DIBOSON AS PROBE TO HIGGS (NEW) PHYSICS

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Based on work with S. Lee, M Park arXiv: 1812.02679
S. Kang, J. Song, Y. Yoon: 1810.05229
MOTIVATION

- Since the Higgs discovery, studying its properties has been main focus.

- Likely connection between Higgs and new physics: Extended Scalar Sector, EW symmetry breaking, Fermion masses, Higgs portal DM etc.

- Currently, the Higgs data agrees with the SM, but still allows sizable space for simple extensions to the standard model, which may further link to complete theories.

- Collider possibilities: LHC, future lepton colliders
LHC HIGGS MEASUREMENT

**Higgs on-shell signal Measurement**

**Higgs off-shell signal**

* arXiv:1811.10215: Higgs measurement at LHC run2
LHC HIGGS MEASUREMENT

**ATLAS** Preliminary

\[ \sqrt{s} = 13 \text{ TeV}, \ 36.1 - 79.8 \text{ fb}^{-1} \]

\[ m_{H} = 125.09 \text{ GeV}, \ |y_{H}| < 2.5 \]

- \( B_{BSM} = 0 \)
- \( \kappa_{Z} \)
- \( \kappa_{W} \)
- \( \kappa_{t} \)
- \( \kappa_{b} \)
- \( \kappa_{t} \)
- \( \kappa_{g} \)
- \( \kappa_{\gamma} \)

1 \( \sigma \) interval

2 \( \sigma \) interval

\[ |\kappa_{V}| \leq 1 \]

\[ B_{BSM} \cong 0 \]

**ATLAS** Simulation

\[ \sqrt{s} = 13 \text{ TeV} \]

\[ \text{do/d}m_{4l} \text{[fb/GeV]} \]

- q\( \bar{q} \rightarrow 4l \)
- gg\( \rightarrow 4l \) (inclusive)
- gg\( \rightarrow H \rightarrow 4l \)
- gg\( \rightarrow ZZ \rightarrow 4l \)
- VH/ttH/VBF H\( \rightarrow 4l \)

\[ m_{4l} \text{[GeV]} \]

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**Conclusions**

Higgs boson measurements based on 35 to 80 fb\(^{-1}\) of proton-proton collision data recorded at the LHC by the ATLAS and CMS experiments have been reviewed. With this dataset, important milestones for Higgs boson physics at the LHC have been reached with the observation of the \( t\bar{t}H \) production and of the decay \( H \rightarrow b\bar{b} \). The four main production processes and five main decay modes of the Higgs boson are now established. In addition, measurements involving bosons in the final state reach higher precision allowing quasi-model independent measurements of differential cross-sections. Studies of the Higgs boson couplings using the combination of all investigated production and decay modes are reported with accuracy on coupling modifier parameters reaching 10 to 20%. The results are consistent with the Standard Model expectations.

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**References**


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* arXiv:1811.10215: Higgs measurement at LHC run2
LHC HIGGS MEASUREMENT

**ATLAS Preliminary**

<table>
<thead>
<tr>
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1 $\sigma$ interval →

2 $\sigma$ interval →

---

**ATLAS Simulation**

$\sqrt{s} = 13$ TeV

$\sigma_H^{on-shell}$

$\sigma_H^{off-shell}$

* arXiv:1811.10215: Higgs measurement at LHC run2
LHC HIGGS MEASUREMENT

* arXiv:1811.10215: Higgs measurement at LHC run2
DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

At High energy scale, each diagram diverges:

$$A_{gg\to ZZ} \rightarrow \log^2\left(\frac{s}{m_t^2}\right)$$

Prominent in Z-longitudinal mode

S. Lee, M. Park, ZQ: arXiv:1812.02679
DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

\[ A_{gg \rightarrow Z_L Z_L} \rightarrow \log^2 \left( \frac{s}{m_t^2} \right) \]
DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

\[ \mathcal{A}_{gg \to Z_LZ_L} \rightarrow \log^2(s/m_t^2) \]

\[ H \]

\[ Z_LZ_L, \quad Z_TZ_T, \quad Z_LZ_T(Z_TZ_L), \quad ZZ \]
DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

\[ A_{gg \rightarrow Z_L Z_L} \rightarrow \log^2(s/m_t^2) \]

\[ g \quad t \quad Z \quad g \quad t \quad Z \]

**H**
- \( Z_L Z_L \)
- \( Z_T Z_T \)
- \( Z_L Z_T(Z_T Z_L) \)
- \( ZZ \)

**BOX**
- \( Z_L Z_L \)
- \( Z_T Z_T \)
- \( Z_L Z_T(Z_T Z_L) \)
- \( ZZ \)
DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

\[ A_{gg \to ZZ} \rightarrow \log^2(s/m_t^2) \]

**H**
- \( Z_LZ_L \)
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- \( Z_LZ_T(Z_TZ_L) \)
- \( ZZ \)

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- \( Z_TZ_T \)
- \( Z_LZ_T(Z_TZ_L) \)
- \( ZZ \)

**TOT**
- \( Z_LZ_L \)
- \( Z_TZ_T \)
- \( Z_LZ_T(Z_TZ_L) \)
- \( ZZ \)
DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

Extended SM models:
Modified Higgs sector

- SM(?) BOX-CONTRIBUTION

- Modified Higgs sector
- Extended SM models:
DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

As a result of the negative interference between the gg contribution and the Higgs contribution, the amplitude for vector-vector type scales with 1/p, where p is the energy.

Depending on the di-boson channel, the LL mode becomes important and even dominant starting from the light quark box-loop. The box diagram amplitude scales with the square of the form factor, due to vector current conservation.

In the large t limit, the amplitude from the Higgs contribution is dominated. The amplitude from the longitudinally polarized Z's. Thus the axial-axial and axial-axial parts could contribute in the two-photon processes.

Closely related to the electroweak symmetry breaking, the vector bosons have been long discussed. For example, the behavior of the Higgs in the o-shell region may contain a crucial information of the underlying model, the total cross section of the process, and showed that such modifications would generically increased the distribution.

We focus on a study of the gg process, and through the massive top top quark in the loop.

The box diagram amplitude scales with the square of the form factor, due to vector current conservation. Through the separate contributions of the top triangle and box diagrams, the LL mode becomes important and even dominant starting from the light quark box-loop. The box diagram amplitude scales with the square of the form factor, due to vector current conservation.

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DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS
DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

Case A: Higgs Sector Light scalar with $Z_2$ symmetry

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \partial_\mu S \partial^\mu S^* - \mu^2 |S|^2 - \kappa |S|^2 |\Phi|^2.$$
DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

• **Case A: Higgs Sector Light scalar with** $Z_2$ **symmetry**

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \partial_{\mu}S\partial^{\mu}S^* - \mu^2 |S|^2 - \kappa|S|^2|\Phi|^2. \]

• **Case B: Heavy Higgs with broad decay width**

\[ \mathcal{L} \supset \mathcal{L}_{\text{SM}} - \mu_S S|\Phi|^2. \quad H = \sin \alpha \, S^{\text{phy}} + \cos \alpha \, H^{\text{phy}} \]
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• Case C: Quantum Critical Higgs modifying the Scalar Sector at high scale

$$G_{\tilde{h}}(p) = -\frac{i Z_{\tilde{h}}}{(\mu^2 - p^2 + i\epsilon)^{2-\Delta} - (\mu^2 - m_{\tilde{h}}^2)^{2-\Delta}}.$$
DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

- **Case A**: Higgs Sector Light scalar with $Z_2$ symmetry
  \[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \partial_{\mu} S \partial^\mu S^* - \mu^2 |S|^2 - \kappa |S|^2 |\Phi|^2. \]

- **Case B**: Heavy Higgs with broad decay width
  \[ \mathcal{L} \ni \mathcal{L}_{\text{SM}} - \mu_S S |\Phi|^2. \quad H = \sin \alpha \ S^{\text{phy}} + \cos \alpha \ H^{\text{phy}} \]

- **Case C**: Quantum Critical Higgs modifying the Scalar Sector at high scale
  \[ G_h(p) = -\frac{i Z_h}{(\mu^2 - p^2 + i \epsilon)^2 - \Delta - (\mu^2 - m_h^2)^2 - \Delta}. \]

- **Case D**: EFT Operator for Example:
  \[ (\bar{\psi} \{\mu \partial^\nu\} \psi) D_{\mu} H^\dagger D_{\nu} H \]
DI-BOSON PRODUCTION TO PROBE HIGGS SECTOR NEW PHYSICS

![Graph showing di-boson production cross-sections as a function of the ZZ mass, with different lines for different production processes.]

- **Light scalar**
- **Heavy Higgs**
- **Quantum Critical Higgs**
- **Effective Operator**

The graph illustrates the differential cross-sections for different production processes, such as $q\bar{q} \to ZZ$ and $gg \to ZZ$, with distinct lines for each process type and variations. The x-axis represents the ZZ mass in GeV, and the y-axis shows the differential cross-section in pb/GeV. The inset figure highlights the TOT channel, providing a visual comparison of the cross-sections across different mass ranges.
For the major background final is flat, as expected from a s-channel scalar mediator.

center of mass frame. The cos from the angle between one final state

SM

olated by LL mode. We set require in the final state a pair of electrons and muons

GeV,

in Sec. II. Generator level cuts are applied as

and QCH model (case C) with model parameters given the light scalar case (case A), heavy Higgs case (case B)

der, and rescale with a k-factor of 1.8 (1.5) for the

gg

high energy scale.

on generic Higgs sector new physics, that shows up in the

physical feature, we enhance the experimental sensitivity from deviation in the LL mode (Right plot). Given this

cases, from Fig. 1, we see the deviation of BSM com-

FIG. 1: (Left top) The di


Quantum Critical Higgs

Effective Operator

Light scalar

Heavy Higgs
Di-Boson Production to probe Higgs Sector New Physics

- Light scalar
- Heavy Higgs
- Quantum Critical Higgs
- Effective Operator

$\Rightarrow$ Through tagging the polarization of Z's
(Cuts, Multi-Variable Analysis on the final states)
Light scalar

Heavy Higgs

Quantum Critical Higgs

Effective Operator

⇒ Through tagging the polarization of Z's
(Cuts, Multi-Variable Analysis on the final states)

<table>
<thead>
<tr>
<th></th>
<th>case A</th>
<th>case B</th>
<th>case C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance σ with basic cuts</td>
<td>2.01</td>
<td>0.634</td>
<td>4.71</td>
</tr>
<tr>
<td>with basic + angle cuts</td>
<td>2.32</td>
<td>0.838</td>
<td>5.78</td>
</tr>
<tr>
<td>with basic cuts + BDT</td>
<td>2.45</td>
<td>0.92</td>
<td>7.01</td>
</tr>
<tr>
<td>Luminosity for 3σ discovery</td>
<td>4.2ab⁻¹</td>
<td>29ab⁻¹</td>
<td>0.5ab⁻¹</td>
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</tbody>
</table>
4TH GEN FERMION REVEALED BY HEAVY HIGGS

4TH GEN FERMION REVEALED BY HEAVY HIGGS

- Model: \{ 2HDM + \begin{pmatrix} t_L' \\ b_L' \end{pmatrix}, t_R', b_R', \begin{pmatrix} \nu_L' \\ \tau_L' \end{pmatrix}, \nu_R', \tau_R' \}
4TH GEN FERMION REVEALED BY HEAVY HIGGS

- Model: \{ \text{2HDM} + (t'_L, t'_R, b'_R, (\nu'_L, \nu'_R, \tau'_R) \}

- Motivation:

\[
\frac{g_{ggH}}{g_{ggH}^{SM}} = \frac{\kappa_t A_h^{1/2}(\tau_t) + \sum_{F} \kappa_F A_h^{1/2}(\tau_F)}{A_1^{1/2}(\tau_t)}
\]

\[
(\kappa_q = \frac{y_q}{y_q^{SM}})
\]

4TH GEN FERMION REVEALED BY HEAVY HIGGS

- **Model:** \( \{ 2\text{HDM} + (t'_L, t'_R, b'_L, b'_R, (\nu'_L, \nu'_R, \tau'_L, \tau'_R) \} \)

- **Motivation:**

- **Solution:** \( \kappa_u = 1, \quad \kappa_d = -1, \quad \delta \kappa_g \to 0 \)

\[
\frac{g_{g g H}}{g_{g g H}^{\text{SM}}} = \frac{\kappa_t A^h_{1/2}(\tau_t) + \sum_F \kappa_F A^h_{1/2}(\tau_F)}{A^h_{1/2}(\tau_t)}
\]

\[
(\kappa_q = \frac{y_q}{y_q^{\text{SM}}})
\]

4TH GEN FERMION REVEALED BY HEAVY HIGGS

- Model: \{ 2HDM + (t'_L, t'_R, b'_R, (\nu'_L, \nu'_R, \tau'_R) ) \}
- Motivation:
- Solution: \( \kappa_u = 1, \quad \kappa_d = -1, \quad \delta \kappa_g \to 0 \)

\[
\delta \kappa_{\gamma \gamma} \propto \sum_{f=t',b',\tau'} Q_f^2 N_C^f \kappa_f = 0,
\]

\[
\delta \kappa_{Z \gamma} \propto \sum_{f=t',b',\tau'} Q_f (T_3^f)_L N_C^f \kappa_f = 0,
\]

4TH GEN FERMION REVEALED BY HEAVY HIGGS

Figure: arXiv1710.10410
4TH GEN FERMION REVEALED BY HEAVY HIGGS

\[ M_i = y_i \frac{v}{\sqrt{2}} \]

2HDM

\[ \mathcal{L}_Y = y^1_{ij} \bar{\psi}_i \psi_j \Phi_1 + y^2_{ij} \bar{\psi}_i \psi_j \Phi_2 \]

\[ M_{ij} = y^1_{ij} \frac{v_1}{\sqrt{2}} + y^2_{ij} \frac{v_2}{\sqrt{2}} \]

\[ Z^2 : \delta_{ij} \]

FCNC

Figure: arXiv1710.10410
4TH GEN FERMION REVEALED BY HEAVY HIGGS

\[ M_i = y_i \frac{v}{\sqrt{2}} \]

\[ V_\Phi = m_{11}^2 \Phi_1 \dagger \Phi_1 + m_{22}^2 \Phi_2 \dagger \Phi_2 - m_{12}^2 (\Phi_1 \dagger \Phi_2 + H.c.) + \frac{1}{2} \lambda_1 (\Phi_1 \dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2 \dagger \Phi_2)^2 + \lambda_3 (\Phi_1 \dagger \Phi_1)(\Phi_2 \dagger \Phi_2) + \lambda_4 (\Phi_1 \dagger \Phi_2)(\Phi_2 \dagger \Phi_1) + \frac{1}{2} \lambda_5 [(\Phi_1 \dagger \Phi_2)^2 + H.c.] \]

\[ \Rightarrow \{ m_h, m_H, m_A, m_{H^+/-}, v, \lambda, \tan \beta, \cos \alpha \} \]
4TH GEN FERMION REVEALED BY HEAVY HIGGS

\[ M_i = y_i \frac{v}{\sqrt{2}} \]

\[ \mathcal{L}_Y = y_{ij}^1 \bar{\psi}_i \psi_j \Phi_1 + y_{ij}^2 \bar{\psi}_i \psi_j \Phi_2 \]

\[ M_{ij} = y_{ij}^1 \frac{v_1}{\sqrt{2}} + y_{ij}^2 \frac{v_2}{\sqrt{2}} \]

\[ V_\Phi = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{H.c.}) \]

\[ + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \]

\[ + \frac{1}{2} \lambda_5 \left[ (\Phi_1^\dagger \Phi_2)^2 + \text{H.c.} \right] . \]

\[ \Rightarrow \{ m_h, m_H, m_A, m_{H^\pm}, v, \lambda, \tan \beta, \cos \alpha \} \]

**Exact Wrong Sign Limit (EWS):** \[ \alpha = \frac{\pi}{2} - \beta \]

(Realized in 2HDM Type II)

**Decoupling through Alignment:** \[ \sin(\beta - \alpha) = 1 \]

\[ \beta: \text{Ratio between the VEV scale of the two scalar fields} \]

\[ \alpha: \text{Neutral Higgs mixing angle} \]

Figure: arXiv1710.10410
**4TH GEN FERMION REVEALED BY HEAVY HIGGS**

\[ M_i = y_i \frac{v}{\sqrt{2}} \]  

\[ \mathcal{L}_Y = y_{ij}^1 \bar{\psi}_i \psi_j \Phi_1 + y_{ij}^2 \bar{\psi}_i \psi_j \Phi_2 \]

\[ M_{ij} = y_{ij}^1 v_1 + y_{ij}^2 v_2 \]

2HDM scalar potential (CP-conserving):

\[ V_\Phi = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + H.c.) \]

\[ + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \]

\[ + \frac{1}{2} \lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + H.c. \right] . \]

\[ \Rightarrow \{ m_h, m_H, m_A, m_{H^+/-}, v, \lambda, \tan \beta, \cos \alpha \} \]

- **Exact Wrong Sign Limit (EWS):** \[ \alpha = \frac{\pi}{2} - \beta \]

(Realized in the type II 2HDM)

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Figure: arXiv1710.10410
4TH GEN FERMION REVEALED BY HEAVY HIGGS

\[ M_i = y_i \frac{v}{\sqrt{2}} \]

2HDM

\[ \mathcal{L}_Y = y_{ij}^1 \bar{\psi}_i \psi_j \Phi_1 + y_{ij}^2 \bar{\psi}_i \psi_j \Phi_2 \]

\[ M_{ij} = y_{ij}^1 \frac{v_1}{\sqrt{2}} + y_{ij}^2 \frac{v_2}{\sqrt{2}} \]

2HDM scalar potential (CP-conserving)

\[ V_\Phi = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + H.c.) \]

\[ + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \]

\[ + \frac{1}{2} \lambda_5 \left[ (\Phi_1^\dagger \Phi_2)^2 + H.c. \right] . \]

\[ \Rightarrow \{ m_h, m_H, m_A, m_{H^\pm}^+, v, \lambda, \tan \beta, \cos \alpha \} \]

- **Exact Wrong Sign Limit (EWS):** \( \alpha = \frac{\pi}{2} - \beta \)

  (Realized in Fig.)

- **Decoupling through Alignment:** \( \sin(\beta - \alpha) = 1 \)

- **EWS Cannot Approach Alignment** \( \Rightarrow \) Upper bound on \( M_{H, A, H^\pm} \leq 900 \) GeV

Figure: arXiv1710.10410
## 4TH GEN FERMION REVEALED BY HEAVY HIGGS

### Direct Search for the Additional Higgs

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<thead>
<tr>
<th>process</th>
<th>target</th>
<th>mass range</th>
<th>experiment</th>
</tr>
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<tbody>
<tr>
<td>$e^+e^- \rightarrow 4b, 4\tau, b\bar{b}\tau\tau$</td>
<td>$A$</td>
<td>$[2m_\tau, 100\text{ GeV}]$</td>
<td>LEP [57]</td>
</tr>
<tr>
<td>$pp \rightarrow \tau\tau$</td>
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<td>$[100\text{ GeV}, 1\text{ TeV} \newline [90\text{ GeV}, 3.2\text{ TeV}]$</td>
<td>LHC Run 1 [58, 59] \newline LHC Run 2 [60, 61]</td>
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<tr>
<td>$pp \rightarrow ZZ^{(*)}$</td>
<td>$H$</td>
<td>$[110\text{ GeV}, 1\text{ TeV}]$</td>
<td>LHC Run-2 [62–65]</td>
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![Graphs illustrating the branching ratios for different processes](image1)

![Graphs illustrating the branching ratios for different processes](image2)
4TH GEN FERMION REVEALED BY HEAVY HIGGS

- Direct Search in ZZ channel for the Additional Higgs

\[ q = \text{SM quarks} + 4\text{th Gen} \{t', b'\} \]

2HDM-4SM signal shows a large mass threshold and broad resonance peak, and constrained by LHC ZZ data

\[ t_\beta = 4, M_H = 900 \text{GeV} \]
SUMMARY & FUTURE

Discovery of the Higgs completes the SM roster, now what?

LHC at High invariant mass tail and Future Lepton Colliders:

- ZZ channel as Effective probe for Higgs (New) Physics
- ZZ or Z+(Heavy) Higgs Indirect probe of heavy particles contributing through loop