New physics search by helicity decomposition of heavy fermion pair-production from W-boson fusion at the ILC

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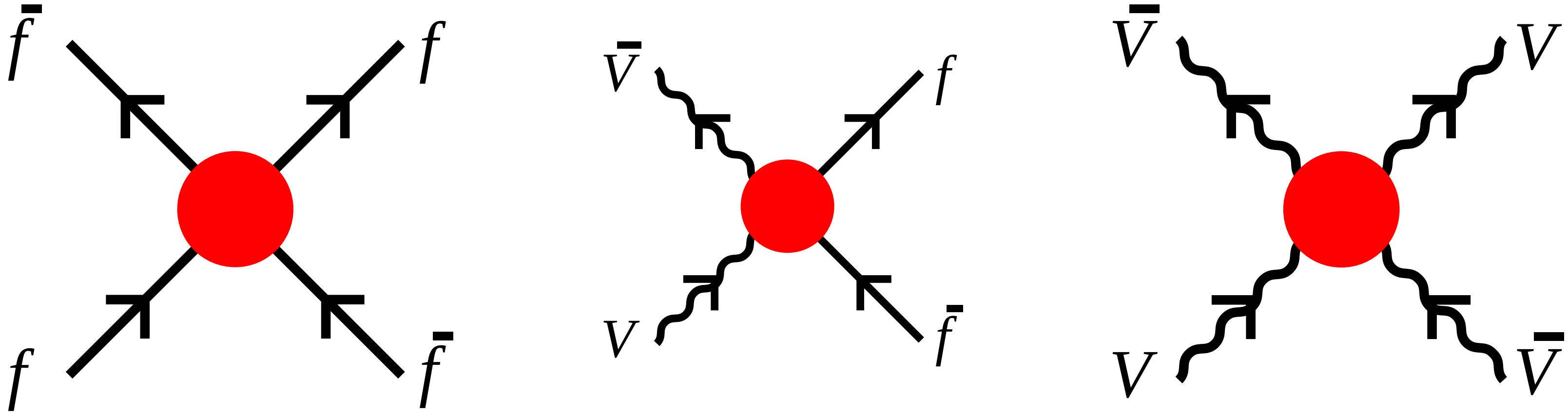
Introduction

- The following $2 \to 2$ processes are very important to test the Standard Model (SM) and to search for new physics.

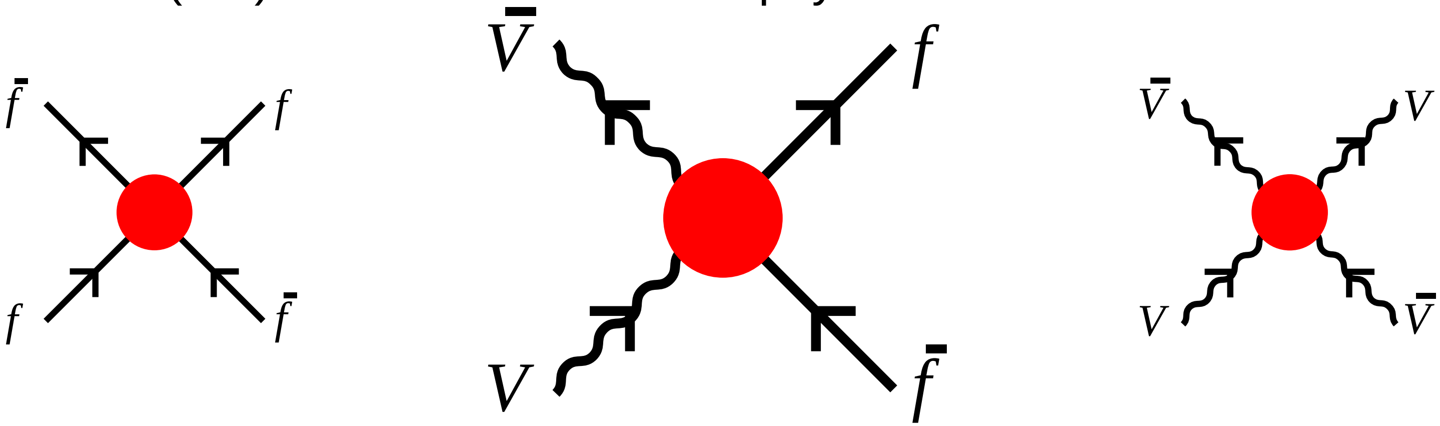


- Four Fermi interactions have been precisely measured at the LEP exp, and brought the very useful information and predictions such as top mass and the STU parameters of gauge boson 2-point functions.

- Four gauge boson interactions have never well known, yet.
However future experiments can give the information for the essence of gauge interaction.

Introduction

- The following $2 \to 2$ processes are very important to test the Standard Model (SM) and to search for new physics.

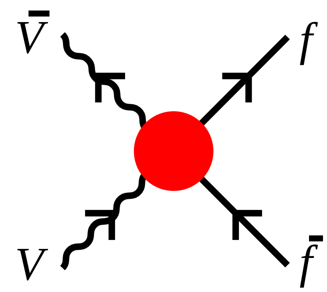


- The $VVff$ ($ffVV$) processes are also very interesting, but we only know about the interactions with *e*+*e*- which have been measured at LEP II. And the processes such as
  - $WWff$: Hagiwara et al, NPB496('97) 66 ; Larios et al, PRD57:('98) 3106; Godfrey, Zhu, PRD72 ('05) 074011; Yuan, NPB310('88)1; Kanemura, Nomura, Tsumura, PRD74 ('06):076007 ; …
  - $\gamma\gamma ff$: Asakawa, Hagiwara, EPJ.C31('03)351: Grzadkowski et al, JHEP0511('05)029,
  - $WZff$: Asakawa et al, PLB626(2005)111, hep-ph/0612271
  - $Z\gamma ff$, $ZZff$ …

will have an important part to search new physics at future experiments such as LHC, ILC, and photon collider.

Introduction

- In this talk, we concentrate on the VVff process with heavy fermions, so that we can study the **h-ff** coupling in the s-channel.

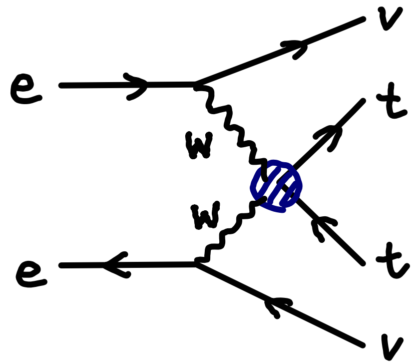


- Top is mysterious particle.
  - Top is much heavier than other quarks.

$$m_t \gg m_i$$

  - Top may be related to the electro weak symmetry breaking.

$$m_t \simeq \frac{v}{\sqrt{2}}$$



- Therefore, it is very interesting to study Top Yukawa coupling at ILC.
  - How to extract the h-tt int. from the W fusion processes?
  - How to extract the effect of new physics?
- We can see the VVff process in W fusion in the Heavy Higgs case.

Outline

- Introduction
  - I have already talked.
- Beyond the standard model
  - Dim-6 operators
  - Their constraints from exp. and unitarity bounds
- W boson fusion
  - Total cross sections
  - Helicity amplitudes
- Conclusions

Beyond the SM theory

- Below a new physics scale, the $\mathrm{dim}=6$ gauge invariant operators Oi appear in the effective Lagrangian.

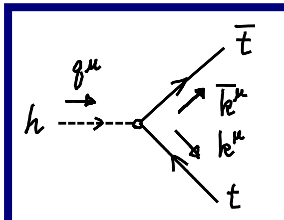
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{C_i}{\Lambda^2} O_i$$

K.Hagiwara, et.al, NPB496(1997) 66
G.J. Gounaris et.al, Z. Phys. C 76, 333-341 (1997)

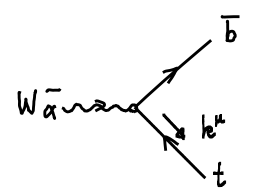
- The complete list of the $\mathrm{dim}=6$ gauge invariant operators are shown in G.J. Gounaris et.al, Z. Phys. C 76, 333-341 (1997).

- In these operators, we focus on the O_{t1} , O_{t3} and O_{Dt} operators.

	h-tt	t-channel	
$O_{t1} = (\Phi^\dagger\Phi - \frac{v^2}{2})(\bar{q}_L t_R \tilde{\Phi} + h.c)$	○	×	} ← Higgs int.
$O_{Dt} = (\bar{q}_L D_\mu t_R)(D^\mu \tilde{\Phi} + h.c)$	○	○	} ← Higgs int.
$O_{t3} = i(\tilde{\Phi}^\dagger D_\mu \Phi)(\bar{t}_R \gamma^\mu b_R) + h.c$	×	○	← no severe restriction

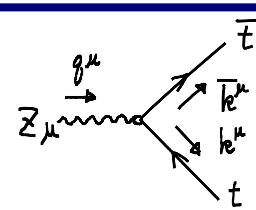


$$-i\left\{\frac{g m_t}{2m_W} - \frac{v^2}{\sqrt{2}}\frac{C_{t1}}{\Lambda^2} - \frac{g^2}{2\sqrt{2}}\frac{C_{Dt}}{\Lambda^2}\right\}$$



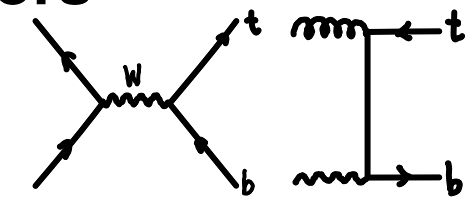
$$-(1+\gamma_5)\frac{ig}{2\sqrt{2}}\left\{\gamma_\alpha + \frac{C_{Dt}}{\Lambda^2}\frac{v}{\sqrt{2}}k_\alpha\right\}$$

$$-i\frac{C_{t3}}{\Lambda^2}\frac{g v^2}{2\sqrt{2}}(1-\gamma_5)\gamma_\alpha$$



$$-i\frac{g_Z}{2}\left[\gamma^\mu\{v_f - a_f\gamma^5\} + \frac{C_{Dt}}{\Lambda^2}\frac{v}{2\sqrt{2}}\{K^\mu + g^\mu\gamma^5\}\right]$$

Several bounds for dimension-six operators



The C_{t1} , C_{t3} and C_{Dt} have been studied by many people,

- From direct search
  (Hikasa, Whisnant, Young PRD58,114003 (1998))

C_{t1}, C_{Dt}, C_{t3}: free at present, $|C_{Dt}| \le 9.8$ for $\int \mathcal{L}\,dt = 100\,\mathrm{fb}^{-1}$
(Tevatron)

- From indirect search
  (Gounaris, Renard, and Verzegnassi, PRD52, 451 (1995))

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

- From unitarity bounds
  (Gounaris, Papadamou, Renard Z phys C76,333)

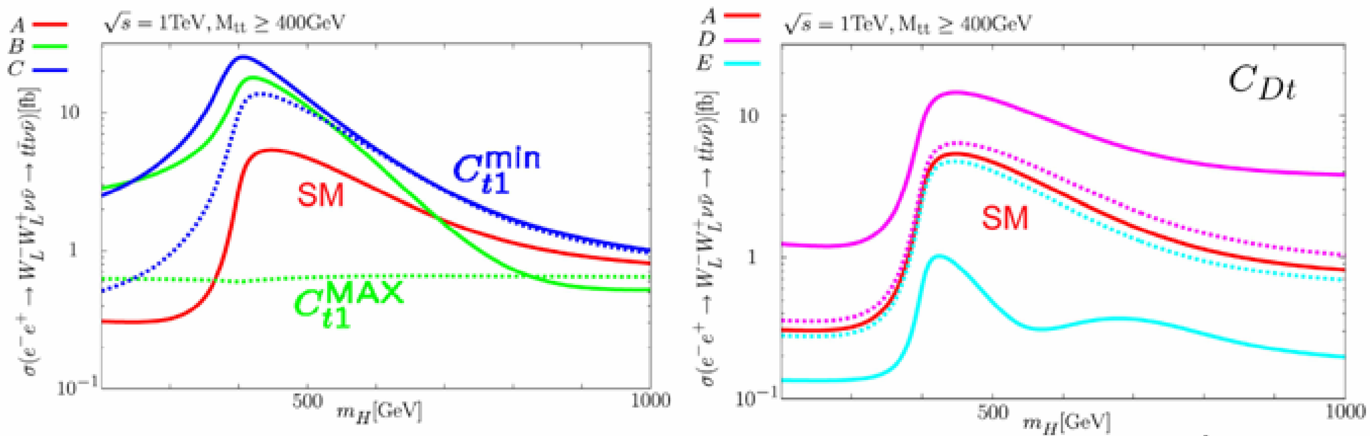
$$|C_{t1}| \le \frac{16\pi}{3\sqrt{2}}\left(\frac{\Lambda}{v}\right), \quad -6.4 \le C_{Dt} \le 10.4, \quad |C_{t3}| \le 8\pi\sqrt{6}$$

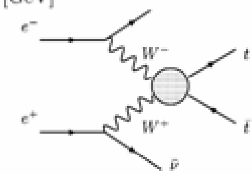
For example, we use the following values.

	Set A	Set B	Set C	Set D	Set E	Set F
C_{t1}	0	$+\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	$-\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	0	0	0
C_{Dt}	0	0	0	$+10.2$	-6.2	0
C_{t3}	0	0	0	0	0	$8\pi\sqrt{6}\times 0.5$

The review of Kanemura, Nomura, Tsumura, PRD74(2006)

Total cross sections $\sigma(e^-e^+ \to W^-W^+\nu\bar{\nu} \to t\bar{t}\nu\bar{\nu})$





- Solid $\Lambda = 1$TeV , dotted $\Lambda = 3$TeV
- We only impose cut $M_{t\bar{t}} \geq 400$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 $\mathcal{O}_{t1}$.

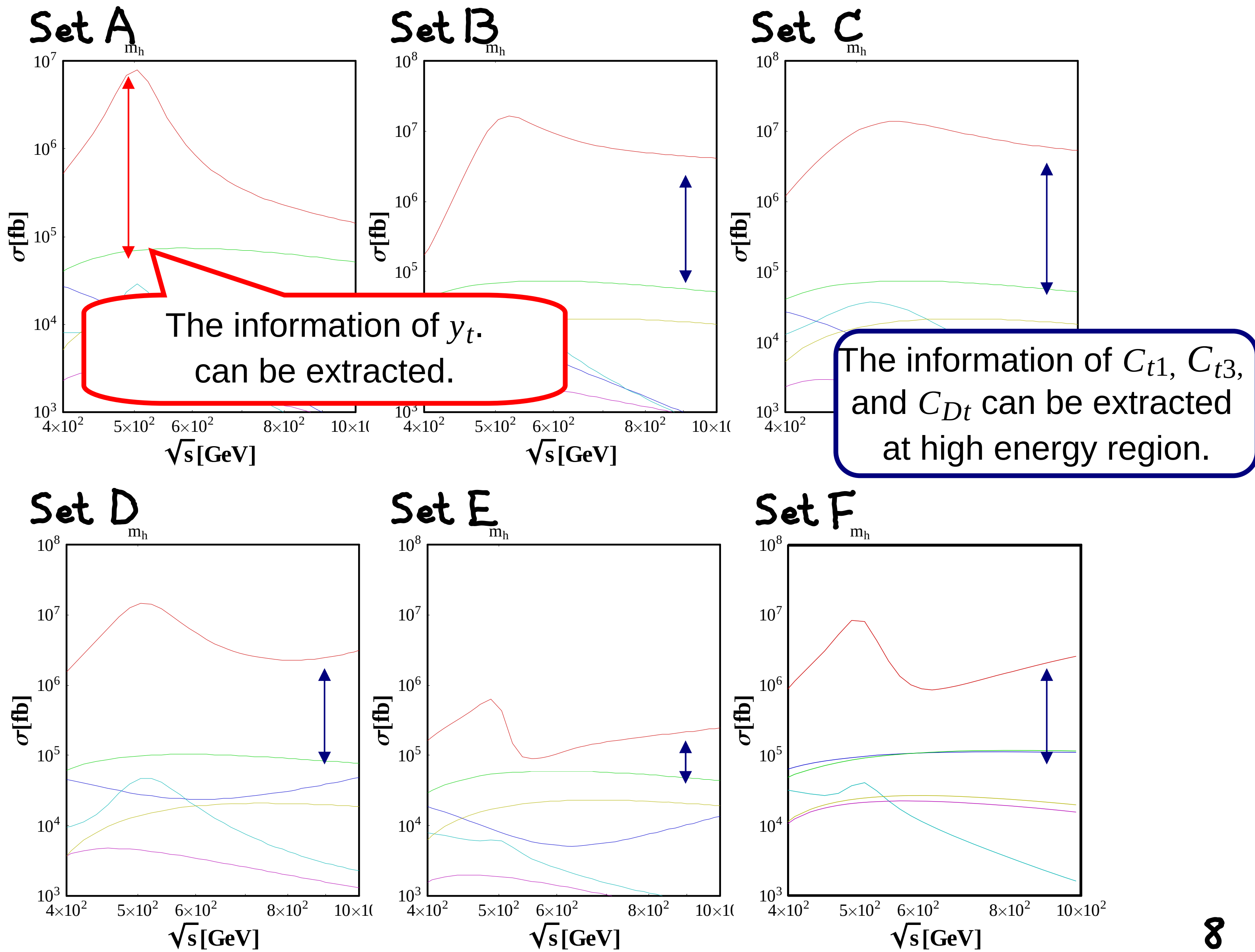
C_i	Set A	Set B	Set C	Set D	Set E
C_{t1}	0	$-\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	$+\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	0	0
C_{Dt}	0	0	0	$+10.2$	-6.2

Cross sections of WW→tt vs energies ($m_h = 500$GeV)

$(\lambda\ \bar{\lambda})$

(00)
(++), (--)
(0+), (-0)
(0-), (+0)
(+-)
(-+)

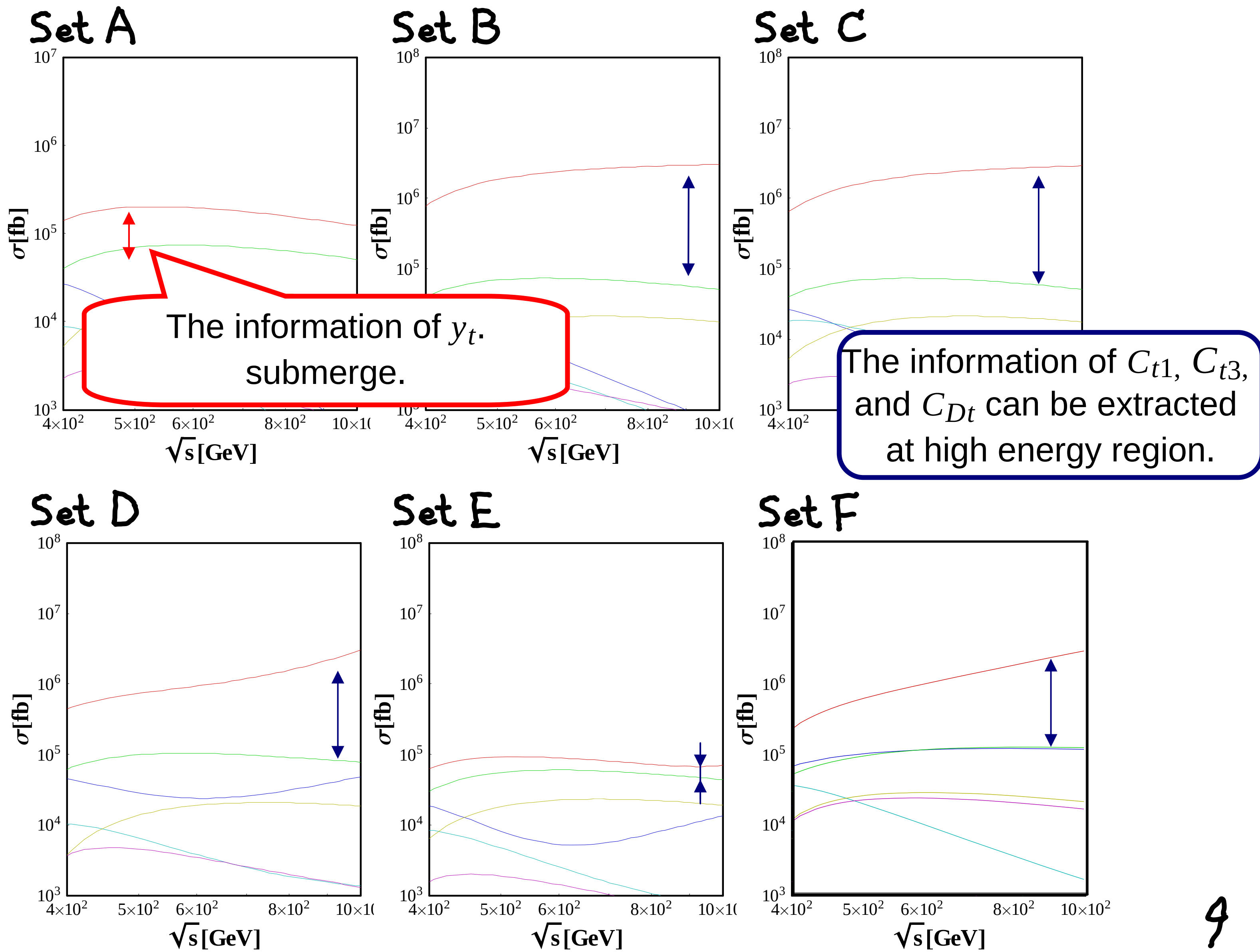
	Set A	Set B	Set C	Set D	Set E	Set F
C_{t1}	0	$+\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	$-\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	0	0	0
C_{Dt}	0	0	0	+10.2	−6.2	0
C_{t3}	0	0	0	0	0	$8\pi\sqrt{6}\times 0.5$
Γ	62.9487	92.3927	221.292	109.050	52.4566	62.9487



Cross sections of $WW \to tt$ vs energies ($m_h = 200\,\mathrm{GeV}$)

$(\lambda\ \bar{\lambda})$
- (00)
- (++), (--)
- (0+), (-0)
- (0-), (+0)
- (+-)
- (-+)

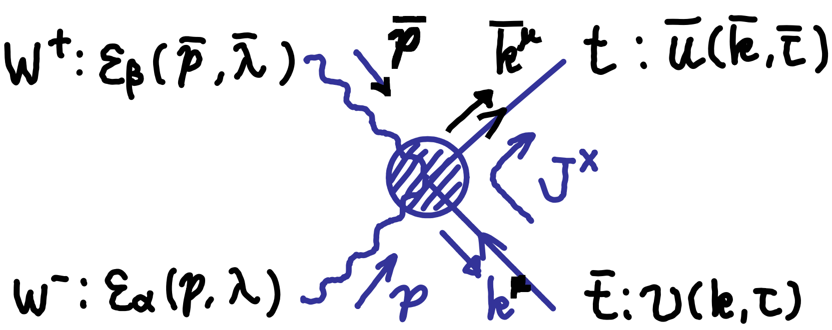
	C_{t1}	C_{Dt}	C_{t3}	Γ
Set A	0	0	0	1.407
Set B	$+\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	0	0	1.407
Set C	$-\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	0	0	1.407
Set D	0	+10.2	0	1.407
Set E	0	−6.2	0	1.407
Set F	0	0	$8\pi\sqrt{6}\times 0.5$	1.407

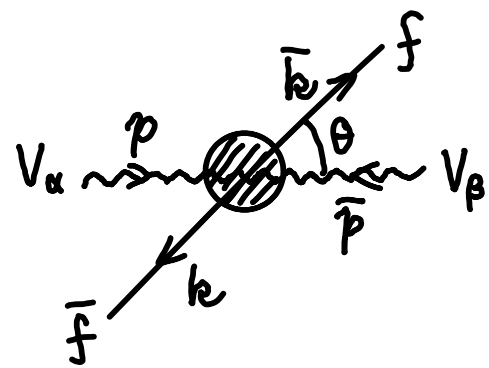


Reclaim

- The remained problems in the work of Kanemura, Nomura, Tsumura.
  - The information of large C_{t1} and C_{Dt} can be extracted at high energy region.
  - However, the information of h-tt int. submerge in the light Higgs case and small C_{t1} and C_{Dt} case.
  - Because the experimental restriction of O_{t3} is not severe, there is a possibility to observe the effect of O_{t3} which is not discussed in the work of KNT.
  - The information of helicities is not fully discussed in the work of KNT.

- In order to improve the results of KNT and in order to distinguish the $\mathrm{dim}=6$ operators, we now proceed to consider the helicity analysis of the sub-process $WW \to ff$.



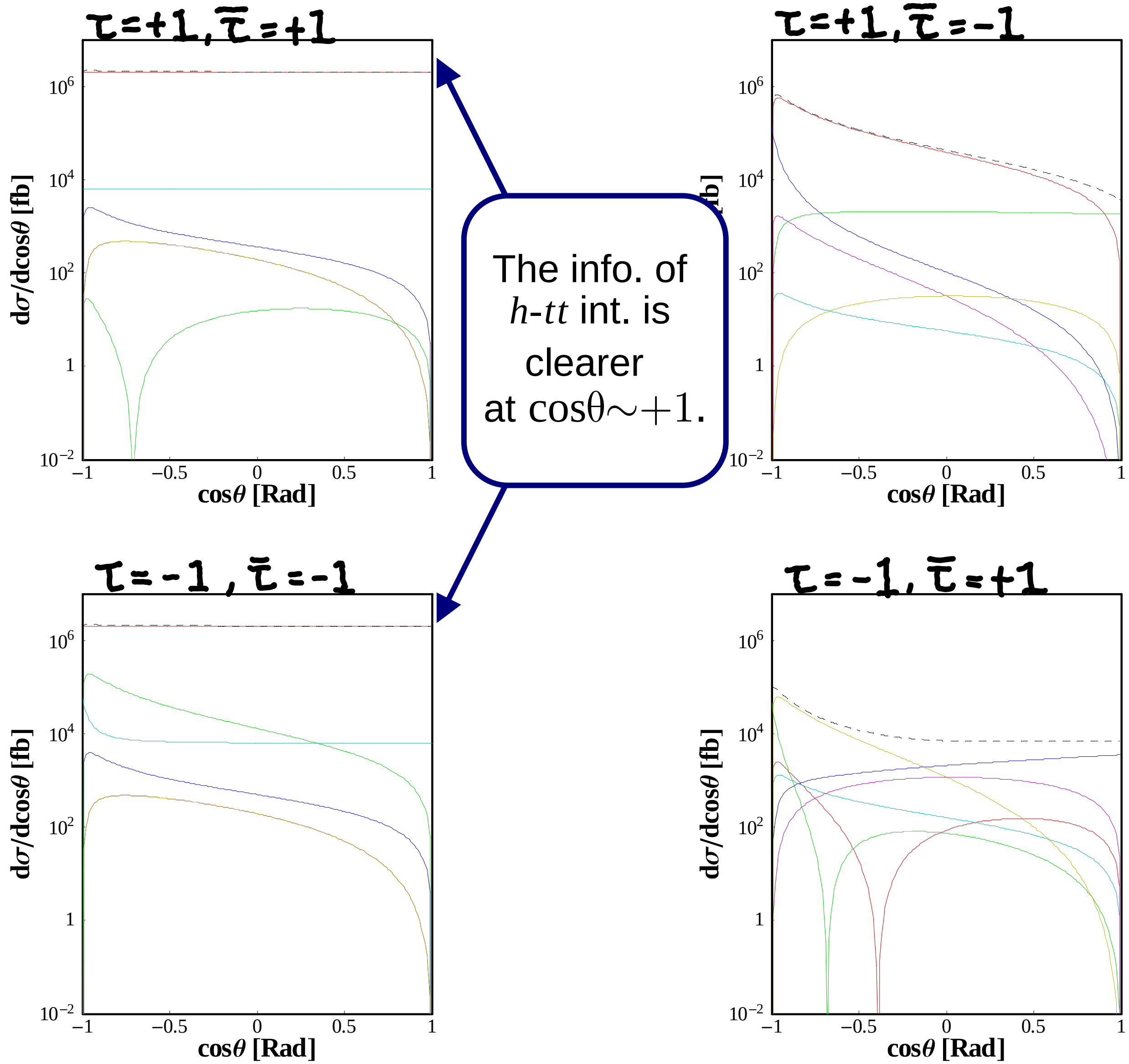


Set A : $m_h = 500$ GeV, $\sqrt{s} = 500$ GeV : SM

$(\lambda\,\bar{\lambda})$

- (00)
- (++), (- -)
- (0+), (-0)
- (0-), (+0)
- (+-)
- (-+)

	Set A	Set B	Set C	Set D	Set E	Set F
C_{t1}	0	$+\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	$-\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	0	0	0
C_{Dt}	0	0	0	+10.2	−6.2	0
C_{t3}	0	0	0	0	0	$8\pi\sqrt{6}\times 0.5$
Γ	62.9487	92.3927	221.292	109.050	52.4566	62.9487

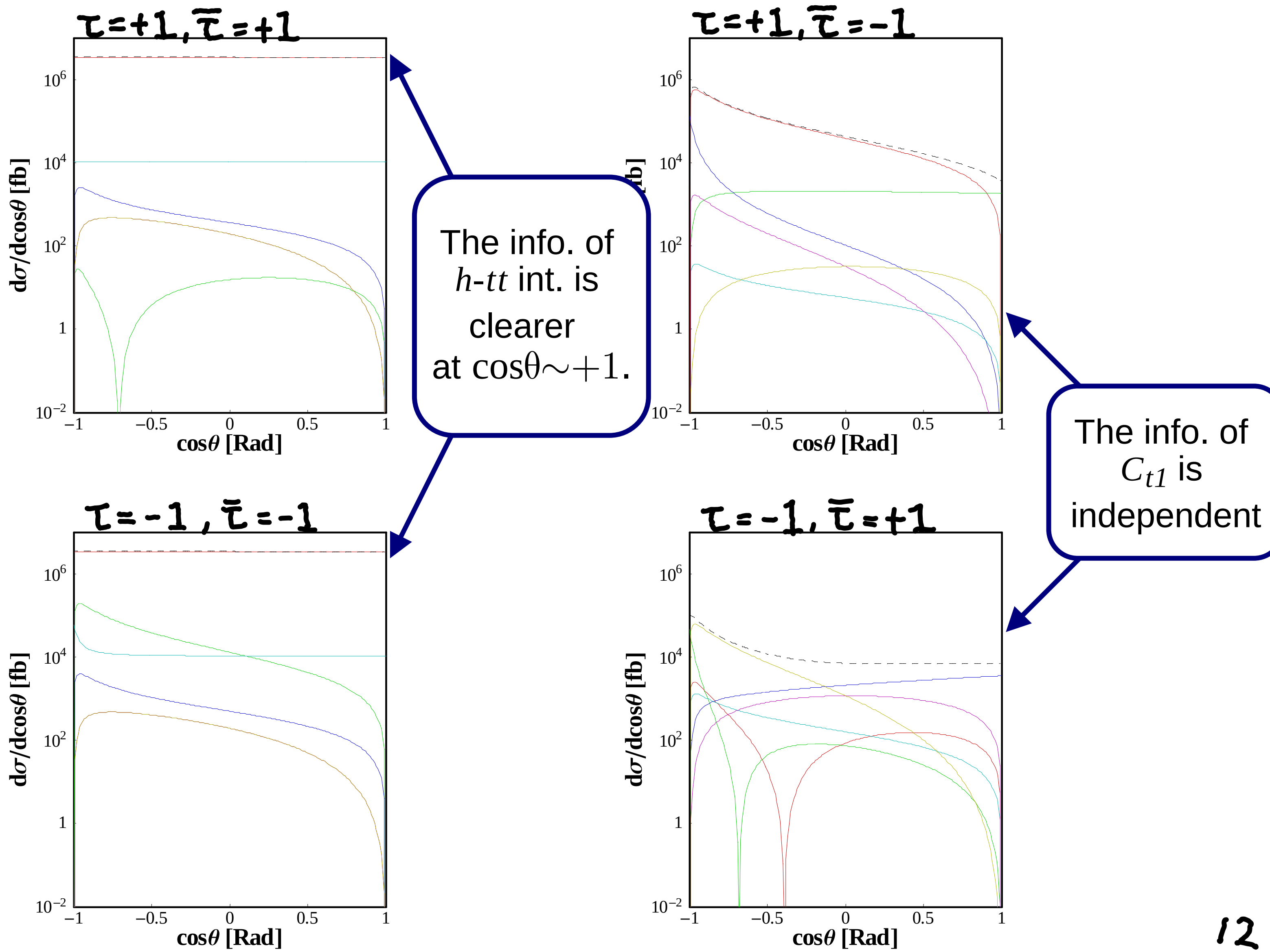


Set B : $m_h = 500$ GeV, $\sqrt{s} = 500$ GeV : $C_{t1} = +\frac{16\pi}{3\sqrt{2}} \frac{\Lambda}{v} = 48.1$

$(\lambda\,\bar{\lambda})$

- (00)
- (++), (--)
- (0+), (-0)
- (0-), (+0)
- (+-)
- (-+)

	Set A	Set B	Set C	Set D	Set E	Set F
C_{t1}	0	$+\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	$-\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	0	0	0
C_{Dt}	0	0	0	+10.2	−6.2	0
C_{t3}	0	0	0	0	0	$8\pi\sqrt{6}\times 0.5$
Γ	62.9487	92.3927	221.292	109.050	52.4566	62.9487

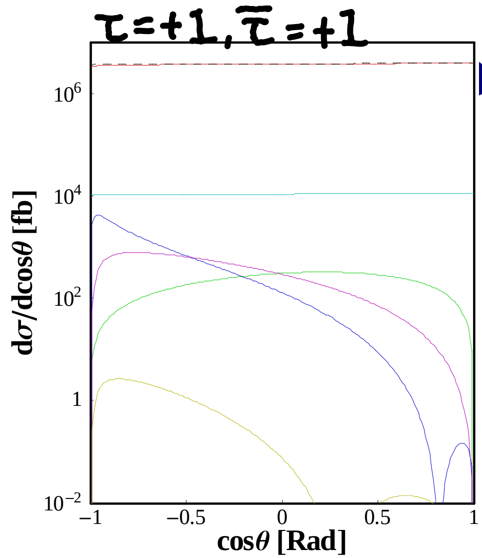


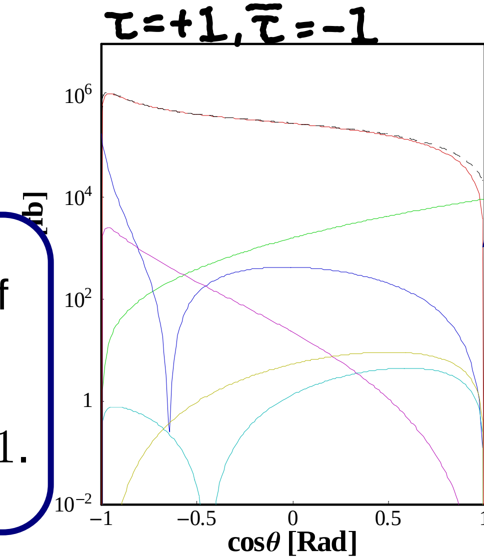
Set D : $m_h = 500$ GeV, $\sqrt{s} = 500$ GeV : $C_{Dt} = +10.2$

$(\lambda\,\bar{\lambda})$

(00)
(++), (--)
(0+), (-0)
(0-), (+0)
(+-)
(-+)

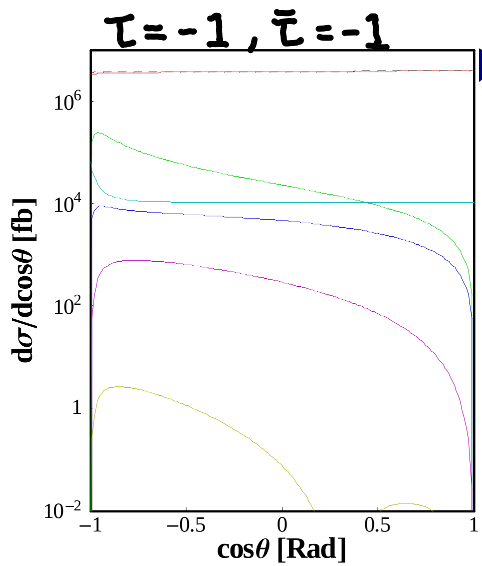
	C_{t1}	C_{Dt}	C_{t3}	Γ
Set A	0	0	0	62.9487
Set B	$+\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	0	0	92.3927
Set C	$-\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	0	0	221.292
Set D	0	$+10.2$	0	109.050
Set E	0	-6.2	0	52.4566
Set F	0	0	$8\pi\sqrt{6}\times 0.5$	62.9487

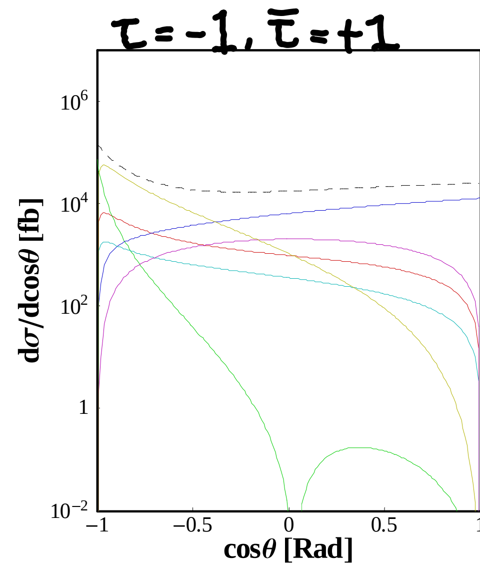




The info. of h-tt int. is clearer at $\cos\theta \sim +1$.

The info. of C_{Dt} appears at $\cos\theta \sim +1$.





Set A : $m_h = 500$ GeV, $\sqrt{s} = 500$ GeV : SM

$(\lambda\,\bar{\lambda})$

(00)

(++), (--)

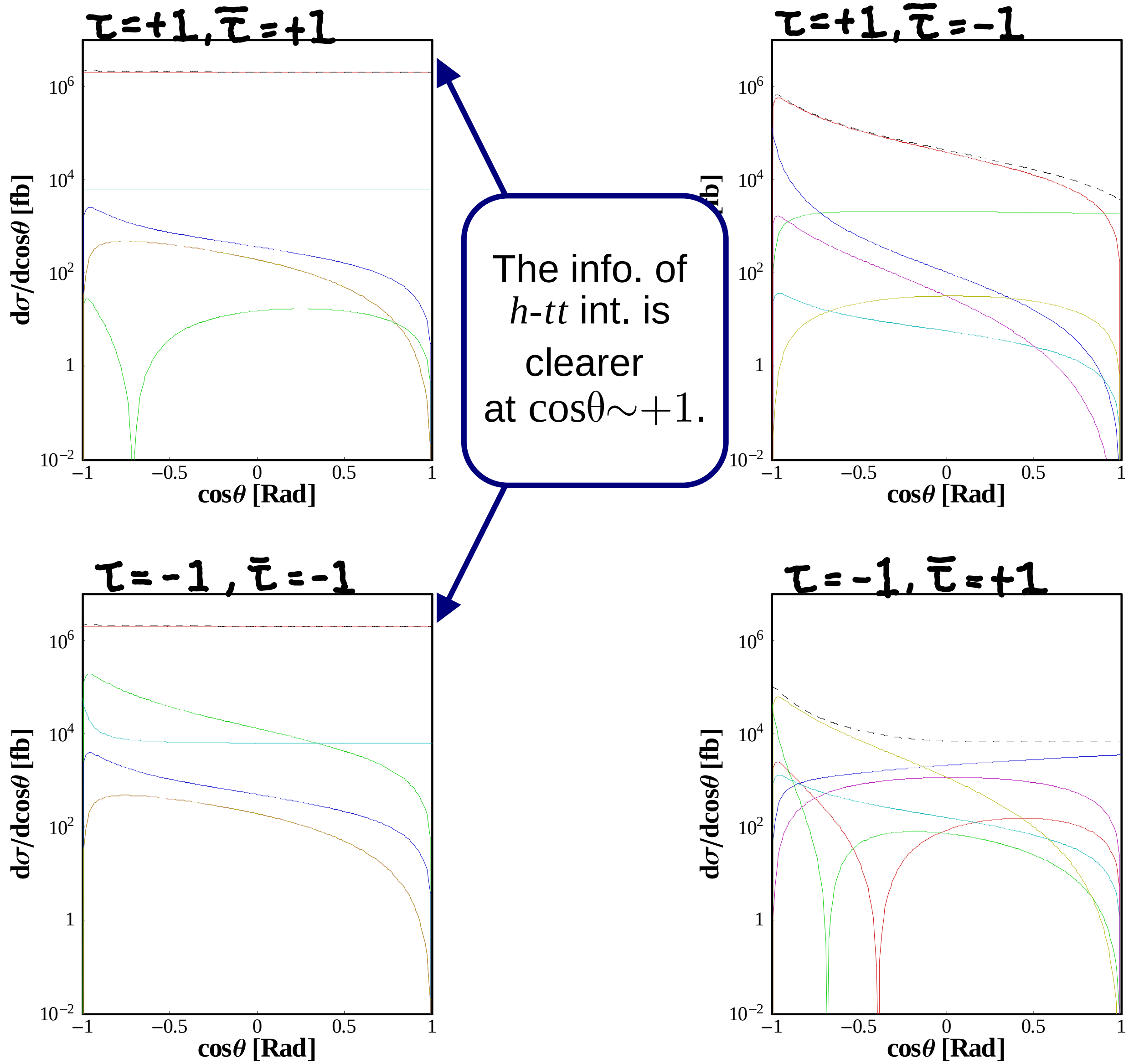
(0+), (-0)

(0-), (+0)

(+-)

(-+)

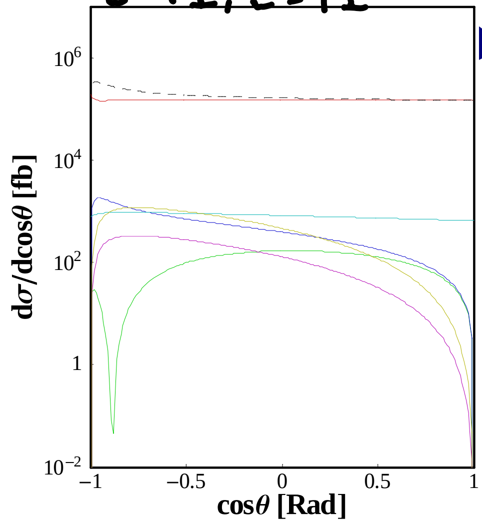
	Set A	Set B	Set C	Set D	Set E	Set F
C_{t1}	0	$+\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	$-\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	0	0	0
C_{Dt}	0	0	0	$+10.2$	-6.2	0
C_{t3}	0	0	0	0	0	$8\pi\sqrt{6}\times 0.5$
Γ	62.9487	92.3927	221.292	109.050	52.4566	62.9487



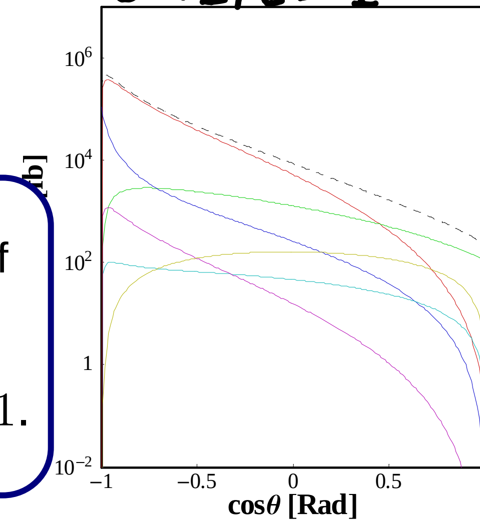
Set E : $m_h = 500$ GeV , $\sqrt{s} = 500$ GeV : $C_{Dt} = -6.2$

	Set A	Set B	Set C	Set D	Set E	Set F
C_{t1}	0	$+\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	$-\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	0	0	0
C_{Dt}	0	0	0	$+10.2$	-6.2	0
C_{t3}	0	0	0	0	0	$8\pi\sqrt{6}\times 0.5$
Γ	62.9487	92.3927	221.292	109.050	52.4566	62.9487

$\tau=+1, \bar{\tau}=+1$



$\tau=+1, \bar{\tau}=-1$



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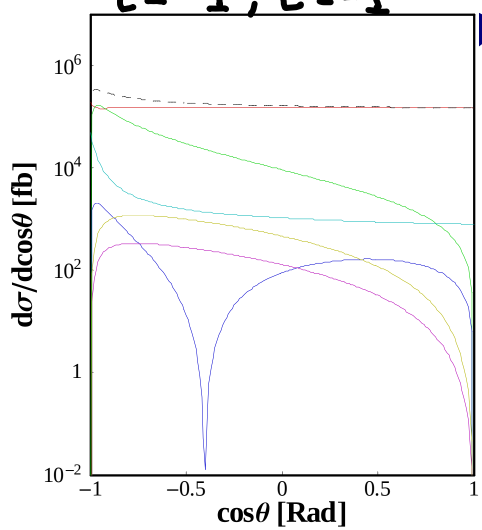
(++) , (--)
(0+) , (-0)
(0-) , (+0)
(+-)
(-+)

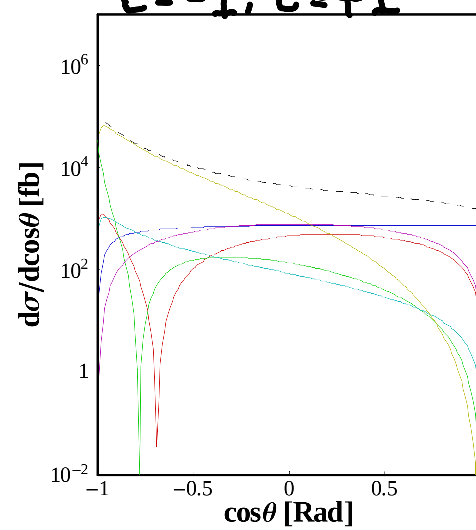
The info. of h-tt int. is clearer at $\cos\theta \sim +1$.

The info. of C_{Dt} appears at $\cos\theta \sim +1$.

$\tau=-1, \bar{\tau}=-1$



$\tau=-1, \bar{\tau}=+1$



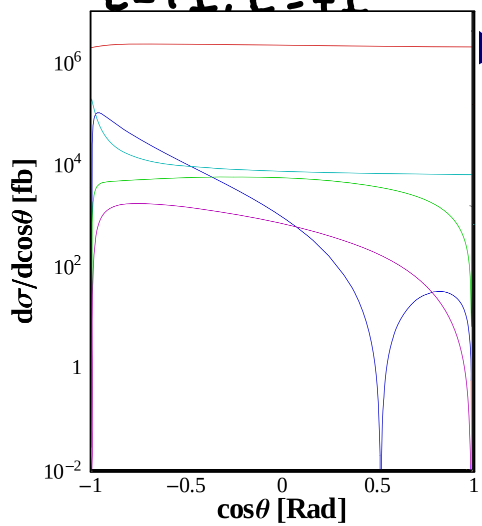
Set F : $m_h = 500$ GeV , $\sqrt{s} = 500$ GeV : $C_{t3} = 8\pi\sqrt{6} \times 0.5$

$= 61.6 \times 0.5$

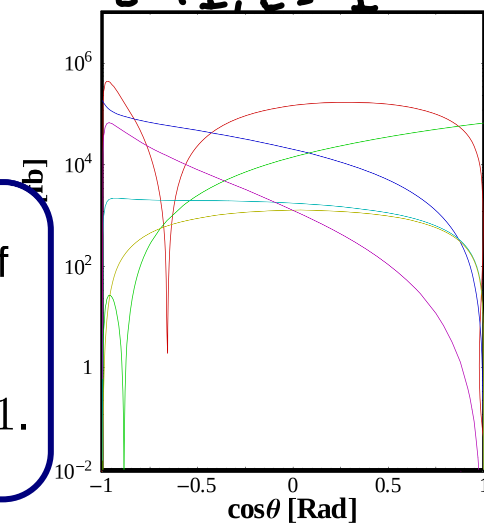
$(\lambda\, \bar{\lambda})$
- (00)
- (++), (- -)
- (0+), (-0)
- (0-), (+0)
- (+-)
- (-+)

	Set F	Set E	Set D	Set C	Set B	Set A
C_{t1}	0	0	0	$-\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	$+\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	0
C_{Dt}	0	-6.2	$+10.2$	0	0	0
C_{t3}	$8\pi\sqrt{6}\times 0.5$	0	0	0	0	0
Γ	62.9487	52.4566	109.050	221.292	92.3927	62.9487

$\tau = +1, \bar{\tau} = +1$

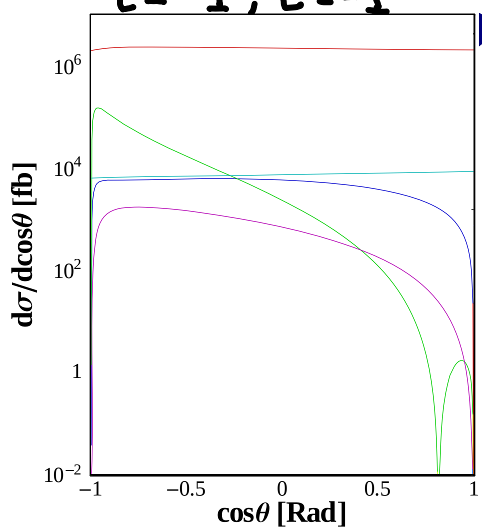


$\tau = +1, \bar{\tau} = -1$

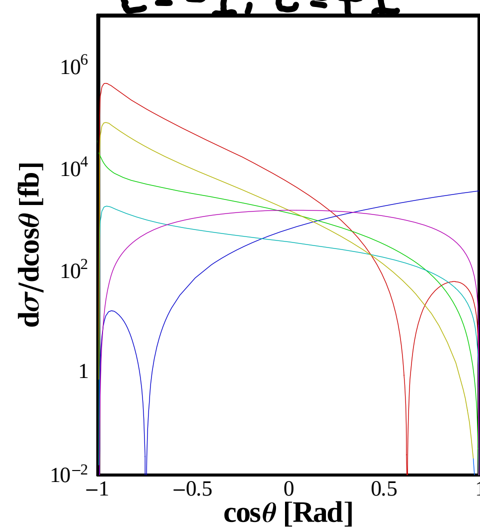


The info. of h-tt int. is clearer at $\cos\theta \sim +1$.

$\tau = -1, \bar{\tau} = -1$



$\tau = -1, \bar{\tau} = +1$



The info..of C_{t3} appears.

Conclusions

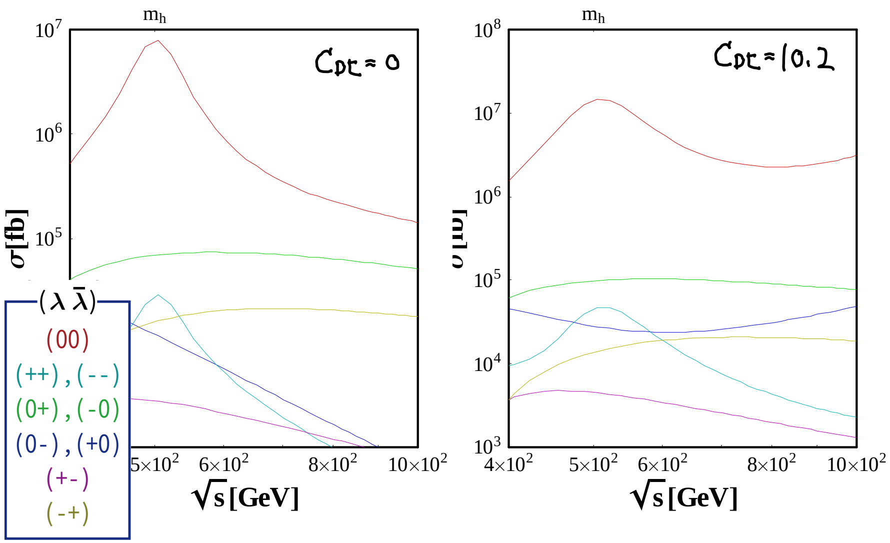
- We have discussed the W boson fusion with dim-6 operators.
  - How to extract the h-tt int. from the W fusion processes?
  - How to extract the effect of the dim-6 operators?
- We use the helicity amplitudes in order to extract the information of new physics.
- We have only discussed the sub-process in the W fusion.
  - When m_h, C_{t1} and C_{Dt} are small, the information of h-tt int. submerge.
  - If we can measure energy dependence, the effects of O_{t1} , O_{t3} and O_{Dt} appear.
  - If we can measure angular dependence and select the helicities, the effects of O_{Dt} and O_{t3} appear.
- Can such information of new physics really be extracted?
  - We are studying the full-process now.

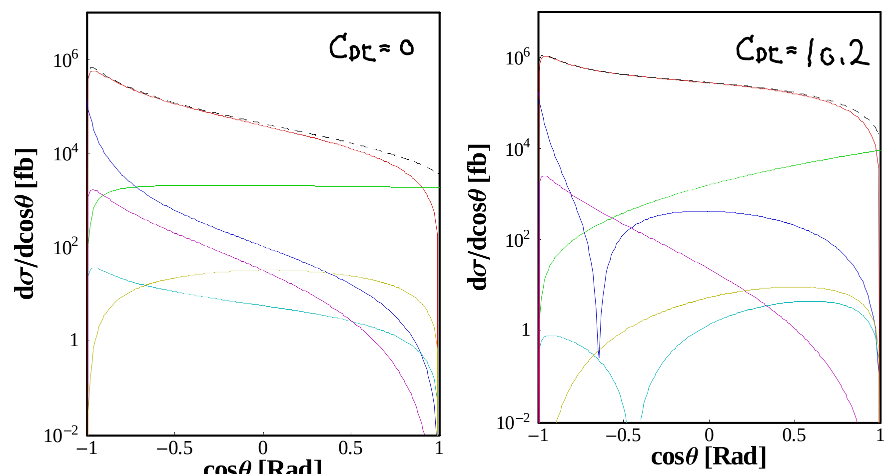
New physics search by helicity decomposition of heavy fermion pair-production from W-boson fusion at the ILC

Koichi Matsuda (Tsinghua Univ.),
Shinya Kanemura (Univ. of Toyama), Koji Tsumura (Osaka Univ.)

- We have discussed the helicity amplitudes of the W boson fusion ($W^+W^- \to t\bar{t}$) with dim-6 operators in order to extract the information of new physics..
  - If we can measure energy dependence, the effects of O_{t1} , O_{t3} and O_{Dt} appear.
  - If we can measure angular dependence and select the helicities ($W : \lambda\bar{\lambda}$, $t : \tau\bar{\tau}$), the effects of O_{Dt} and O_{t3} appear

- Ex.) $\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{C_{Dt}}{\Lambda^2} O_{Dt}, \quad O_{Dt} = (\bar{q}_L D_\mu t_R)(D^\mu \tilde{\Phi} + h.c)$

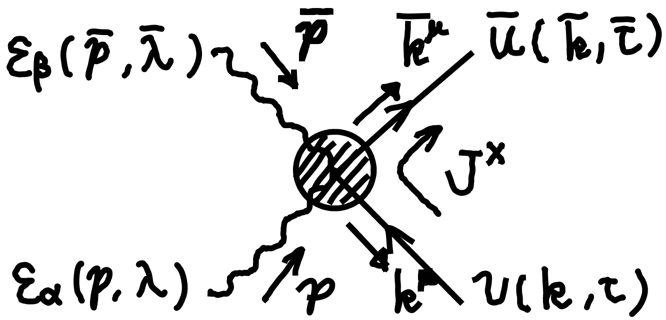


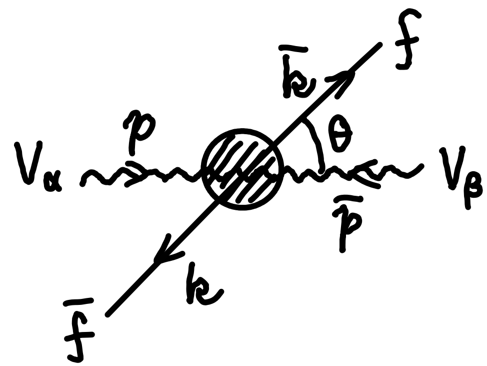


$\sqrt{s} = 500\,GeV$, $\tau = +1$, $\bar{\tau} = -1$

The process $VV \to ff$

- In the center of momentum (CM) frame, we determine the following parameters;





The $\varepsilon^\alpha(p, l)$ and $\varepsilon^\beta(p, l)$ are the physical and unphysical (scalar) polarizations for the vector bosons

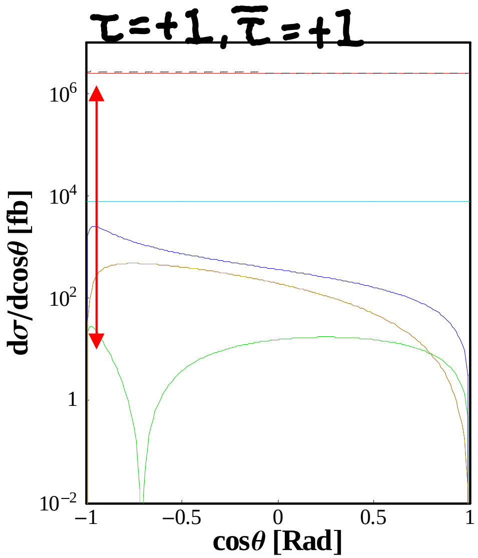
$$\varepsilon^\alpha(p,\pm) = \frac{1}{\sqrt{2}}(0, \mp, i, 0), \quad \varepsilon^\alpha(p,0) = \gamma_v(\beta_v, 0, 0, 1), \quad \varepsilon^\alpha(p,s) = \gamma_v(1, 0, 0, \beta_v)$$

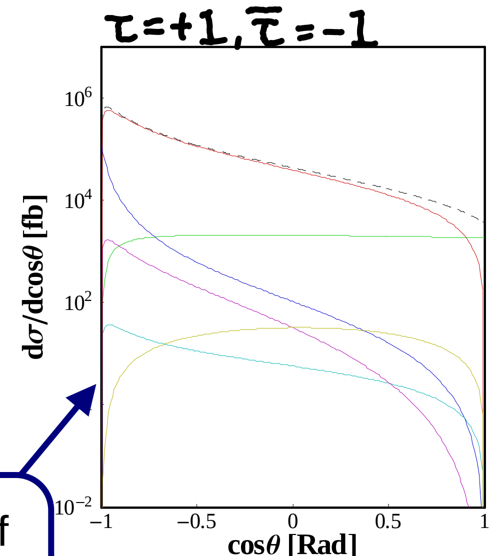
$$\varepsilon^\beta(p,\pm) = \frac{1}{\sqrt{2}}(0, \mp, -i, 0), \quad \varepsilon^\beta(p,0) = \gamma_v(\beta_v, 0, 0, -1), \quad \varepsilon^\beta(p,s) = \gamma_v(1, 0, 0, -\beta_v)$$

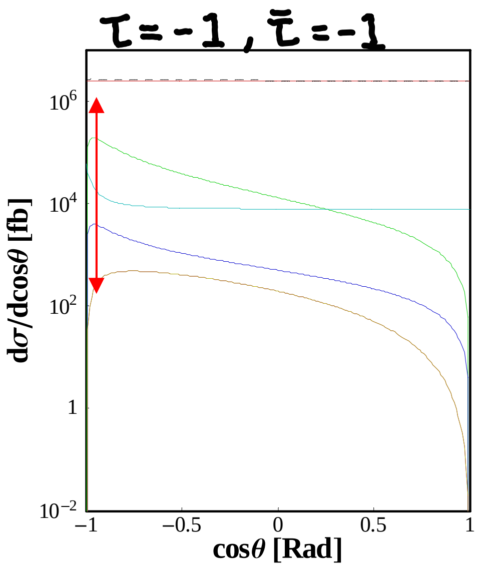
Unphysical (scalar) polarized boson is needed, when we discuss the BRS identities which is powerful tool for checking calculations.

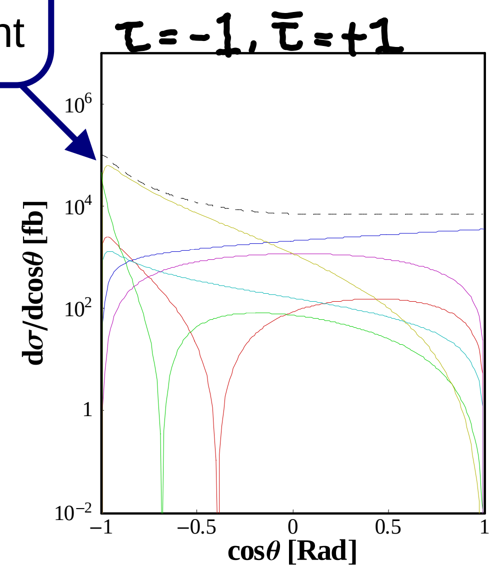
S.Alam, K.Hagiwara, S.Kanemura, R.Szalapski, Y.Umeda NPB541(1999) 50.

Set C : $m_h = 500\,\text{GeV}$, $\sqrt{s} = 500\,\text{GeV}$: $C_{t1} = -\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$









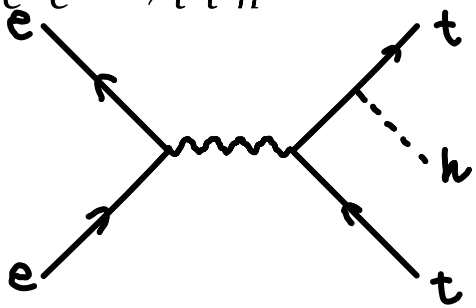
(00)
(++), (--)
(0+), (-0)
(0-), (+0)
(+-)
(-+)

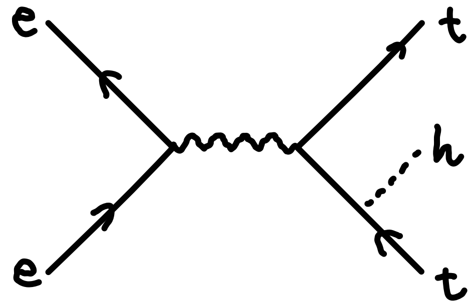
The info. of C_{t1} is independent

	C_{t1}	C_{Dt}	C_{t3}	Γ
Set A	0	0	0	62.9487
Set B	$+\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	0	0	92.3927
Set C	$-\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	0	0	221.292
Set D	0	+10.2	0	109.050
Set E	0	−6.2	0	52.4566
Set F	0	0	$8\pi\sqrt{6}\times 0.5$	62.9487

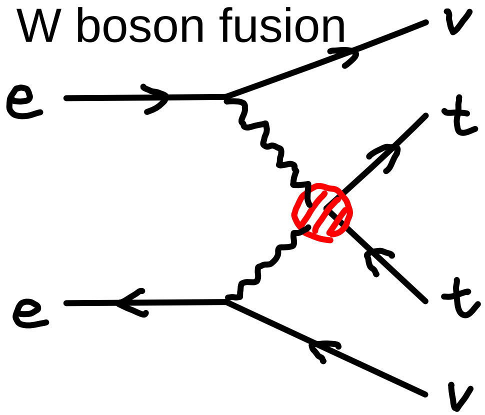
Top Yukawa coupling at ILC

- In the Light Higgs case $(m_h < 150\mathrm{GeV})$ –
  - $e^+e^- \rightarrow t\ t\ h$





- In the Heavy Higgs case. (we concentrate on this case.)
  - W boson fusion



Several bounds for dimension-six operators

The C_{t1} and C_{Dt} have been studied by many people,

- From unitarity bounds
  (Gounaris, Papadamou, Renard Z phys C76,333)

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

$$i\mathcal{M}^{t\bar{t}\to hh} \sim \frac{1}{s-m_h^2}\left(\frac{m_t}{v} - \frac{v^2}{\sqrt{2}}\frac{C_{t1}}{\Lambda^2} + \frac{s}{\sqrt{2}}\frac{C_{Dt}}{\Lambda^2}\right)(-i\lambda)\,\bar{v}u\,3! + i\frac{C_{t1}}{\sqrt{2}}\frac{v}{\Lambda^2}\bar{u}v\,2!$$

etc...

$$\to |C_{t1}| \le \frac{16\pi}{3\sqrt{2}}\left(\frac{\Lambda}{v}\right), \qquad -6.4 \le C_{Dt} \le 10.4$$

For example, we use the followin values.

	Set A	Set B	Set C	Set D	Set E	Set F
C_{t1}	0	$+\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	$-\frac{16\pi}{3\sqrt{2}}\frac{\Lambda}{v}$	0	0	0
C_{Dt}	0	0	0	$+10.2$	-6.2	0
C_{t3}	0	0	0	0	0	$8\pi\sqrt{6}\times 0.5$
Γ	1.407	1.407	1.407	1.407	1.407	1.407