New Physics effect on the Top-Yukawa coupling

KOJI TSUMURA (KEK)

in collaboration with Shinya Kanemura (U-Toyama), Koichi Matsuda (Tsinghua-U), Daisuke Nomura (KEK)

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This talk is based on PRD74,076007(2006)

Plan of talk

- **Introduction**
  - **Top-Yukawa coupling at a LC**
- **Effective Theory**
  - **Dimension-six operators as a new physics**
  - **Constraints on dim.6 ops.**
- **New physics effect on the Top-Yukawa coupling at a LC**
- **Summary**

Introduction

Why Top-Yukawa coupling

- **Why the Yukawa coupling ?**
  - **Gauge interactions are well examined.**
  - **To understand the mass generation mechanism. It is necessary to measure mass and Yukawa coupling separately.**
- **Why the top ?**
  - **Large Y_t is essentially important at future colliders.**
  - **Why the top exceptionally heavy ?**
  - **Are the top and EWSB related ?**

Top-quark might have new physics !?

Top-Yukawa coupling at a LC

- **For lighter Higgs boson (SM or SUSY like scenario)**

  T. Han, et. al. PRD61, 015006 (2000)

  – **ee -> ttH associate production**

  $$\sqrt{s} > m_H + 2m_t \quad m_H \lesssim 150\text{GeV}$$

- **For heavier or intermediate Higgs masses**

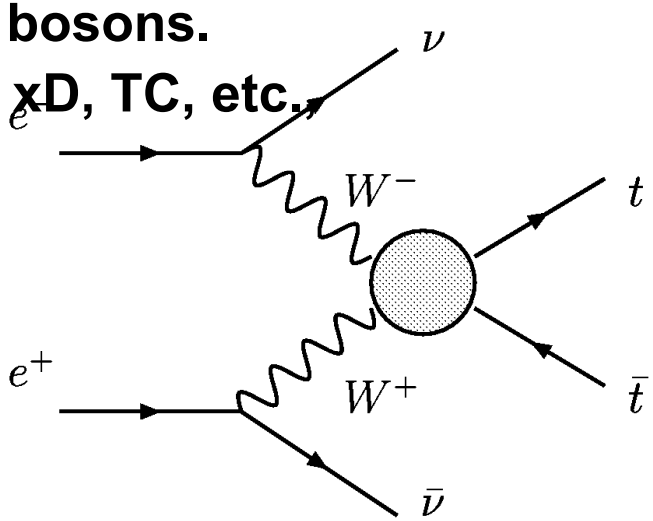
  $$m_H > 2m_t \qquad 2m_t > m_H > 2m_W$$

Kanemura, Nomura, KT PRD74,076007(2006)

– **If theory has relatively heavy Higgs bosons.**

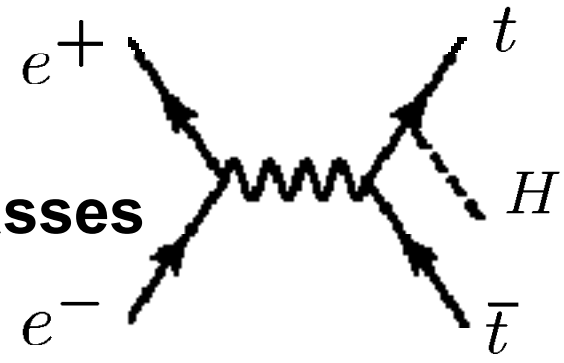
In the non-SM, non-SUSY such as LH, xD, TC, etc.,

WW-fusion can be an useful probe.

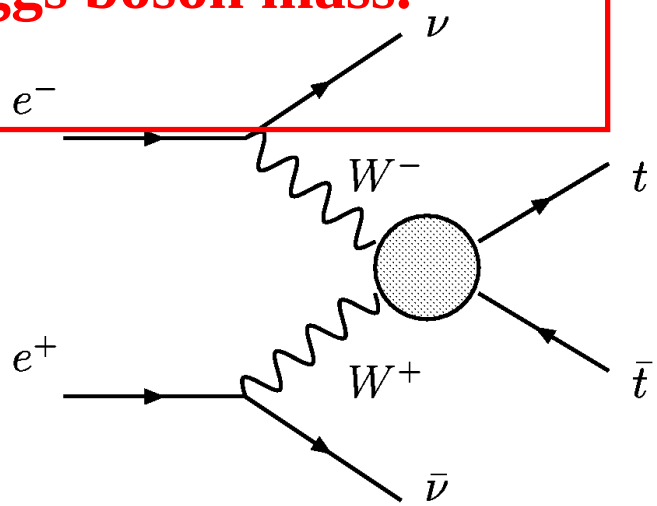


Top-Yukawa coupling at a LC

- **For lighter Higgs boson (SM or SUSY like scenario)**
  - **ee -> ttH associate production**



- **For heavier or intermediate Higgs masses** $\sqrt{s} > m_H + 2m_t$ $m_H \lesssim 150\mathrm{GeV}$
  - **W** $m_H > 2m_t$ **nu** $2m_t > m_H > 2m_W$
  - **We discuss the new physics effect on the top-Yukawa coupling in the wide range of Higgs boson mass.**



Effective theory description

Dimension-six operators as a new physics

Effective theory

- **Eff. Lagrangian below the new physics scale** Λ

$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{dim.6}} + \mathcal{L}_{\text{dim.8}} + \cdots$$

Buchmuller et. al in NPB268, 621 (1986)

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

  - **The non-SM interactions are characterized by dim.6 gauge invariant operators at leading order.**
  - **There are so many dim.6 operators. We introduce these dim.6 ops. for 3rd generation quarks.**
    - **Bottom quark operators are strongly constrained by Z→bb.**

Dimension-six top-quark operators

Buchmuller et. al in NPB268, 621 (1986)

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

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

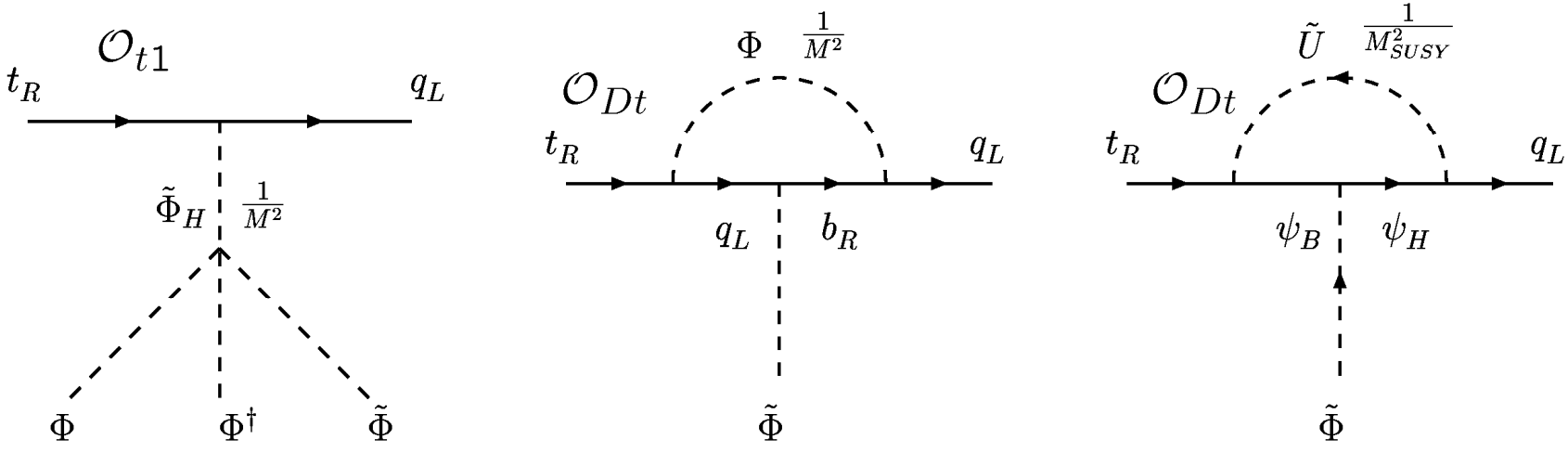
$$\mathcal{O}_{t3} = i(\tilde{\Phi}^\dagger D_\mu \Phi)\bar{t}_R \gamma^\mu b_R + \text{h.c.}$$

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

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

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

Origin of dim.6 operators



- MSSM **PRD69,115007 Feng, Li, Maalampi**

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

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

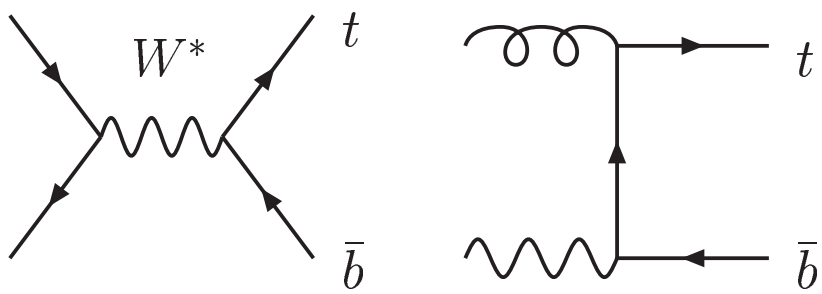
Experimental limits on dim.6 ops.

- Direct search

K. i. Hikasa et al PRD58, 114003 (1998)

  - **No experimental bound for** C_{t1} **.**
  - C_{Dt} **can be constrained by Tevatron.**

$|C_{Dt}| \leq 0.8$ **for** $\int \mathcal{L} dt = 100 \mathrm{fb}^{-1}$

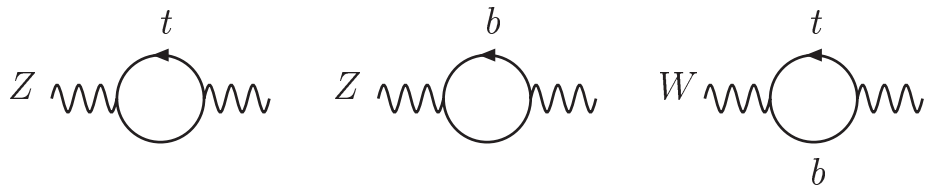


Experimental limits

G. J. Gounaris et al PRD 52, 451 (1995)
S. Kanemura, D. Nomura. KT PRD74, 076007(2006)

- Precision data
  - $C_{t2,t3,Dt,tW\Phi,tB\Phi}$ **can give oblique corrections. It can be allowed in the SM-like situation with heavier Higgs bosons.**
  - **Ex.**

$$\Delta\rho_{Dt} \sim -\frac{N_c}{16\pi^2}\left(\frac{m_t^2}{\Lambda^2}\right)\left\{-\frac{\sqrt{2}m_t}{v}C_{Dt}\ln\frac{\Lambda^2}{m_t^2}+C_{Dt}^2\right]$$



Perturbative unitarity

- Amplitudes **G. J. Gounaris et al Z. Phys. C 76, 333 (1997)**

$$i\mathcal{M}^{t\bar{t}\to t\bar{t}} \sim \frac{i}{s-m_h^2}\left(\frac{m_t}{v} - \frac{v^2}{\sqrt{2}}\frac{C_{t1}}{\Lambda^2} + \frac{s}{\sqrt{2}}\frac{C_{Dt}}{\Lambda^2}\right)^2 \bar{v}u\bar{u}v + \cdots$$

$$i\mathcal{M}^{t\bar{t}\to hh} \sim \frac{1}{s-m_h^2}\left(\frac{m_t}{v} - \frac{v^2}{\sqrt{2}}\frac{C_{t1}}{\Lambda^2} + \frac{s}{\sqrt{2}}\frac{C_{Dt}}{\Lambda^2}\right)(-i\lambda)\bar{u}v3! + i\frac{C_{t1}}{\sqrt{2}}\frac{v}{\Lambda^2}\bar{u}v2!$$

  - **Imposing unitarity @** $\sqrt{s} = \Lambda$

$$|C_{t1}| \leq 8\pi\left(\frac{\Lambda}{v}\right), \quad |C_{Dt} + \frac{\sqrt{2}m_t}{v}| \leq \sqrt{8\pi}$$

  - **Considering 2-body scattering channels (hh, W_LW_L, Z_LZ_L, and t anti-t), chirality and color factors.**

$$|C_{t1}| \leq \frac{16\pi}{3\sqrt{2}}\left(\frac{\Lambda}{v}\right)$$
$$-6.2 \leq C_{Dt} \leq 10.2$$

C_i	Set A	Set B	Set C	Set D	Set E
C_{t1}	0	¡ $\frac{16}{3}\pi\frac{1}{2}\frac{\Lambda}{v}$	+ $\frac{16}{3}\pi\frac{1}{2}\frac{\Lambda}{v}$	0	0
C_{Dt}	0	0	0	+ 10:2	¡ 6:2

We will use above sample values of dim.6 couplings.

- Operators t1 and Dt only contribute to the Top-Yukawa coupling

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

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Effect of dim.6 on Higgs decay

- Eff. Top-Yukawa

$$y_t^{\mathrm{eff}}(-q^2,\Lambda) = y_t^{\mathrm{SM}} - v^2\frac{C_{t1}}{\Lambda^2} - q^2\frac{C_{Dt}}{2\Lambda^2}$$

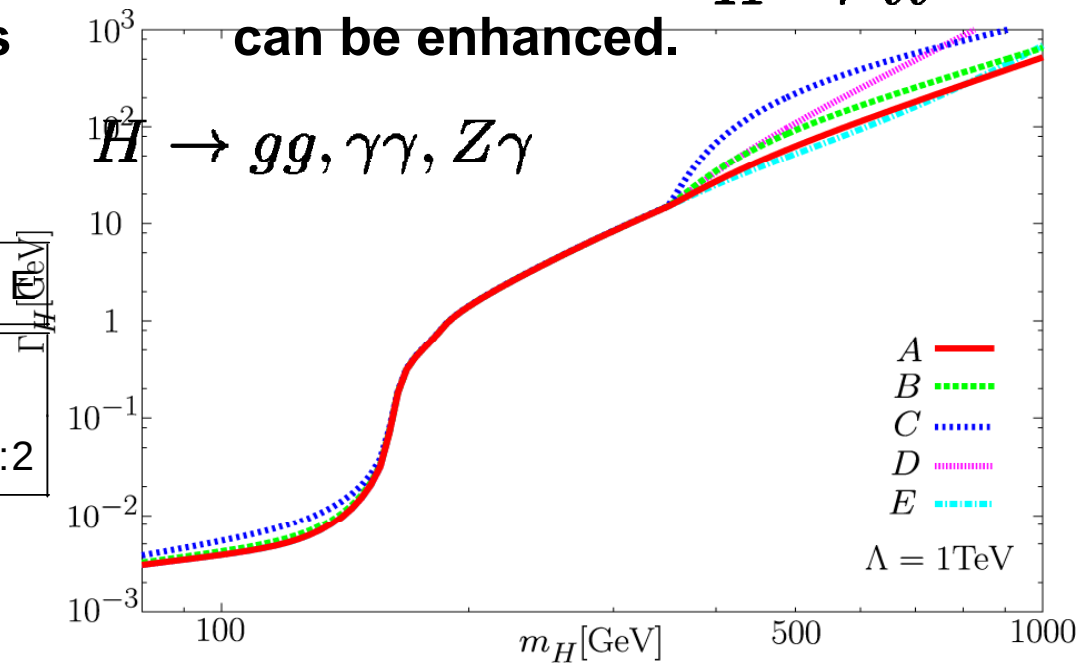
  - $y_t^{\mathrm{SM}} \sim 1$ **is restricted by m_t.**
  - **Dim.6 couplings are only constrained by unitarity.**

- Decay width

Kanemura, Nomura, KT PRD74,076007(2006)

  - **At the tree level, top-pair production $H \to tt$ can be modified.**
  - **Loop induced decays $H \to gg, \gamma\gamma, Z\gamma$ can be enhanced.**

C_i	Set A	Set B	Set C	Set D	Set E
C_{t1}	0	¡ $\frac{16¼}{3}$ þ $\frac{¼}{2}$ ¤ v	+ $\frac{16¼}{3}$ þ $\frac{¼}{2}$ ¤ v	0	0
C_{Dt}	0	0	0	+ 10:2	¡ 6:2



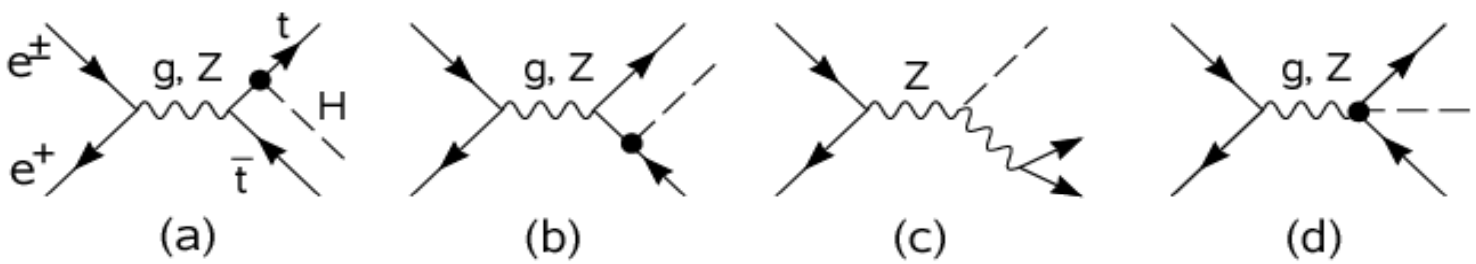
New physics effect on the Top-Yukawa coupling at a LC

ee -> ttH Associate production

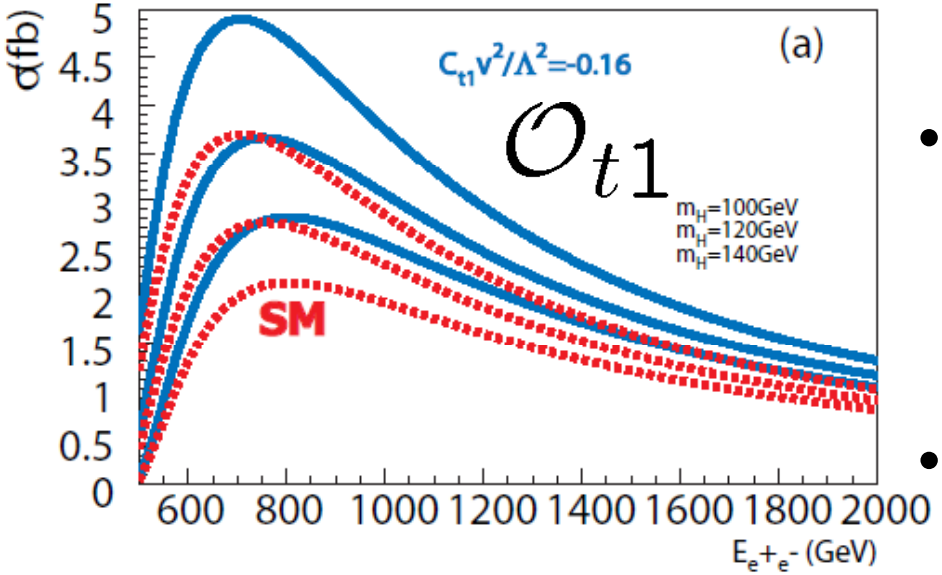
- For lighter Higgs boson

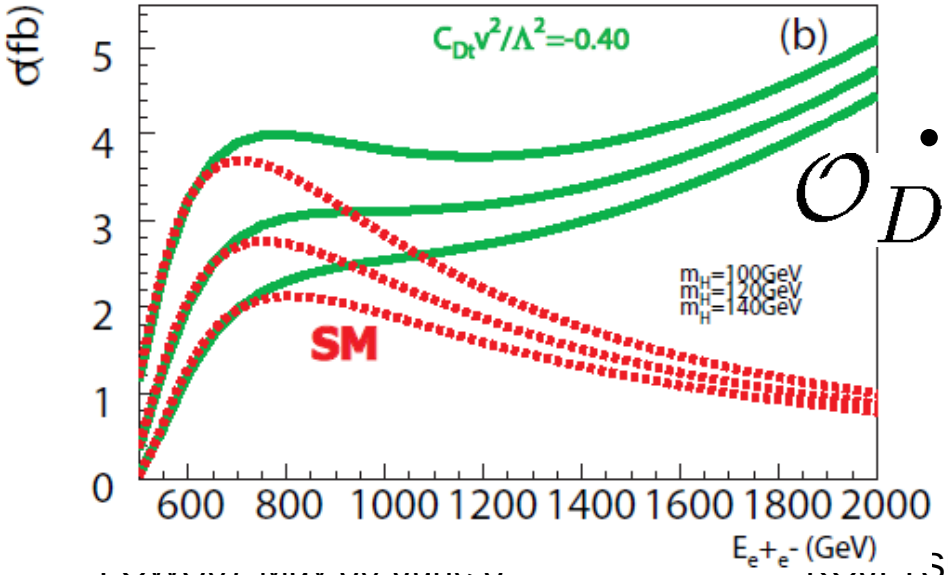
PRD61,015006 Han et al

  – ee -> ttH associate production can be a useful probe to constrain the new physics effect on dim.6 Top-Higgs interaction.



ee -> ttH associate production

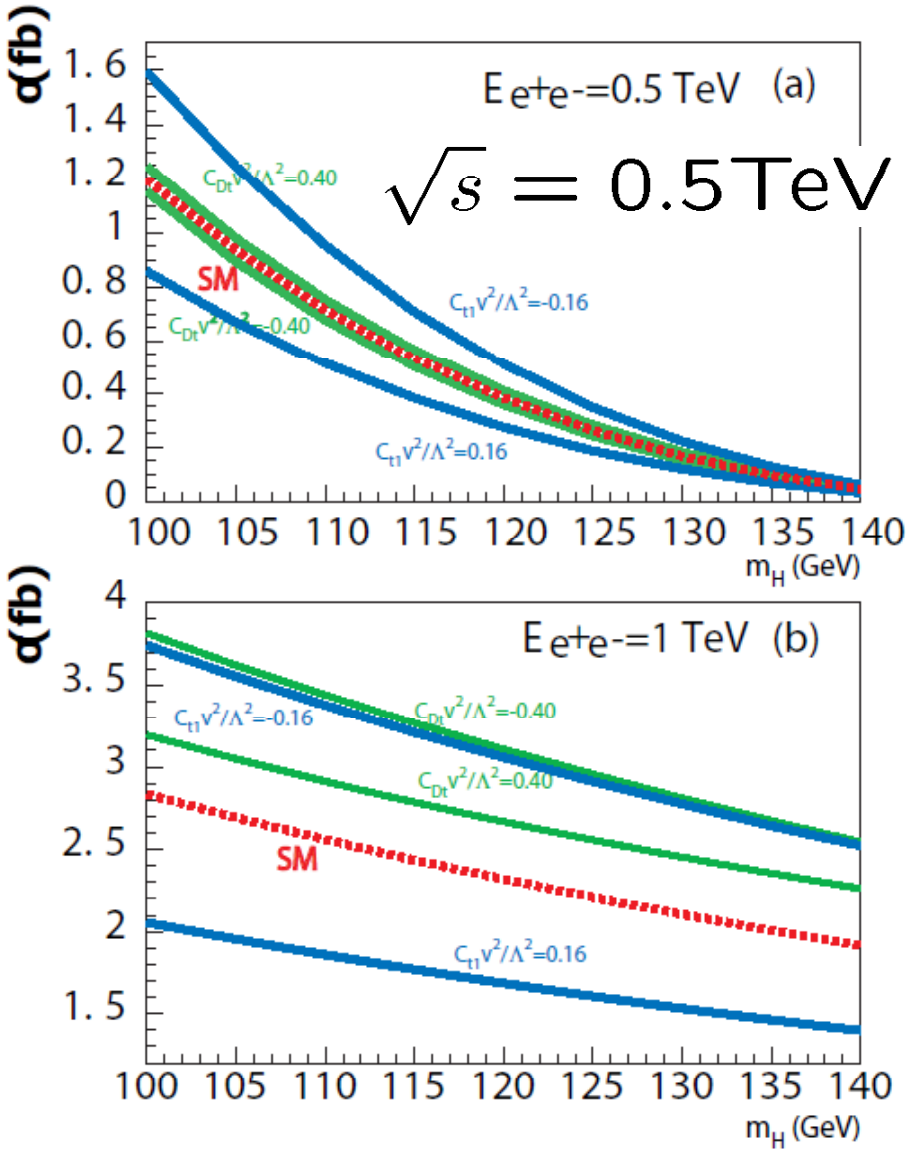




PRD61,015006 Han et al

- **The X sections of the process ee -> ttH as a function of CM energy $\sqrt{s}$ for $m_h = 100, 120, 140$ GeV**
- **The dashed curves are the SM predictions.**
- **New physics effect can be easily observed in the ee -> ttH process.**

ee -> ttH associate production



PRD61,015006 Han et al

- **m_H dependence of the X sections of the process ee -> ttH with operators**
  $\mathcal{O}_{t1}$, $\mathcal{O}_{Dt}$
- **When m_H becomes large, the X sections and its deviation from the SM are quickly decrease.**

How to study the top-Yukawa coupling for relatively heavy m_H ?

Top-Yukawa coupling at a LC

Kanemura, Nomura, KT PRD74,076007(2006)

In this talk, we examine the possibility to study the new physics effect on the top-Yukawa coupling in the W-boson fusion process for large m_H.

- **For heavier or intermediate Higgs masses**

$$m_H > 2m_t \qquad 2m_t > m_H > 2m_W$$

Kanemura, Nomura, KT PRD74,076007(2006)

– **If theory has relatively heavy Higgs bosons.**

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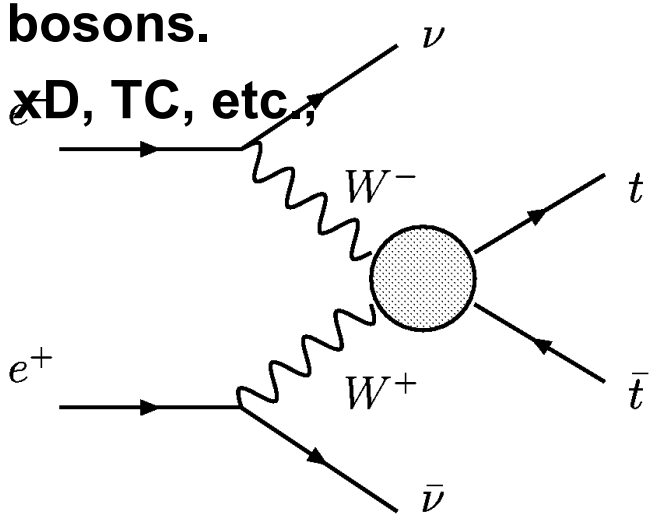
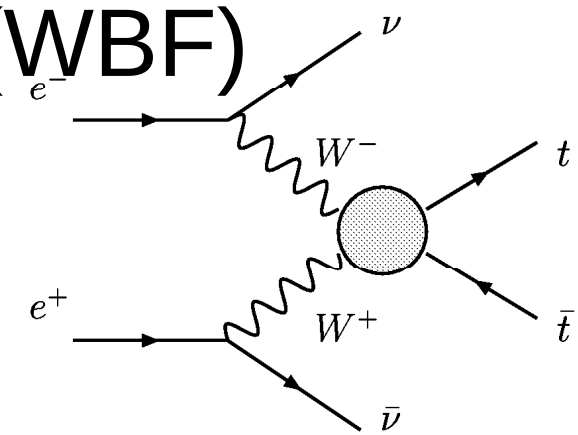
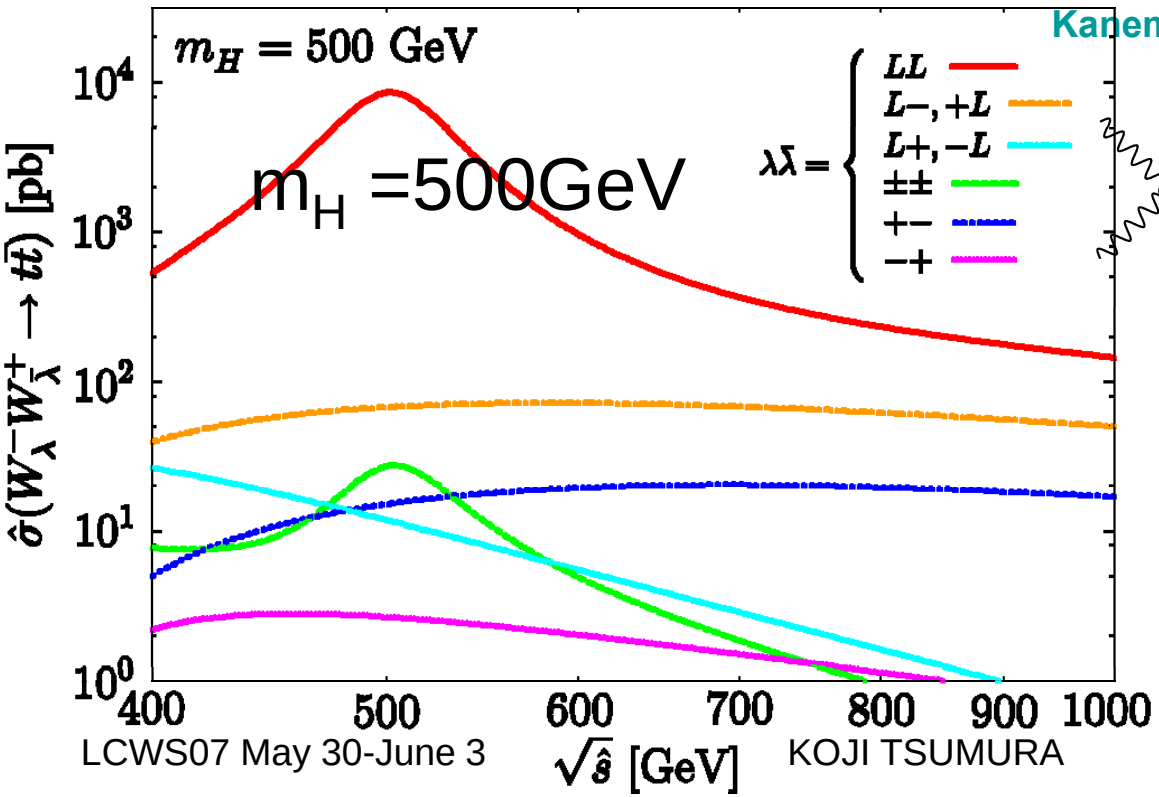


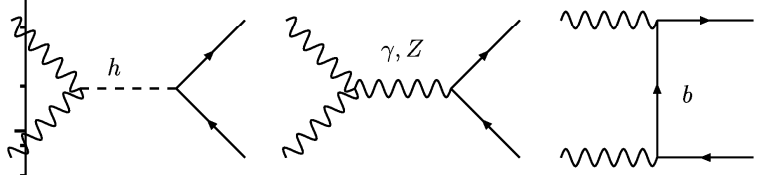
W boson fusion (WBF)

- At the high energy LC, WBF is an important Higgs production channel.
- A few thousands of top-pair events produced via WBF.
- BGs have been studied.



Godfrey, Zhu PRD72,074011
Kanemura, Nomura, KT PRD74,076007(2006)

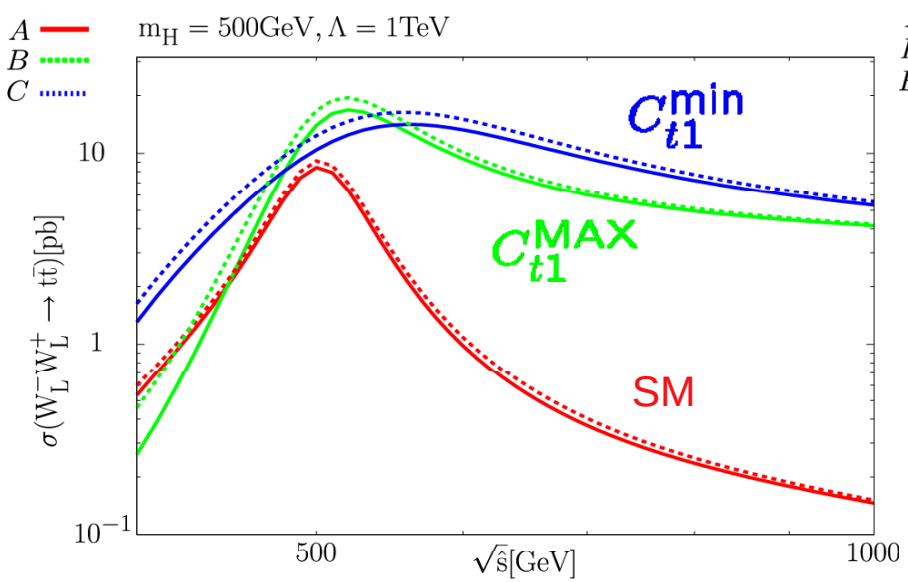


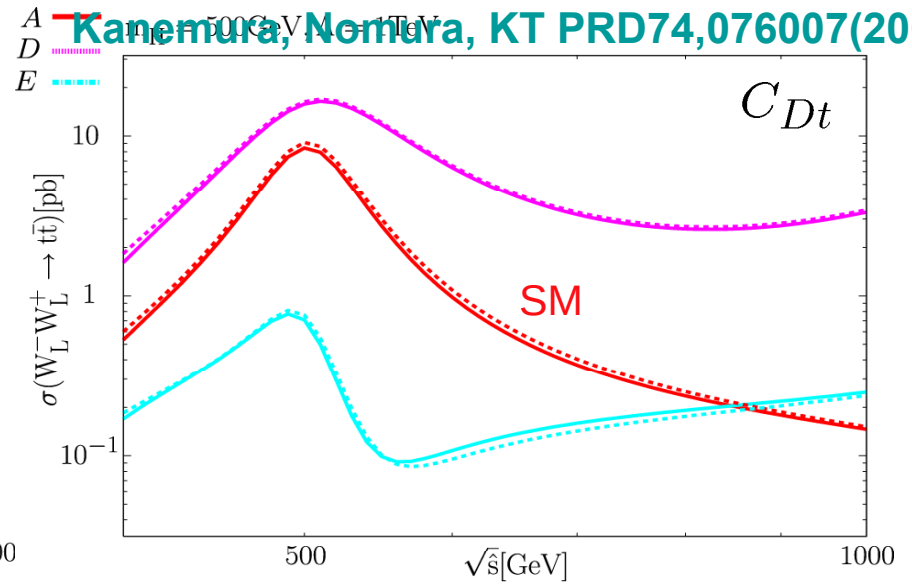


The X sections for WBF sub -process are calculated in the SM, longitudinally polarized W-boson gives dominant contribution

$W^-W^+ \to t\bar{t}$ with dim.6 ops.

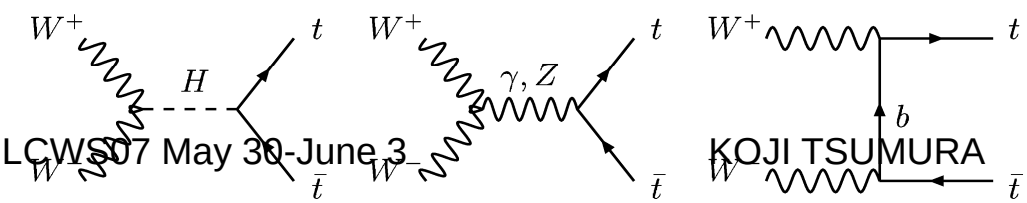
Kanemura, Nomura, KT PRD74,076007(2006)





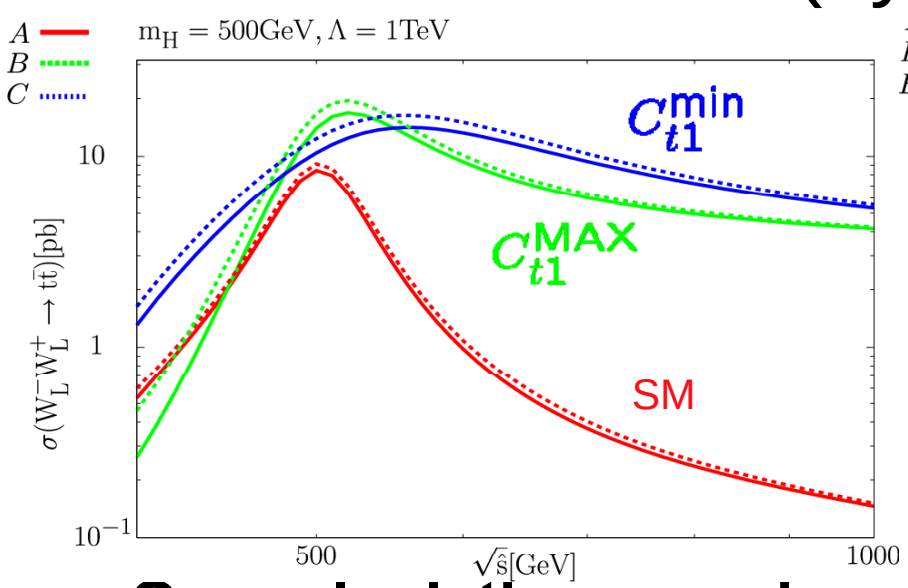
- **Cutoff scale Λ set to be 1TeV.**
- **Dim.6 couplings can change the cross sections by a factor.**
- **Since Higgs decay width grow wider, X sections can be enhanced not only the sub-process energy equal to m_H pole.**

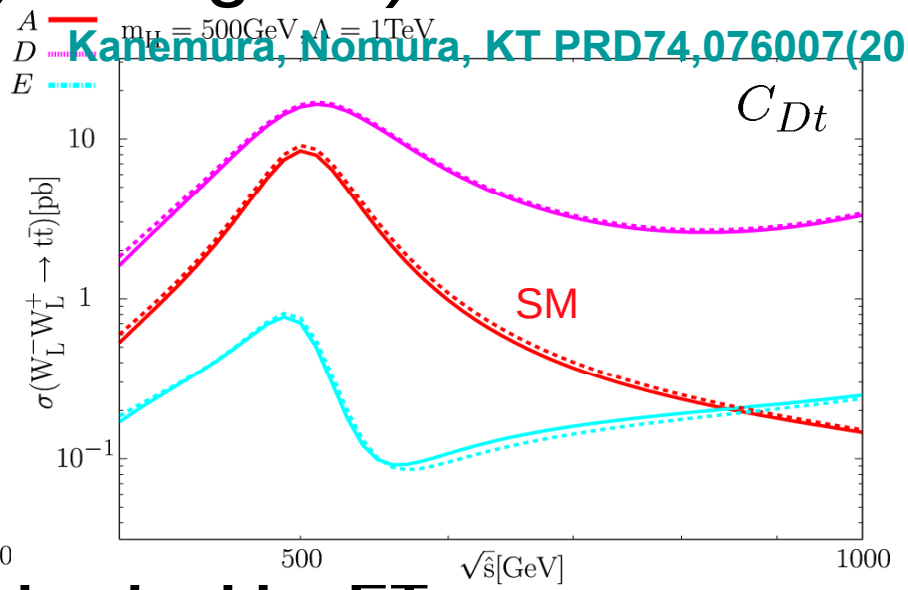
m_H =500GeV



C_i	Set A	Set B	Set C	Set D	Set E
C_{t1}	0	¡ $\frac{16}{3}$¼ $\frac{¤}{2}$ v	+ $\frac{16}{3}$¼ $\frac{¤}{2}$ v	0	0
C_{Dt}	0	0	0	+ 10:2	¡ 6:2

Check (by using ET)



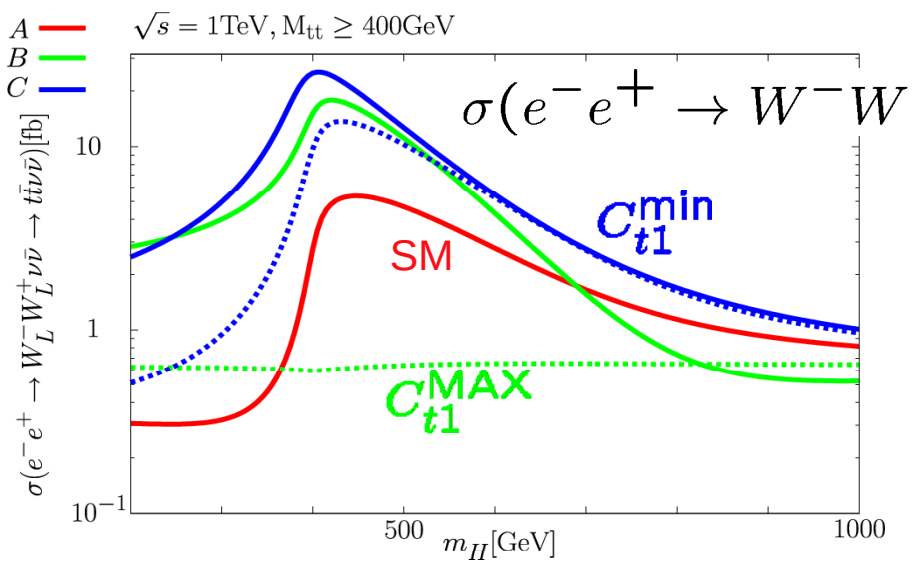


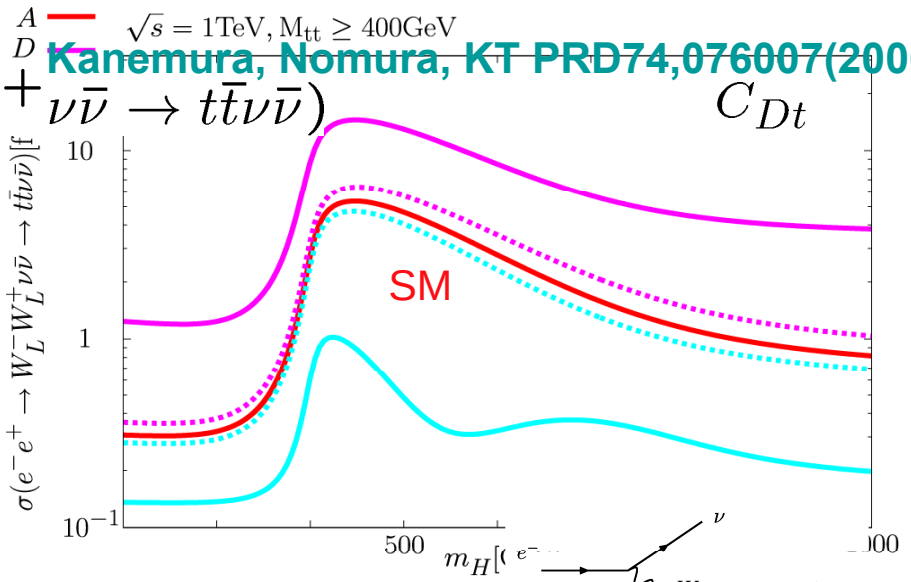
Kanemura, Nomura, KT PRD74,076007(2006)

- **Our calculations can be checked by ET.**
  - **S-matrix for W_L scattering is equivalent to those for NG-boson up to m/E. Dotted curves indicate the process** $\omega\omega \to t\bar{t}$ **.**

$$\mathcal{M}(W_L W_L \to t\bar{t}) \simeq \mathcal{M}(\omega\omega \to t\bar{t}) + \mathcal{O}(m_W/\sqrt{s})$$

Effect of dim.6 on tot.X section in WBF





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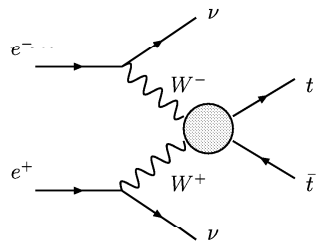
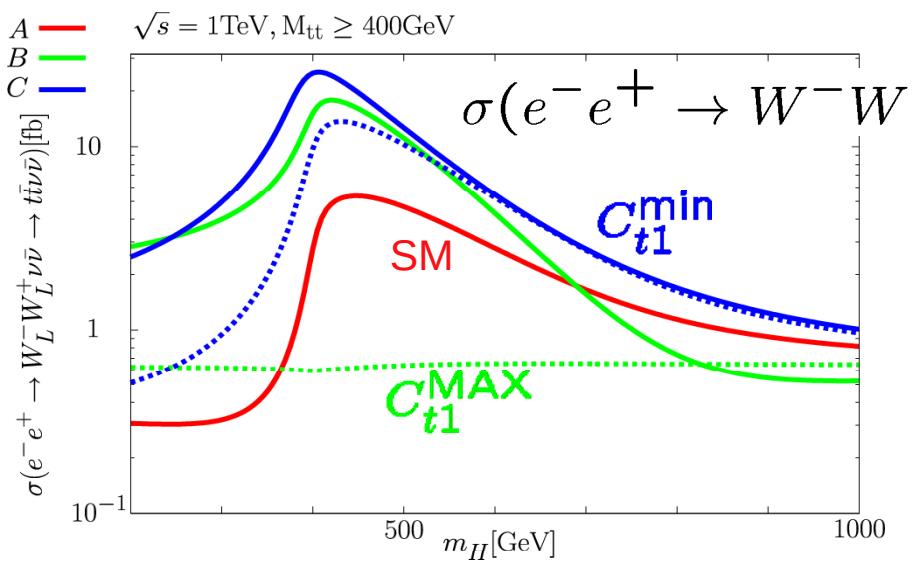
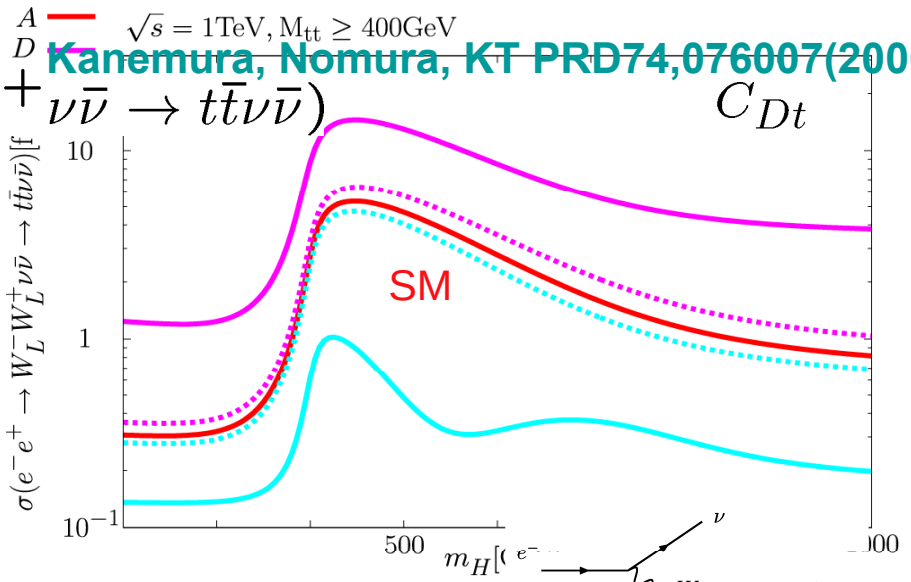


- **Solid** $\Lambda = 1\text{TeV}$ $\Lambda = 3\text{TeV}$
- **We only impose cut** $M_{t\bar{t}} \geq 400\text{GeV}$
- **The total cross section can be enhanced by factor of 2 in the range** $400\text{GeV} \leq m_H \leq 500\text{GeV}$
- **The effects of** $\mathcal{O}_{Dt}$ **become large for heavier Higgs compare to those of** $\mathcal{O}_{t1}$ **.**

C_i	Set A	Set B	Set C	Set D	Set E
C_{t1}	0	¡ $\frac{16}{3}\frac{¼}{2}\frac{¤}{v}$	+ $\frac{16}{3}\frac{¼}{2}\frac{¤}{v}$	0	0
C_{Dt}	0	0	0	+ 10:2	¡ 6:2

Effect of dim.6 on tot.X section in WBF





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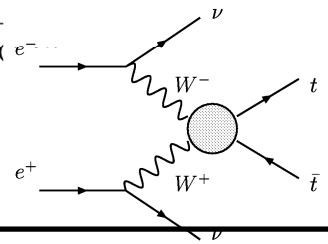


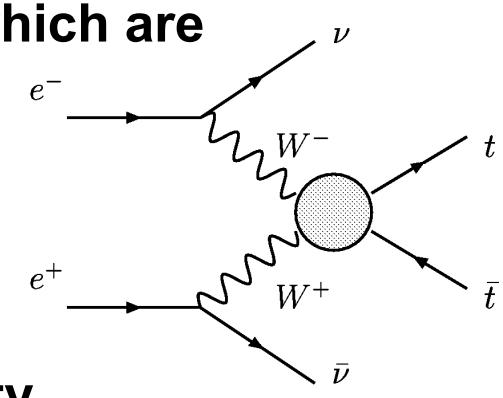
<u>At the ILC</u> with $\sqrt{s} = 1\text{TeV}$, and $\int \mathcal{L}dt = 500\text{fb}^{-1}$, several hundred events are expected. Statistical error is less than 10 %. Therefore <u>the effect of dim.6 couplings can be observed.</u>

C_i	Set A	Set B	Set C	Set D	Set E
C_{t1}	0	¡ $\frac{16}{3}\frac{¼}{2}\frac{¤}{v}$	+ $\frac{16}{3}\frac{¼}{2}\frac{¤}{v}$	0	0
C_{Dt}	0	0	0	+ 10:2	¡ 6:2

Summary

Summary

- **We discuss the W-fusion with the non-SM Y_t which are characterized by dim.6 operators.**



$$y_t^{\text{eff}}(-q^2,\Lambda) = y_t^{\text{SM}} - v^2\frac{C_{t1}}{\Lambda^2} - q^2\frac{C_{Dt}}{2\Lambda^2}$$

- **They are constrained by EXP. data and unitarity.**
  - **Our calculations have been checked by ET.**
  - **Dim.6 couplings can enhance cross sections.**

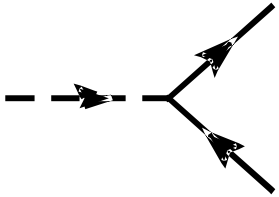
Conclusion

Dim.6 couplings can enhance cross sections,
the effect can be observed in the WBF for heavier Higgs bosons.

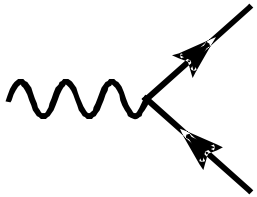
Thank you for your listening !!

Feynman rules

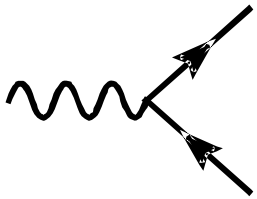
- **Feynman rules for dimension-six operators.**



$$-i\left(\frac{m_t}{v}-\frac{C_{t1}}{\sqrt{2}}\frac{v^2}{\Lambda^2}+\frac{C_{Dt}}{2\sqrt{2}}\frac{s}{\Lambda^2}\right)$$



$$-\frac{g_Z}{2}\left\{\gamma^\mu(v_t+a_t\gamma_5)-i\frac{C_{Dt}}{\Lambda^2}\frac{v}{\sqrt{2}}K^\mu\right\}$$

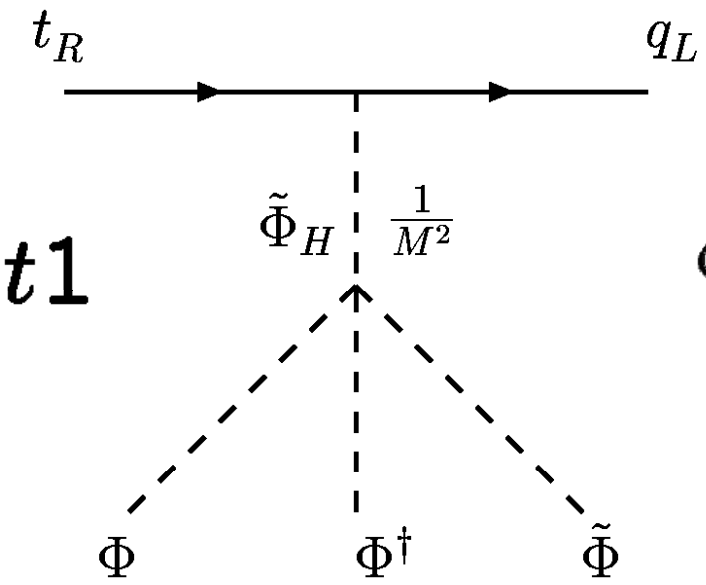


$$-\frac{g}{2}\left(\gamma^\mu-ik^\mu\frac{C_{Dt}}{\sqrt{2}}\frac{v}{\Lambda^2}\right)$$

Origin of dim.6 ops.

PRD69,115007 Feng, Li, Maalampi

$\mathcal{O}_{t1}$



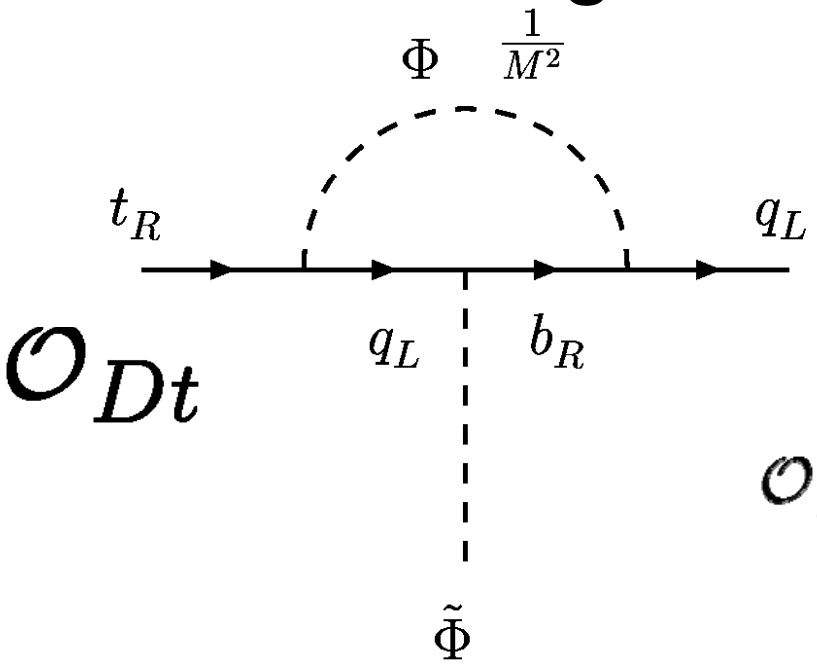
$$\mathcal{O}_{t1} = \left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)\left(\bar{q}_L t_R \tilde{\Phi} + \text{h.c.}\right)$$

$$S \sim y_t' \left(\bar{q}_L \cdot \tilde{\Phi}_H t_R\right) \lambda' \left((\Phi_H^\dagger \Phi)(\Phi^\dagger \Phi)\right)$$

$$\sim y_t' \lambda' \frac{1}{s - m_H^2} \bar{q}_L \cdot \tilde{\Phi} t_R (\Phi^\dagger \Phi)$$

Origin of dim.6 ops.

PRD69,115007 Feng, Li, Maalampi



$\mathcal{O}_{Dt}$

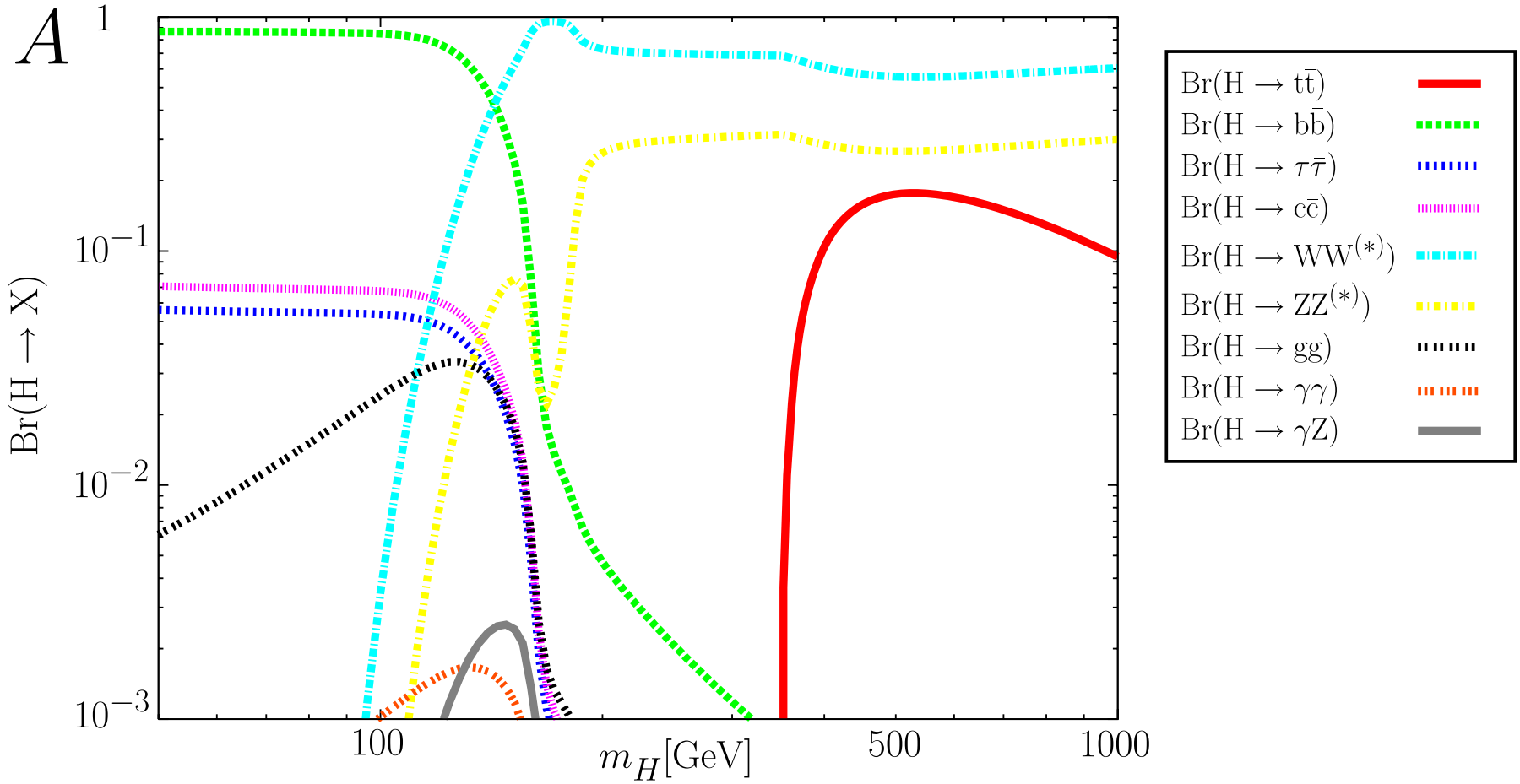
$$\mathcal{O}_{Dt} = (\bar{q}_L D_\mu t_R)\left(D^\mu \tilde{\Phi}\right) + \text{h.c.}$$

$$S \sim y_t' \left(\bar{q}_L \cdot \tilde{\Phi}_H t_R\right) y_b' \left(\bar{q}_L \Phi_H b_R\right) y_b \left(\bar{b}_R q_L \cdot \tilde{\Phi}\right)$$

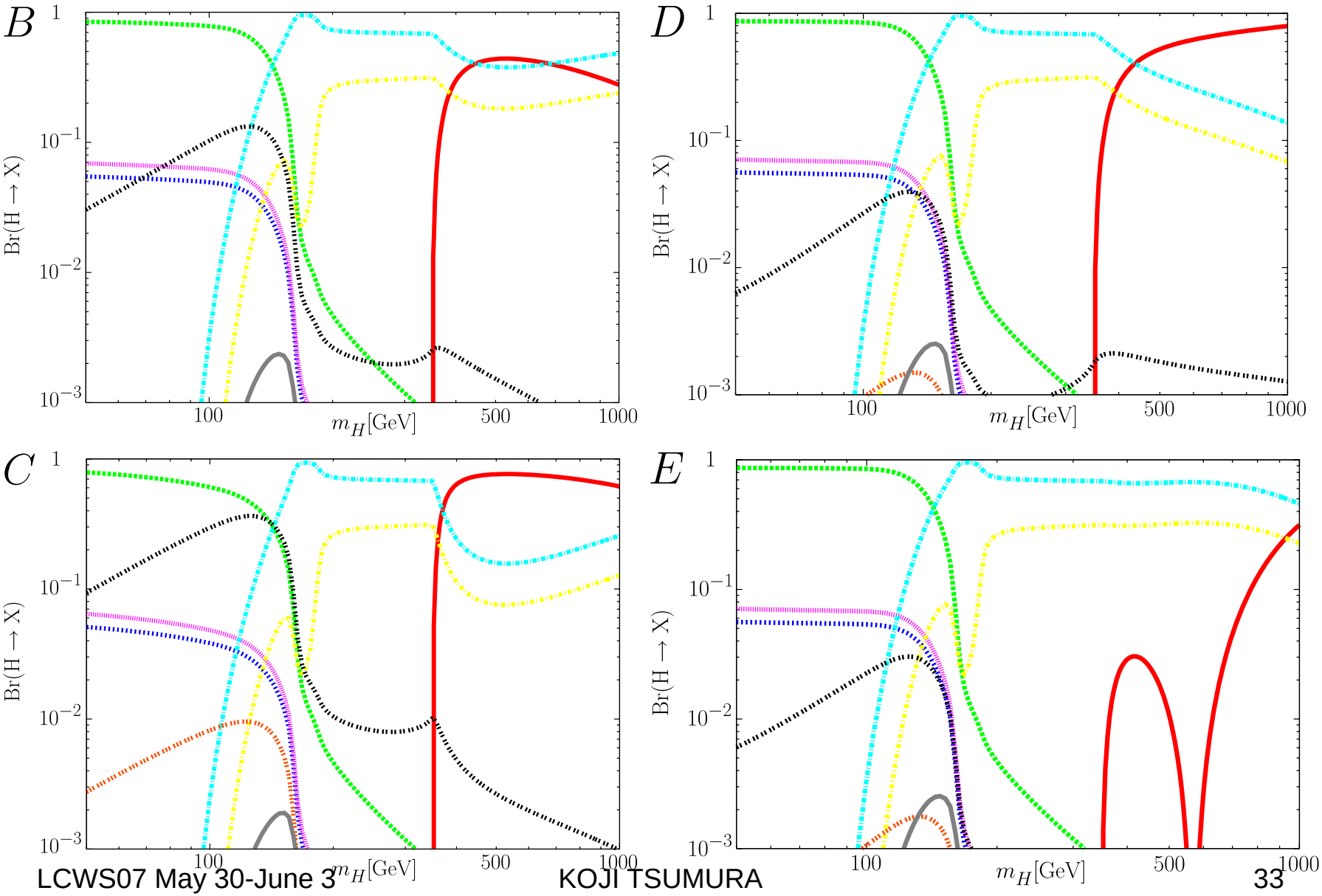
$$\sim y_t' y_b' y_b \int dk \frac{1}{s - m_{H'}^2} \bar{q}_L \cdot \tilde{\Phi} \frac{1}{\not{k} - m_q} \frac{1}{\not{k} - m_b} t$$

Higgs decay branching ratios

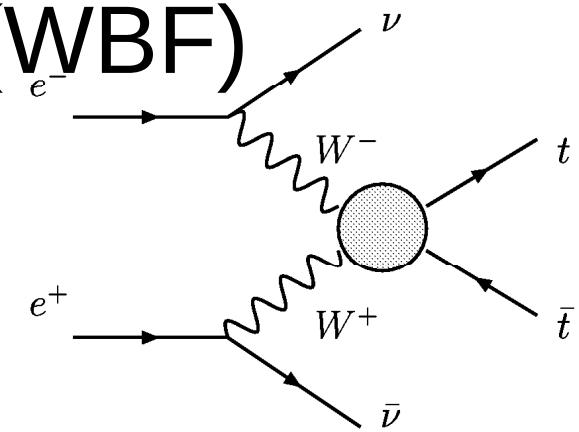
- Higgs decay branching ratio in the SM



Higgs decay branching ratios with dim.6 coupling

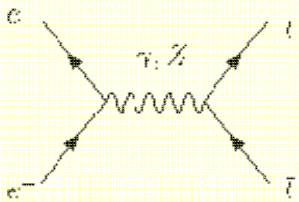


W boson fusion (WBF)



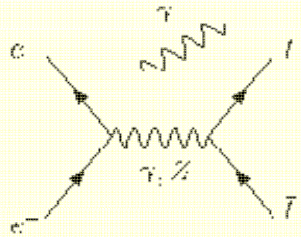
- At the high energy LC, W-fusion is an important probe.
- A few thousands of top-pair events produced via vector boson fusion.
- BGs have been studied.

$e^-e^+ \to t\bar{t}$ J. Alcaraz and E. Ruiz Morales, Phys. Rev. Lett. 86, 3726 (2001)



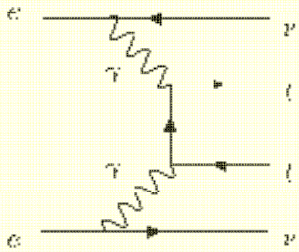
$M_{t\bar{t}} \neq \sqrt{s}$

$e^-e^+ \to t\bar{t}\gamma$ F. Larios, T. Tait, and C. P. Yuan, Phys. Rev. D 57, 3106 (1998)



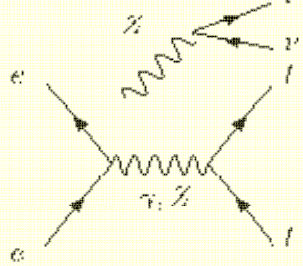
$p_T \geq 20\text{GeV}$

$e^-e^+ \to t\bar{t}\nu\bar{\nu}$ J. Alcaraz and E. Ruiz Morales, Phys. Rev. Lett. 86, 3726 (2001)



$E_T \geq 50\text{GeV}$

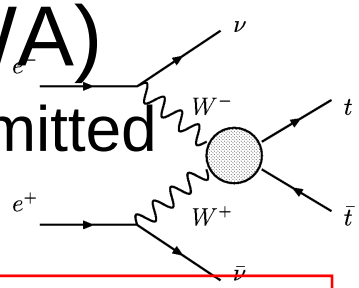
$e^-e^+ \to t\bar{t}\nu\bar{\nu}$



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

S. Dawson, Nucl. Phys. B249, 42 (1985)

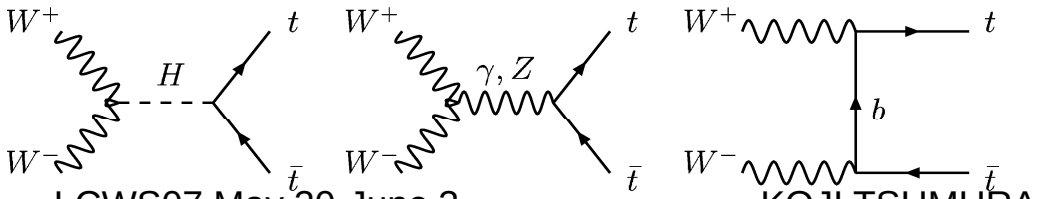
Effective W approximation (EWA)

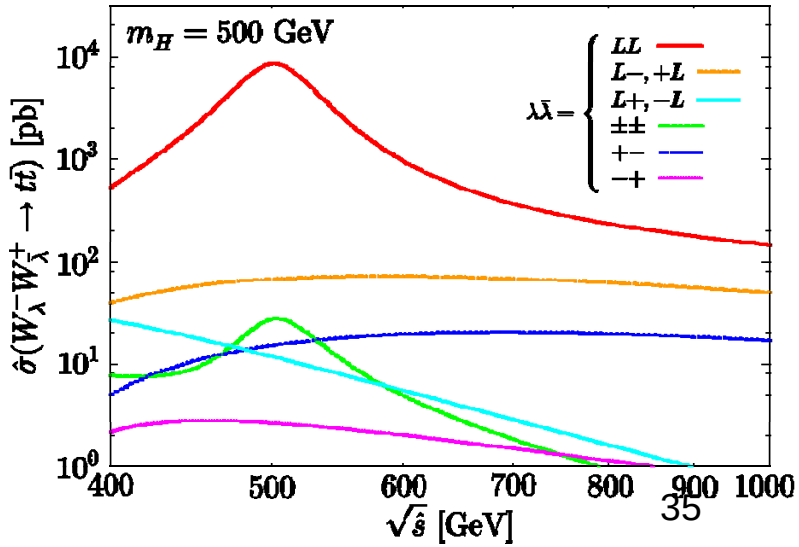


- W-bosons are treated as a parton which are emitted by initial electron and positron.

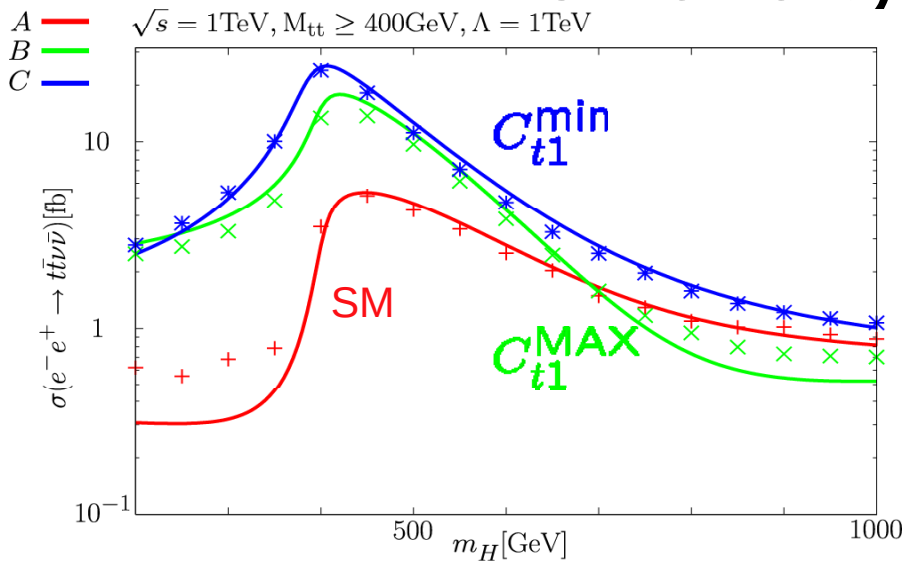
$$\sigma(e^-e^+ \to W^-W^+\nu\bar{\nu} \to t\bar{t}\nu\bar{\nu};\sqrt{s})$$
$$= \int_{m_W/E}^{1} dx_1 \int_{m_W/E}^{1} dx_2 f_{e/W_\lambda}(x_1) f_{e/W_{\lambda'}}(x_2)\sigma(W^-W^+ \to t\bar{t};\sqrt{\hat{s}})$$

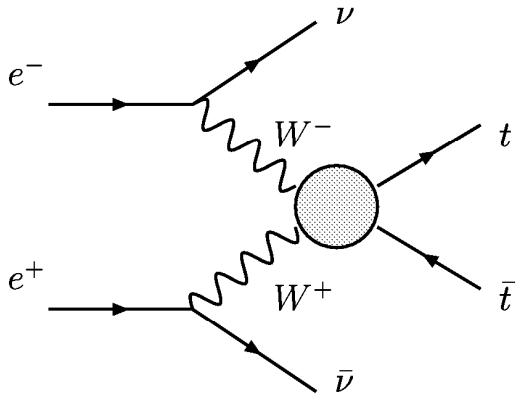
- At the leading order, parton distributions for W_L consists the process $e^-e^+ \to H\nu\bar{\nu}$ ximatio $p_T \ll \sqrt{s}$.
  - The validity of EWA will be shown by using the package CalcHEP.





The validity of EWA





- Dotted curves are calculated by using the package CalcHEP. **A. Pukhov, hep-ph/0412191**
  - The EWA results agree with those of CalcHEP in about 20-30 % error for heavier Higgs boson.

At the ILC with $\sqrt{s} = 500\text{GeV}$, and $\int \mathcal{L}dt = 500\text{fb}^{-1}$, several hundred events are expected. Statistical error is less than 10%.

Amplitudes with dim.6 couplings for WW scattering

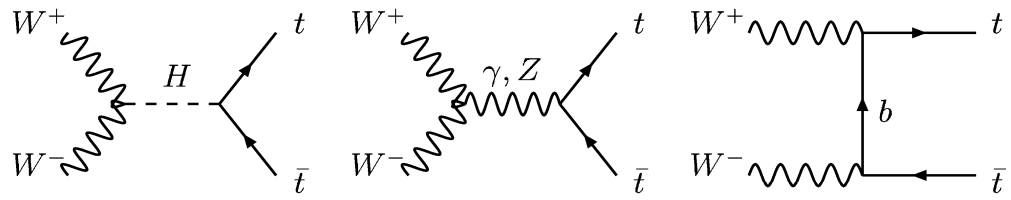
$$\mathcal{M}_h = \frac{2m_W^2/v}{s - m_h^2 + i m_h \Gamma_h}\left(\frac{m_t}{v} - \frac{C_{t1}}{\sqrt{2}}\frac{v^2}{\Lambda^2} + \frac{C_{Dt}}{2\sqrt{2}}\frac{s}{\Lambda^2}\right)(e_\lambda \cdot \bar{e}_{\bar{\lambda}})\bar{u}v.$$

$$\mathcal{M}_\gamma = -\frac{iQ_t e^2}{s} A^\mu_{\lambda\bar{\lambda}}\bar{u}\gamma_\mu v.$$

$$\mathcal{M}_Z = -\frac{2im_W^2/v^2}{s - m_Z^2} A^\mu_{\lambda\bar{\lambda}}\bar{u}\left[\gamma_\mu(v_t + a_t\gamma_5) - iK_\mu \frac{C_{Dt}}{\Lambda^2}\frac{v}{2\sqrt{2}}\right]v.$$

$$\mathcal{M}_b = -\frac{2im_W^2/v^2}{u - m_b^2} e^\mu_\lambda \bar{e}^\nu_{\bar{\lambda}}\bar{u}\left[\left(\gamma_\nu - i\frac{C_{Dt}}{\sqrt{2}}\frac{v}{\Lambda^2}k_\nu\right)P_L\gamma_\rho(p-k')^\rho P_R\left(\gamma_\mu + i\frac{C_{Dt}}{\sqrt{2}}\frac{v}{\Lambda^2}p_\mu\right)\right]v.$$

$$A^\mu_{\lambda\bar{\lambda}} = (e_\lambda \cdot \bar{e}_{\bar{\lambda}})P^\mu + 2(e_\lambda \cdot q)\bar{e}^\mu_{\bar{\lambda}} - 2(\bar{e}_{\bar{\lambda}} \cdot q)e^\mu_\lambda$$



Amplitudes with dim.6 couplings (NG-bosons)

$$\mathcal{M}_\times = -\frac{C_{t1}}{\Lambda^2}\frac{v}{\sqrt{2}}\bar{u}v.$$

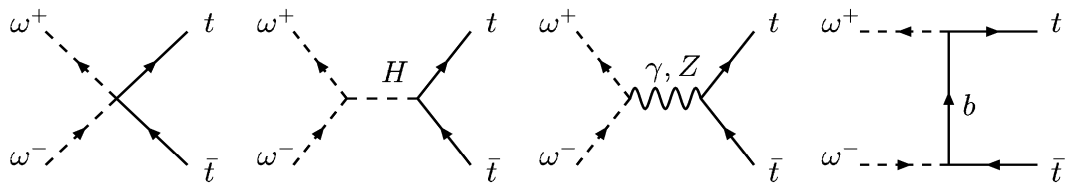
$$\mathcal{M}_h = \frac{2\lambda v}{s - m_h^2 + i m_h \Gamma_h}\left(\frac{m_t}{v} - \frac{C_{t1}}{\sqrt{2}}\frac{v^2}{\Lambda^2} + \frac{C_{Dt}}{2\sqrt{2}}\frac{s}{\Lambda^2}\right)\bar{u}v.$$

$$\mathcal{M}_\gamma = -\frac{iQ_t e^2}{s}P^\mu \bar{u}\gamma_\mu v.$$

$$\mathcal{M}_Z = -\frac{2im_Z^2/v^2}{s - m_Z^2}A^\mu_{\lambda\bar{\lambda}}\bar{u}\left[\gamma_\mu(v_t + a_t\gamma_5) - iK_\mu\frac{C_{Dt}}{\Lambda^2}\frac{v}{2\sqrt{2}}\right]v.$$

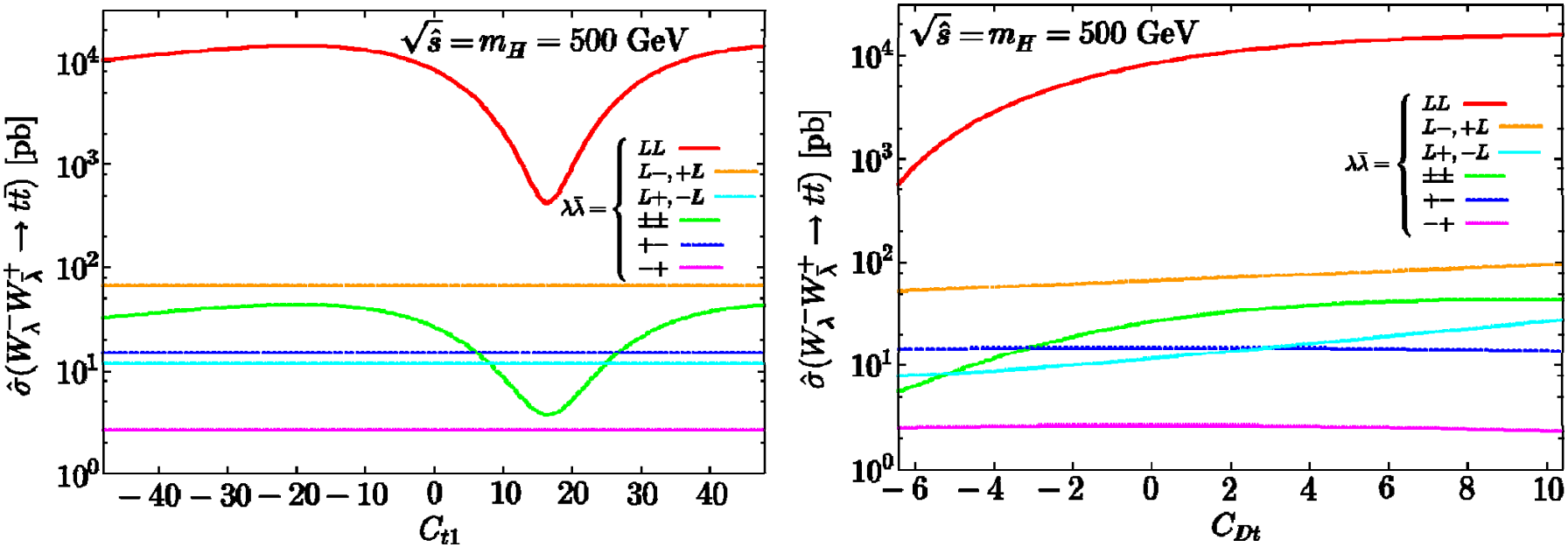
$$\mathcal{M}_b = -\frac{2i}{u - m_b^2}e^\mu_\lambda \bar{e}^\nu_{\bar{\lambda}}\bar{u}\left[\left(\frac{m_t}{v} + \frac{C_{Dt}}{\sqrt{2}\Lambda^2}p'\cdot k\right)P_L\gamma_\rho(p-k')^\rho P_R\left(\gamma_\mu + \frac{C_{Dt}}{\sqrt{2}\Lambda^2}p\cdot k'\right)\right]v.$$

$$A^\mu_{\lambda\bar{\lambda}} = (e_\lambda\cdot\bar{e}_{\bar{\lambda}})P^\mu + 2(e_\lambda\cdot q)\bar{e}^\mu_{\bar{\lambda}} - 2(\bar{e}_{\bar{\lambda}}\cdot q)e^\mu_\lambda$$

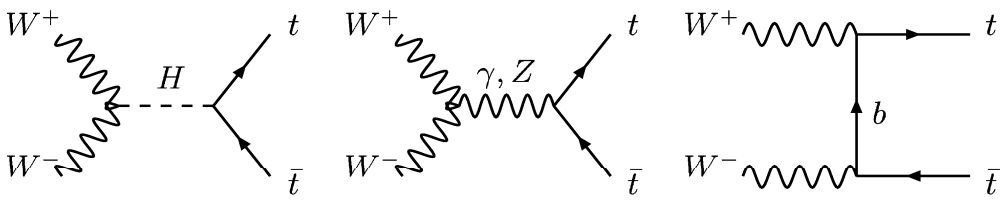


Sub-process X section vs dim.6 couplings

- Cross sections for the sub-process $W^-W^+ \to t\bar{t}$



  – Dim.6 coupling can give negative contributions.



Equivalence theorem

- Our calculations can be checked by equivalence theorem.
  - S-matrix for longitudinally polarized W boson scattering is equivalent to those for NG-boson up to mass/energy.

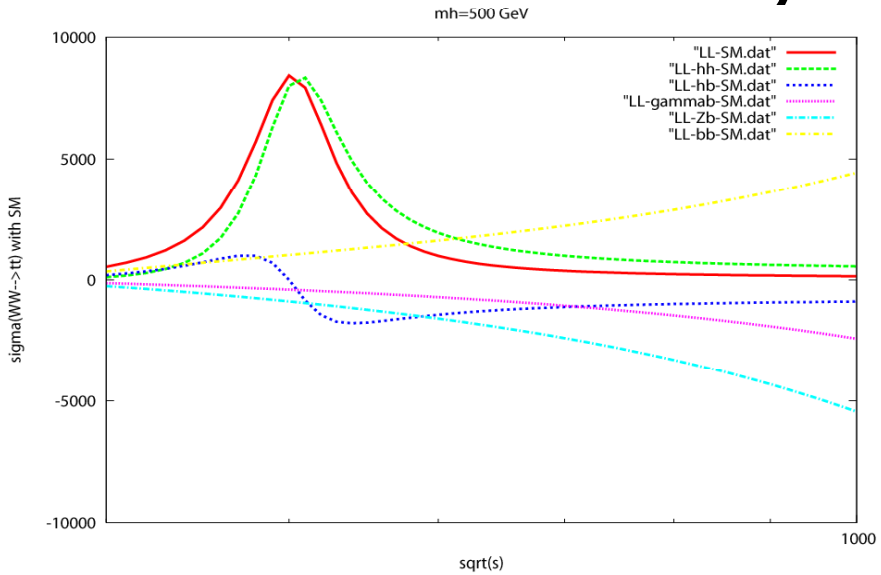
$$\boxed{\mathcal{M}(W_L W_L \to t\bar{t}) \simeq \mathcal{M}(\omega\omega \to t\bar{t}) + \mathcal{O}(m_W/\sqrt{s})}$$

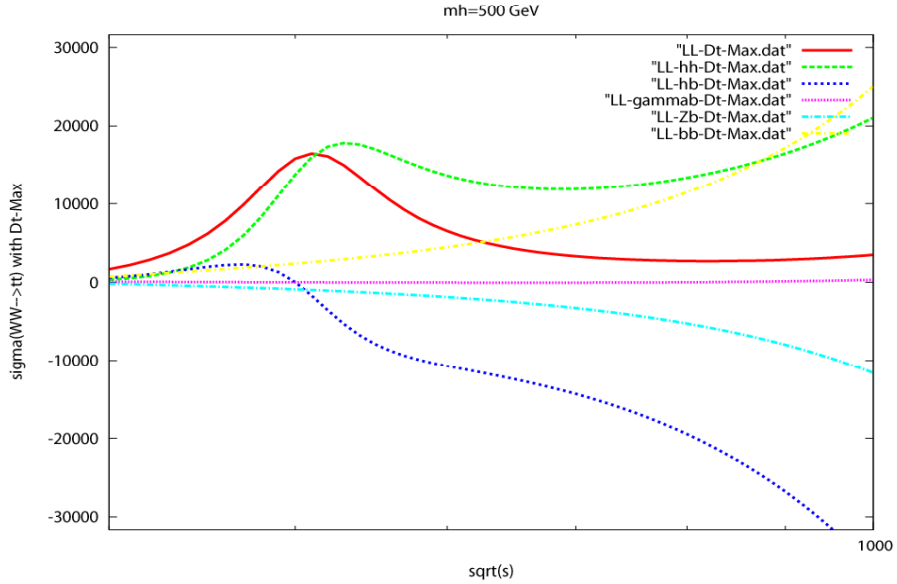
    - BRS identity $\partial^\mu W^\pm_\mu - i m_W \omega^\pm = 0$
    - Equivalence between longitudinal pol. and scalar pol. at high energies.

$$e_S^\mu = \frac{1}{m_W} p^\mu = \gamma_W(1, 0, 0, \beta_W), \;\; e_L^\mu = \gamma_W(\beta_W, 0, 0, 1)$$

$$\gamma_W = \frac{\sqrt{s}}{2m_W}, \beta_W = \sqrt{1 - \frac{4m_W^2}{s}}$$

Unitarity cancellation



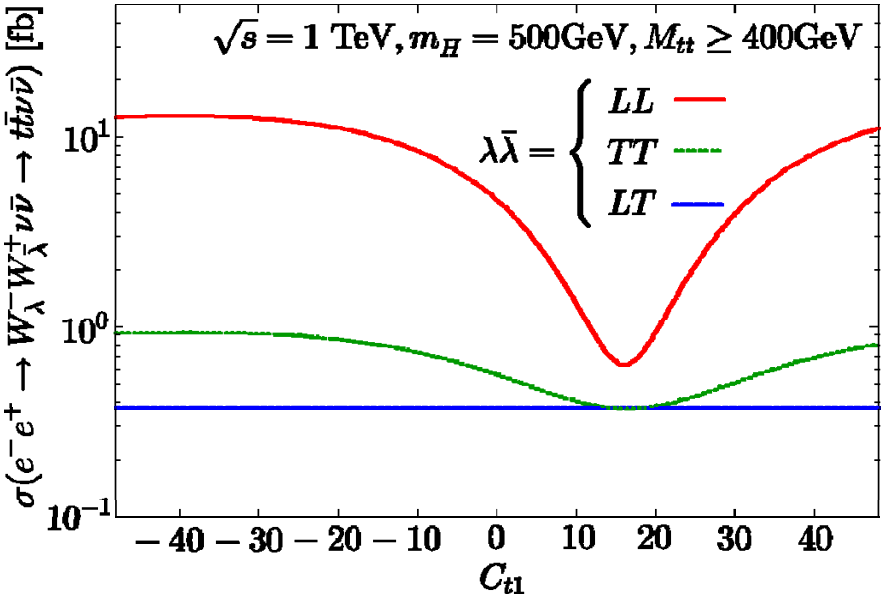


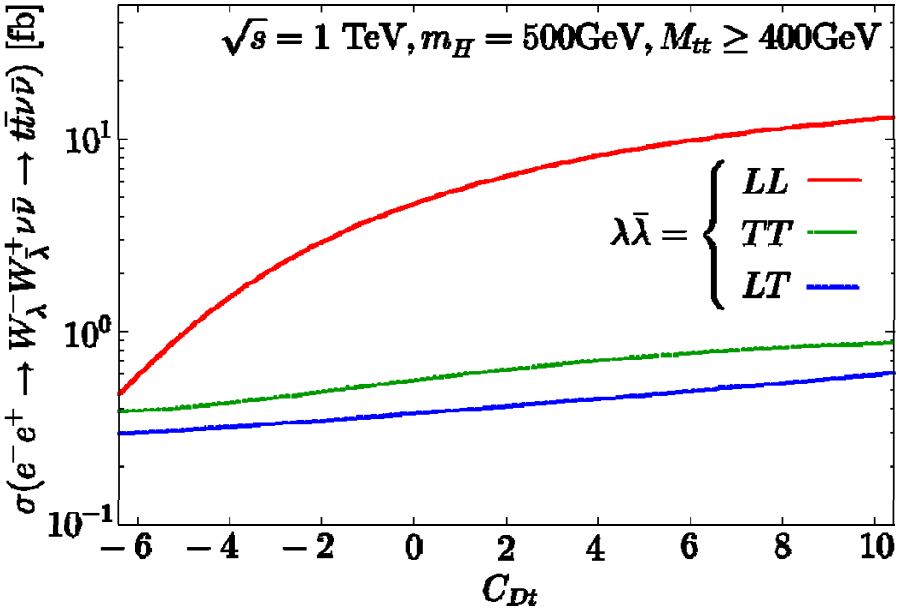
- In the SM, the amplitude for WW scattering does not divergent at high energies due to unitarity cancellation.
- The effects of dimension-six operator ra$\mathcal{O}_{Dt}$ grow higher energy.
- However, the SM-like unitarity cancellation can take place, the total cross section is stabilized up to the cutoff scale.

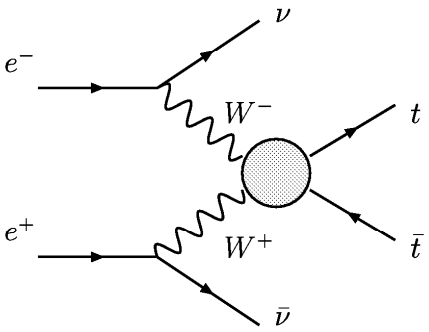
Tot.X section vs dim.6 couplings

- Total cross section for the process

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



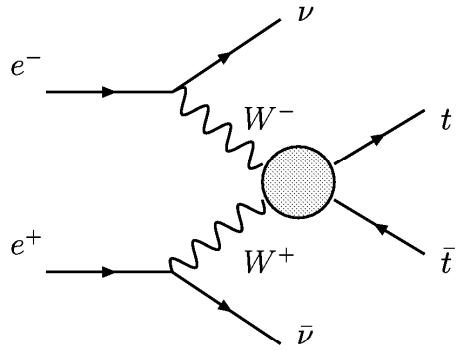




New Physics effect on the Top-Yukawa coupling

– WBF process with the non-SM Y_t which are characterized by dim.6 operators is discussed.

– They are constrained by EXP. data and unitarity.



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

- Dim.6 couplings can enhance cross sections, the effect can be observed in the WBF.