Probe Light Scalars in 2HDMs at FASER

Huayang Song

in collaboration with:

Felix Kling, Shuailong Li, Shufang Su and Wei Su

Work in progress

May 24, 2021
Light Scalars @ FASER

Many Beyond Standard Models including extended Higgs sector permit the light and weakly coupled scalars, such as Dark Higgs (SM+Singlet), 2HDM, NMSSM, ....

Simplest prototype model: Dark Higgs

\[ \mathcal{L} = -m_\phi^2 \phi^2 - \sin \theta \frac{m_f}{v} \phi \bar{f} f - \lambda v h \phi \phi + \ldots \]
Two Higgs Doublet Model

- Many Beyond Standard Models include extended Higgs sector permit the light and weakly coupled scalars, such as Dark Higgs (SM+Singlet), 2HDM, NMSSM, ...

- The Two-Higgs Doublet Model (2HDM) is another prototype model which contains two Higgs doublets

- The 2HDM contains five Higgs states:

\[ h, H, A, H^\pm \]

- \( H \) and \( A \) are the CP-even and CP-odd neutral Higgses in the 2HDM that are allowed to be light and weakly coupled.

- Richer parameters \( m_H, m_A, m_{H^\pm}, \cos(\beta - \alpha), \tan\beta \)

- Couplings near the alignment limit \( \cos(\beta - \alpha) \sim 0 \)

<table>
<thead>
<tr>
<th>Type</th>
<th>( g_{uu} )</th>
<th>( g_{dd} )</th>
<th>( g_{ll} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-I</td>
<td>( \cot\beta )</td>
<td>( \cot\beta )</td>
<td>( \cos\beta )</td>
</tr>
<tr>
<td>Type-II</td>
<td>( \cot\beta )</td>
<td>( \tan\beta )</td>
<td>( \tan\beta )</td>
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<tr>
<td>Type-L</td>
<td>( \cot\beta )</td>
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<td>Type-F</td>
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</tbody>
</table>

\[ g_{HVV} \sim \cos(\beta - \alpha) \]

- In Type-I, neutral scalars \( H/A \) are weakly coupled when \( \tan\beta \) is large

- Those scalars can escape the detection at the ATLAS/CMS, but are suitable for FASER
constraints on Parameter Space

- Theoretical Constraints
  - Perturbativity
  - Unitarity
  - Vacuum Stability
- Electroweak precision measurement
  - Oblique parameters: S, T, U
    - For $m_H \sim 0$, $m_A \sim m_H^\pm < 600 \text{ GeV}$
    - For $m_A \sim 0$, $m_H \sim m_H^\pm < m_h$
- Flavor Physics Constraints
  - Set limits on $\tan \beta$ and $m_{H^\pm}$
  - $\tan \beta$ is unbounded from above in Type-I
- Invisible Higgs decay

\[
\text{Br}(h \to HH) \approx \frac{1}{\Gamma_h^{\text{SM}} \frac{g_{H^HH}^2}{8\pi m_h^2}} \left(1 - \frac{4m_h^2}{m_h^2}\right)^{\frac{1}{2}} \approx 4700 \left(\frac{g_{H^HH}}{v}\right)^2
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\[
g_{H^HH} \approx -\frac{s_\beta-a}{2v} m_h^2 s_\beta-a c_\beta-a \left[\left(t_\beta-a - \frac{1}{t_\beta-a}\right) + \left(t_\beta - \frac{1}{t_\beta}\right)\right]
\]

For $c_\beta-a \sim 0$, $t_\beta \approx c_\beta-a$ can give a suppressed $g_{H^HH}$

- $\text{Br}(h \to HH) < 0.24 \implies t_\beta > 4$

arXiv: 1610.09218
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  \[ \max\{\tan \beta, \cot \beta\} \approx \sqrt{8\pi v^2/(3\lambda v^2)} \]
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\[\text{arXiv: 1610.09218}\]
**Light CP-even Higgs H Decay**

- We calculate the scalar decay width in the very low mass regime
  - \(m_H < 1.3\) GeV: Dispersive analysis
  - \(1.3\) GeV < \(m_H < 2\) GeV: Dispersive analysis+\(\Gamma_{4\pi,\eta,\rho,\ldots}\)
  - \(m_H > 2\) GeV: Perturbative partonic model

- A wide range of extremely large \(\tan \beta\) that can hardly be reached at the LHC will be sensitive @ FASER.
Light CP-even Higgs $H$ Decay

- We calculate the scalar decay width in the very low mass regime $\sqrt{s} < 1.3$ GeV:
  - Dispersive analysis $\sqrt{s} > 1.3$ GeV $< 2$ GeV: Dispersive analysis + $\Gamma(m)$,
  - Perturbative spectator model $\sqrt{s} > 2$ GeV:

- A wide range of extremely large $\tan \beta$ that can hardly be reached at the LHC will be sensitive @ FASER.
**Light CP-odd Higgs $A$ Decay**

- We calculate the scalar decay width in the very low mass regime
  - $m_A < 1.3$ GeV: Chiral Lagrangian
  - $1.3$ GeV $< m_H < 3$ GeV: Spectator Model
  - $m_H > 3$ GeV: Perturbative partonic decay
- The all-around sharp peaks and dips are caused by the $A$-meson mixing
- A wide range of extremely large $\tan \beta$ that can hardly be reached at the LHC will be sensitive @ FASER.
Light CP-odd Higgs $A$ Decay

- We calculate the scalar decay width in the very low mass regime $\tilde{m}_A < 1.3$ GeV:
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- A wide range of extremely large $\tan \beta$ that can hardly be reached at the LHC will be sensitive at FASER.
Explore Beyond the (Type-1) 2HDM

- We build a code that is able to handle
  - Both CP-even and CP-odd light scalar decays and productions
  - All kinds of scalar couplings: four types of 2HDMs, dark (pseudo)scalar, general scalar models with extra particles
  - Full low mass regime with g
  - t calculations

- We are exploring the NMSSM (2HDM + Singlet) @ FASER
  - Richer parameter space to explore
  - More particles involved in neutral scalar decay, e.g. charginos, sfermions

- We will make the code public for further studies on long-lived light scalars at other experiments. Contact us if interested.
Summary

- **Type-I 2HDM** allows the light and weakly coupled CP-even and CP-odd neutral Higgs states at large $\tan \beta$.
- **FASER** will be suitable for searching the light weakly coupled scalars (like in **Type-I 2HDM**) that can hardly be reached at the LHC.
- We build a **code** that is able to handle the CP-even and CP-odd light scalar decays and productions in the **most general models**.
- We will continue to explore models beyond the 2HDM @ FASER, such as the **NMSSM**.
Backup
Production channels of Light Scalars

- **Semi-leptonic Pion and Kaon Decay** \( \pi/K \rightarrow \ell\nu\phi \)
- **Kaon Decays**
- **Meson Decays**
  - **D-meson Decays** \( K/D/B \rightarrow X\phi \)
  - **B-meson decays**
- **Eta Decays** \( \eta \rightarrow \pi\phi, \eta' \rightarrow \eta\phi \)
- **Bottomonium Decays** \( \Upsilon \rightarrow \gamma\phi \)
- **Scalar Bremsstrahlung**
- **Weak Decays** \( h \rightarrow \phi\phi, Z \rightarrow HA, W \rightarrow HH^\pm \)
Production channels of Light Scalars

Effective Lagrangian of flavor changing quark interactions with the scalar $\phi$ particle

$$\mathcal{L}_{\text{eff}} = \frac{\phi}{v} \sum_{ij} \xi^{ij}_\phi m_{f_j} \bar{f}_i P_R f_j + h.c.$$