# **di-Higgs day**

# **Di-Higgs bosons in the SM**

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**Konkuk University, 2019.6.27**

# References

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Unravelling an extended quark sector through multiple Higgs production?

S. Dawson, E. Furlan, and I. Lewis

### Higgs boson pair production in new physics models additional quarks. In these models, we compute double Higgs production from gluon fusion exactly at at hadron, lepton, and photon colliders

Eri Asakawa,<sup>1,∗</sup> Daisuke Harada,<sup>2, 3,†</sup> Shinya Kanemura,<sup>4,‡</sup> the Standard Model prediction as well as well as well as well as well as  $\sim$  the Higgs decay into photons. The two photons in the two photons in the two photons. The two photons in the two photons in the two photons. The Yasuhiro Okada,<sup>2, 3, §</sup> and Koji Tsumura<sup>5, ¶</sup>

### Higgs triple coupling  $\overline{\mathbf{v}}$ And the section of the section of the contraction of the calculation of the calculation of the calculation of the contraction of the contraction of the contraction of the contraction on the contraction on the contraction o sections in each model, we first consider the results in the SM with a constant shift of the

$$
\lambda_{hhh}^{\rm SM} = -3m_h^2/v
$$
 at the tree level

#### 2 At the order order, the effection have been evaluated as  $\frac{1}{2}$  $\Delta t$  the ene leep ender the effective bbb venter **At the one-loop order, the effective hhh vertex function**

$$
\Gamma_{hhh}^{\rm SM}(\hat s,m_h^2,m_h^2)\simeq -\frac{3m_h^2}{\upsilon}\left\{1-\frac{N_c m_t^4}{3\pi^2\upsilon^2m_h^2}\left[1+\mathcal{O}\left(\frac{m_h^2}{m_t^2},\frac{\hat s}{m_t^2}\right)\right]\right\}
$$

# The double Higgs boson production at the e+e− collider







#### The double Higgs boson production at the LHC a gluon-gluon-gluon initial state arises from the Feynman initial state arises from the Feynman initial state diagrams in Fig. 1. The result is sensitive to result in Fig. 1. The result is sensitive to result in Fig. 1. new colored objects (fermions or scalars) in the loops of scalars (fermions or scalars) in the loops of the lo for ga;!ðp1Þgb;"ðp2Þ ! Hðp3ÞHðp4Þ is <sup>8</sup>\$v<sup>2</sup> %ab½P!" YNS<sup>N</sup> i hnsnn  $H = H = \frac{1}{2}$ at tr 2  $\mathsf{P} \cap \mathsf{P} \cap \mathsf{$ Higgs couplings 'u;d <sup>i</sup> are purely scalar. In the following



**The amplitude for**  ne amplitude for  $g^{a,\mu}(p_1)g^{b,\nu}(p_2)\to H(p_3)H(p_4)$ for amplication  $\delta$   $(P1/\delta)$   $(P2)$ 

$$
A_{ab}^{\mu\nu} = \frac{\alpha_s}{8\pi v^2} \delta_{ab} [P_1^{\mu\nu}(p_1, p_2) F_1(s, t, u, m_t^2) + P_2^{\mu\nu}(p_1, p_2, p_3) F_2(s, t, u, m_t^2)],
$$

$$
P_1^{\mu\nu}(p_1, p_2) = g^{\mu\nu} - \frac{p_1^{\nu} p_2^{\mu}}{p_1 \cdot p_2}, \quad \text{Projection op. for spin-0}
$$
  

$$
P_2^{\mu\nu}(p_1, p_2, p_3) = g^{\mu\nu} + \frac{2}{sp_T^2} (m_H^2 p_1^{\nu} p_2^{\mu} - 2p_1 p_3 p_2^{\mu} p_3^{\nu})
$$

$$
- 2p_2 p_3 p_1^{\nu} p_3^{\mu} + sp_3^{\mu} p_3^{\nu});
$$

#### $f_{\alpha}$   $\alpha$   $\sin$   $\alpha$ FIG. 1. Feynman diagrams for gg ! HH in the Standard Model. s, t, and u are the participation of the participation **Projection op. for spin-2**

#### In this paper, we study the effects of heavy colored anic cross s e carti  $\overline{\mathbf{a}}$ F2 are known and the participant of  $\mathcal{S}$ **partonic cross section**

$$
\frac{d\hat{\sigma}(gg \to HH)}{dt} = \frac{\alpha_s^2}{2^{15} \pi^3 v^4} \frac{|F_1(s, t, u, m_t^2)|^2 + |F_2(s, t, u, m_t^2)|^2}{s^2},
$$

#### ci ui L In the SM, the top quark contribution is dominant.

**LET (Low energy theorem) :**  $m_t^2 \gg s$ In the Standard Model, the dominant come from top  $\iota$  $U<sub>1</sub> = -1$ 

# **Projection for spin-0**<br> **Projection for spin-0**

$$
F_1(s, t, u, m_t^2) \equiv F_1^{\text{tri}}(s, t, u, m_t^2) + F_1^{\text{box}}(s, t, u, m_t^2),
$$
  
\n
$$
F_1^{\text{tri}}(s, t, u, m_t^2) = \frac{4m_H^2}{s - m_H^2} s \Big\{ 1 + \frac{7}{120} \frac{s}{m_t^2} + \frac{1}{168} \frac{s^2}{m_t^4} + \mathcal{O}\Big(\frac{s^3}{m_t^6}\Big) \Big\},
$$
  
\n
$$
F_1^{\text{box}}(s, t, u, m_t^2) = -\frac{4}{3} s \Big\{ 1 + \frac{7}{20} \frac{m_H^2}{m_t^2} + \frac{90m_H^4 - 28m_H^2 s + 12s^2 - 13p_T^2 s}{840m_t^4} + \mathcal{O}\Big(\frac{s^3}{m_t^6}\Big) \Big\};
$$

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$$

o angular dependence Higgs triple coupling): No angular dependence<br>as triple coupling): as welch dependence in **Triangle diagram (Higgs triple coupling): No angular dependence** 

#### The leading terms in the inverse top mass expansion of **The Searth Starte Search**<br>The Couplin<br>The Starte Couplin  $\frac{1}{2}$ ar depe  $\overline{\phantom{a}}$ Box diagram (Higgs triple coupling): angular dependence in Eq. (8) are called the ''low energy theorem'' result and give momentum dependence. For the box diagrams, at the lowest angular dependence in **Box diagram (Higgs triple coupling): angular dependence in mt^(-4)**

$$
F_1^{\text{box}}(s, t, u, m_t^2) = -\frac{4}{3} s \Biggl[ \Biggl( 1 + \frac{7}{20} \frac{m_H^2}{m_t^2} + \frac{540 m_H^4 - 116 m_H^2 s + 59 s^2}{5040 m_t^4} \Biggr) d_{0,0}^0(\theta) + \frac{13 s^2 - 52 m_H^2 s}{5040 m_t^4} d_{0,0}^2(\theta) + \mathcal{O}\Biggl(\frac{s^3}{m_t^6}\Biggr) \Biggr],
$$
  

$$
F_2^{\text{box}}(s, t, u, m_t^2) = -\frac{11}{45} s \frac{s - 4 m_H^2}{\sqrt{6} m_t^2} \Biggl[ 1 + \frac{62 m_H^2 - 5 s}{154 m_t^2} + \mathcal{O}\Biggl(\frac{s^2}{m_t^4}\Biggr) \Biggl] d_{2,0}^2(\theta).
$$

<sup>t</sup> <sup>Þ</sup>jLET ! <sup>0</sup>: (9)

 $\overline{ }$ 

 $\ddot{}$ 

m<sup>6</sup>

 $\frac{1}{2}$ Wigner *d*-functions,  $d_{s_i,s_f}$  $\begin{array}{ccc} \hline \text{Hence} & \text{Hence} \\ \text{Hence} & \text{Hence} \end{array}$ Wigner d-functions,  $d_{s_i,s_f}^j$  $\mathbf{W}^{\star}$  is the angular dependence of  $\mathbf{U}$ wighth *a*-functions,  $a_{s_i,s_f}$  $\mathbf{u}$ r  $\mathbf{v}$  $VDEICI U-TU$  $\dot{\mathbf{r}}$ ions,  $d_{s_i,s_f}$ 

 $\overline{\phantom{a}}$ 

 $\mathbf{r}$ 

H

þ O

1 þ

 $\sqrt{2}$ 

p2

s

Wigner d-functions, dj

þ O

Ts

m<sup>4</sup>

F2ðs; t; u; m<sup>2</sup>

þ

168

m<sup>2</sup>

m<sup>4</sup> t

120

 $\overline{a}$ 

 $j$  is the total and invariant mass distribution, and is the total and  $i$  $\frac{1}{2}$  is t  $\operatorname{lar}$  $\boldsymbol{J}$  $\frac{1}{\sqrt{2}}$ the to  $\mathcal{O}(\mathcal{A})$  $\ddot{\cdot}$  $\alpha$  ange  $j$  is the total angular  $\dot{i}$  is the total angular  $\int$  15 cm  $s$  , where  $\frac{1}{2}$  is the total angular angular angular angular ang unit  $\frac{1}{2}$  is the total angular angular angular angular ang unit  $\frac{1}{2}$  is the total angular angular angular ang unit  $\frac{1}{2}$  is the total an

Since the initial and final states for the F<sup>1</sup> contribution are

<sup>2</sup> , the functions can be decomposed into

<sup>T</sup> component of Fbox  $\sim 1$ to  $\sim 1$  $s_i$  (s<sub>f</sub>) is the initial (final) st  $\tilde{z}$  (s) is the initial (final) state spins:  $\frac{1}{2}$  , we can see the expected spin-0 s-wave component, we can see the expected spin-0 s-wave component,  $\frac{1}{2}$  $s_i$  (s<sub>f</sub>) is the initial (final) state spin:

signal angular  $\sim$  , where  $\sim$  , where  $\sim$ 

both spin-0, this is a somewhat surprising result. To gain

$$
F_2(s, t, u, m_t^2) = -\frac{11}{45} s \frac{p_T^2}{m_t^2} \left\{ 1 + \frac{62m_H^2 - 5s}{154m_t^2} + \mathcal{O}\left(\frac{s^2}{m_t^4}\right) \right\}.
$$

### **Angular dependence**

**the multipude manufacture and architecture and architecture and architecture and architecture and architecture** At leading order, **At leading order,** 

$$
F_1(s, t, u, m_t^2)|_{\text{LET}} \to \left(-\frac{4}{3} + \frac{4m_H^2}{s - m_H^2}\right)s,
$$
  

$$
F_2(s, t, u, m_t^2)|_{\text{LET}} \to 0.
$$

# LET is a poor approximation for di-Higgs





How to deviate the SM result for the gluon fusion?



1. New  $\lambda_{hhh}$ 

2. New Scalar

3. New colored fermions



1. New  $\lambda_{hhh}$ 

2. New Scalar

3. New colored fermions



- 1. New  $\lambda_{hhh}$
- 2. New Scalar
- 3. New colored fermions



2HDM FIG. 1. Feynman diagrams for gg ! HH in the Standard Model.

# **MO HIGGS DOUDIELS** Two Higgs doublets

 $\Phi_1$  and  $\Phi_2$  $\Phi_1$  and  $\Phi_2$ 

**In order to suppress FCNC at tree level, we impose Z2 symmetry** In order to suppress FCNC at tree level, In order to suppress FCNC at tree level,<br>We impose 72 symmetry

 $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  symmotory  $\Phi_1 \rightarrow \Phi_1$  and  $\Phi_2 \rightarrow -\Phi_2$ 

### Higgs potential √2 ⎟⎠ *, i* = 1*,* <sup>2</sup> *.* (1)

$$
V = m_{11}^2 \Phi_1^{\dagger} \Phi_1 + m_{22}^2 \Phi_2^{\dagger} \Phi_2 - m_{12}^2 (\Phi_1^{\dagger} \Phi_2 + \text{H.c.})
$$
  
\n
$$
+ \frac{1}{2} \lambda_1 (\Phi_1^{\dagger} \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^{\dagger} \Phi_2)^2 + \lambda_3 (\Phi_1^{\dagger} \Phi_1) (\Phi_2^{\dagger} \Phi_2) + \lambda_4 (\Phi_1^{\dagger} \Phi_2) (\Phi_2^{\dagger} \Phi_1)
$$
  
\n
$$
+ \frac{1}{2} \lambda_5 \left[ (\Phi_1^{\dagger} \Phi_2)^2 + \text{H.c.} \right]
$$

**Algorithment limit**  
\n
$$
H^{SM} = s_{\beta-\alpha}h^0 + c_{\beta-\alpha}H^0
$$
\nFor  $h^0 = h_{125}$   $s_{\beta-\alpha} = 1$ 

$$
\sin(\beta - \alpha) : g_{hW^+W^-}, g_{hZZ}, g_{ZAH}, g_{W^{\pm}H^{\mp}H},
$$
  

$$
\cos(\beta - \alpha) : g_{HW^+W^-}, g_{HZZ}, g_{ZAh}, g_{W^{\pm}H^{\mp}h}, g_{Hhh}.
$$

ZERO!

The coupling of the alignment vanish in the alignment value of the alignment value No resonance decay into hh!



### 2HDM following discussion; i.e., m <sup>H</sup> ¼ m <sup>A</sup> ¼ m <sup>H</sup> ! . FIG. 1. Feynman diagrams for gg ! HH in the Standard Model. The one-loop correction to the hhh coupling constant in



 $\text{Unless } M \approx m_{H^\pm} \approx m_H \approx m_A$  $\Delta\lambda_{hhh}$  can be large!  $n_{h}$  van de large.



### peaks around  $M_{hh} \sim 400$





### $F$  interference of facts h/w  $\Lambda$  and  $\Gamma$  $\ldots$  information choose  $\omega$ , w 1. interference effects b/w  $\Delta$  and  $\square$

2. Enhanced  $\lambda_{hhh}$  decreases  $\sigma(gg \to hh)$ .

## At leading order, which we have a set of the 'nergy theorem' result and given and



At 
$$
\sqrt{s} = 400 \text{ GeV}, \frac{m_H^2}{s - m_H^2} \sim 0.1.
$$

 $\mathbf{F}_{\mathbf{F}}$  $\mathbf{A}$ u e  $e$  commer At  $e^+e^-$  collider





# Not in the aligned 2HDM

1. New  $\lambda_{hhh}$ 

2. New Scalar

3. New colored fermions

# S.C. Park



# New heavy quarks!

But we have to satisfy the single Higgs rate & EWPD

#### Mirror fermions a generation of heavy mirror fermions  $\overline{\phantom{a}}$  ,  $\$ the gg ! H rate found in Ref. [5]. This model is an example of a case which will be extremely difficult to the e  $innc$ Lagrangian parameters !<sup>i</sup> can be expressed in terms of the  $\frac{e}{2}$  case  $\frac{e}{2}$ differentiate from the Standard Model.

a generation of heavy mirror fermions a conoration of how mirror formions a generation of heavy million feminons ror fermions

$$
\psi_L^1 = \begin{pmatrix} \mathcal{T}_L^1 \\ \mathcal{B}_L^1 \end{pmatrix}, \mathcal{T}_R^1, \mathcal{B}_R^1; \quad \psi_R^2 = \begin{pmatrix} \mathcal{T}_R^2 \\ \mathcal{B}_R^2 \end{pmatrix}, \mathcal{T}_L^2, \mathcal{B}_L^2.
$$

with charges 
$$
\frac{2}{3}
$$
 and  $-\frac{1}{3}$ 

representations,

The couplings of the fermion mass eigenstates to the Higgs boson  $\overline{m}$  $T$  in eliminates the need to  $T$ lings of the fermion mass

$$
-\mathcal{L}_{M}^{H} = \frac{c_{T_{1}T_{1}}}{2v} \bar{T}_{1L} T_{1R} H + \frac{c_{T_{2}T_{2}}}{2v} \bar{T}_{2L} T_{2R} H \n+ \frac{c_{T_{1}T_{2}}}{2v} \bar{T}_{1L} T_{2R} H + \frac{c_{T_{2}T_{1}}}{2v} \bar{T}_{2L} T_{1R} H \n+ \frac{c_{B_{1}B_{1}}}{2v} \bar{B}_{1L} B_{1R} H + \frac{c_{B_{2}B_{2}}}{2v} \bar{B}_{2L} B_{2R} H \n+ \frac{c_{B_{1}B_{2}}}{2v} \bar{B}_{1L} B_{2R} H + \frac{c_{B_{2}B_{1}}}{2v} \bar{B}_{2L} B_{1R} H + \text{H.c.},
$$

For single Higgs production through top quark and mirror fermion loops, yields  $\mathbf{f}$  $F_{01}$  $1 - 00 - 1$ <sup>R</sup> ) 0 the diagonal Yukawa couplings go to zero

$$
A_{gg\to H} = A_{gg\to H}^{\text{SM}} \left( 1 + \frac{c_{T_1 T_1}}{2M_{T_1}} + \frac{c_{T_2 T_2}}{2M_{T_2}} + \frac{c_{B_1 B_1}}{2M_{B_1}} + \frac{c_{B_2 B_2}}{2M_{B_2}} \right)
$$

### LET

 $h h$  $B_{\rm eff}$  is simplicity and because one expects large corresponding large corresponding large corresponding large corresponding  $\sim$ For  $gg \to hh$ ror gg From the low energy theorem of Eq. (21), the box  $h h$ 

$$
F_1^{\text{box}} = F_1^{\text{box,SM}} (1 + \Delta_{\text{box}});
$$
  
\n
$$
\Delta_{\text{box}} = \frac{c_{T_1 T_1}^2}{4M_{T_1}^2} + \frac{c_{T_2 T_2}^2}{4M_{T_2}^2} + \frac{c_{B_1 B_1}^2}{4M_{B_1}^2} + \frac{c_{B_2 B_2}^2}{4M_{B_2}^2} + \frac{c_{T_1 T_2} c_{T_2 T_1}}{2M_{T_1} M_{T_2}} + \frac{c_{B_1 B_2} c_{B_2 B_1}}{2M_{B_1} M_{B_2}}
$$







# Conclusions

- *•* Di-Higgs process is elusive.
- In the SM, the signal rate is very small.
- It is very difficult to have large NP effects.