# Probe Light Scalars in 2HDMs at FASER

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**in collaboration with:**

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**Work in progress**

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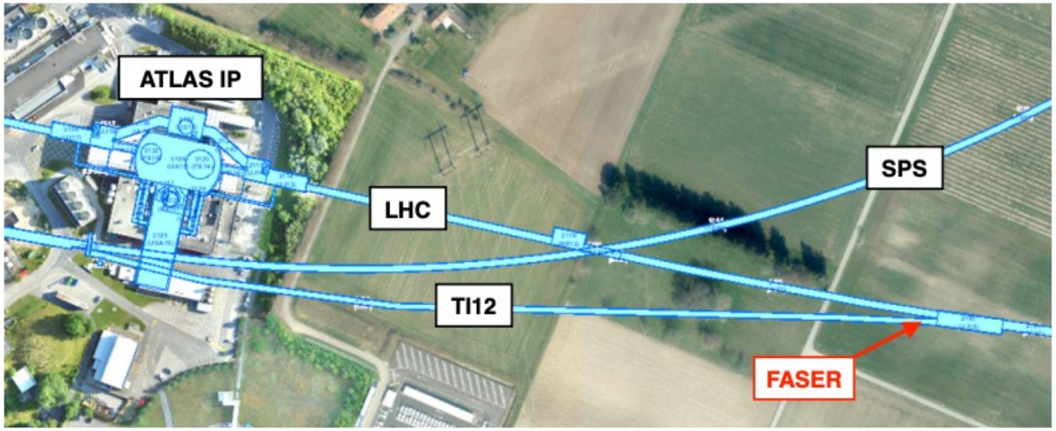
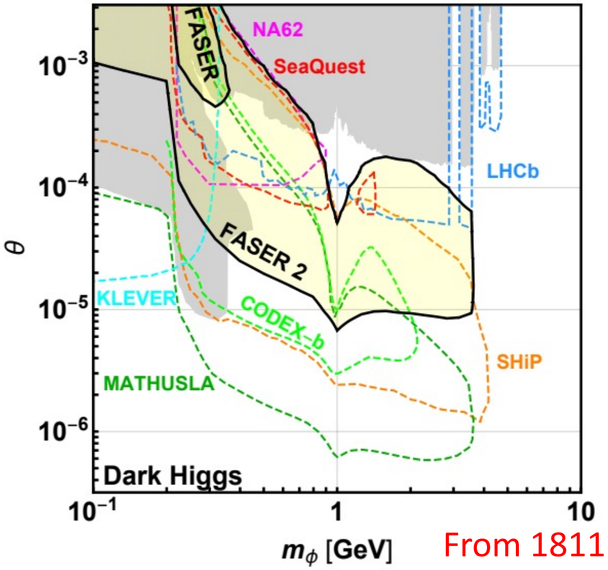
# Light Scalars @ FASER

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

$$\mathcal{L} = -m_\phi^2 \phi^2 - \sin\theta \frac{m_f}{v} \phi \bar{f} f - \lambda v h \phi \phi + \ldots$$




From 1811.12522

# 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 scontains two Higgs doublets

- The 2HDM contains five Higgs states:

125 GeV SM Higgs → $h$, $H$, $A$, $H^{\pm}$

- 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 $\cos(\beta-\alpha) \sim 0$

| | $g_{uu}^{H/A}$ | $g_{dd}^{H/A}$ | $g_{\ell\ell}^{H/A}$ |
|---|---|---|---|
| Type-I | $\cot\beta$ | $\cot\beta$ | $\cot\beta$ |
| Type-II | $\cot\beta$ | $\tan\beta$ | $\tan\beta$ |
| Type-L | $\cot\beta$ | $\cot\beta$ | $\tan\beta$ |
| Type-F | $\cot\beta$ | $\tan\beta$ | $\cot\beta$ |

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

- 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 $m_H \sim 0$, $m_A \sim m_{H^\pm} < 600$ 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 β is unbounded from above in Type-I
- **Invisible Higgs decay**

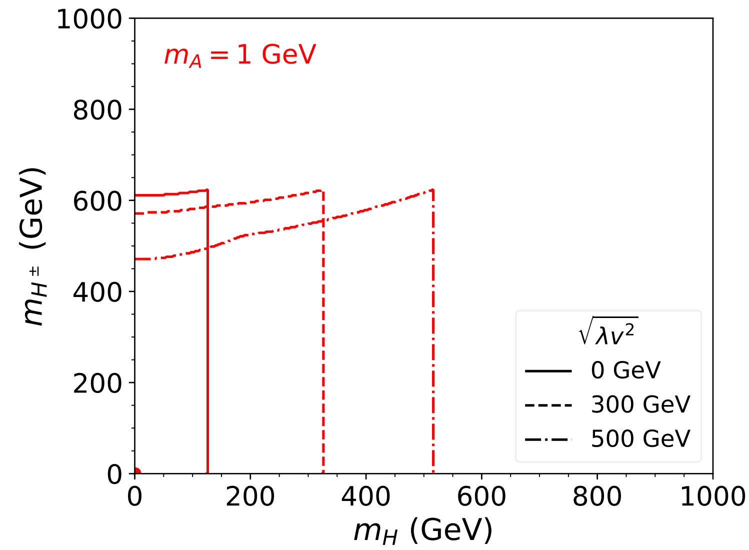
$$\mathrm{Br}(h \to HH) \approx \frac{1}{\Gamma_h^{\rm SM}} \frac{g_{hHH}^2}{8\pi m_h^2}\left(1-\frac{4m_H^2}{m_h^2}\right)^{\frac{1}{2}} \simeq 4700\left(\frac{g_{hHH}}{v}\right)^2$$

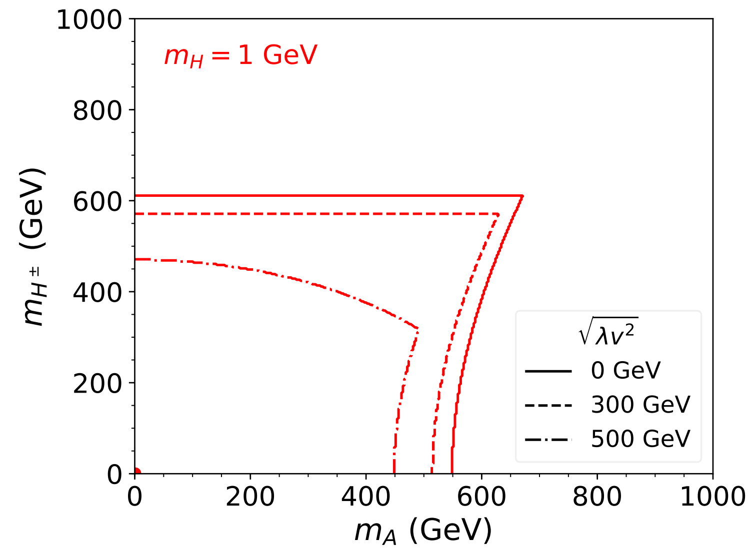
$$g_{hHH} \simeq -\frac{s_{\beta-\alpha} m_h^2}{2v} s_{\beta-\alpha} c_{\beta-\alpha}\left[\left(t_{\beta-\alpha}-\frac{1}{t_{\beta-\alpha}}\right)+\left(t_\beta-\frac{1}{t_\beta}\right)\right]$$

For $c_{\beta-\alpha} \sim 0, t_\beta \approx c_{\beta-\alpha}$ can give a suppressed $g_{hHH}$

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

arXiv: 1610.09218



# Constraints on Parameter Space

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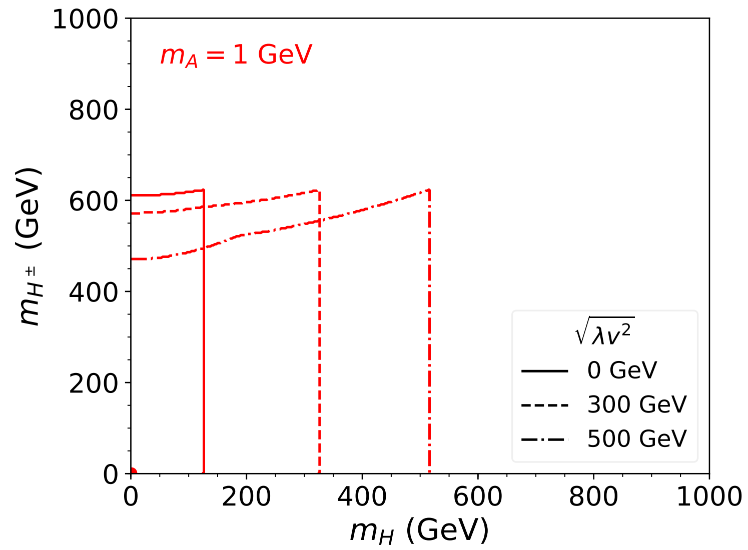


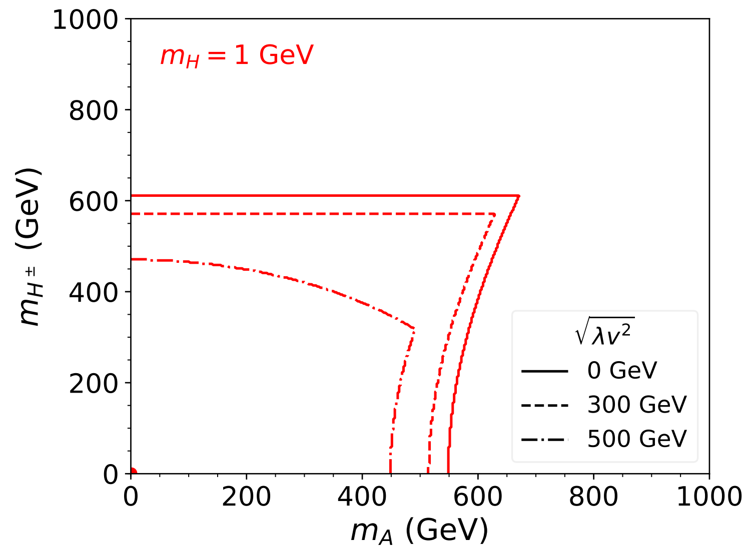

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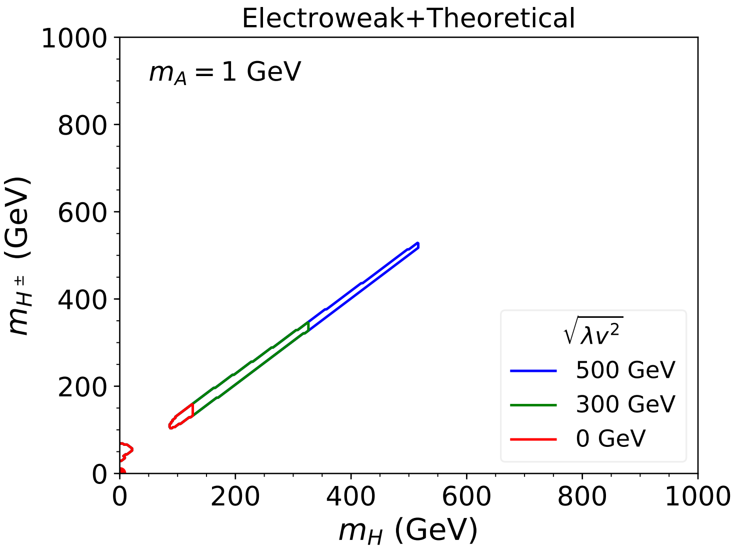


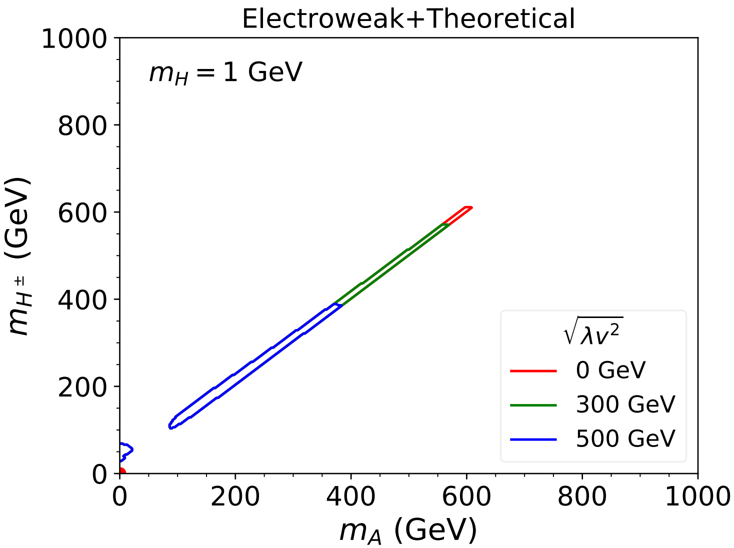

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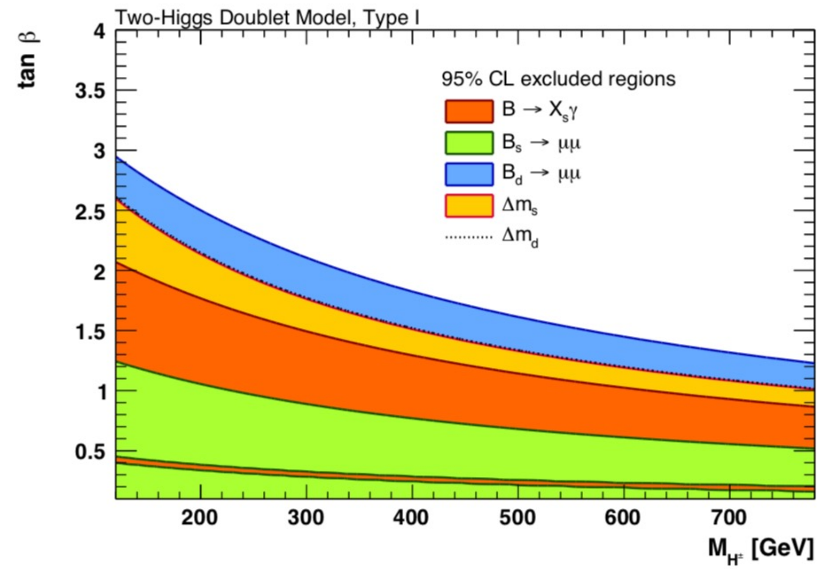
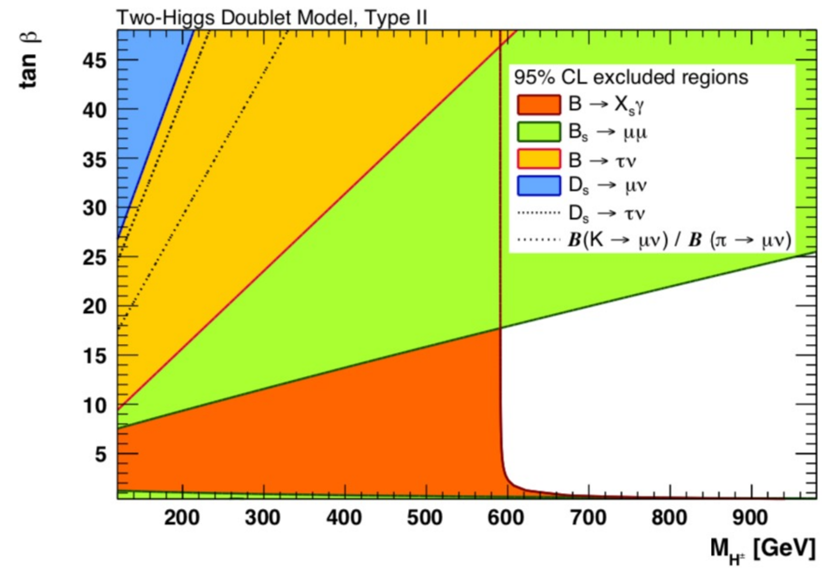
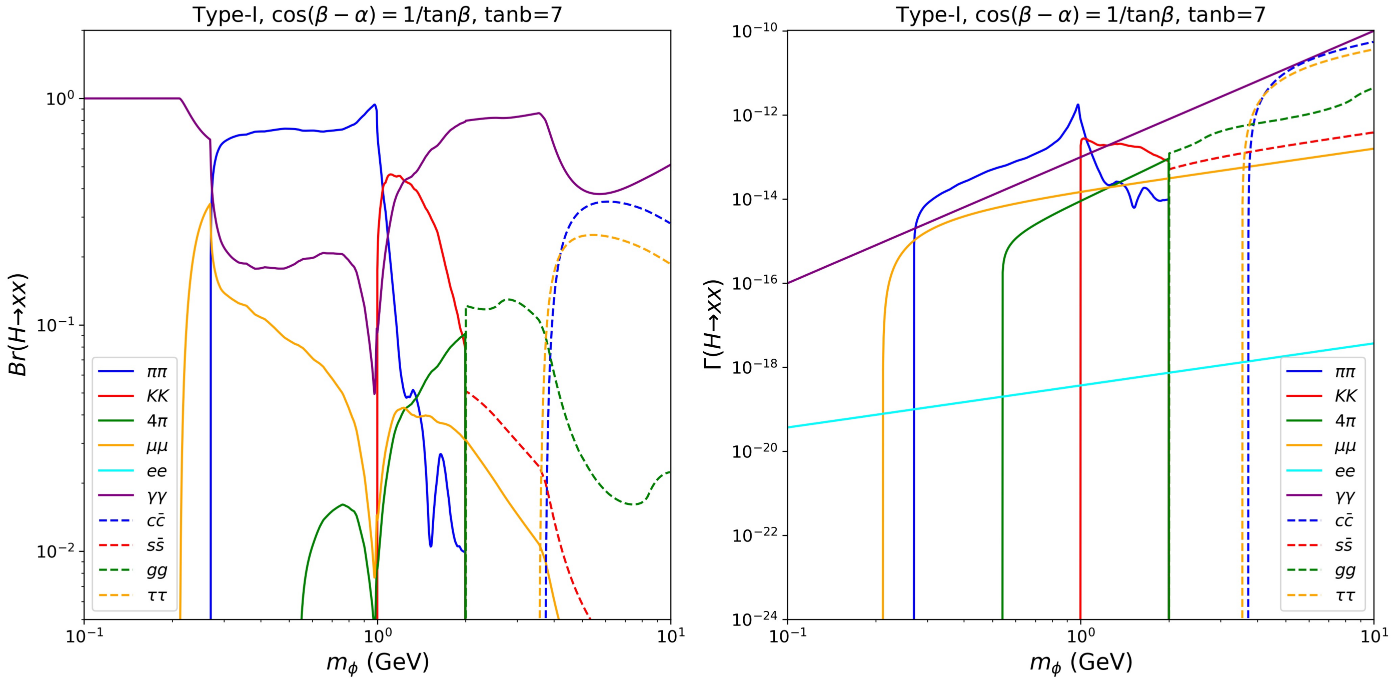


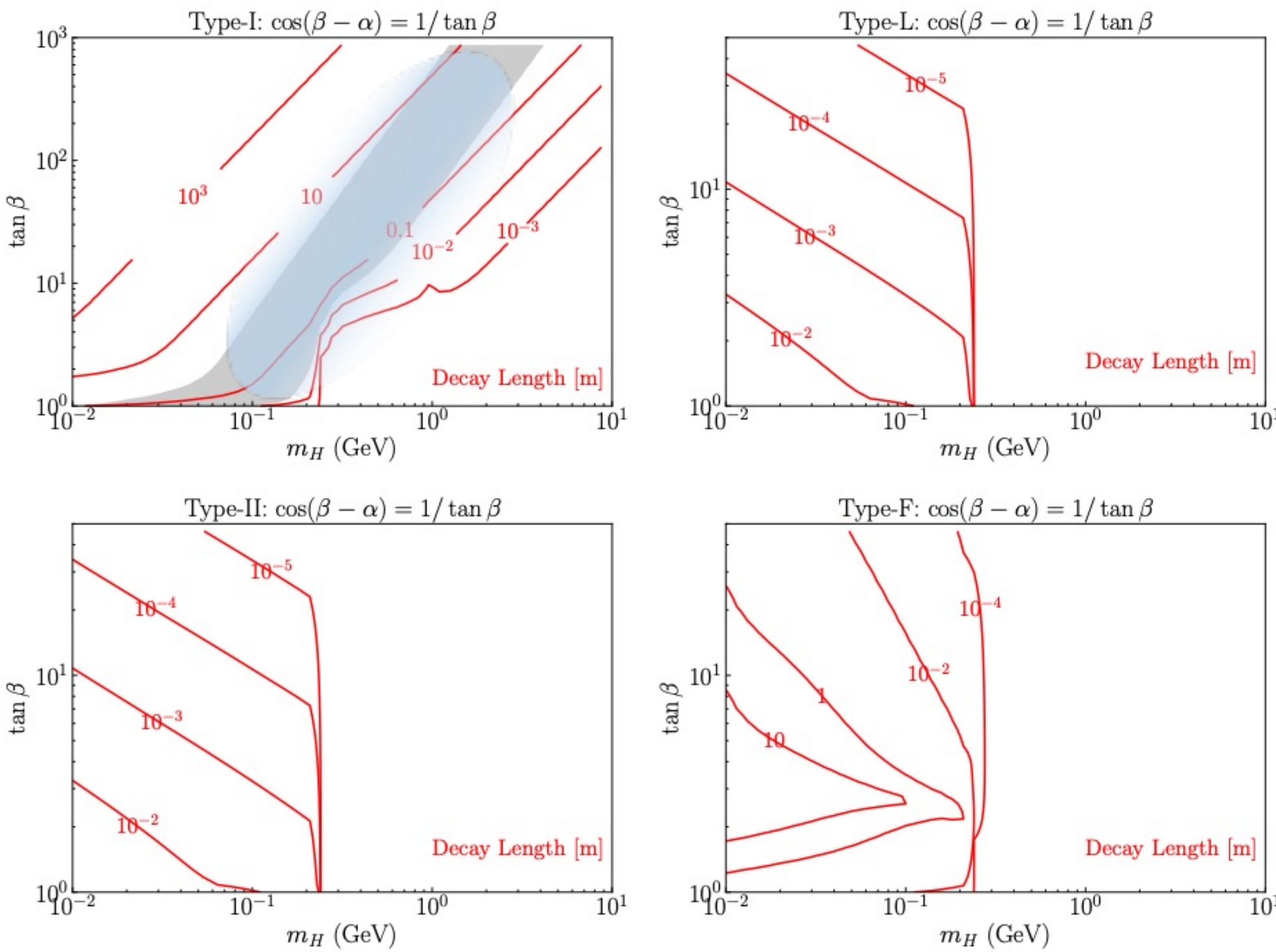
# Light CP-even Higgs H Decay




- 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+$\Gamma_{4\pi,\eta\eta,\rho\rho,\cdots}$
  - $m_H$>2 GeV: Perturbative partonic model

- A wide range of extremely large tan β that can hardly be reached at the LHC will be sensitive @ FASER.

# Light CP-even Higgs H Decay

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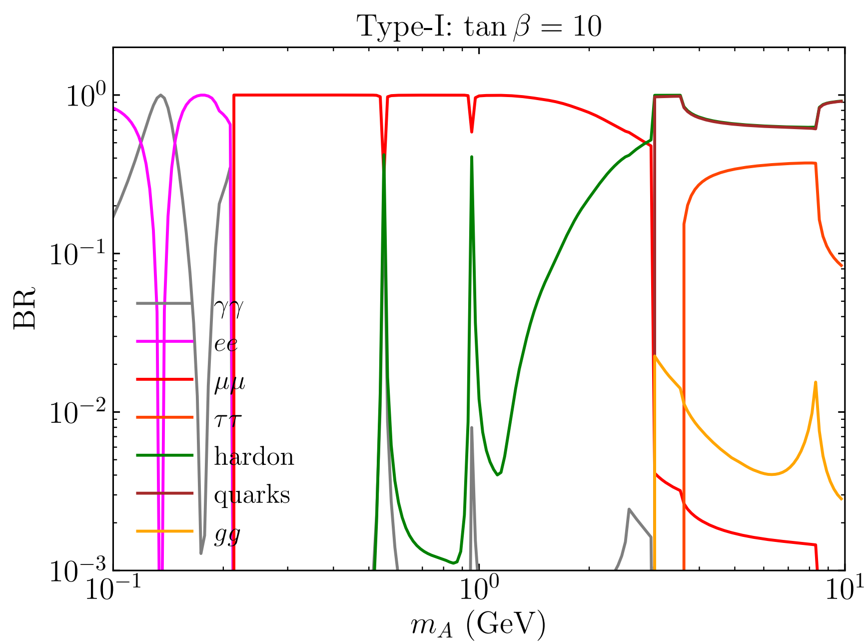
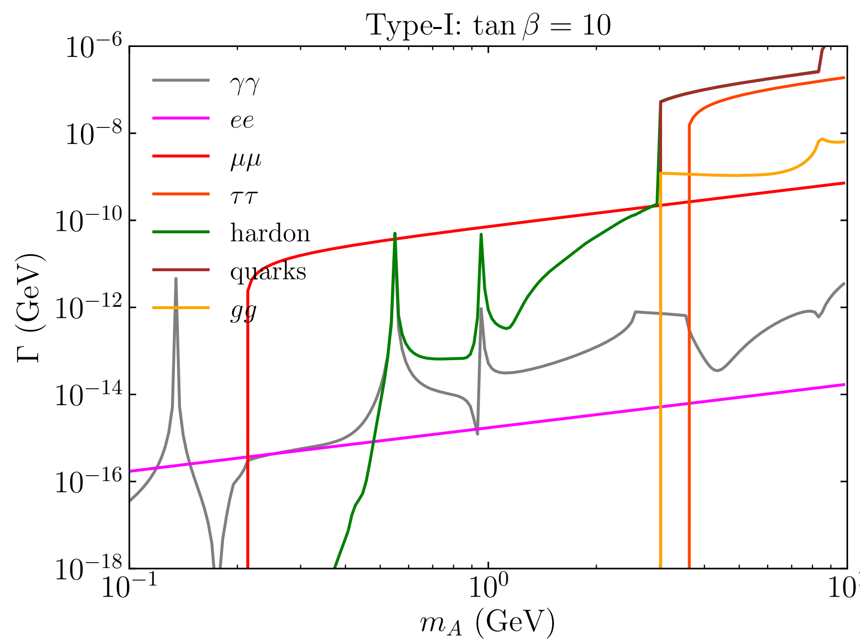
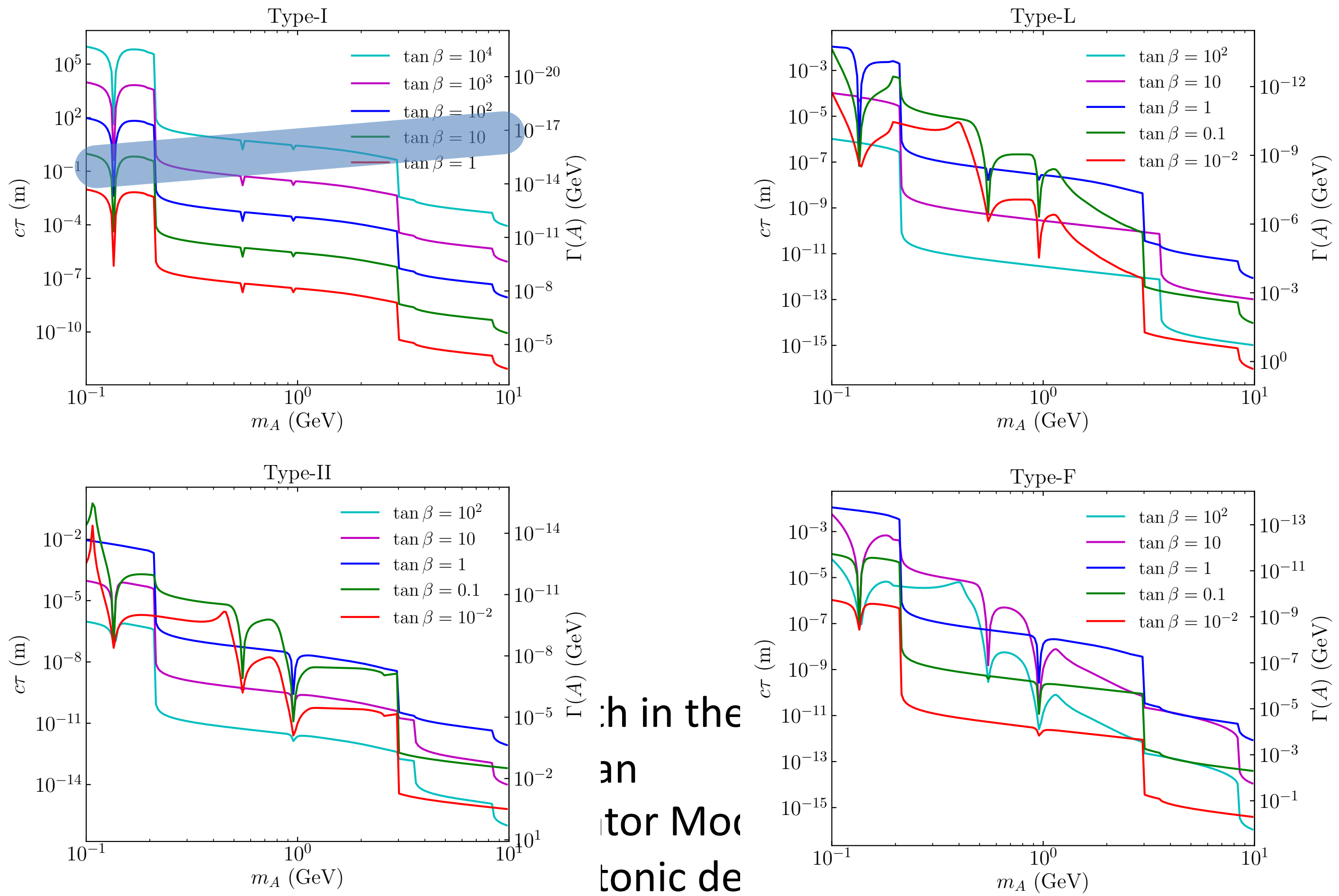
# Light CP-odd Higgs A Decay




- 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 β that can hardly be reached at the LHC will be sensitive @ FASER.

# Light CP-odd Higgs *A* Decay




- W … h in the … an … tor Mo … tonic de
- The all-around sharp peaks and dips are caused by the *A*-meson mixing
- A wide range of extremely large tan β that can hardly be reached at the LHC will be sensitive @ FASER.

# Explore Beyond the (Type-I) 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

CP-even

$$\mathcal{L}_\phi = -\frac{1}{2}m_\phi^2\phi^2 - \sum_f \xi_\phi^f \frac{m_f}{v}\phi\bar{f}f - \xi_\phi^W \frac{2m_W^2}{v}\phi W^{\mu+}W_\mu^- -\xi_\phi^Z\frac{m_Z^2}{v}\phi Z^\mu Z_\mu + \xi_\phi^g \frac{\alpha_s}{12\pi}\frac{\phi}{v}G_{\mu\nu}^a G^{a\mu\nu} + \xi_\phi^\gamma \frac{\alpha}{4\pi}\frac{\phi}{v}F_{\mu\nu}F^{\mu\nu} + \sum_S \lambda_{\phi SS}\phi S^+ S^-.$$

CP-odd

$$\mathcal{L}_A = -\frac{1}{2}m_A^2 A^2 + \sum_{f=u,d,e}\frac{im_f}{v}\xi_A^f \bar{f}\gamma_5 f A + \xi_A^g \frac{\alpha_s}{4\pi}\frac{A}{v}G_{\mu\nu,a}\tilde{G}^{\mu\nu,a} + \xi_A^\gamma \frac{\alpha}{4\pi}\frac{A}{v}F_{\mu\nu}\tilde{F}^{\mu\nu}.$$

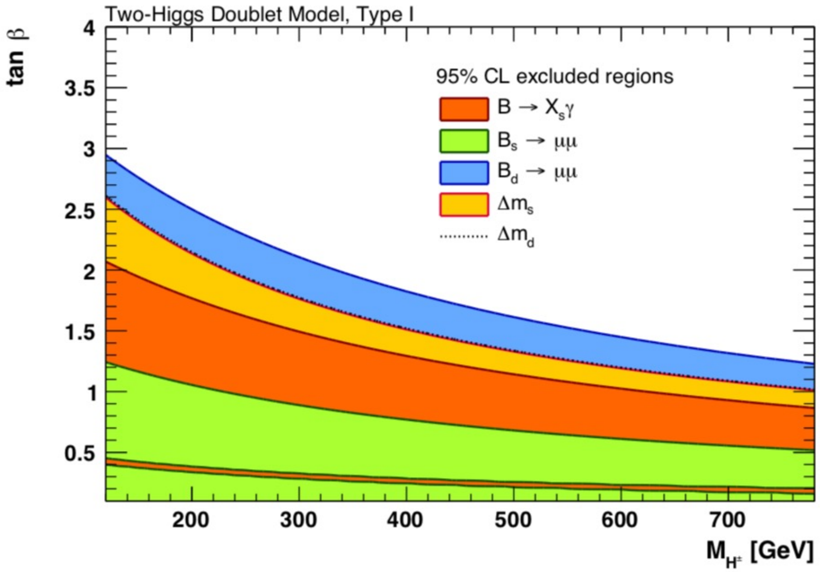
- We are exploring the NMSSM (2HDM + Singlet) @ FASER
  - Richer parameter space to explore
  - More particles involved in neutral scalar decay, e.g. charginos, sfermions

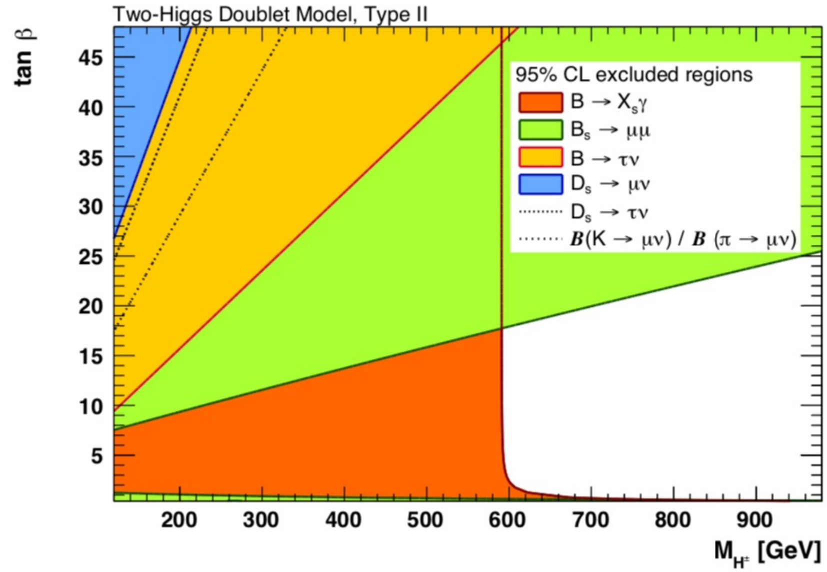
- We will make the code public for further studies on long-lived light scalars at other experiments. Contact us if interested.

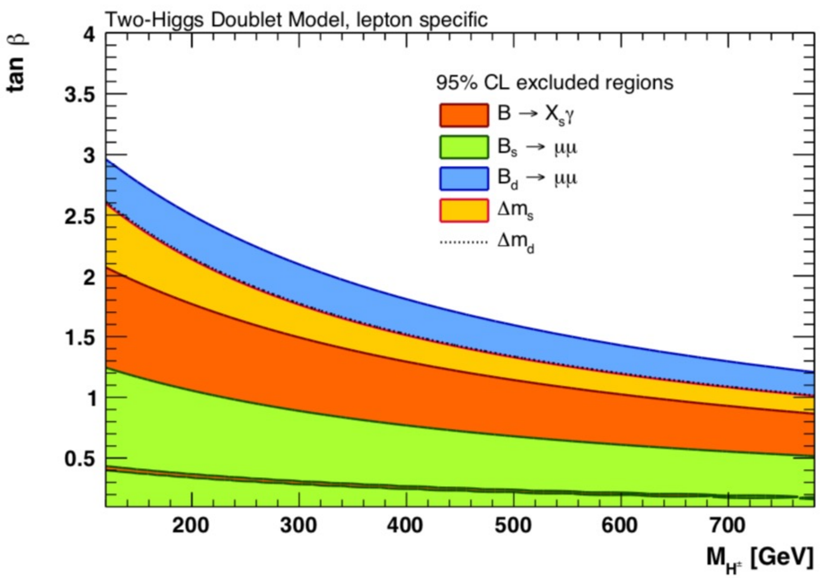
# Summary

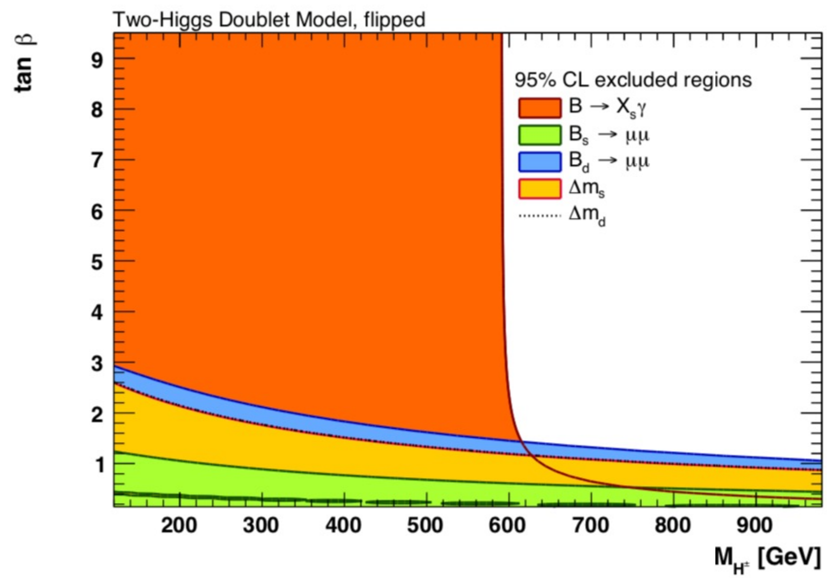
- Type-I 2HDM allows the light and weakly coupled CP-even and CP-odd neutral Higgs states at large $\tan\beta$.
- FASER will be suitable for searching the light weakly coupled scalars (like in Type-I 2HDM ) that can hardly be reached at the LHC.
- We build a code that is able to handle the CP-even and 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


Two-Higgs Doublet Model, Type I
95% CL excluded regions
B → X_sγ
B_s → μμ
B_d → μμ
Δm_s
Δm_d
tan β
M_H± [GeV]
0.5
1
1.5
2
2.5
3
3.5
4
200
300
400
500
600
700


Two-Higgs Doublet Model, Type II
95% CL excluded regions
B → X_sγ
B_s → μμ
B → τν
D_s → μν
D_s → τν
B(K → μν) / B (π → μν)
tan β
M_H± [GeV]
5
10
15
20
25
30
35
40
45
200
300
400
500
600
700
800
900


Two-Higgs Doublet Model, lepton specific
95% CL excluded regions
B → X_sγ
B_s → μμ
B_d → μμ
Δm_s
Δm_d
tan β
M_H± [GeV]
0.5
1
1.5
2
2.5
3
3.5
4
200
300
400
500
600
700


Two-Higgs Doublet Model, flipped
95% CL excluded regions
B → X_sγ
B_s → μμ
B_d → μμ
Δm_s
Δm_d
tan β
M_H± [GeV]
1
2
3
4
5
6
7
8
9
200
300
400
500
600
700
800
900

# Production channels of Light Scalars

- Semi-leptonic Pion and Kaon Decay $\pi/K \longrightarrow \ell\nu\phi$
- Meson Decays
  - Kaon Decays
  - D-meson Decays
  - B-meson decays

  $K/D/B \longrightarrow X\phi$
- Eta Decays $\eta \longrightarrow \pi\phi, \eta' \longrightarrow \eta\phi$
- Bottomonium Decays $\Upsilon \longrightarrow \gamma\phi$
- Scalar Bremsstrahlung
- Weak Decays $h \longrightarrow \phi\phi, Z \longrightarrow HA, W \longrightarrow HH^{\pm}$

# Production channels of Light Scalars

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

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