Impact of higher dimensional operators on Higgs boson phenomenology

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Plan of talk

- Introduction
  - Higgs coupling

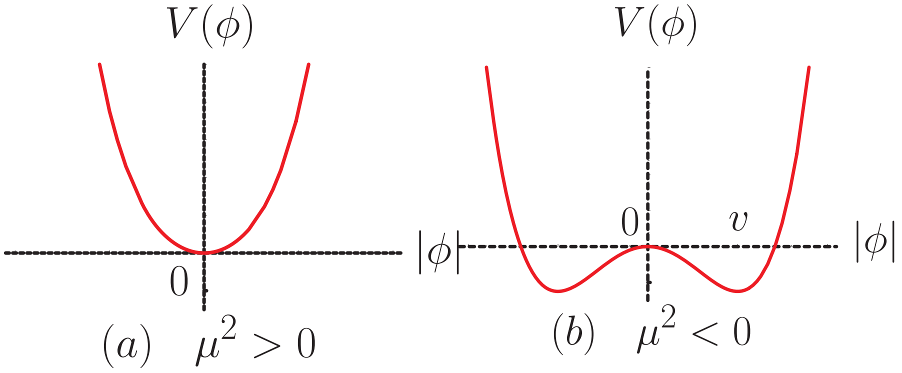
- Effective theory as a new physics description
  - Current constraints (Theory and data)
  - Higgs boson decays with Dim6 operators
  - Effect on the production cross section at future colliders

- Summary

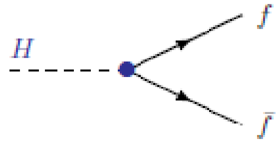
Higgs couplings

- **To understand the EWSB:**

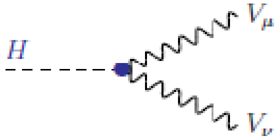
$$V(\Phi) = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2$$



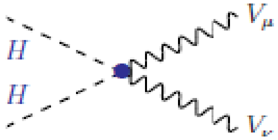
- **To confirm the SM predictions:**



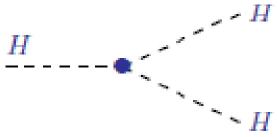
$$\sqrt{2}m_f/v$$



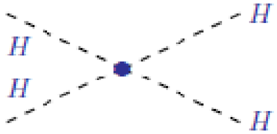
$$2m_V^2/v$$



$$2m_V^2/v^2$$



$$2m_H^2/v$$



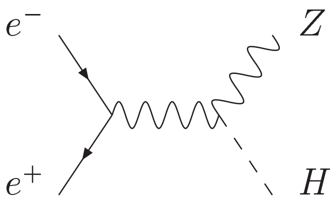
$$3m_H^2/v^2$$

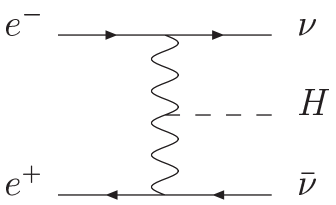
SM or not ?

Independent determination of the mass and the coupling is essentially important

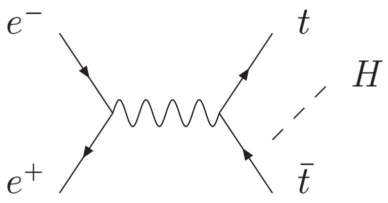
Higgs couplings @ future colliders

- Higgs-strahlung and W fusion: Higgs gauge coupling

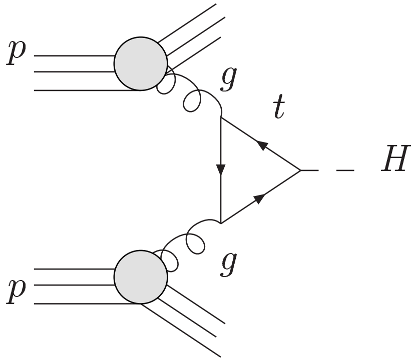




- Top radiation off : Yukawa coupling

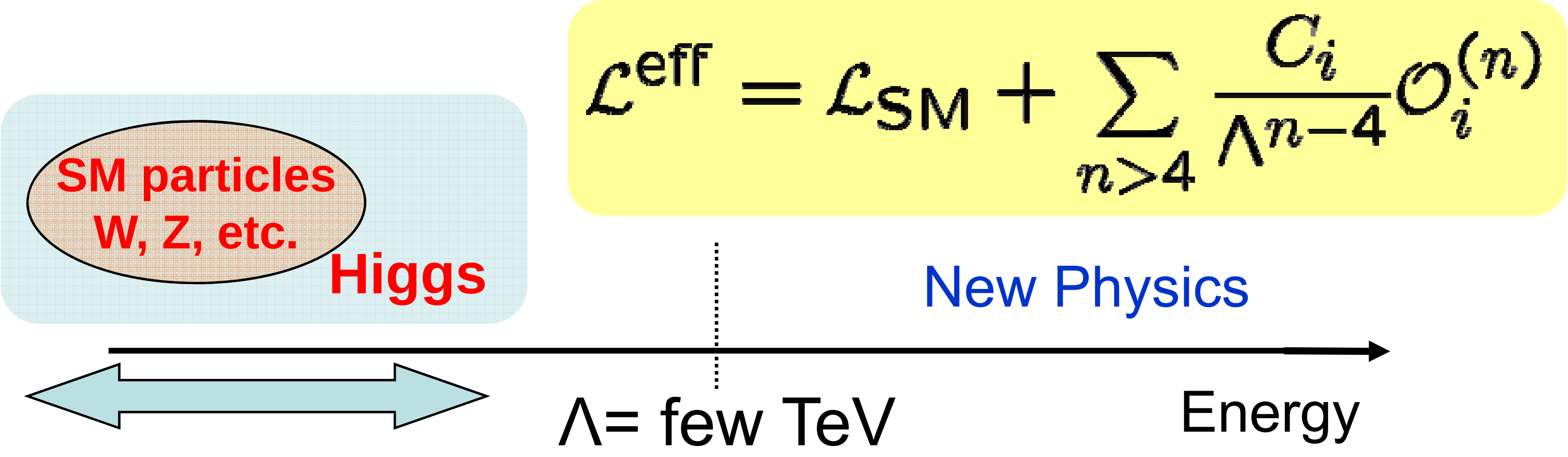


- Double Higgs production: Higgs self-coupling
- Gluon fusion: combination of "g" and "yt"



Dim-6 operators as New physics

- Our setup: Higgs boson is discovered, but no other new particle in the low energy scale.
- Effective theory can be described by the SM with higher dimensional operators.
- Leading order contributions come from gauge invariant dim-6 operators.



$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{n>4} \frac{C_i}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$

Effective theory with dim-6 operators

- **List of dim-6 fermion-Higgs and genuine Higgs operators.**

$$\mathcal{O}_{t1} = \left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)\left(\bar{q}_L t_R \tilde{\Phi} + \text{h.c.}\right)$$

$$\mathcal{O}_{t2} = i(\Phi^\dagger D_\mu \Phi)\bar{t}_R \gamma^\mu t_R + \text{h.c.}$$

$$\mathcal{O}_{t3} = i(\tilde{\Phi}^\dagger D_\mu \Phi)\bar{t}_R \gamma^\mu b_R + \text{h.c.}$$

$$\mathcal{O}_{Dt} = (\bar{q}_L D_\mu t_R)\left(D^\mu \tilde{\Phi}\right) + \text{h.c.}$$

$$\mathcal{O}_{tW\Phi} = (\bar{q}_L \sigma^{\mu\nu} \vec{\tau} t_R)\tilde{\Phi}\vec{W}_{\mu\nu} + \text{h.c.}$$

$$\mathcal{O}_{tB\Phi} = (\bar{q}_L \sigma^{\mu\nu} t_R)\tilde{\Phi} B_{\mu\nu} + \text{h.c.}$$

$\cdots$ those for bottom quark $\cdots$

$$\mathcal{O}_{H1} = \frac{1}{2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$$

$$\mathcal{O}_{H2} = -\frac{1}{3}(\Phi^\dagger\Phi)^3$$

$$\mathcal{O}_{H3} = (D_\mu\Phi)^\dagger\Phi\Phi^\dagger(D^\mu\Phi)$$

Buchmuller et al (86)
Han et.al. (99)

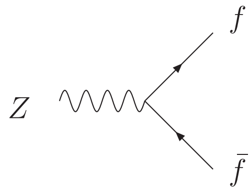
Bosonic operators with gauge interaction are strongly constrained by LEP data. Hagiwara et al （97)

We consider the extension of the Yukawa interaction and the Higgs potential.

Let me check the constraints.

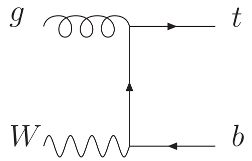
Current constraints

- **Direct searches:**
  - No Higgs boson is observed.
    - Any Higgs couplings are not constrained directly.
  - dim-6 bottom operators are strongly constrained by Z → bb data at LEP.
  - Gauge interaction for top quarks can be constrained by Tevatron data, but now we have very few statistics.



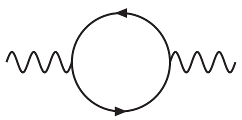
Gounaris et al(95)

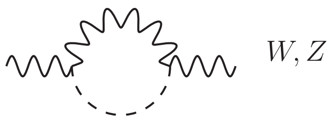
K. i. Hikasa et al(98)

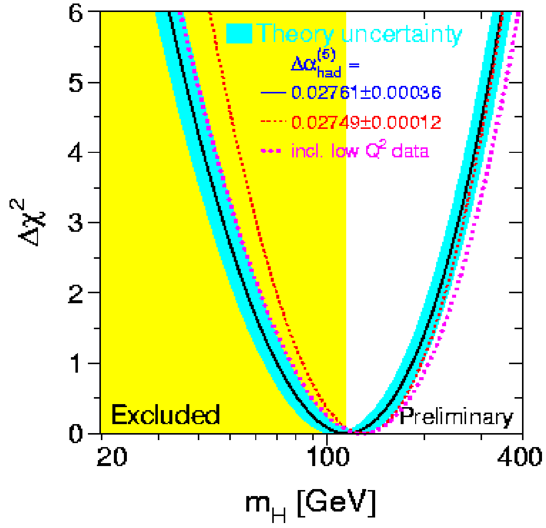


- **Indirect searches:**
  - mH is expected around 100-200 GeV from Δρ

$$\Delta\rho_{\mathrm{SM}} = \Delta\rho_t + \Delta\rho_H$$







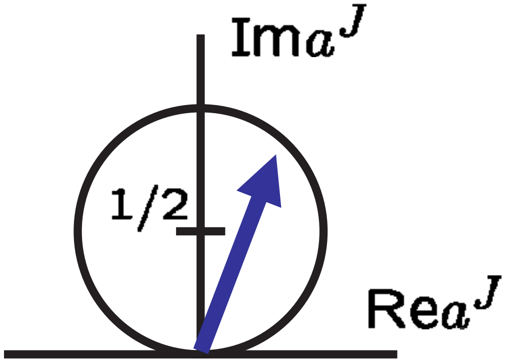
Current constraints

- The dim-6 operators involving gauge interactions contribute to Δρ which are severely constrained. Gounaris et.al. (95)
- On the other hand, its contribution to Δρ can change the situation. Larger mH can be allowed with dim-6 operators.

$$\Delta\rho = \Delta\rho_{\mathrm{SM}} + \Delta\rho_{\mathrm{dim6}}$$

- **Theoretical bound** Gounaris et.al. (97) Han et.al. (99)
  - Unitarity arguments can give weaker bound for the dim-6 operators which guarantee the validty of perturbative calculation.
  - ex.

$$|a_{t1}| < \begin{cases} 1.0 \text{ for } \Lambda = 1\,\mathrm{TeV} \\ 3.0 \text{ for } \Lambda = 3\,\mathrm{TeV} \end{cases}$$



Less constrained dim-6 operators

From above discussions,

Higgs coupling and Top-Yukawa coupling are less constrained:

- Effective y_t and λ can be large which are related to the dim-6 operators O_{t1}, O_{H1} and O_{H2}.

- $\mathcal{O}_{H1} = \frac{1}{2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$
  - wave function renormalization for Higgs fields $Z_H = 1/(1 + a_{H1})$

$$g_{HVV} \to Z_H^{1/2} g_{HVV},\quad g_{HHVV} \to Z_H g_{HHVV},\quad y_f \to Z_H^{1/2} y_f$$

a_{H1} can be measured by the Higgs-strahlung process.

- $\mathcal{O}_{H2} = -\frac{1}{3}(\Phi^\dagger\Phi)^3$
  - shift the Higgs self-coupling
  - a_{H2} can be determined by Higgs self-coupling measurement which is challenging at LHC.

$$\lambda^{SM} \to \lambda^{SM} - \frac{a_{H2}}{2}$$

Less constrained dim-6 operators

From above discussions,

Higgs coupling and Top-Yukawa coupling are less constrained:

- Effective y_t and λ can be large which are related to the dim-6 operators O_{t1}, O_{H1} and O_{H2}.

- $\mathcal{O}_{t1} = \left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)\left(\bar{q}_L t_R \tilde{\Phi} + \text{h.c.}\right)$

$$y_t^{\text{SM}} \to y_t^{\text{SM}} - a_{t1}, \left(a_i = \frac{v^2}{\Lambda^2} C_i\right)$$

- shift the top-Yukawa coupling

$$|a_{t1}| < \begin{cases} 1.0 \text{ for } \Lambda = 1\text{TeV} \\ 3.0 \text{ for } \Lambda = 3\text{TeV} \end{cases}$$

This talk*

- Focus on the less constrained coupling a_{t1} (a_{H1}).
  - The values of dim-6 couplings are chosen in the allowed region from unitarity bounds.
    - reference value: a_{t1} = -0.5, 0, 0.5 (50% deviation from the SM value)

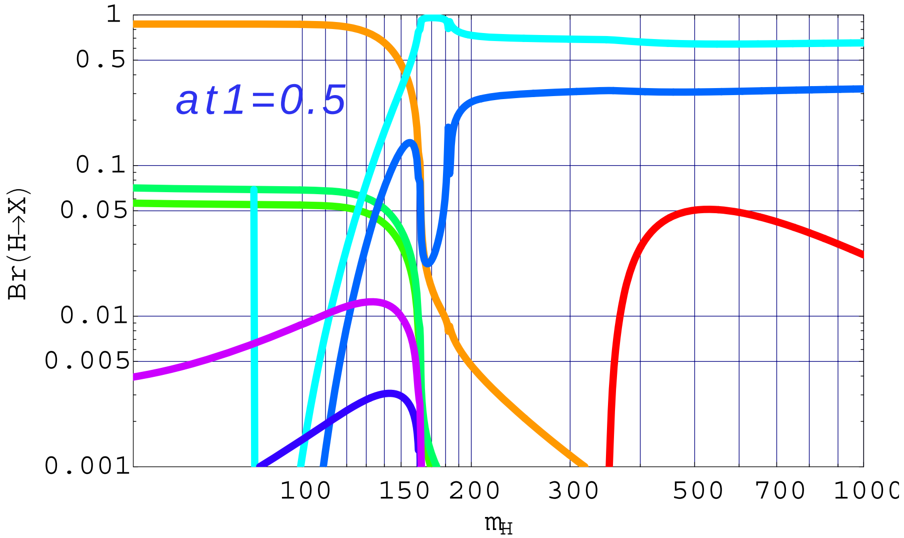
What's the impact of a_{t1}?

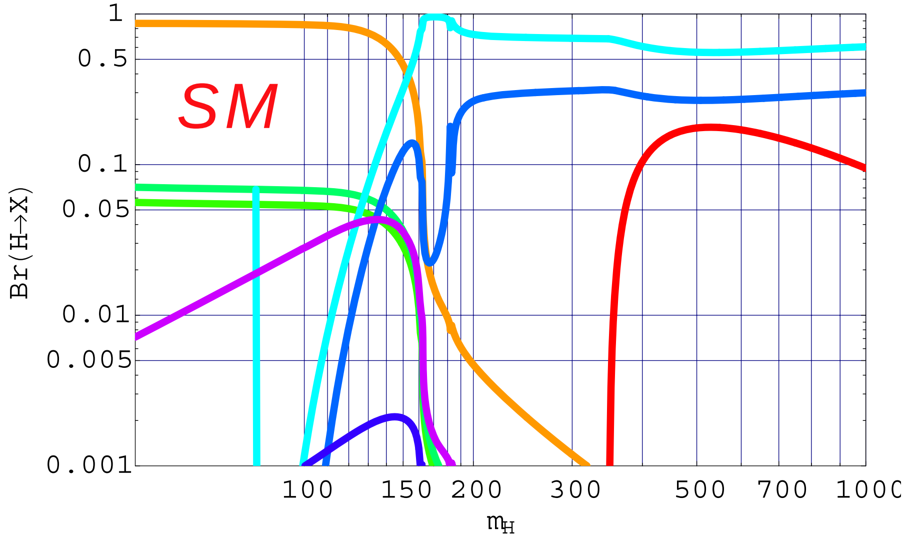
Higgs decay branching ratio

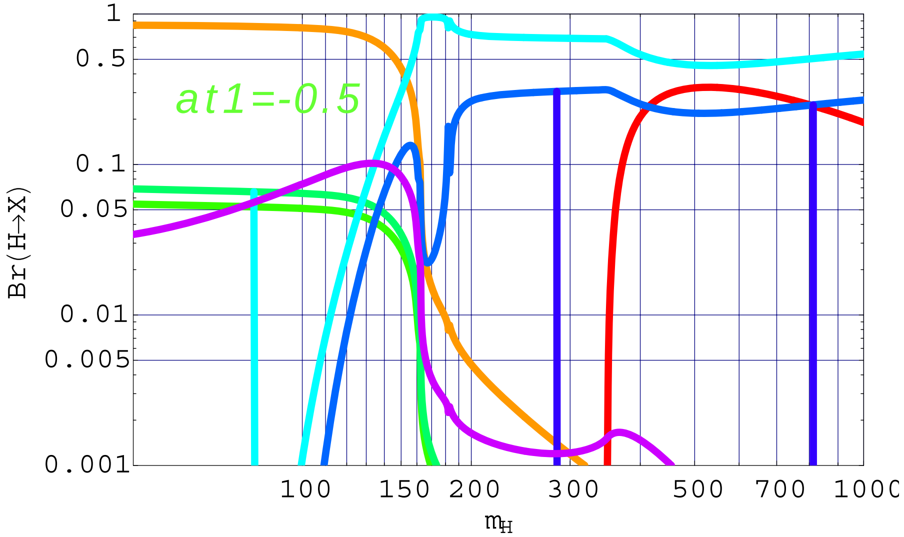
- Branching ratios H→ tt are corrected by a_{t1}.
  - a_{t1}=0.5: destructive ~1/4
  - a_{t1}=-0.5: constructive ~9/4
- When the Br(H →gg) is suppressed, Br(H →γγ) can become large at mH=100-150GeV.

H → tt, H → bb, H → ττ , H → cc
H → WW, H → ZZ, H → gg, H → γγ

Kanemura Numura KT(06)





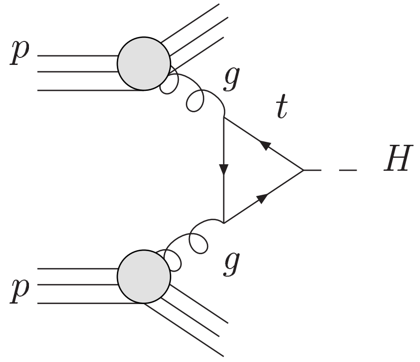


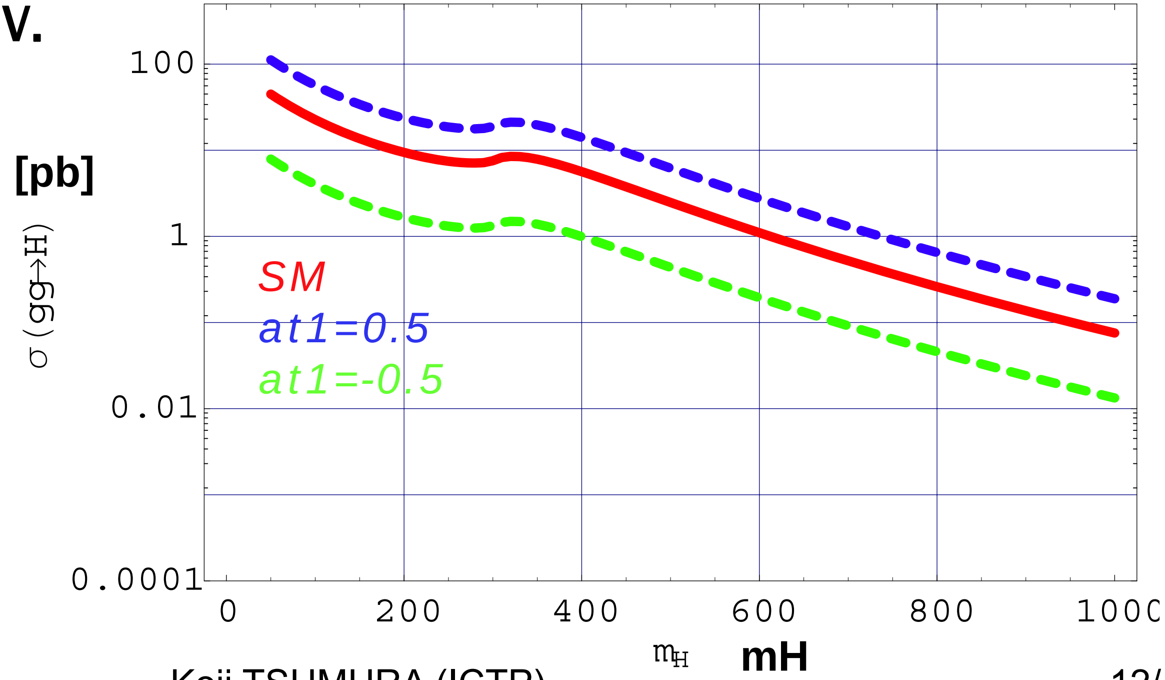
Gluon fusion @ LHC

- Effect of a_{t1} and a_{H1}:
  - Not distinguish a_{t1} and a_{H1} in the Higgs production.

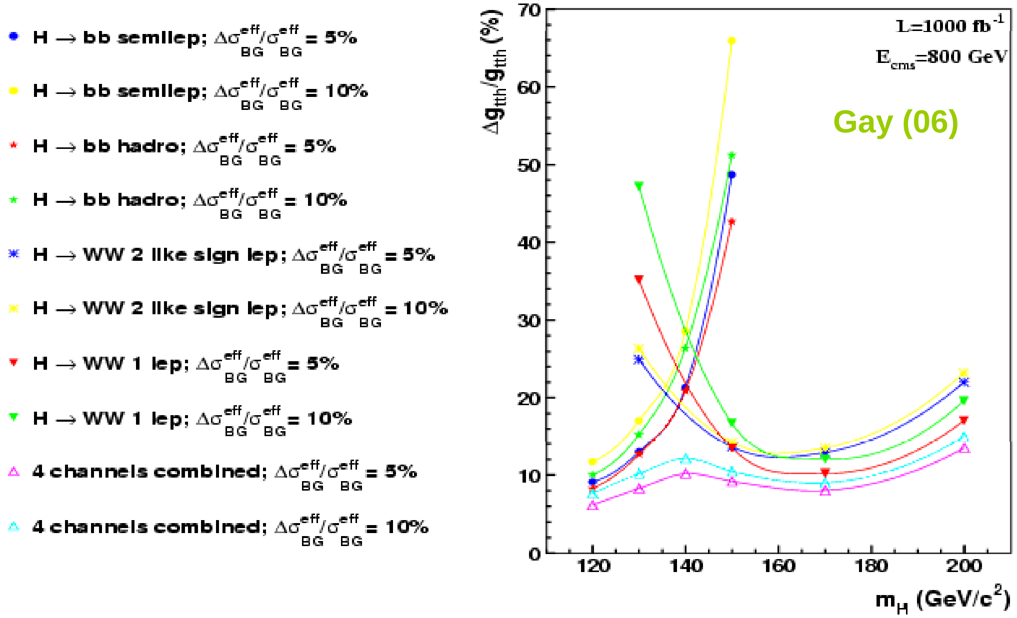
$$y_t^{\text{eff}} = (y_t^{\text{SM}} - a_{t1})/\sqrt{1 + a_{H1}}$$

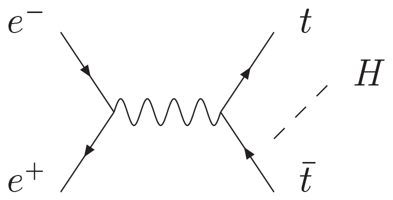
  - a_{t1} can enhance (suppress) production cross section, but reduce (enhance) Br(H → γγ). In this case, it is difficult to search Higgs boson with mH~120 GeV.



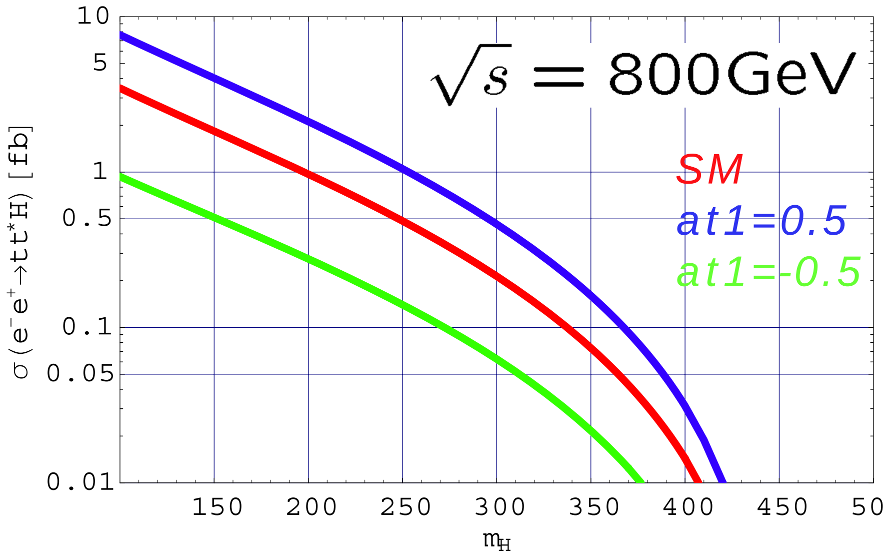


Measurement of top-Yukawa coupling via ee → ttH





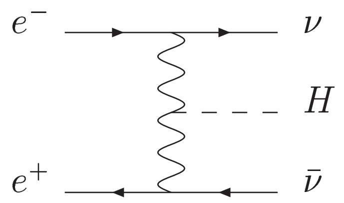
- Once a_{H1} is determined by Higgs-strahlung, yt (a_{t1}) can be measured at 10-% level for mH<200 GeV.



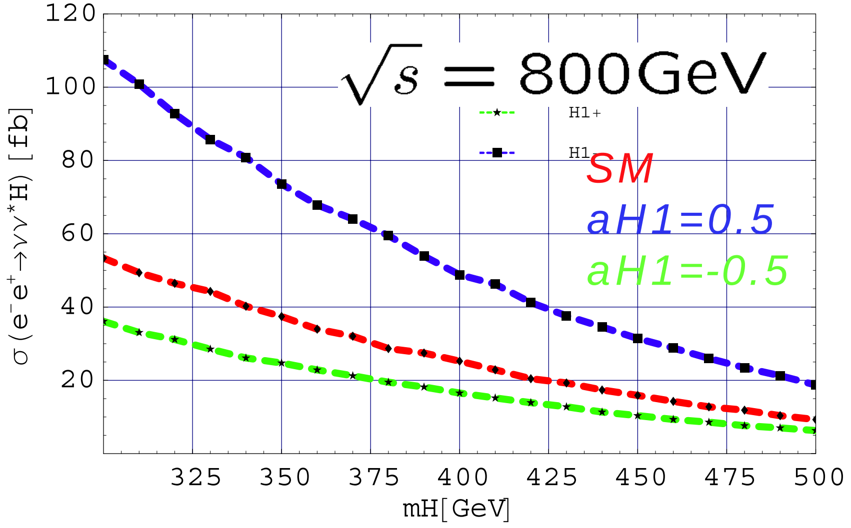
- But, top radiation off process **quickly decreases** for large mH values. Han rt al (99)

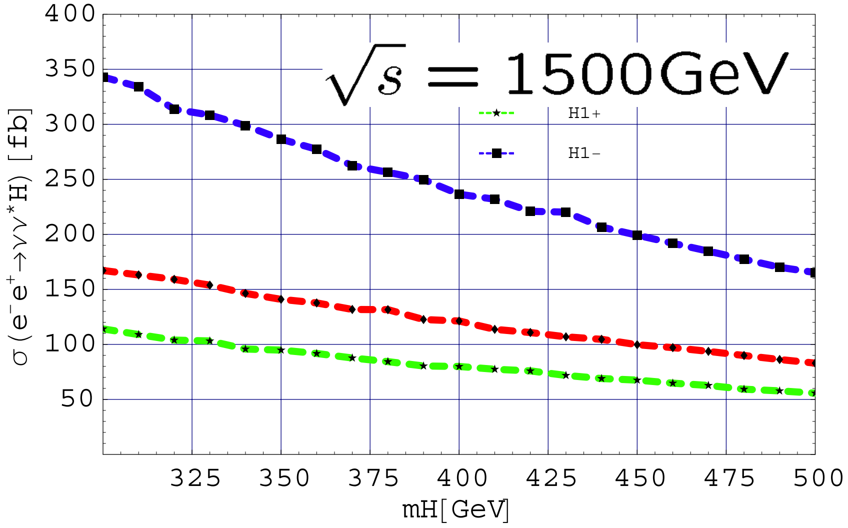
What's the impact of a_{t1} for large mH values ?

Effect on "ee → Hνν" (W-fusion)



Kanemura Numura KT(06)





- **When the Higgs-strahlung is suppressed at high energy, the cross section of W-boson fusion becomes significant.**

  a_{H1} *can be measured precisely even in large mH values.*

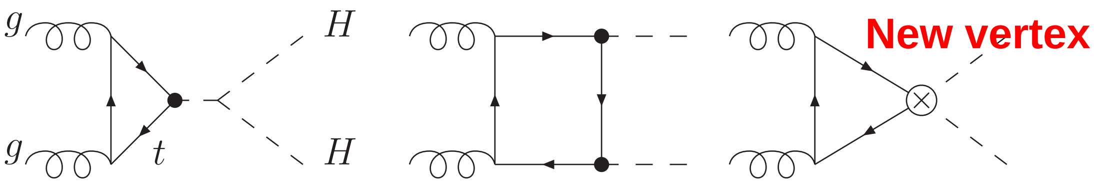
- **Once Higgs gauge coupling is fixed, a_{t1} can be determined by Higgs deay modes (H → tt, H → WW, H → ZZ).**

a_{t1} *can be measured precisely for mH>2mt at high energy collider*

Double Higgs production: gg→ HH

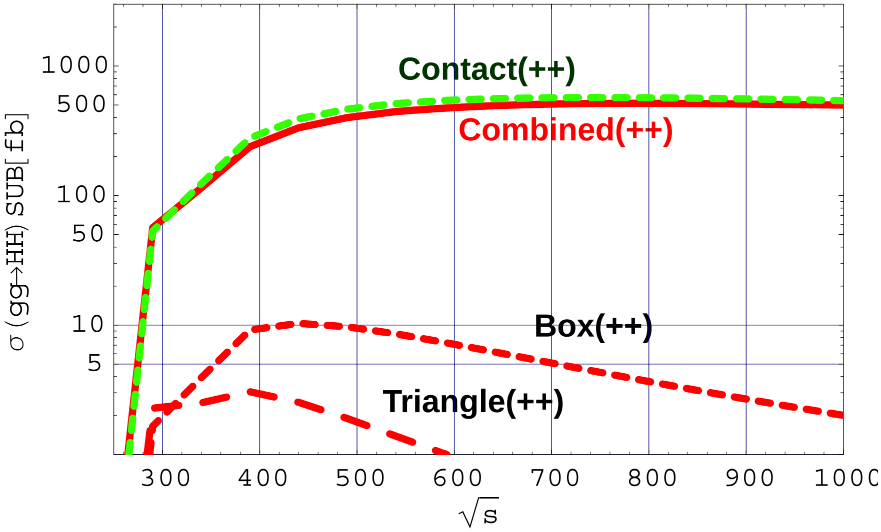
- **Effect of a_{t1}:**

$$y_t^{\text{eff}} = y_t^{\text{SM}} - a_{t1}$$

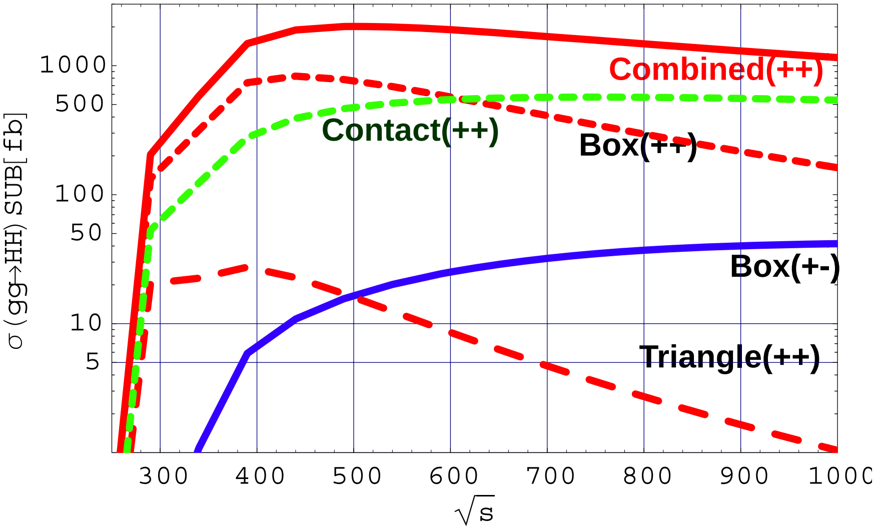


  - **Contributions from Triangle diagram becomes important for large mH values, because Higgs self-coupling depends on the Higgs mass.**

$$m_H = 120\text{GeV}, a_{t1} = +0.5$$



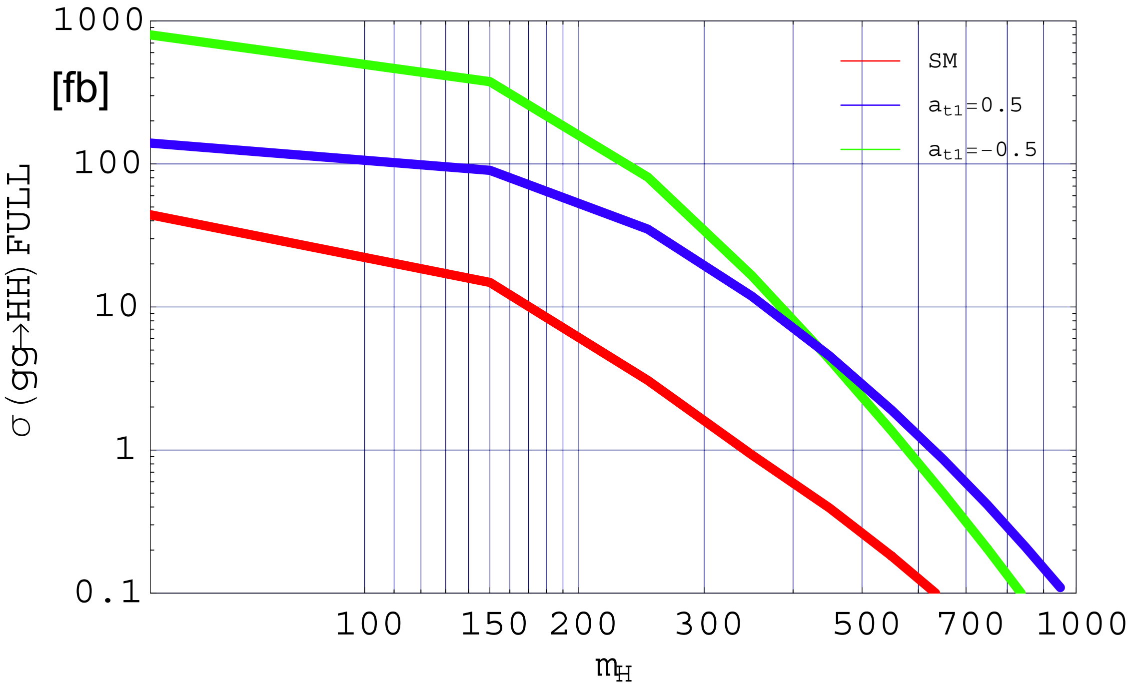
$$m_H = 120\text{GeV}, a_{t1} = -0.5$$



  - **Dim-6 contact interaction becomes important !!**

Effect on “gg→ HH”

- **Full cross section: pp→ HHX (pdf-ctex6)**



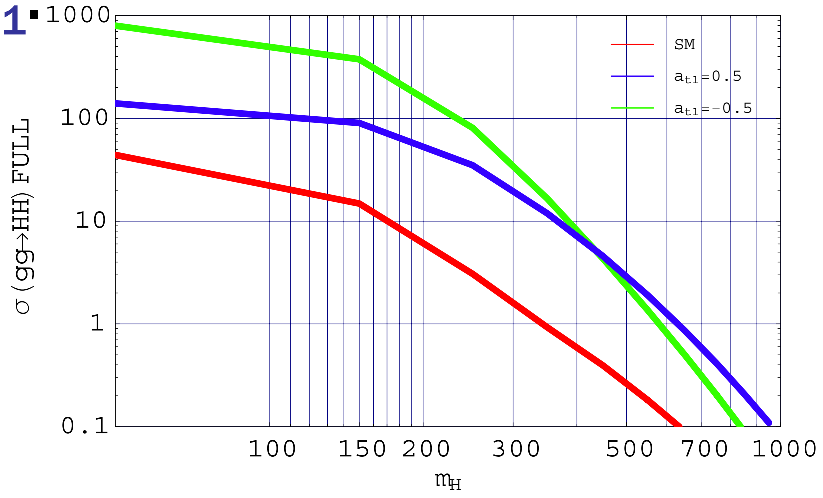
  - By introducing the dim-6 top-Higgs operators, the double-Higgs production can be enhanced drastically.
  - gg→ HH is very sensitive process for such operators.
  - At γγ→ HH, enhancement may be weakend by W-boson loop.

(Work in progress; Asakawa, Harada, Kanemura, Okada, Tsumura)

Summary

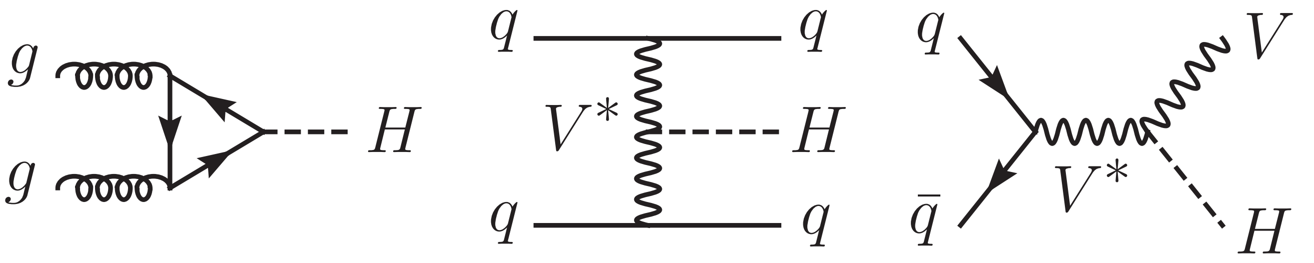
- Constraints on the dim-6 Higgs-fermion and genuine-Higgs operators are studied.
- a_{H1} can be measured precisely by Higgs-strahlung and W-fusion.
- a_{t1} can enhance (suppress) production cross section, but reduce (enhance) Br(H → γγ).
- a_{t1} can be measured less than several × 10% level for wide range of mH.
- gg→ HH can be a good probe of a_{t1}.

$$\mathcal{O}_{t1} = \left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)\left(\bar{q}_L t_R \tilde{\Phi} + \text{h.c.}\right)$$

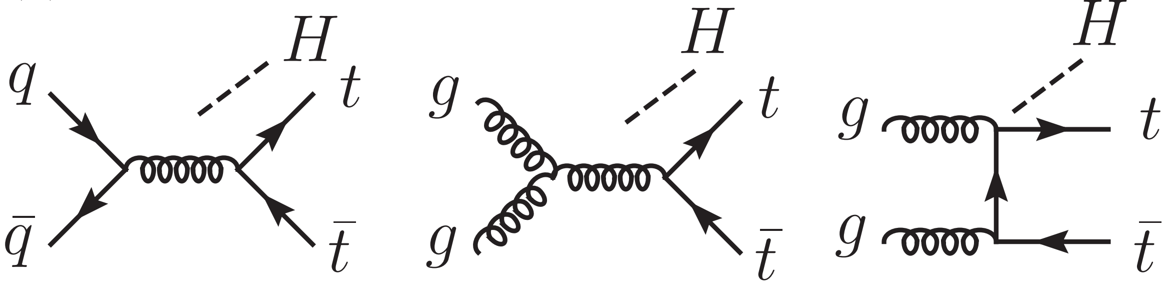


Higgs couplings @ LHC

- Higgs-strahlung: extract g_ZZH
- Gluon fusion: yt * AlpS
- Fermion radiation off: yf
- W boson fusion: g_WWH



$(a)\, gg \to H$ $(b)\, qq \to qqV^*V^* \to qqH$ $(c)\, q\bar{q} \to V^* \to VH$



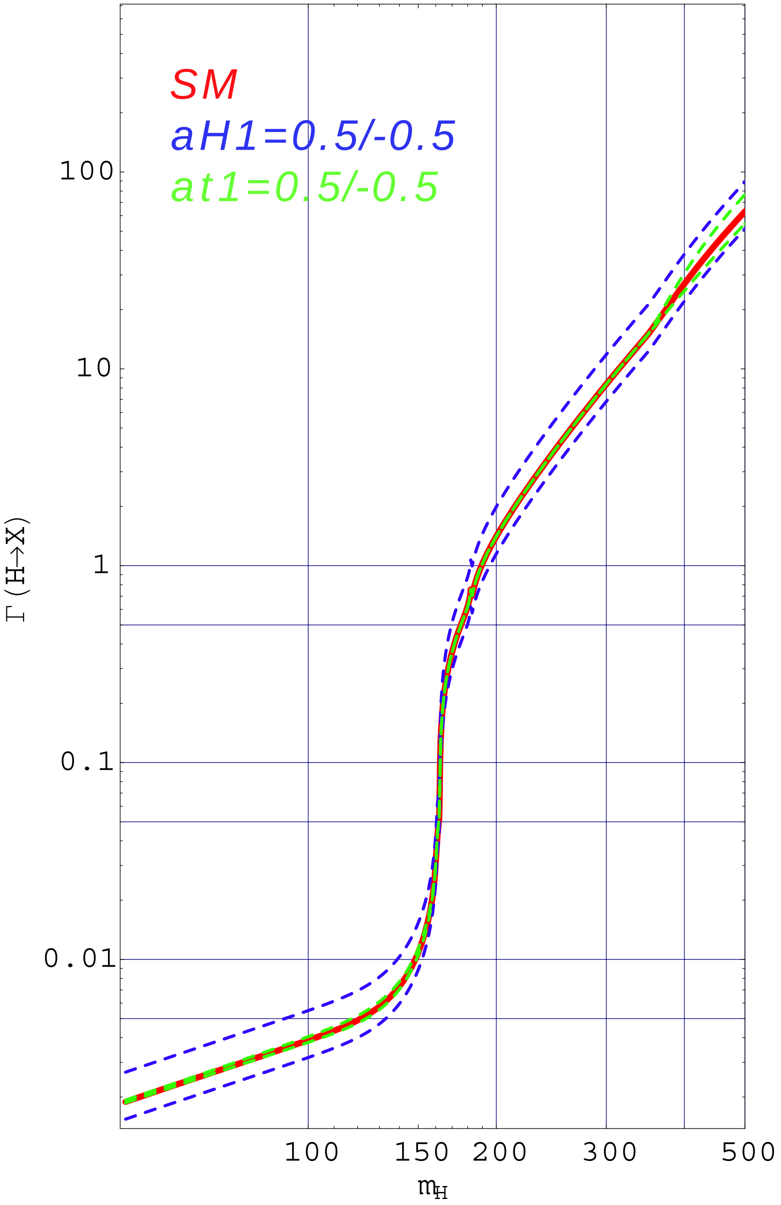
$(d)\, q\bar{q}, gg \to t\bar{t}H$

Decay width for the Higgs boson

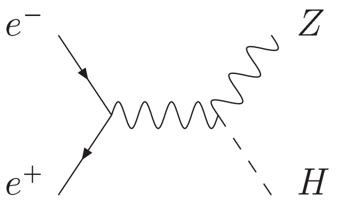
- Width and Branching ratios
  - We here include the processes,

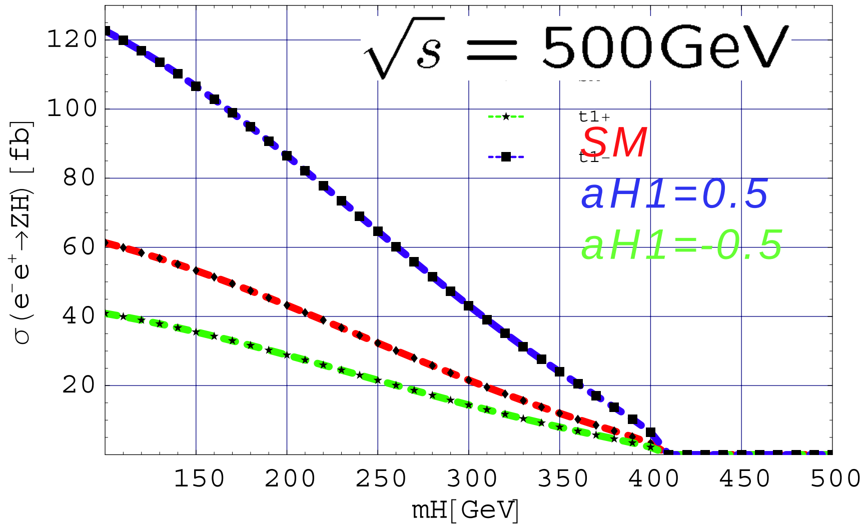
    H → tt, bb, cc, ττ, WW, ZZ, gg, γγ.
  - The values of dim-6 couplings are chosen in the unitarity bounds.
  - **t1** and **H1** contribute to the total decay width Γ of Higgs boson.

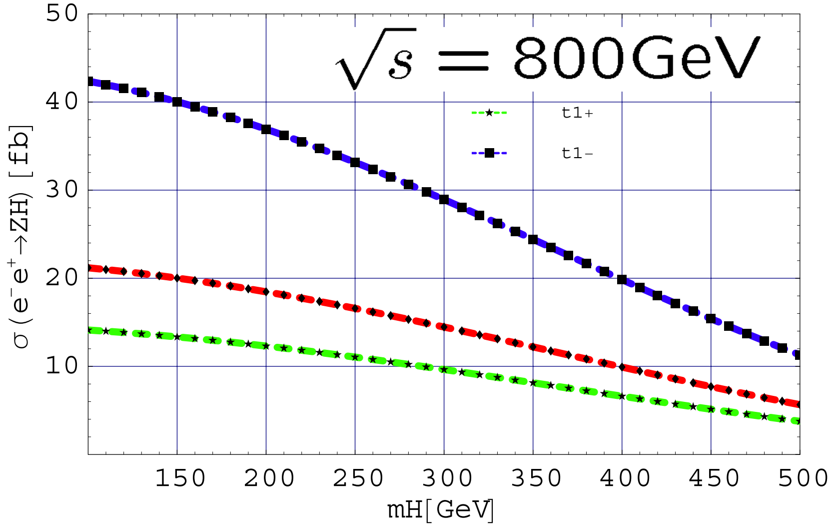
    - **H1** simply shifts Γ, but does not change Br(H → X).
    - H →tt is modified by **t1** for large mH (mH>2mt).
    - Loop induced decays H →gg, γγ are received corrections by **t1**.



Results; ee→ ZH (Higgs-stahlung)



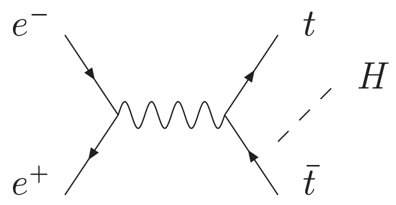


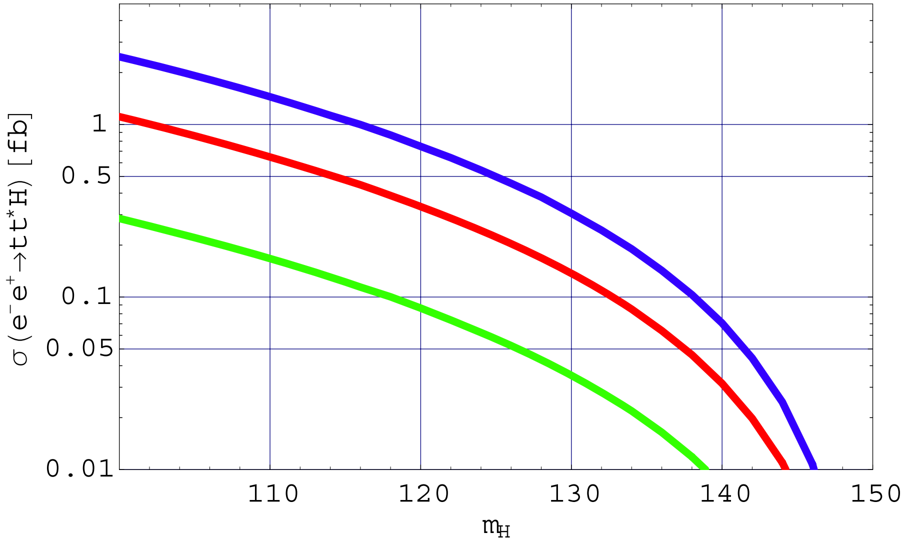


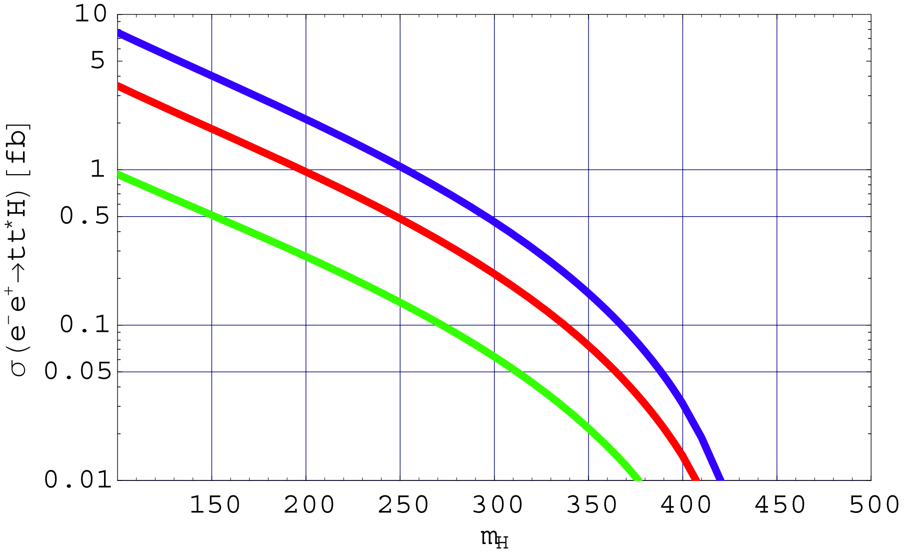
- **The cross section decreases for higher energy due to s-channel process.**
- **The coupling H1 will be precisely measured by Higgs-strahlung.**

H1 can be measured precisely for wide range of mH.

Results; ee → ttH







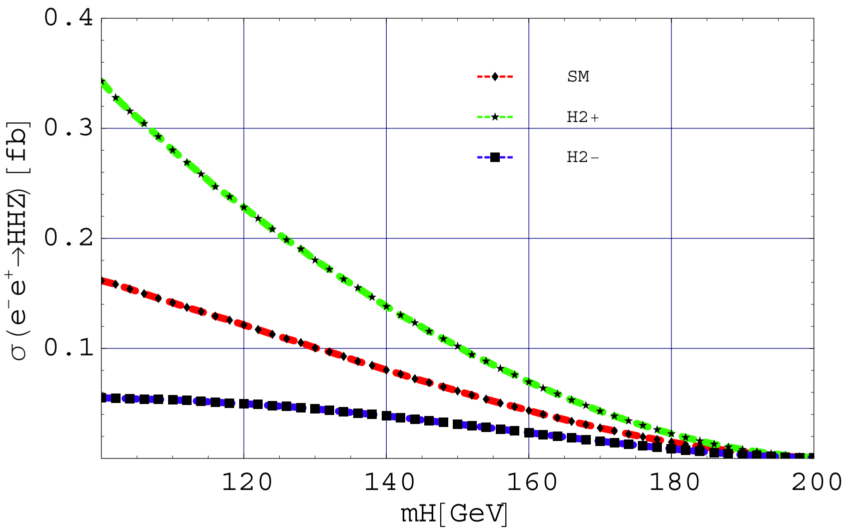
- **Effect of t1 can be observed in the top radiation off Higgs production.**
- **Even in the higher sq(s), this process is sensitive to t1 only for the lighter Higgs boson (mH<200-250GeV).**

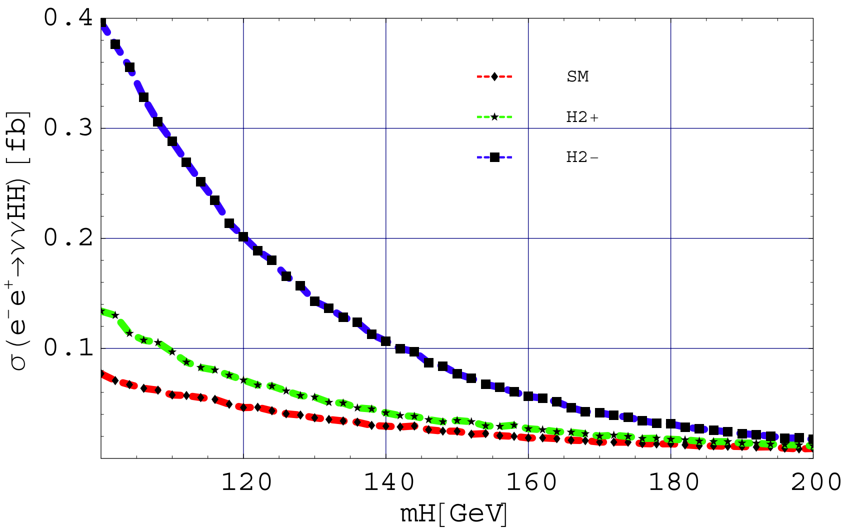
t1 can be measured for small values of mH.

- **How to measure t1 for large mH values ?**

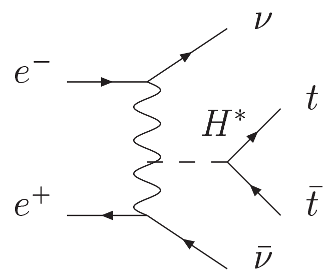
Back up: Double-Higgs production @ ILC

- **ee → HHZ, ννHH**

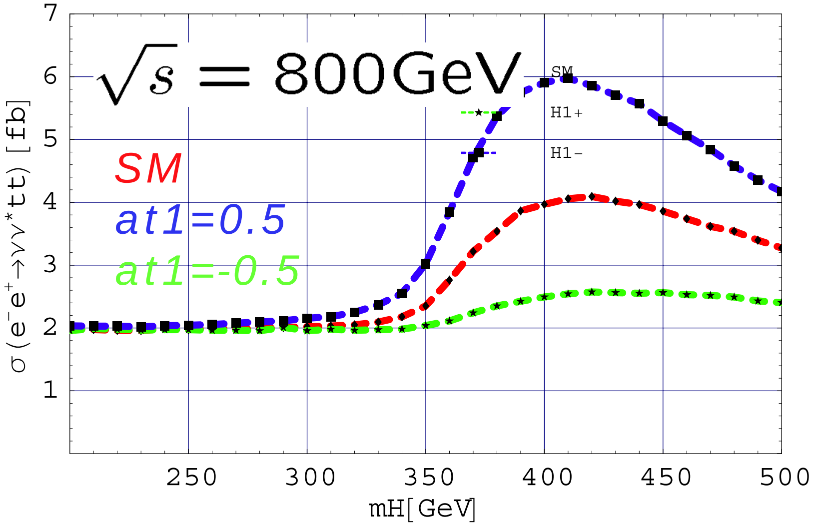


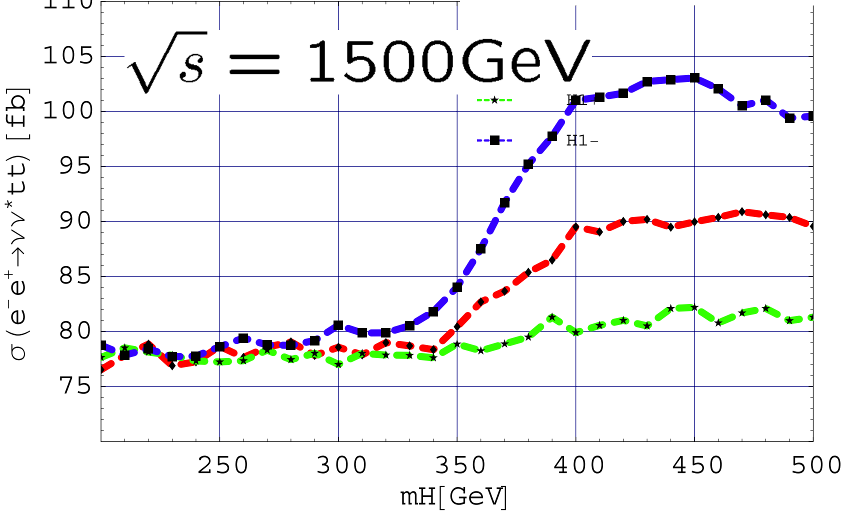


Results; Virtual Higgs



- ee →ttνν





– **Effect of t1 (deviation from the SM) can be observed near tt threshold, which is >10% (when at1=-0.5) for mH>320GeV with sq(s)=800GeV.**

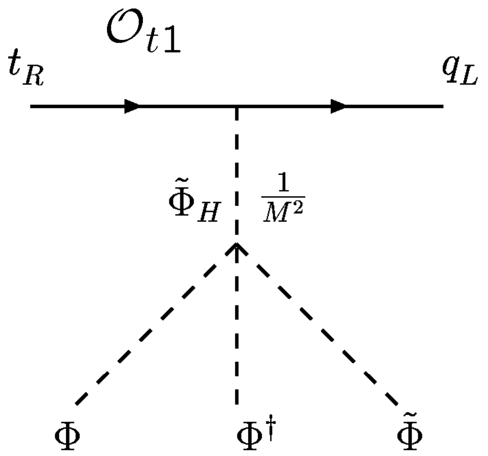
t1 can be measured near tt threshold (mH<2mt)

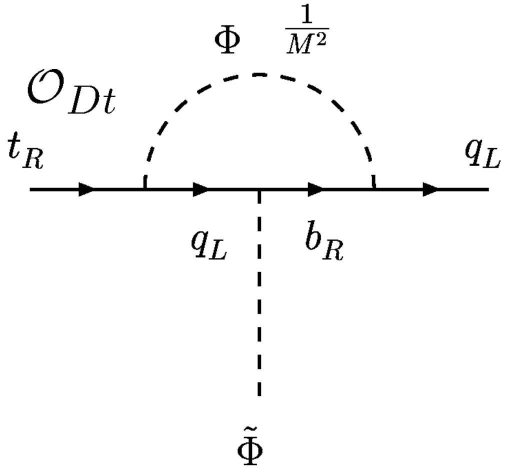
Detailed study should be needed.

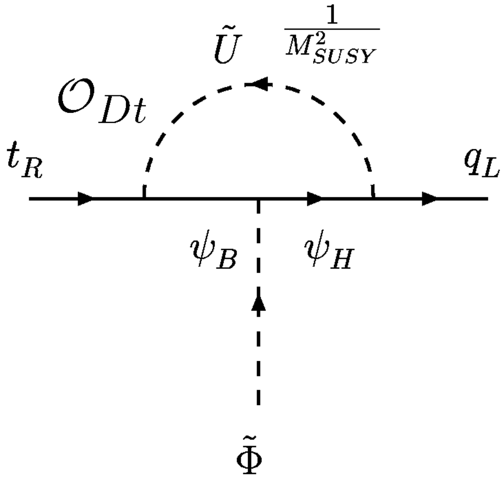
– **For sq(s)=1500 GeV, there is small correction <3% around mH~320 GeV, t-channel diagram is dominated for higher energy.**

t1 measurement at mH~300GeV is still challenging issue

Origin of dim.6 operators







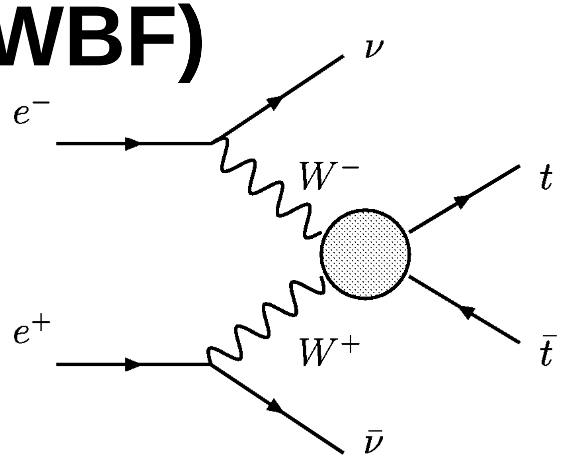
PRD69,115007 Feng, Li, Maalampi

$$\mathcal{L}_{dim.6} = \frac{1}{M_A^2}\sum_i C_i \mathcal{O}_i$$

$$C_{t1} = \frac{g^2+g'^2}{2}\mathrm{Re}(h_U^{33}) s_\beta c_\beta^2 (c_\beta^2 - s_\beta^2),\ \ C_{Dt} = \cdots$$

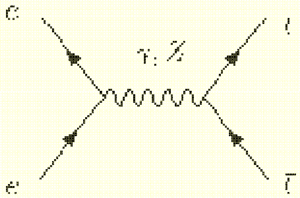
W boson fusion (WBF)

- At the high energy LC, W-fusion is an important probe.
- A few thousands of top-pair events produced via vector boson fusion.
- BGs have been studied.



$e^-e^+ \to t\bar{t}$

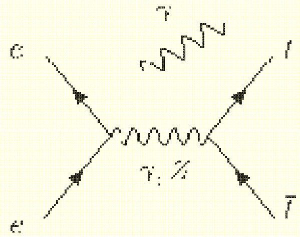
J. Alcaraz and E. Ruiz Morales,
Phys. Rev. Lett. 86, 3726 (2001)



$M_{t\bar{t}} \neq \sqrt{s}$

$e^-e^+ \to t\bar{t}\gamma$

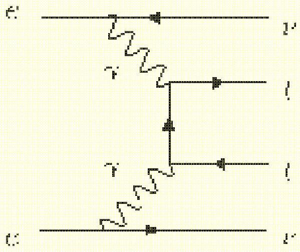
F. Larios, T. Tait, and C. P. Yuan,
Phys. Rev. D 57, 3106 (1998)



$p_T \geq 20\text{GeV}$

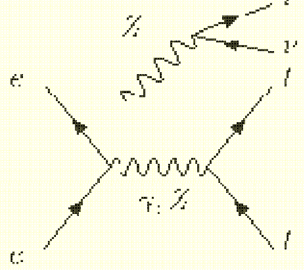
$e^-e^+ \to t\bar{t}\nu\bar{\nu}$

J. Alcaraz and E. Ruiz Morales,
Phys. Rev. Lett. 86, 3726 (2001)



$E_T \geq 50\text{GeV}$

$e^-e^+ \to t\bar{t}\nu\bar{\nu}$

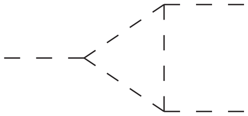


$M_{\nu\bar{\nu}} \neq m_Z$

Comment on the 1-loop calculation with dim-6 operators

- **Regularization:**
  - **We naively set the cut off scale:**
    - **We evaluate scalar loop-integrals in cut off regularization**

$$C_0 = i\pi^2 \int^{\Lambda} \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m^2} \frac{1}{(k+p_1)^2 - m^2} \frac{1}{(k+p_1+p_2)^2 - m^2}$$



    - **To keep the Lorentz invariance, we used Passarino-Veltman reduction in the dimensional regularization.**
    - **Results for cutoff scale infinity are consistent with those of the dimensional regularization.**