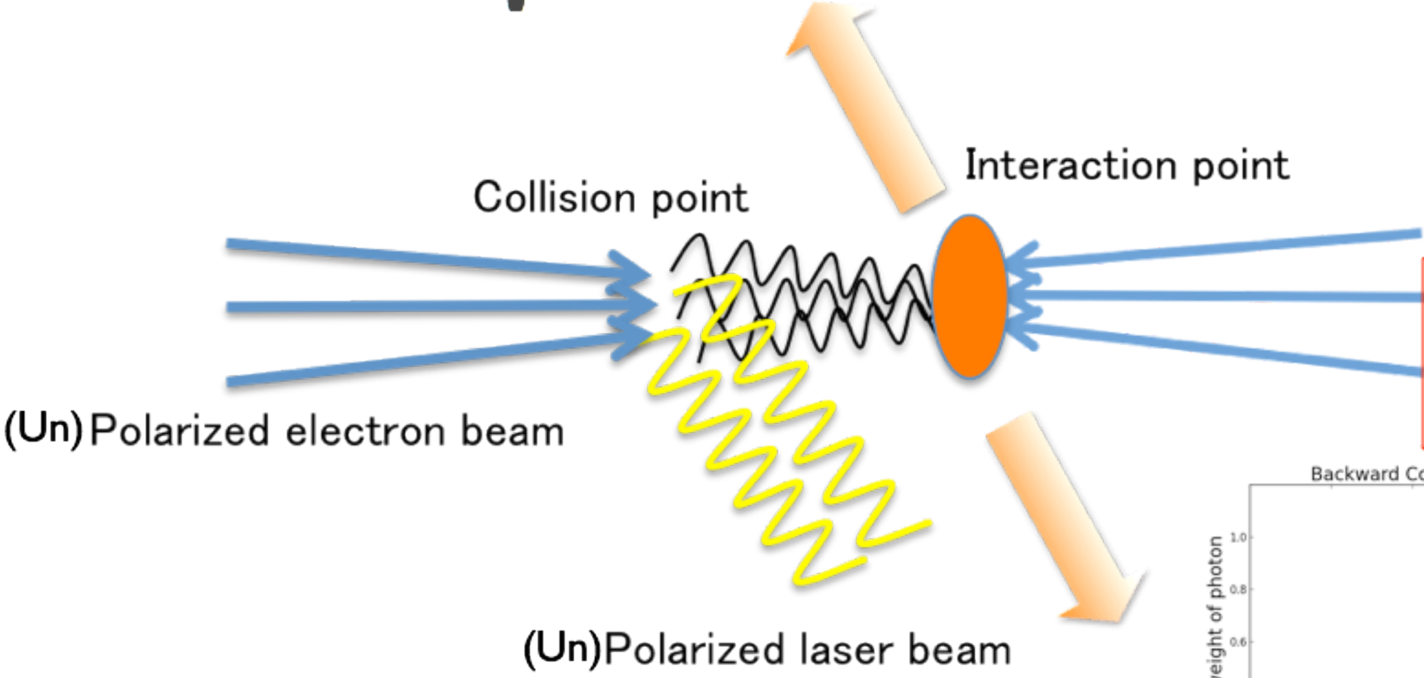
- Future linear collider : ILC
  - $e^+e^-$ collider: $\sqrt{s} = 250$ GeV $\cdots$
  - It may be constructed in Japan.

- Before e+ beams are ready,

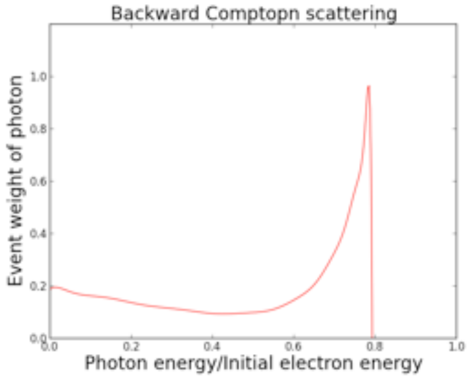
  other options are possible:
  - an $e^-e^-$ option
  - an $e^-\gamma$ option

    use one e- beam to produce high energy photons

# $\gamma e^-$ collider based on $e^-e^-$



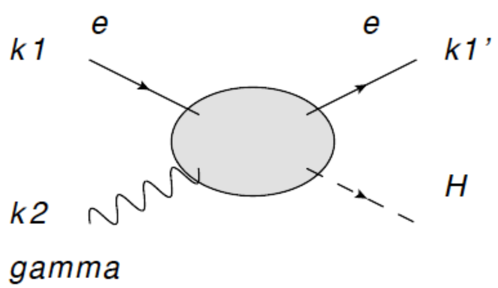

**Compton scattering:**
$e^- \gamma_{laser} \rightarrow e^- \gamma$
**can transfer 80% of e- energy to $\gamma$**




Good test for combining photon science & particle physics!!

# 2 Higgs production in e- and real $\gamma$ collision in SM

➤ Higgs are produced by loop diagrams




At one-loop level

$\gamma\gamma$-fusion diagrams
$\mathbf{Z}\gamma$-fusion diagrams
W-related diagrams
Z-related diagrams

$$k_1^2 = {k'_1}^2 = m_e^2 = 0\ ; \quad p_h^2 = m_h^2,$$

$$\begin{aligned} s &= (k_1 + k_2)^2 = 2k_1 \cdot k_2\ , \quad t = (k_1 - k'_1)^2 = -2k_1 \cdot k'_1 = q^2, \\ u &= (k_1 - p_h)^2 = (k'_1 - k_2)^2 = -2k'_1 \cdot k_2 = m_h^2 - s - t \\ k_2^2 &= 0\ , \qquad k_2^\beta\ \epsilon(k_2)_\beta = 0 \end{aligned}$$

# 2 Higgs production in e- and real $\gamma$ collision in SM

- Calculation is done in unitary gauge
- Use of FeynCalc, PaVeReduce[Oneloop[p,-----]]
- Amplitudes are expressed in analytical form

Denner, Nierste, Scharf (1991)
Keith Ellis, Zanderighi (2008)
Denner, Dittmaier (2010)

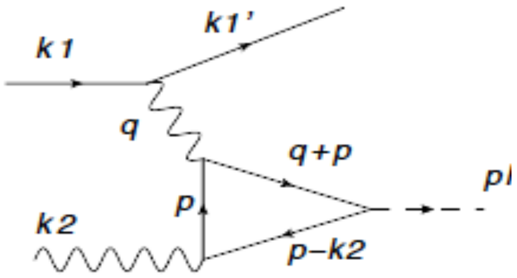
# 3. Two-photon and Z-photon fusion diagrams

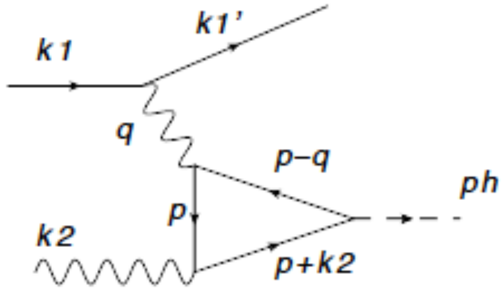
$e \cdot e \cdot \gamma$ coupling : $i(-e)\gamma_\mu$

$t \cdot t \cdot \gamma$ coupling : $i(q_t e)\gamma_\mu$

$e \cdot e \cdot Z$ coupling : $i\dfrac{g}{4\cos\theta_W}\gamma_\mu(f_{Ze}+\gamma_5)$ with $f_{Ze} = -1 + 4\sin^2\theta_W$

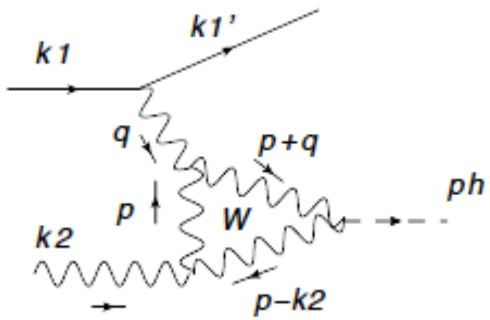
$t \cdot t \cdot Z$ coupling : $i\dfrac{g}{4\cos\theta_W}\gamma_\mu\,[f_{Zt}-\gamma_5]$ with $f_{Zt} = 1 - \dfrac{8}{3}\sin^2\theta_W$

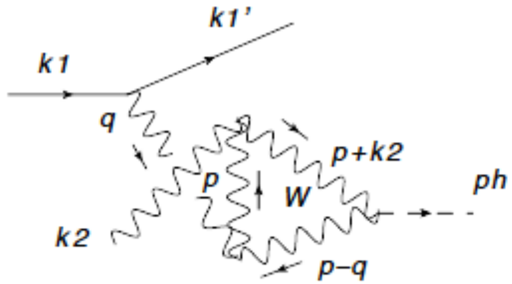


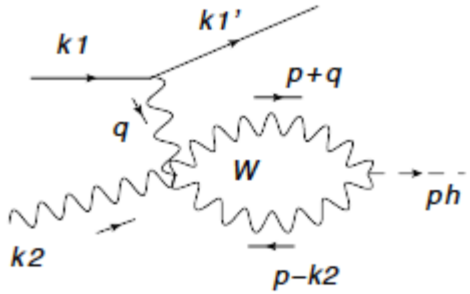




Higgs $\cdot\, t \cdot t$ coupling : $-i\dfrac{gm_t}{2m_W}$

Higgs $\cdot\, W \cdot W$ coupling : $igm_W\, g_{\mu\nu}$




$$Z_\mu(k_1)\text{-}W^+_\nu(k_2)\text{-}W^-_\lambda(k_3) \text{ coupling: } -ig\cos\theta_W\left[(k_1-k_2)_\lambda g_{\mu\nu} + (k_2-k_3)_\mu g_{\nu\lambda} + (k_3-k_1)_\nu g_{\lambda\mu}\right]$$

$$A_\mu\text{-}Z_\nu\text{-}W^+_\alpha\text{-}W^-_\beta \text{ coupling: } \quad -ieg\cos\theta_W\left[2g_{\mu\nu}g_{\alpha\beta} - g_{\mu\alpha}g_{\nu\beta} - g_{\mu\beta}g_{\nu\alpha}\right]$$

# 3. Two-photon and Z-photon fusion diagrams

- Contribution of two-photon fusion diagrams
  - Top quark loops:

$$A^{\gamma}_{(T)} = \left(\frac{i}{16\pi^2}\right)\left[\overline{u}(k_1')\gamma_\mu u(k_1)\right]\frac{1}{t}\left(g^{\mu\beta} - \frac{2k_2^\mu q^\beta}{m_h^2 - t}\right)\epsilon_\beta(k_2)\ \times 2e^3 g\frac{q_t^2 m_t^2}{m_W}\ S^{\gamma}_{(T)}(t, m_t^2, m_h^2)$$

$$S^{\gamma}_{(T)}(t, m_t^2, m_h^2) = 2 - \frac{2t}{m_h^2 - t}B_0(t; m_t^2, m_t^2) + \frac{2t}{m_h^2 - t}B_0(m_h^2; m_t^2, m_t^2)$$
$$+\left\{4m_t^2 - m_h^2 + t\right\}C_0(m_h^2, 0, t; m_t^2, m_t^2, m_t^2)$$

$$B_0(p^2; m_1^2, m_2^2) \equiv \frac{(2\pi\mu)^{4-n}}{i\pi^2}\int \frac{d^n k}{\left[k^2 - m_1^2\right]\left[(k+p)^2 - m_2^2\right]}$$

$$C_0(p_1^2, p_2^2, p_3^2; m_1^2, m_2^2, m_3^2) \equiv \frac{(2\pi\mu)^{4-n}}{i\pi^2}\int \frac{d^n k}{\left[k^2 - m_1^2\right]\left[(k+p_1)^2 - m_2^2\right]\left[(k+p_1+p_2)^2 - m_3^2\right]}$$

  - W boson loops:

$$A^{\gamma}_{(W)} = \left(\frac{i}{16\pi^2}\right)\left[\overline{u}(k_1')\gamma_\mu u(k_1)\right]\frac{1}{t}\left(g^{\mu\beta} - \frac{2k_2^\mu q^\beta}{m_h^2 - t}\right)\epsilon_\beta(k_2)\ \times(-e^3 g m_W)\ S^{\gamma}_{(W)}(t, m_W^2, m_h^2)$$

$$S^{\gamma}_{(W)}(t, m_W^2, m_h^2) = \frac{t\left(12m_W^4 + 2m_W^2\left(m_h^2 - t\right) - m_h^2 t\right)}{2m_W^4\left(m_h^2 - t\right)}\left[B_0(m_h^2; m_W^2, m_W^2) - B_0(t; m_W^2, m_W^2)\right]$$
$$+\left\{\frac{t\left(m_h^2 - 2t\right)}{m_W^2} + 12m_W^2 - 6m_h^2 + 6t\right\}C_0(m_h^2, 0, t; m_W^2, m_W^2, m_W^2)$$
$$-\frac{m_h^2 t}{2m_W^4} + \frac{m_h^2 - t}{m_W^2} + 6$$

# 3. Two-photon and Z-photon fusion diagrams

- Contribution of Z-photon fusion diagrams
  - Top quark loops:

$$A_{(T)} = \left(\frac{i}{16\pi^2}\right)\left[\overline{u}(k_1')\gamma_\mu\left(f_{Ze}+\gamma_5\right)u(k_1)\right]\frac{1}{t-m_Z^2}\left(g^{\mu\beta}-\frac{2k_2^\mu q^\beta}{m_h^2-t}\right)\epsilon_\beta(k_2) \times\left(-\frac{eg^3 q_t f_{Zt}}{8\cos^2\theta_W}\right)\frac{m_t^2}{m_W} S^\gamma_{(T)}(t,m_t^2,m_h^2)$$

  - W boson loops:

$$A_W = \left(\frac{i}{16\pi^2}\right)\left[\overline{u}(k_1')\gamma_\mu\left(f_{Ze}+\gamma_5\right)u(k_1)\right]\frac{1}{t-m_Z^2}\left(g^{\mu\beta}-\frac{2k_2^\mu q^\beta}{m_h^2-t}\right)\epsilon^\beta(k_2) \times\left(\frac{eg^3 m_W}{4}\right) S^\gamma_{(W)}(t,m_W^2,m_h^2)$$

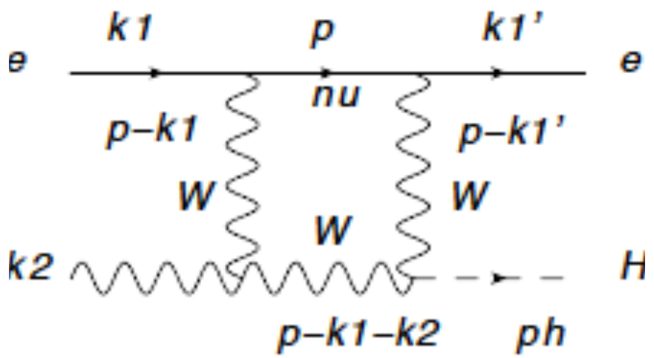
The contribution of two-photon and Z-photon fusion diagrams have the same transition form factors

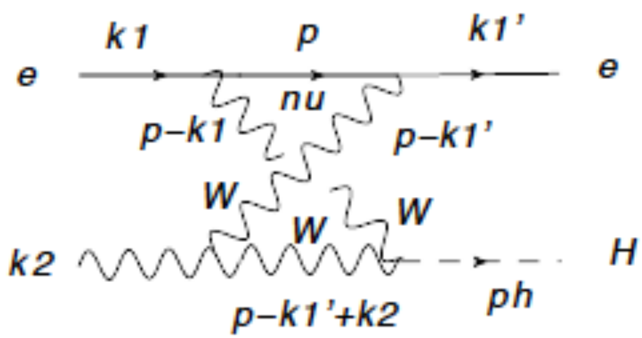
$$S^\gamma_{(T)}(t,m_t^2,m_h^2) \qquad S^\gamma_{(W)}(t,m_W^2,m_h^2)$$

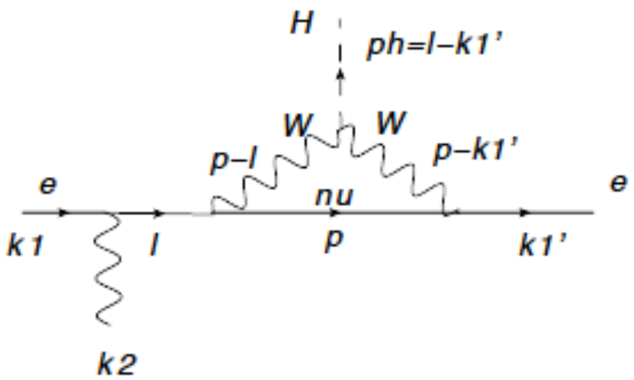
# 4. W-related and Z-related diagrams

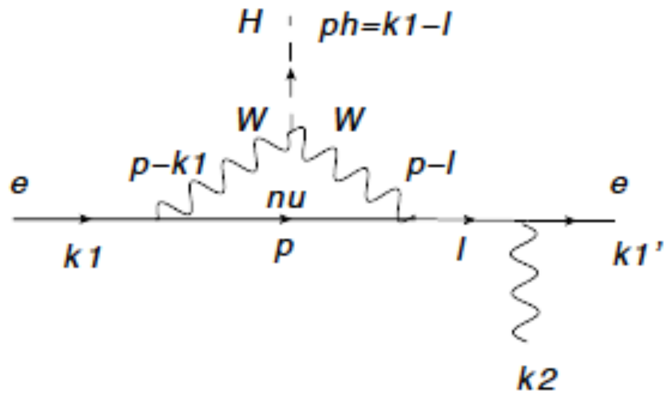
- GRACE gives other contributions to Higgs production in e - $\gamma$ collision

$e \cdot \nu \cdot W$ coupling : $i\frac{g}{2\sqrt{2}}\gamma_\mu(1-\gamma_5)$



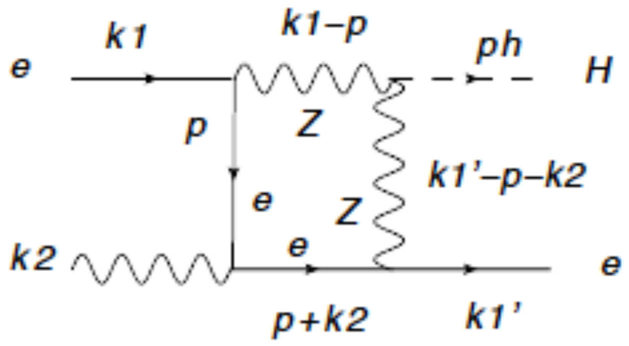



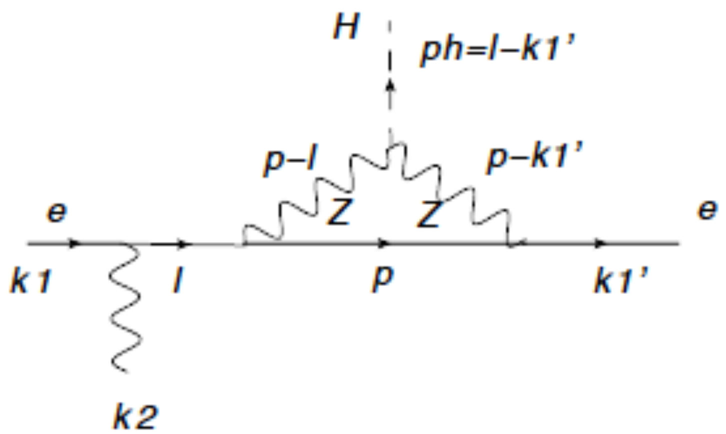



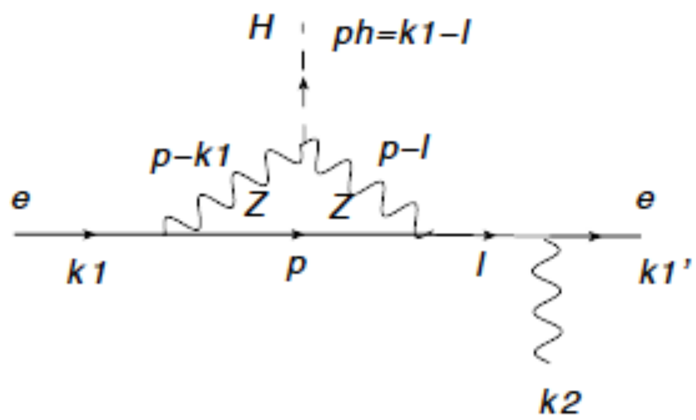
# 4. W-related and Z-related diagrams

$e \cdot e \cdot Z$ coupling : $i\frac{g}{4\cos\theta_W}\gamma_\mu(f_{Z_e}+\gamma_5)$ with $f_{Z_e} = -1 + 4\sin^2\theta_W$

Higgs $\cdot Z \cdot Z$ coupling : $i\frac{g m_Z}{\cos\theta_W} g_{\mu\nu}$



# 4. W-related and Z-related diagrams

- Contribution of W-related diagrams

$$A^W_{e\gamma\to eH} = \frac{eg^3 m_W}{4} \times \left[\overline{u}(k_1')\ F^W_{(e\gamma\to eH)\beta}\ (1-\gamma_5)u(k_1)\right]\epsilon(k_2)^\beta$$

$$F^W_{(e\gamma\to eH)\beta} = \left(k_{1_\beta}\not{k}_2 - \frac{s}{2}\gamma_\beta\right) S^{(W)(k_{1_\beta})}_{(e\gamma\to eH)}(s,t,m_h^2,m_W^2) + \left(k'_{1_\beta}\not{k}_2 + \frac{u}{2}\gamma_\beta\right) S^{(W)(k'_{1_\beta})}_{(e\gamma\to eH)}(s,t,m_h^2,m_W^2)$$

where

$S^{(W)(k_{1_\beta})}_{(e\gamma\to eH)}(s,t,m_h^2,m_W^2)$ and $S^{(W)(k'_{1_\beta})}_{(e\gamma\to eH)}(s,t,m_h^2,m_W^2)$

expressed as a linear combination of

$$B_0(s;0,m_W^2) \quad B_0(u;0,m_W^2) \quad B_0\left(t;m_W^2,m_W^2\right) \quad B_0\left(m_h^2;m_W^2,m_W^2\right)$$

$$C_0\left(0,0,s;m_W^2,m_W^2,0\right) \quad C_0\left(0,0,u;m_W^2,m_W^2,0\right) \quad C_0\left(0,0,t;m_W^2,0,m_W^2\right)$$

$$C_0\left(0,s,m_h^2;m_W^2,0,m_W^2\right) \quad C_0\left(0,u,m_h^2;m_W^2,0,m_W^2\right) \quad C_0\left(0,t,m_h^2;m_W^2,m_W^2,m_W^2\right)$$

$$D_0\left(0,0,0,m_h^2;s,t;m_W^2,m_W^2,0,m_W^2\right) \quad D_0\left(0,0,0,m_h^2;t,u;m_W^2,0,m_W^2,m_W^2\right)$$

# 4. W-related and Z-related diagrams

- Contribution of Z-related diagrams

$$A^{Z}_{e\gamma\to eH} = -\frac{eg^3 m_Z}{16\cos^3\theta_W} \times \left[\overline{u}(k_1')\, F^{Z}_{(e\gamma\to eH)\beta}\, (f_{Ze} + \gamma_5)^2 u(k_1)\right]\epsilon(k_2)^{\beta}$$

$$F^{W}_{(e\gamma\to eH)\beta} = \left(k_{1_\beta}\not{k}_2 - \frac{s}{2}\gamma_\beta\right) S^{(W)(k_{1\beta})}_{(e\gamma\to eH)}(s,t,m_h^2,m_W^2) + \left(k'_{1_\beta}\not{k}_2 + \frac{u}{2}\gamma_\beta\right) S^{(W)(k'_{1\beta})}_{(e\gamma\to eH)}(s,t,m_h^2,m_W^2)$$

where

$S^{(Z)(k_{1\beta})}_{(e\gamma\to eH)}(s,t,m_h^2,m_Z^2)$ and $S^{(Z)(k'_{1\beta})}_{(e\gamma\to eH)}(s,t,m_h^2,m_Z^2)$

: expressed as a linear combination of

$$B_0(s;0,m_Z^2) \qquad B_0(u;0,m_Z^2) \qquad B_0\left(m_h^2;m_Z^2,m_Z^2\right)$$

$$C_0\left(0,0,s;m_Z^2,0,0\right) \qquad C_0\left(0,0,u;m_Z^2,0,0\right) \qquad C_0\left(0,s,m_h^2;m_Z^2,0,m_Z^2\right) \qquad C_0\left(0,u,m_h^2;m_Z^2,0,m_Z^2\right)$$

$$D_0\left(0,0,0,m_h^2;s,u;m_Z^2,0,0,m_Z^2\right)$$

- Collinear divergences appear in $C_0\left(0,0,s;m_Z^2,0,0\right)$ $C_0\left(0,0,u;m_Z^2,0,0\right)$ $D_0\left(0,0,0,m_h^2;s,u;m_Z^2,0,0,m_Z^2\right)$

  but they are cancel out when they are added

# 4. W-related and Z-related diagrams

$$C_0(0,0,s;m_Z^2,0,0) = -\left(\frac{4\pi\mu^2}{m_Z^2}\right)^\epsilon \frac{1}{s}\left\{ \frac{1}{\epsilon}\Big[\log(s_Z-1)-i\pi\Big] - \frac{1}{2}\Big[\log(s_Z-1)-i\pi\Big]^2 - \mathrm{Li}_2\left(\frac{s_Z-1}{s_Z}\right) - \frac{1}{2}\log^2\left(\frac{s_Z}{s_Z-1}\right) + \frac{\pi^2}{3} - i\pi\log\left(\frac{s_Z}{s_Z-1}\right)\right\}$$

$$C_0(0,0,u;m_Z^2,0,0) = -\left(\frac{4\pi\mu^2}{m_Z^2}\right)^\epsilon \frac{1}{u}\left\{ \frac{1}{\epsilon}\log(1-u_Z) + \mathrm{Li}_2\left(\frac{-u_Z}{1-u_Z}\right) - \frac{1}{2}\log^2(1-u_Z)\right\}$$

$$s_Z = \frac{s}{m_Z^2}, \quad u_Z = \frac{u}{m_Z^2}, \quad h_Z = \frac{m_h^2}{m_Z^2}$$

$$x_{Z_+} = \frac{1}{2}\left(1+i\sqrt{\frac{4}{h_Z}-1}\right)$$

$$x_{Z_-} \equiv \frac{1}{2}\left(1-i\sqrt{\frac{4}{h_Z}-1}\right)$$

$$\begin{aligned}
&D_0(0,0,0,m_h^2;s,u;m_Z^2,0,0,m_Z^2) = D_0(0,0,m_h^2,0;s,u;0,0,m_Z^2,m_Z^2) \\
&= \frac{1}{su-m_Z^2(s+u)}\left\{\left(\frac{4\pi\mu^2}{m_Z^2}\right)^\epsilon e^{-\epsilon\gamma_E}\times\frac{1}{\epsilon}\Big[-\Big[\log(s_Z-1)-i\pi\Big]-\log(1-u_Z)\Big]\right. \\
&\quad +2\mathrm{Li}_2\left(\frac{s_Z-1}{s_Z}\right) - 2\mathrm{Li}_2\left(-\frac{u_Z}{1-u_Z}\right) - 2\mathrm{Li}_2\left(\frac{1}{(1-s_Z)(1-u_Z)}\right) \\
&\quad +\mathrm{Li}_2\left(-\frac{x_{Z_+}}{x_{Z_-}(1-s_Z)}\right) + \mathrm{Li}_2\left(-\frac{x_{Z_-}}{x_{Z_+}(1-s_Z)}\right) + \mathrm{Li}_2\left(1+\frac{x_{Z_+}(1-u_Z)}{x_{Z_-}}\right) + \mathrm{Li}_2\left(1+\frac{x_{Z_-}(1-u_Z)}{x_{Z_+}}\right) \\
&\quad +\log^2\left(\frac{s_Z}{s_Z-1}\right) + 2\log\Big((s_Z-1)(1-u_Z)\Big)\log\left(\frac{s_Z+u_Z-u_Zs_Z}{(s_Z-1)(1-u_Z)}\right) + 2\log(s_Z-1)\log(1-u_Z) \\
&\quad +\log^2(1-u_Z) + \log\left(1+\frac{x_{Z_+}}{x_{Z_-}(1-s_Z)}\right)\left\{\log\left(-\frac{x_{Z_+}}{x_{Z_-}}\right) - \log(s_Z-1)\right\} \\
&\quad +\log\left(1+\frac{x_{Z_-}}{x_{Z_+}(1-s_Z)}\right)\left\{\log\left(-\frac{x_{Z_-}}{x_{Z_+}}\right) - \log(s_Z-1)\right\} \\
&\quad +i\pi\left[2\log\left(\frac{s_Z}{s_Z+u_Z-u_Zs_Z}\right) + \log\left(1+\frac{x_{Z_+}}{x_{Z_-}(1-s_Z)}\right) + \log\left(1+\frac{x_{Z_-}}{x_{Z_+}(1-s_Z)}\right)\right] \\
&\quad \left. -\frac{2\pi^2}{3}\right\} \qquad \text{(B3}
\end{aligned}$$

- They appear in combination of $\left\{sC_0\left(0,0,s;m_Z^2,0,0\right) + uC_0\left(0,0,u;m_Z^2,0,0\right) + [m_Z^2(s+u)-su]D_0\left(0,0,0,m_h^2;s,u;m_Z^2,0,0,m_Z^2\right)\right\}$

# 5. Numerical analysis

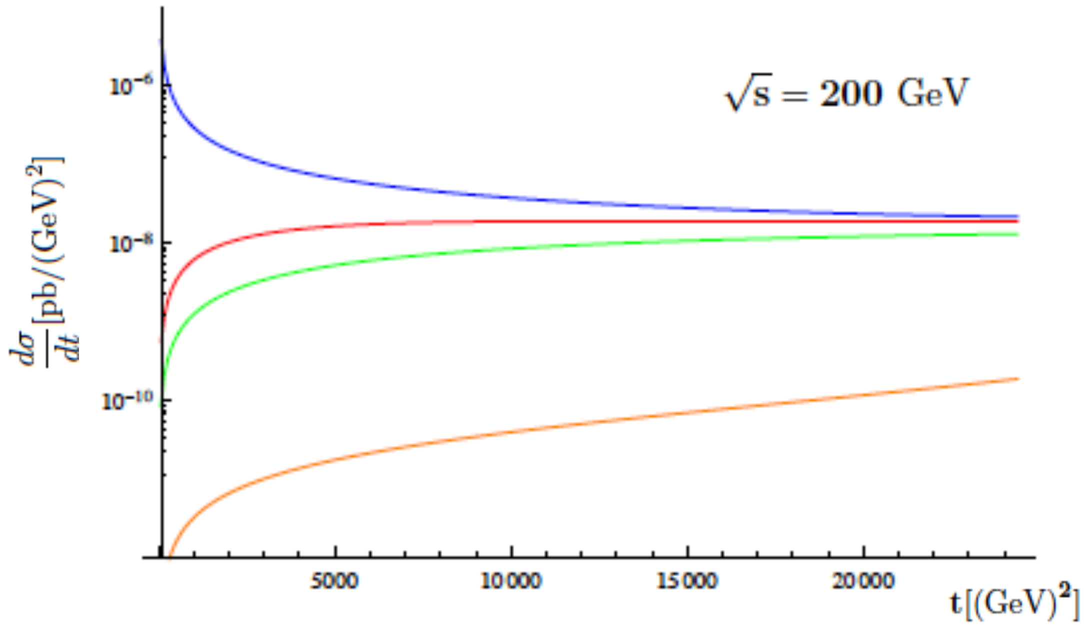
- Parameters

$$m_h = 125 \text{ GeV} , \quad m_t = 173 \text{ GeV} , \quad m_Z = 91 \text{ GeV} , \quad m_W = 80 \text{ GeV}$$

$$\cos\theta_W = \frac{m_W}{m_Z} = \frac{80}{91} , \qquad e^2 = 4\pi\alpha = \frac{4\pi}{128} , \qquad g = \frac{e}{\sin\theta_W} = \sqrt{\frac{4\pi}{137}}\frac{91}{\sqrt{91^2 - 80^2}}$$

- t-dependence

$$\frac{d\sigma}{dt} = \frac{1}{16\pi\ s^2} \times \left\{\frac{1}{4}\sum_{\text{spin}}\sum_{\text{spin}}\sum_{\text{pol}} |A|^2\right\}$$




| | |
|---|---|
| Blue | $\gamma\gamma$ |
| Red | $Z\gamma$ |
| Green | W-related |
| Orange | Z-related |

# 5. Numerical analysis

$$\frac{d\sigma^{(T)}_{(\gamma\gamma\ \text{fusion})}}{dt} = \frac{1}{16\pi\ s^2}\left(\frac{1}{16\pi^2}\right)^2 (ge^3)^2\left(\frac{2m_t^2}{m_W}\right)^2 \times\left(-\frac{1}{t}\right)\left(1-\frac{2su}{(m_h^2-t)^2}\right)(N_c Q_t^2)^2\left|S^{\gamma}_{(T)}(t,m_t^2,m_h^2)\right|^2$$

$$\frac{d\sigma^{(W)}_{(\gamma\gamma\ \text{fusion})}}{dt} = \frac{1}{16\pi\ s^2}\left(\frac{1}{16\pi^2}\right)^2\left(e^3 g m_W\right)^2 \times\left(-\frac{1}{t}\right)\left(1-\frac{2su}{(m_h^2-t)^2}\right)\left|S^{\gamma}_{(W)}(t,m_W^2,m_h^2)\right|^2$$

$$\frac{d\sigma^{(T)}_{(Z\gamma\ \text{fusion})}}{dt} = \frac{1}{16\pi\ s^2}\left(\frac{1}{16\pi^2}\right)^2 (f_{Ze}^2+1)\left(eg^3\frac{f_{Zt}}{8\cos^2\theta_W}\frac{m_t^2}{m_W}\right)^2 \times\frac{-t}{(t-m_Z^2)^2}\left(1-\frac{2su}{(m_h^2-t)^2}\right)(N_c Q_t)^2\left|S^{\gamma}_{(T)}(t,m_t^2,m_h^2)\right|^2$$

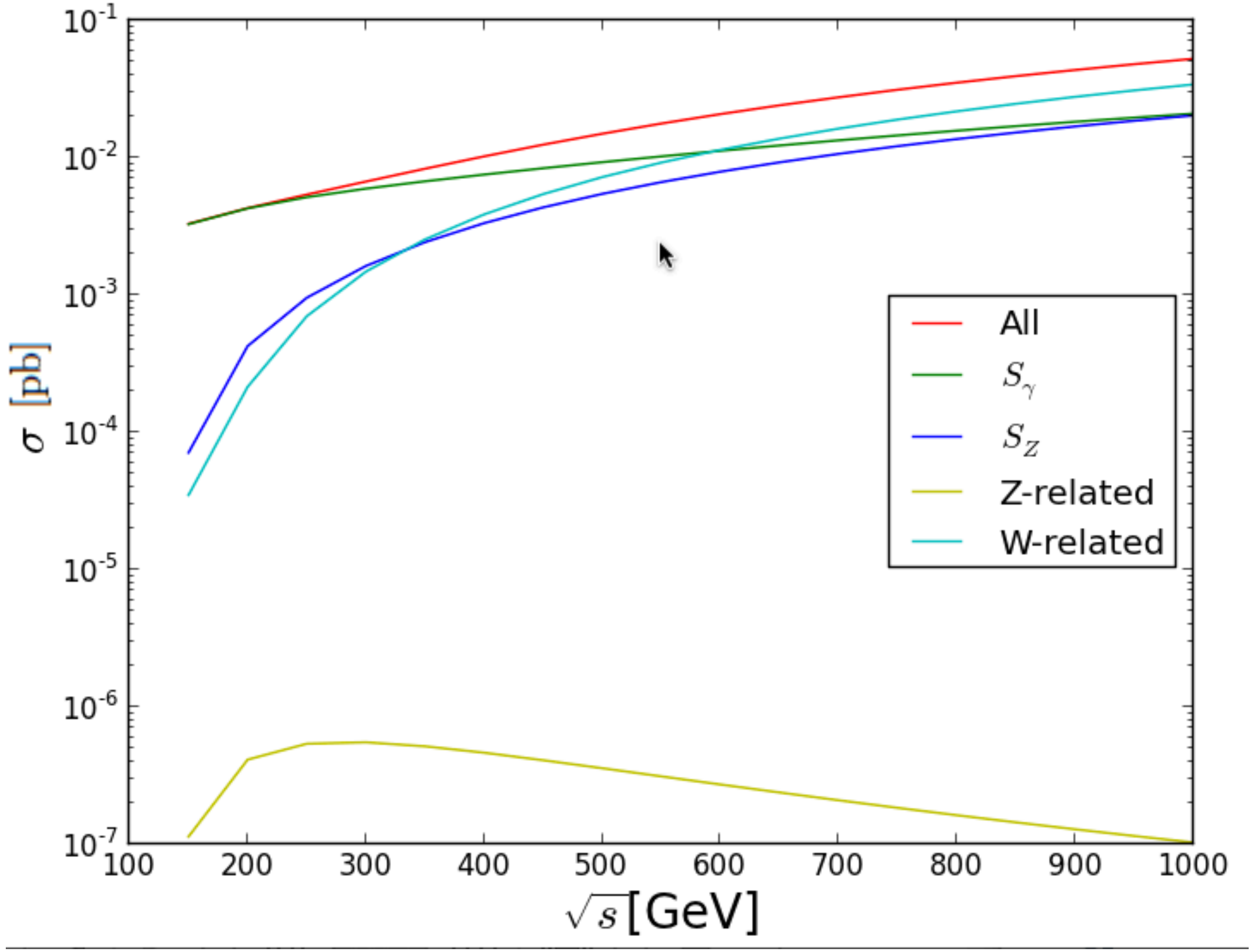
$$\frac{d\sigma^{(W)}_{(Z\gamma\ \text{fusion})}}{dt} = \frac{1}{16\pi\ s^2}\left(\frac{1}{16\pi^2}\right)^2\left(\frac{eg^3 m_W}{4}\right)^2 \times(f_{Ze}^2+1)\frac{-t}{(t-m_Z^2)^2}\left(1-\frac{2su}{(m_h^2-t)^2}\right)\left|S^{\gamma}_{(W)}(t,m_W^2,m_h^2)\right|^2$$

$$\frac{d\sigma^{(W)}_{(e\gamma\to eH)}}{dt} = \frac{1}{16\pi\ s^2}\left(\frac{1}{16\pi^2}\right)^2\left(\frac{eg^3 m_W}{4}\right)^2 \times\left\{-2\ t\left[\left|S^{(W)(k_{1\beta})}_{(e\gamma\to eH)}(s,t,m_h^2,m_Z^2)\right|^2+\left|S^{(W)(k'_{1\beta})}_{(e\gamma\to eH)}(s,t,m_h^2,m_Z^2)\right|^2\right]\right\}$$

$$\frac{d\sigma^{(Z)}_{(e\gamma\to eH)}}{dt} = \frac{1}{16\pi\ s^2}\left(\frac{1}{16\pi^2}\right)^2\left(\frac{eg^3 m_Z}{16\cos^3\theta_W}\right)^2 \times\left\{-(f_{Ze}^4+6f_{Ze}^2+1)\ t\left[\left|S^{(Z)(k_{1\beta})}_{(e\gamma\to eH)}(s,t,m_h^2,m_Z^2)\right|^2+\left|S^{(Z)(k'_{1\beta})}_{(e\gamma\to eH)}(s,t,m_h^2,m_Z^2)\right|^2\right]\right\}$$

# 5. Numerical analysis

s-dependence

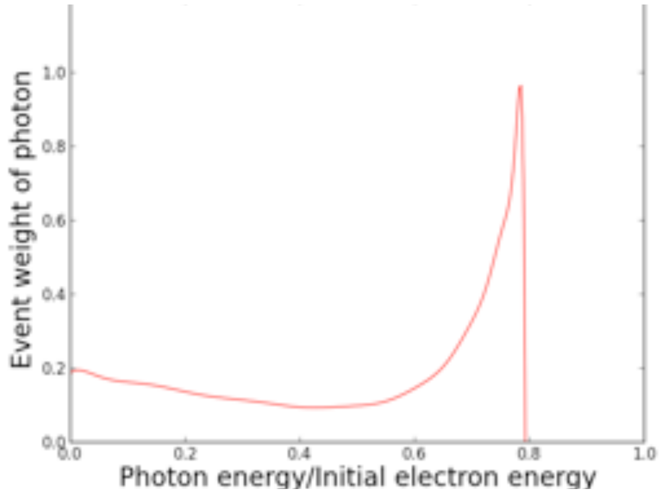


# 5. Numerical analysis

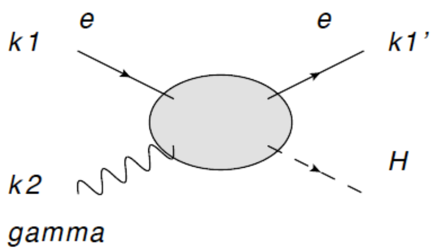
Feasibility to find Higgs in $e+\gamma \to e+b+\bar{b}$ channel

- Compton scattering:
  $e^{-}\gamma_{laser} \to e^{-}\gamma$
- can transfer 80% of e- energy to $\gamma$

Photon beam has a energy band




we examine $$\frac{d\sigma(e+\gamma \to e+b+\bar{b})}{dm_{b\bar{b}}}$$



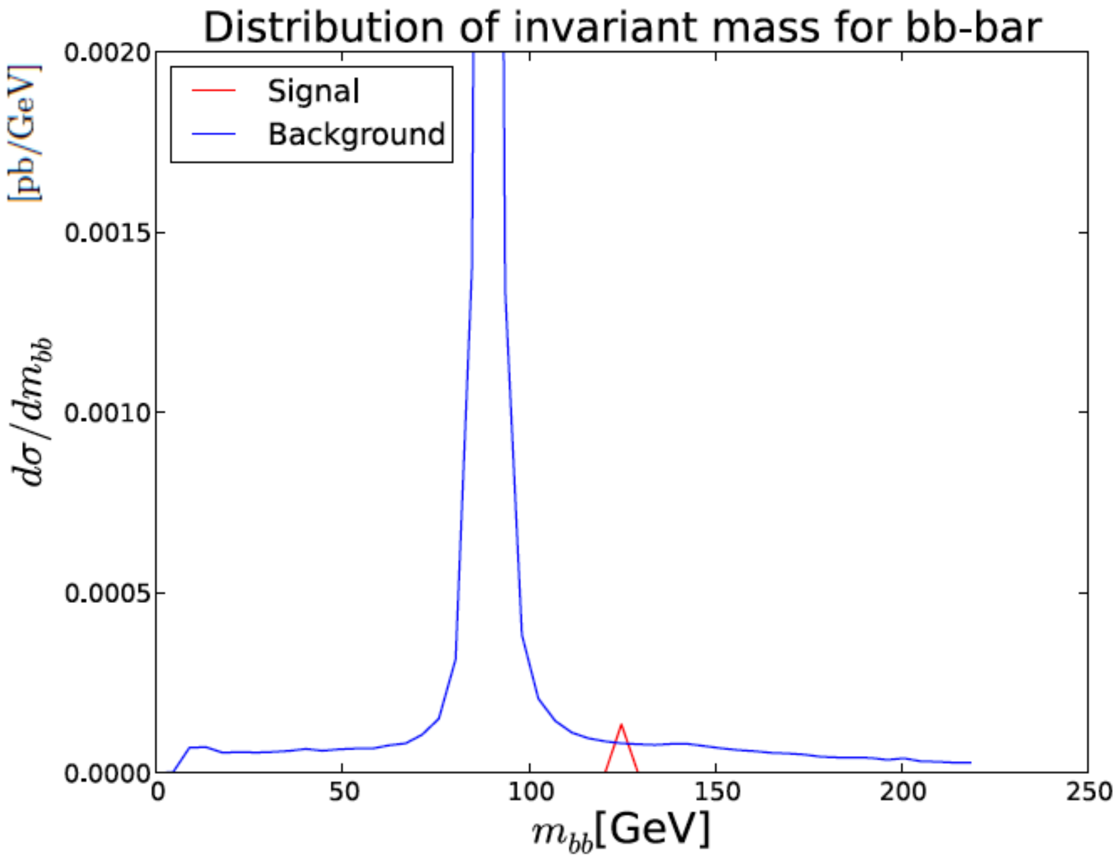

Main background $e+\gamma \to e+Z^{*} \to e+b+\bar{b}$

# 5. Numerical analysis

$$\frac{d\sigma(e+\gamma \to e+b+\overline{b})}{dm_{b\overline{b}}}$$

$E_e = 125\text{GeV}$

$E_\gamma = 0.8 \times E_e$ or less



# 6. Summary

- Higgs production in $\mathbf{e}^{-}\gamma$ collision was investigated in SM.
- The EW one-loop contributions to the amplitude $e+\gamma \Longrightarrow e+H$ were obtained in analytical form.
- Numerical analysis was performed:
  - Contribution of $\gamma\gamma$ -fusion diagrams is dominant for $\sqrt{\mathbf{s}} < \mathbf{250\ GeV}$
  - Contributions of $\gamma\gamma$ -fusion diagrams, $\mathbf{Z}\gamma$ -fusion diagrams and W-related diagrams become the same order at $\sqrt{\mathbf{s}} = \mathbf{500\ GeV}$
  - Contribution of Z-related diagrams is extremely small and can be neglected
  - The feasibility to find Higgs in $\mathbf{e}^{-}\gamma$ collision was studied in $e+\gamma \rightarrow e+b+\bar{b}$ channel
- This work is now in preparation.

Thank you for your attention