第三届地下和空间粒子物理与宇宙物理前沿问题研讨会，西昌，2024

The neutral scalars to Dark matter under the LHC

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2212.06186（F. Kling， S. Li, S. Su, H.Song, WS ）
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outline

- Brief introduction
- 2HDMS scenarios
- IDM at LHC era
- Summary

Brief Introduction

- Two Higgs Doublet Model

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + iG_i)/\sqrt{2} \end{pmatrix}$$

$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$$
$$\tan\beta = v_u/v_d$$

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \quad \begin{aligned} A &= -G_1 \sin\beta + G_2 \cos\beta \\ H^\pm &= -\phi_1^\pm \sin\beta + \phi_2^\pm \cos\beta \end{aligned}$$

	Φ_1	Φ_2
Type I	u,d,l	
Type II	u	d,l
lepton-specific	u,d	l
flipped	u,l	d

- Parameters (CP-conserving, Flavor Limit, Z_2 Symmetry)

$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$ → $v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$

Soft Z_2 symmetry breaking: m_{12}^2

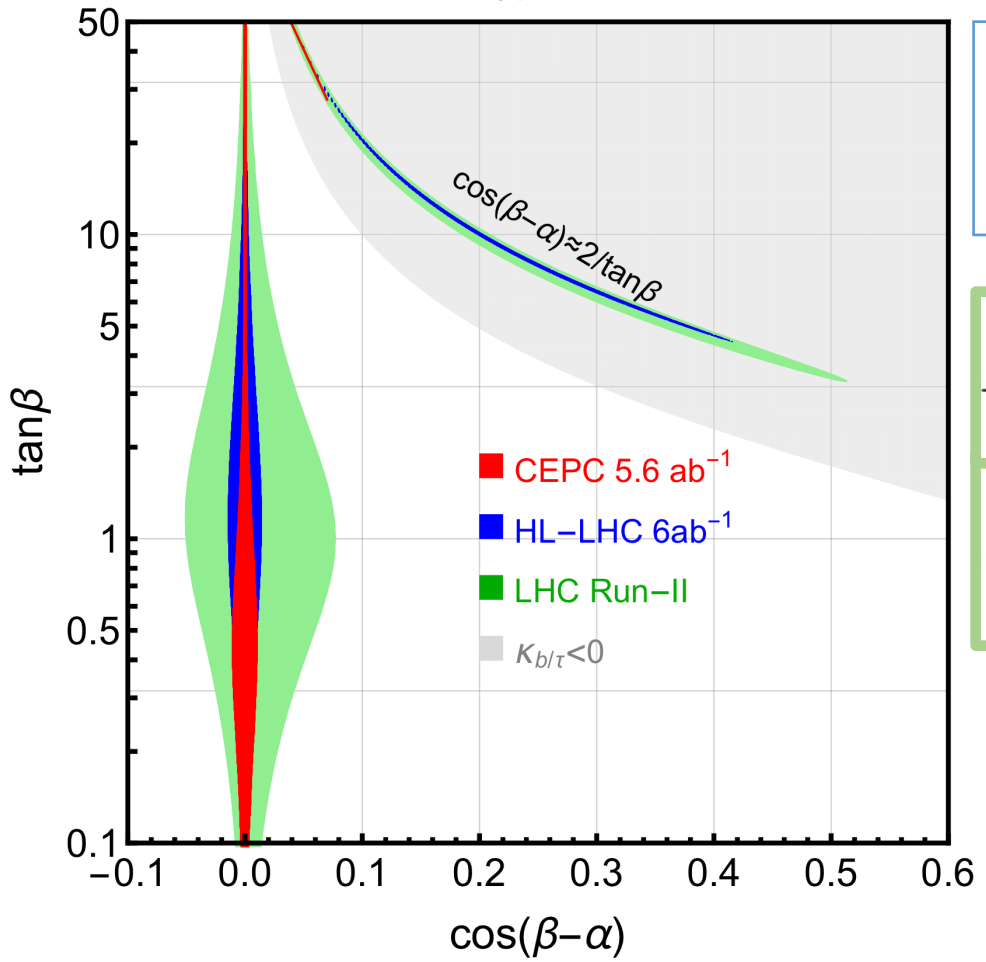
246 GeV

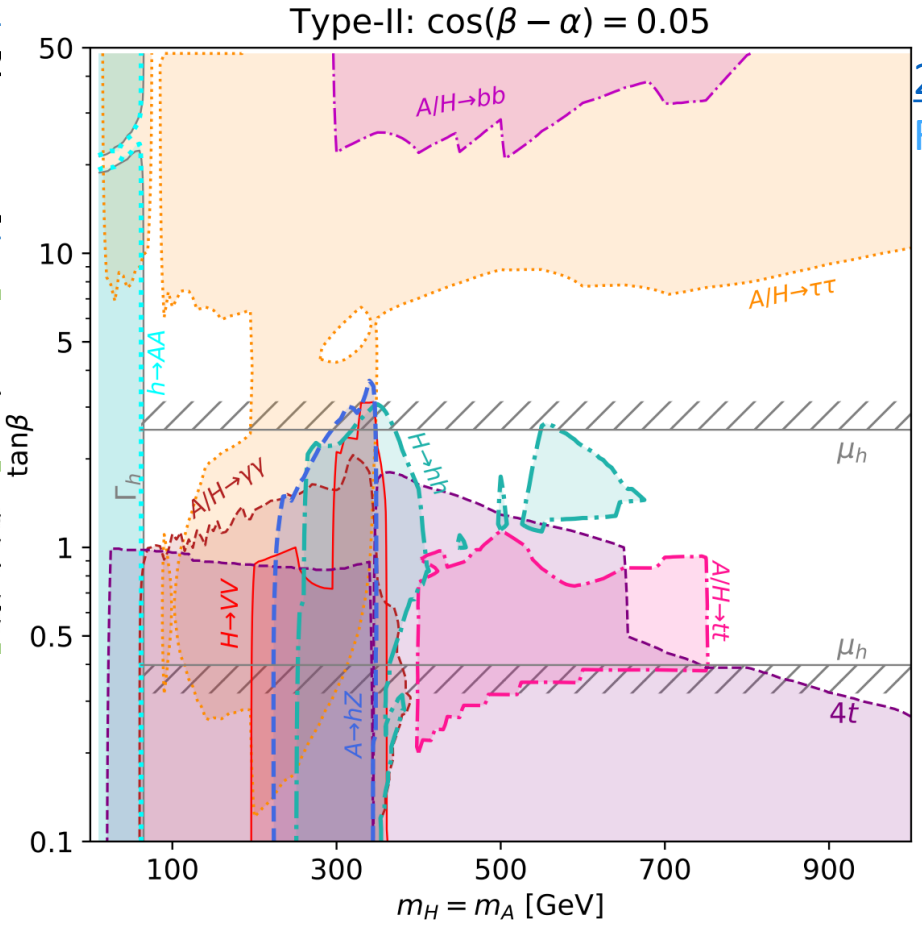
125. GeV

Brief Introduction

Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

2HDM Type-II





2004.04172
F. Kling, S. Su, WS

$\alpha) \times \tan\beta$

$\alpha)$

Brief Introduction： 2HDM => DM ?

- ✓ SUSY
- ✓ IDM
- ✓ 2HDM+ DM => 2HDMS
- ✓ …

2HDM+singlet

$$
\begin{aligned}
V = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\
& + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} \left((\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right) \\
& + m_S^2 S^\dagger S + \frac{m_S'^2}{2} (S^2 + \text{h.c.}) + \left(\frac{\mu_{S1}}{3!} S^3 + \mu_{12} S \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) \\
& + S^\dagger S \left(\lambda_1' (\Phi_1^\dagger \Phi_1) + \lambda_2' (\Phi_2^\dagger \Phi_2) \right) + \left[S^2 \left(\lambda_4' (\Phi_1^\dagger \Phi_1) + \lambda_5' (\Phi_2^\dagger \Phi_2) \right) + \text{h.c.} \right] \\
& + \left(\frac{\lambda_1''}{4!} S^4 + \frac{\lambda_2''}{3!} S^2 (S^\dagger S) + \text{h.c.} \right) + \frac{\lambda_3''}{4} (S^\dagger S)^2 .
\end{aligned}
$$

Models	Symmetries	
$\mathbb{Z}_2'$[11]	$S \to -S$	$\mu_{S1} = \mu_{12} = 0$
U(1)[17]	$S \to e^{i\delta} S$	$\lambda_1'' = \lambda_2'' = \lambda_4' = \lambda_5' = \mu_{S1} = \mu_{12} = 0$
$\mathbb{Z}_3$[18]	$\Phi_2 \to e^{i2\pi/3} \Phi_2, \ S \to e^{-2i\pi/3} S$	$\lambda_5 = m_S' = \lambda_1'' = \lambda_2'' = \lambda_4' = \lambda_5' = 0$

Table 1. Matching conditions to various singlet extended 2HDM

2HDM+singlet

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\alpha_3} & s_{\alpha_3} \\ 0 & -s_{\alpha_3} & c_{\alpha_3} \end{pmatrix} \begin{pmatrix} c_{\alpha_2} & 0 & s_{\alpha_2} \\ 0 & 1 & 0 \\ -s_{\alpha_2} & 0 & c_{\alpha_2} \end{pmatrix} \begin{pmatrix} c_{\alpha_1} & s_{\alpha_1} & 0 \\ -s_{\alpha_1} & c_{\alpha_1} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

SM – singlet

Non-SM – singlet

Doublet mixing

SM limit of 2HDMS

$$\cos(\beta - \alpha_1) = 0, \;\; \alpha_3 = 0.$$

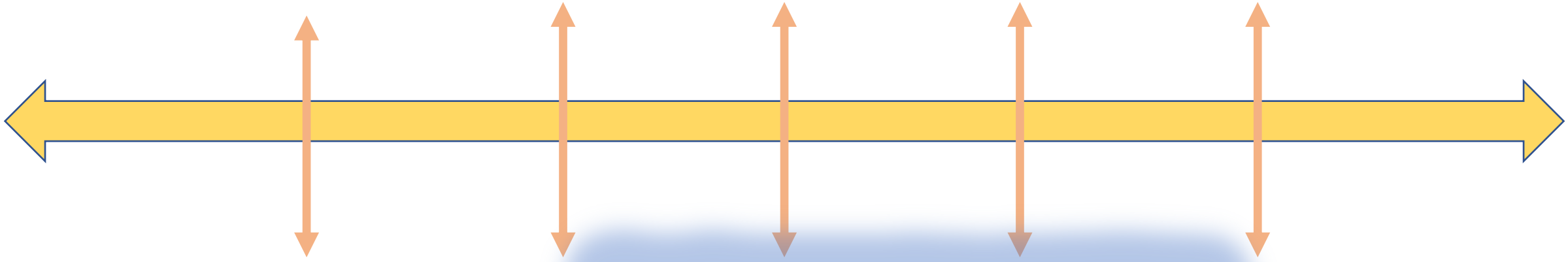
$$R^A = \begin{pmatrix} c_{\alpha_4} & s_{\alpha_4} \\ -s_{\alpha_4} & c_{\alpha_4} \end{pmatrix}$$

A - A_S

2HDM limit of 2HDMS

$$\alpha_2 = \alpha_3 = \alpha_4 = 0$$

Scenarios



Mass hierarchy

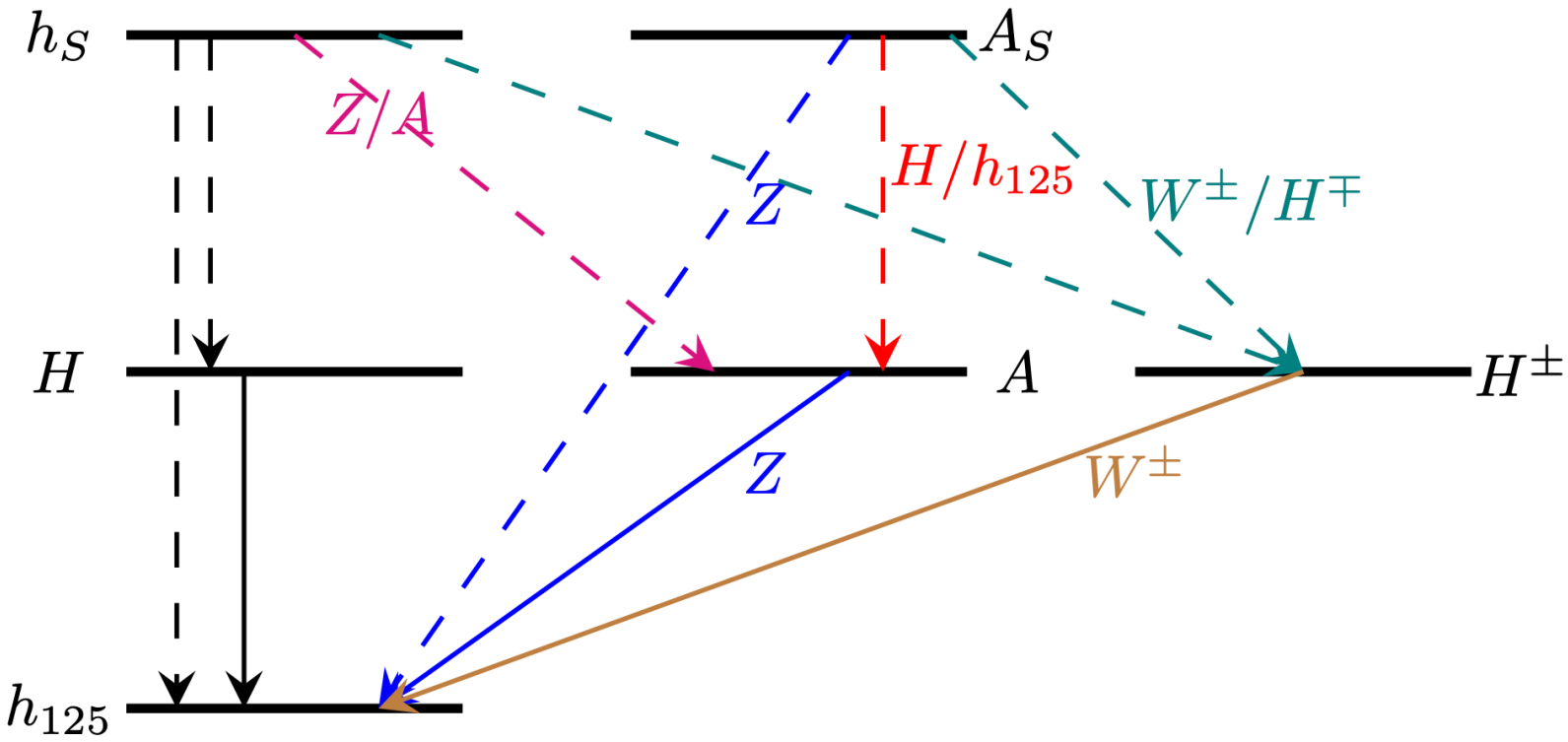
- $m_{h_S} < 0.1$ GeV
- 0.1 GeV$< m_{h_S} <$ 10 GeV
- 10 GeV $< m_{h_S} <$ 62.5 GeV
- 62.5 GeV $< m_{h_S} <$ 1 TeV
- 1 TeV $< m_{h_S} <$ 10TeV
- 10 TeV $< m_{h_S}$

LHC era

2HDM+singlet: Higgs sector

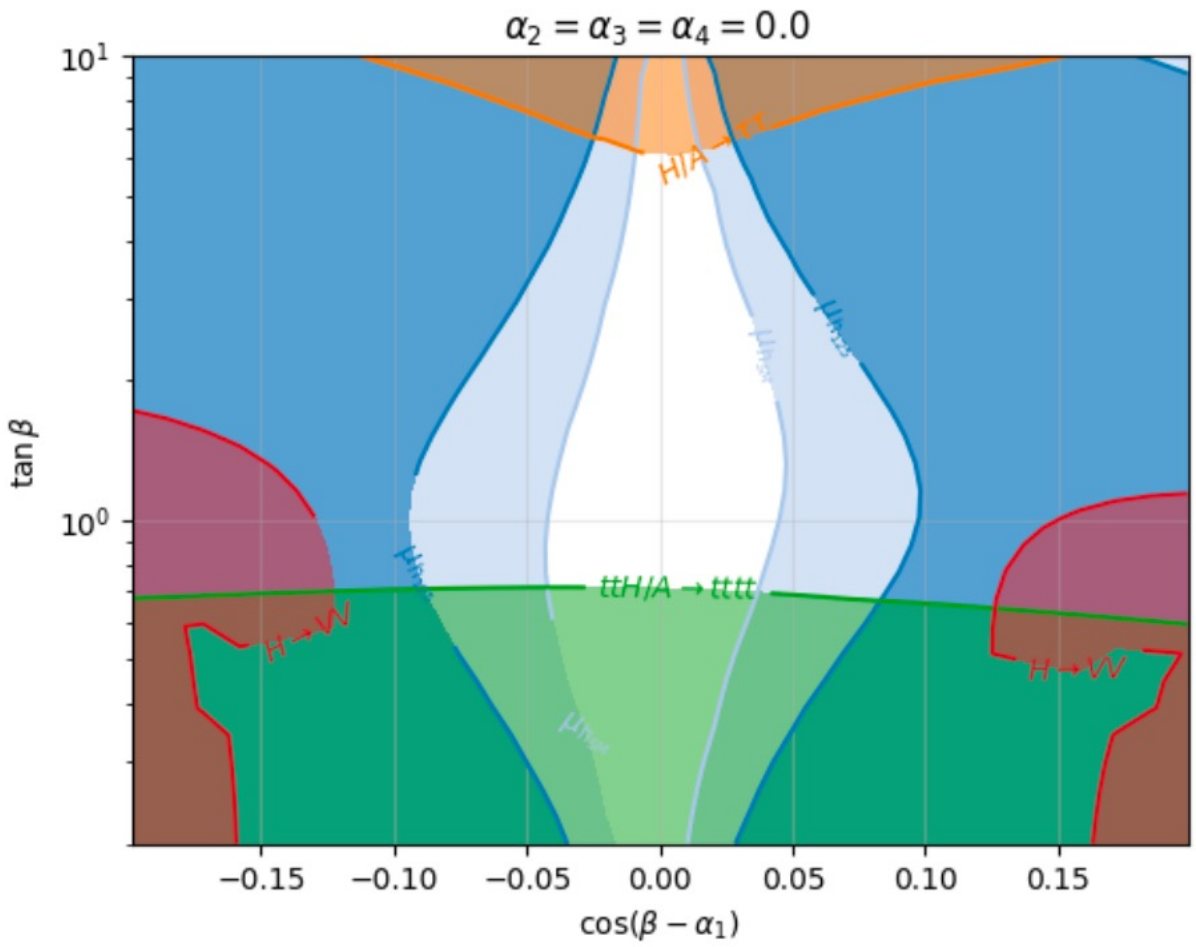
- The scenario with heavier singlet Higgs

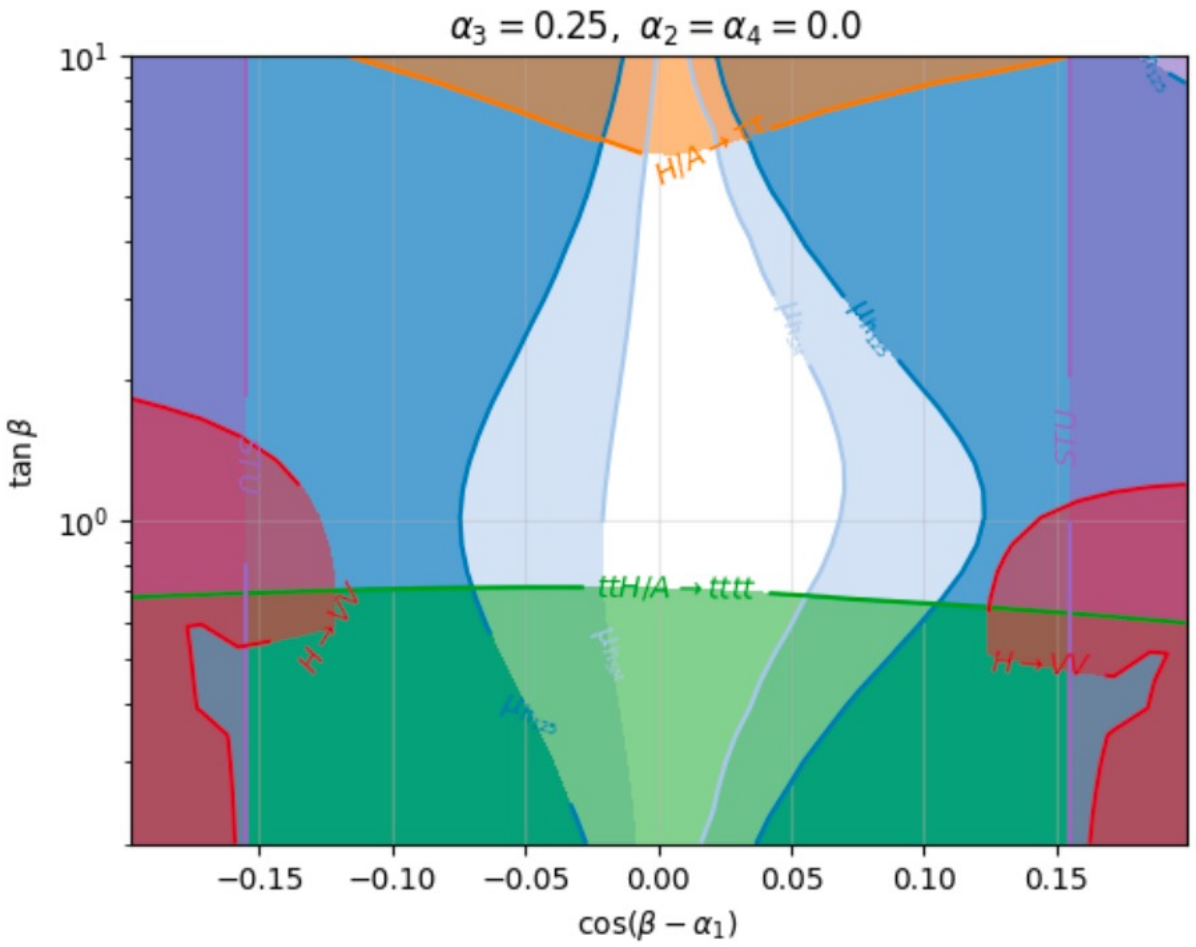
Type-II like 2HDMS



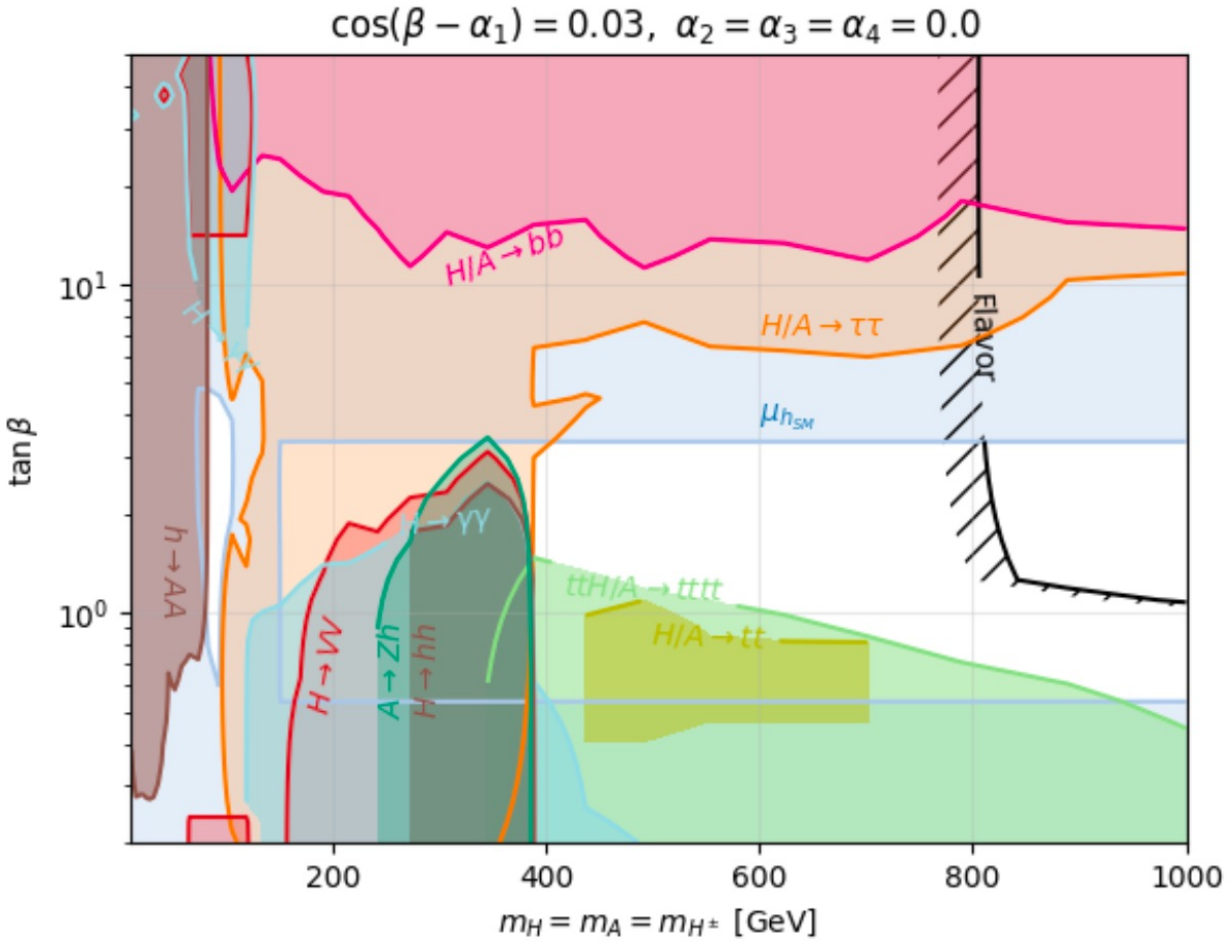
2HDM+singlet

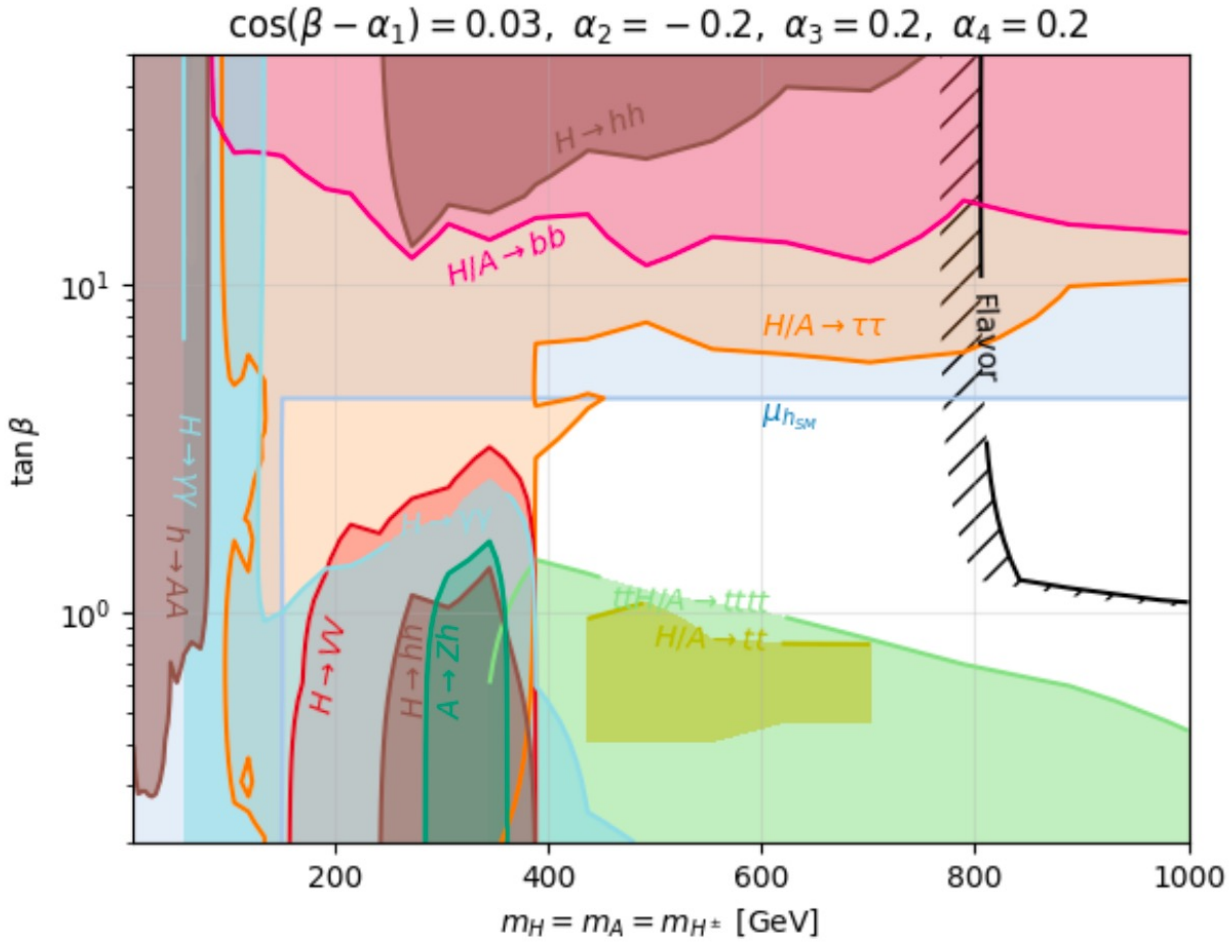
$$m_{h_S} = m_{a_S} = 1500 \text{ GeV}$$





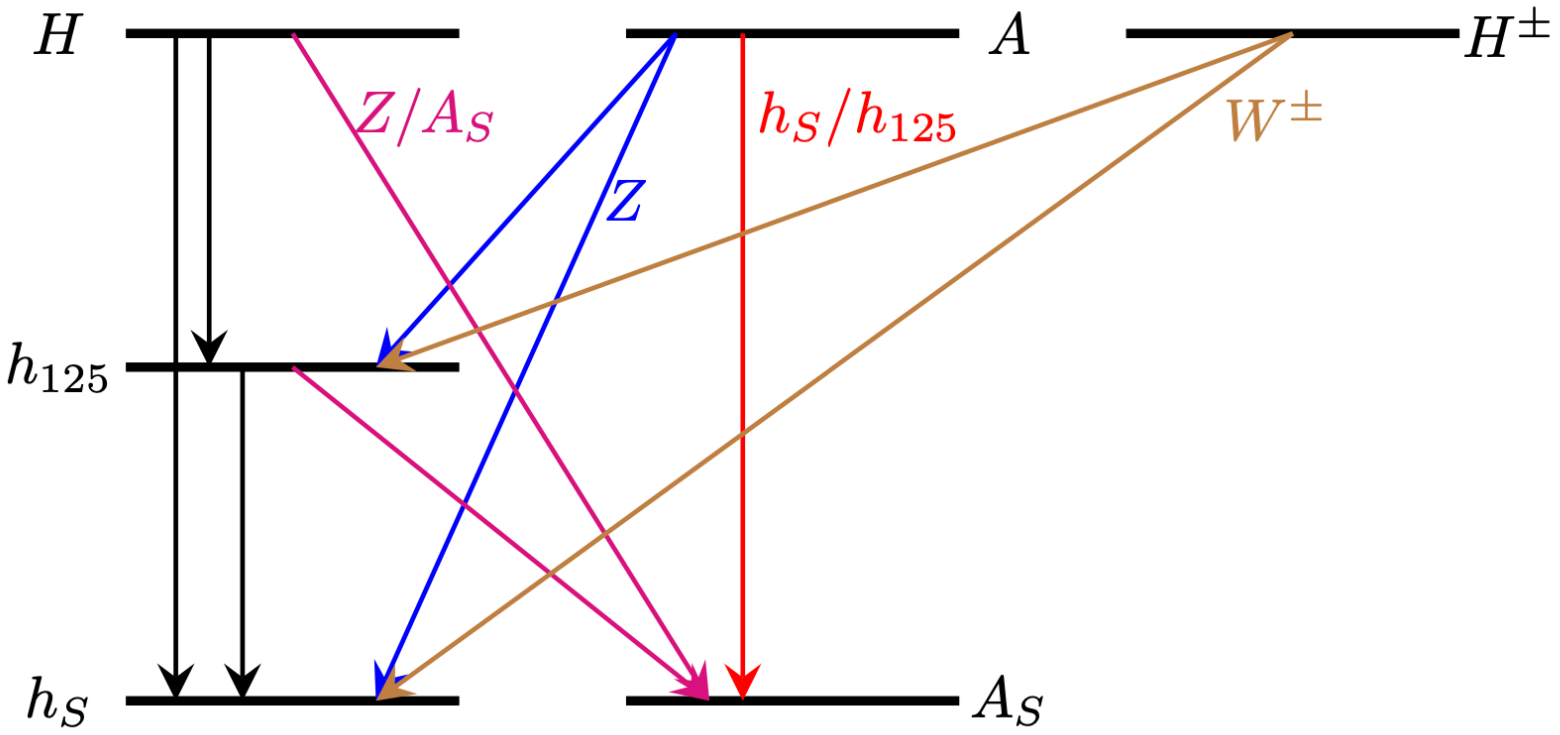
2HDM+singlet





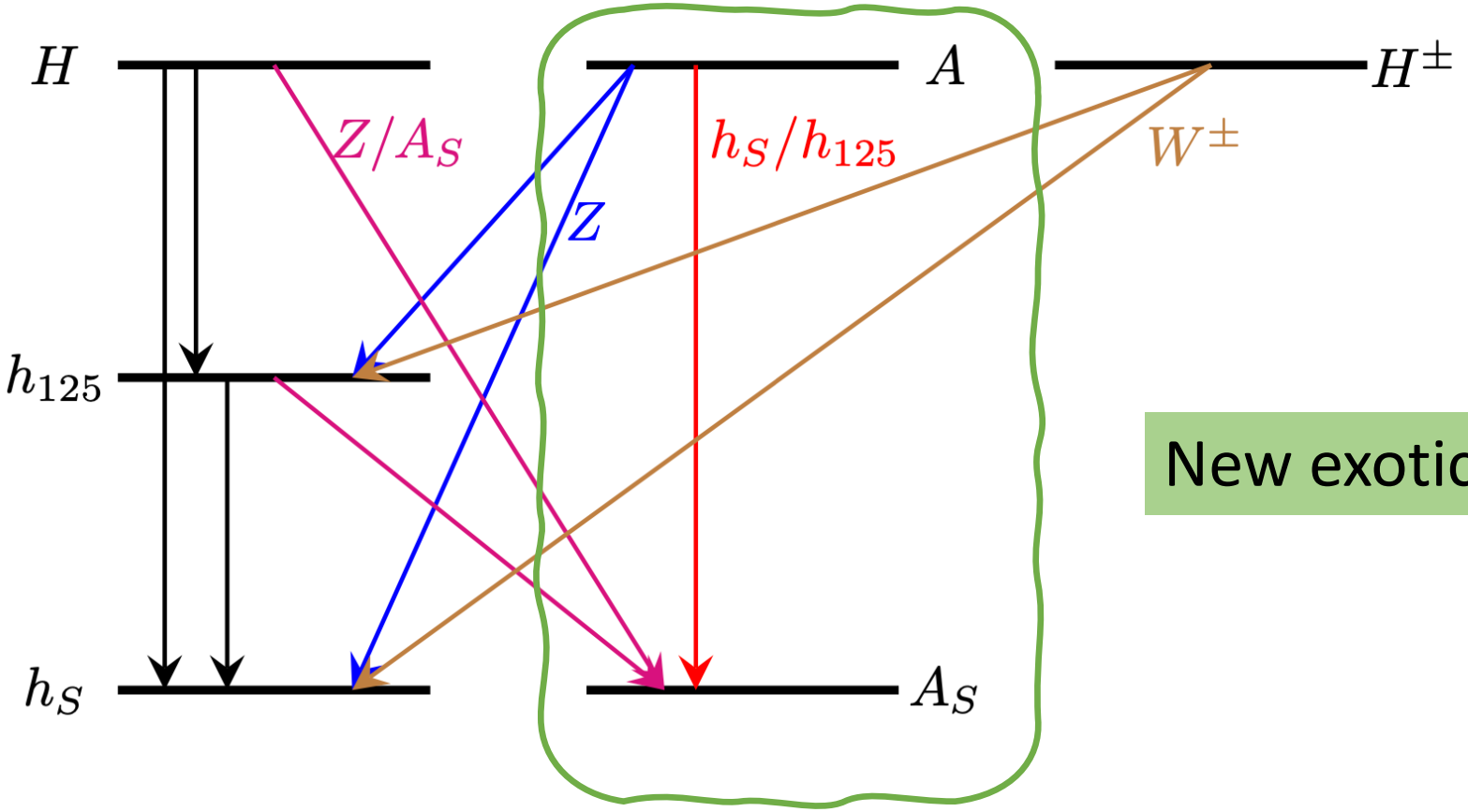
2HDM+singlet

- The scenario with lighter singlet Higgs



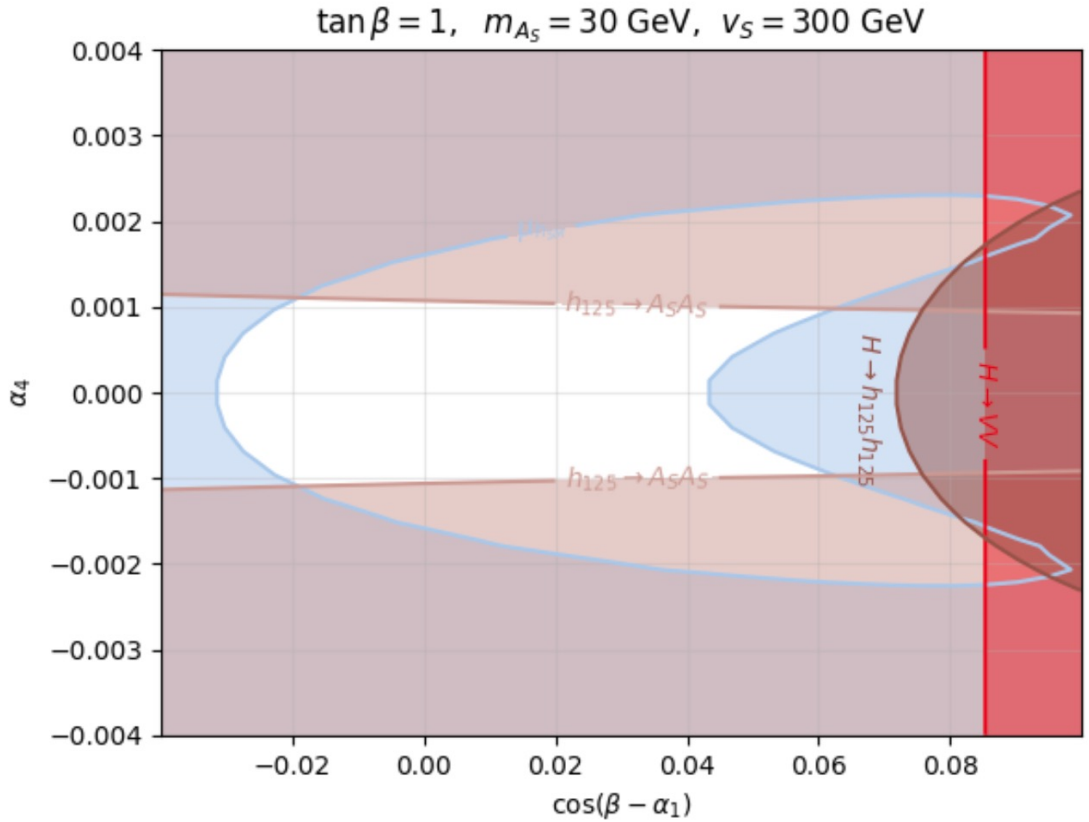
2HDM+singlet

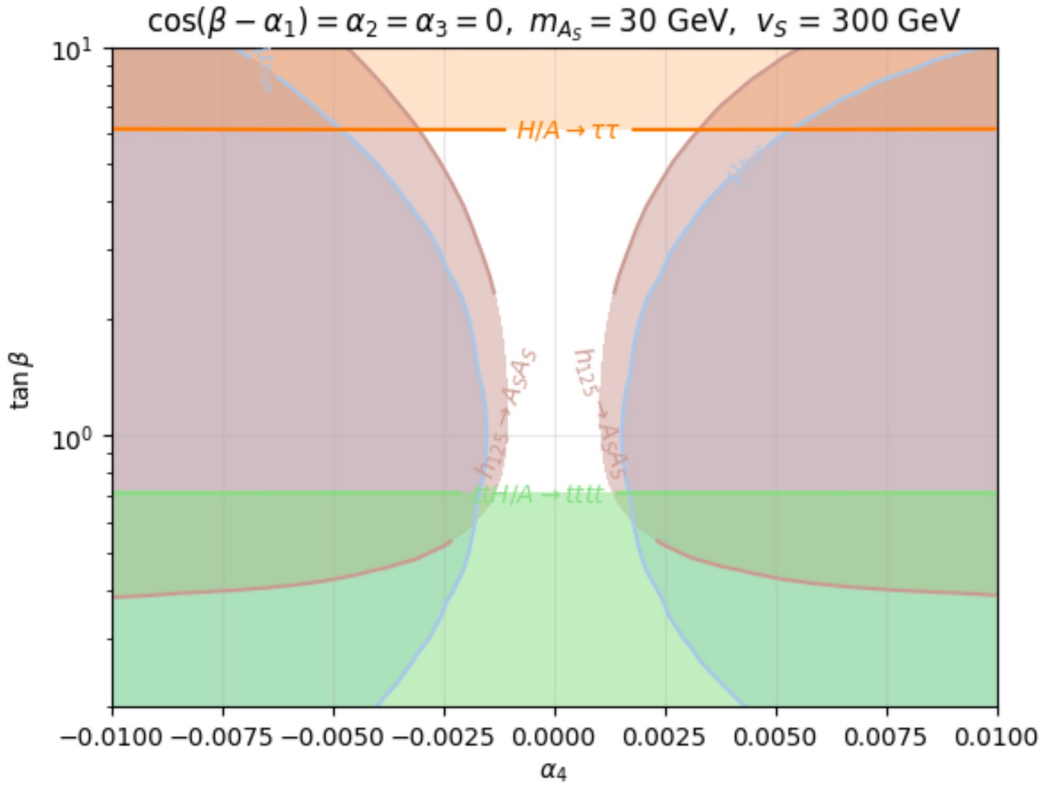
- The scenario with lighter singlet Higgs



New exotic channels

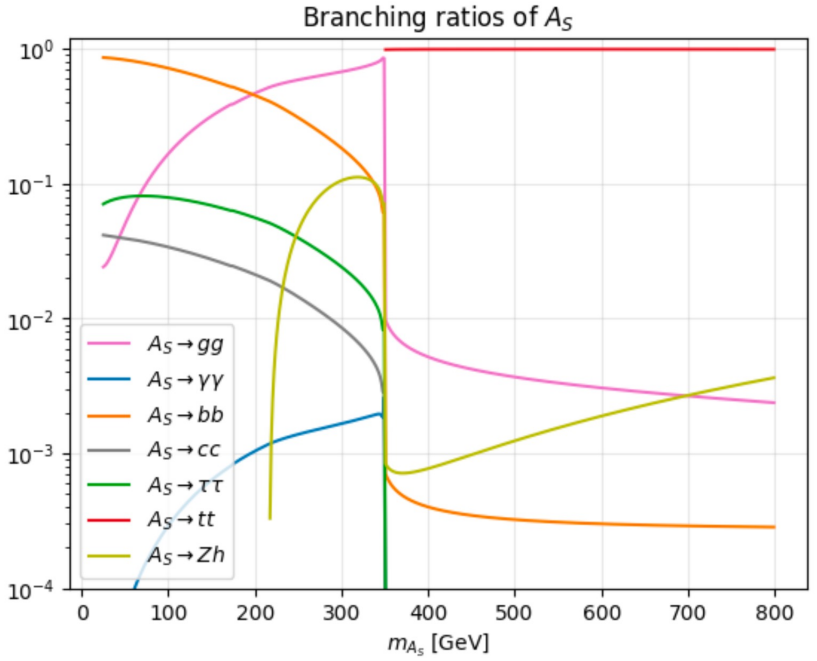
2HDM+singlet

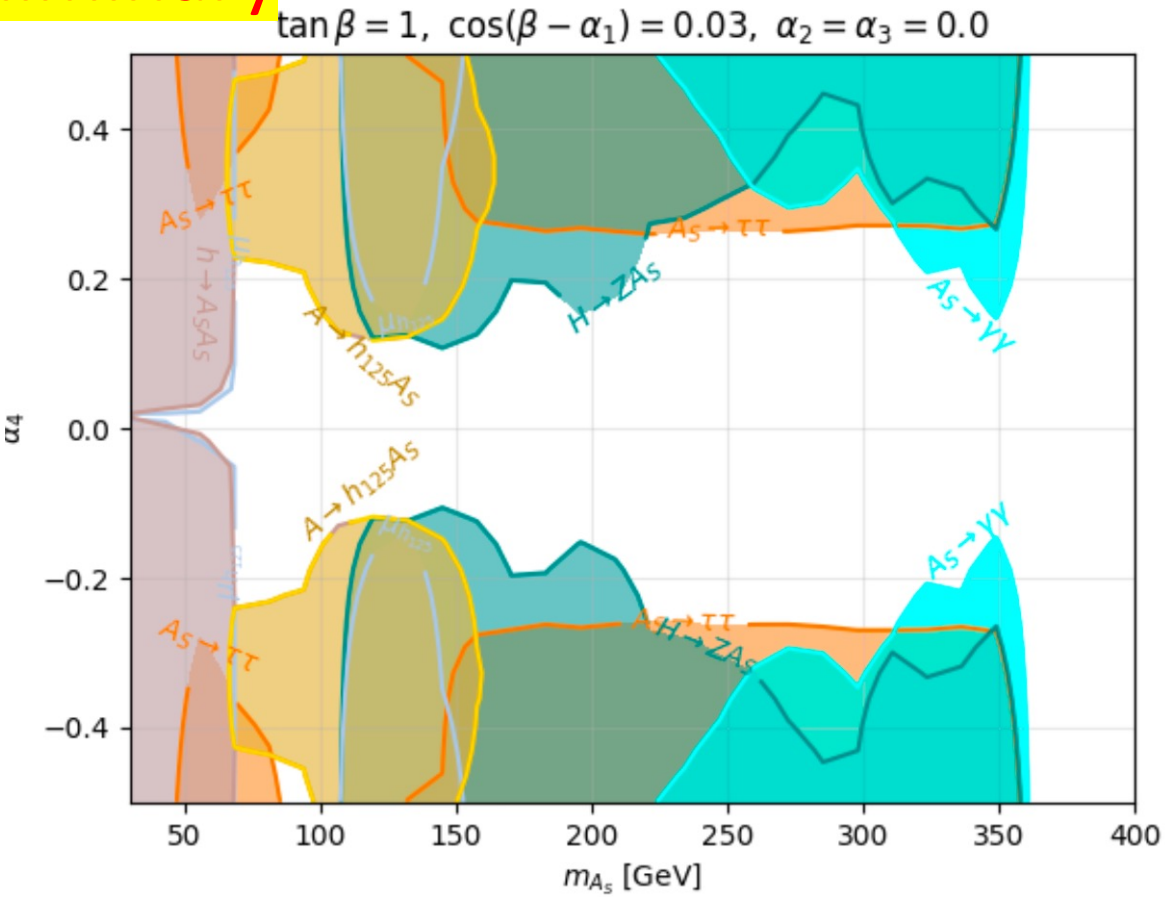




Results : A_S

Preliminary



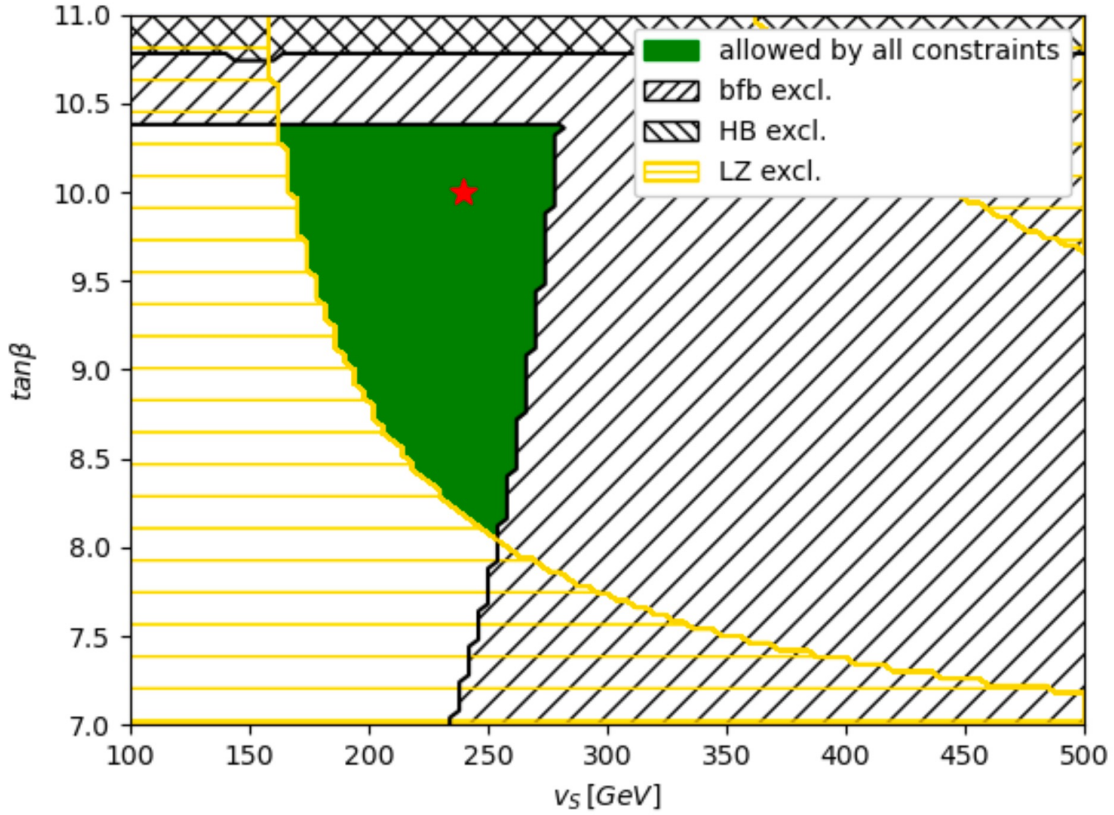


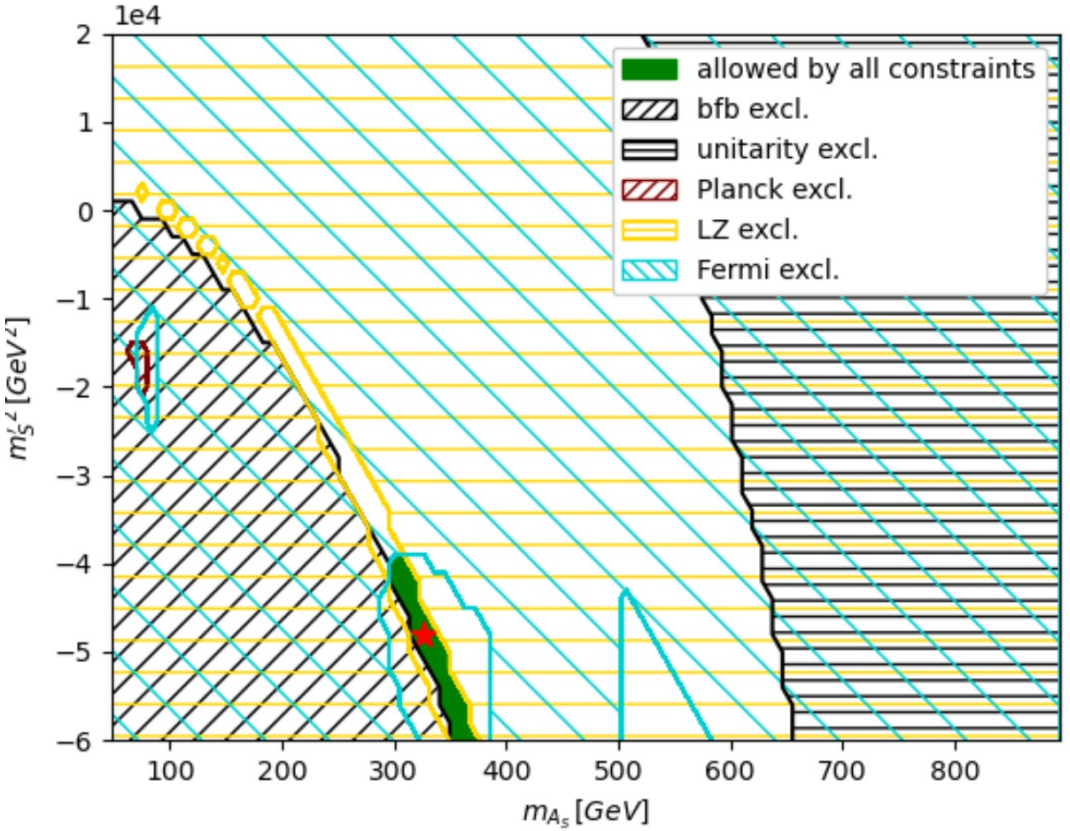
$$\alpha_4 = 0$$

Results: Dark matter

$$\Phi_j \xrightarrow{Z_2'} \Phi_j, \quad S \xrightarrow{Z_2'} -S$$

2310.19962 [hep-ph]





Inert Doublet Model

$$\langle \phi_S \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle \phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

Type-I like
Yukawa Coupling

$$\phi_S = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}G^+ \\ v + h + iG \end{pmatrix}, \quad \phi_D = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}H^+ \\ H + iA \end{pmatrix}.$$

DM with Zγ

$$\mu_{Z\gamma} = 2.2 \pm 0.7$$

2005.05382 **[hep-ex]**

$$\widetilde{R}_{Z\gamma} = \frac{\Gamma(h \to Z\gamma)^{\mathrm{IDM}}}{\Gamma(h \to Z\gamma)^{\mathrm{SM}}} \approx 2$$

$$\Gamma(h \to Z\gamma) = \frac{G_F^2 \alpha}{64\pi^4} M_W^2 M_h^3 \left(1 - \frac{M_Z^2}{M_h^2}\right)^3 \left| 2 \frac{1 - \frac{8}{3}\sin^2\theta_W}{\cos\theta_W} A_{1/2}^h \left(\frac{4m_t^2}{M_h^2}, \frac{4m_t^2}{M_Z^2}\right) \right.$$

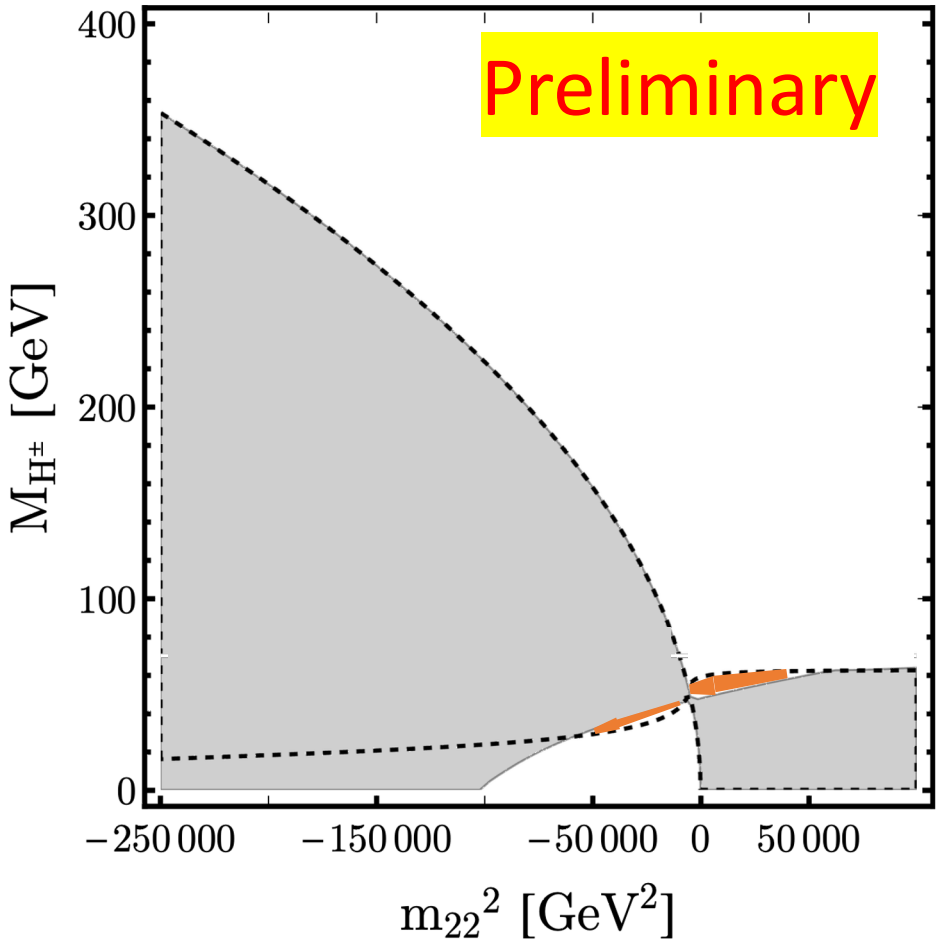
$$+ A_1^h \left(\frac{4M_W^2}{M_h^2}, \frac{4M_W^2}{M_Z^2}\right)$$

$$\left. - \frac{2M_{H^\pm}^2 + m_{22}^2}{2M_{H^\pm}^2} \frac{(1 - 2\sin^2\theta_W)}{\cos\theta_W} I_1 \left(\frac{4M_{H^\pm}^2}{M_h^2}, \frac{4M_{H^\pm}^2}{M_Z^2}\right) \right|^2,$$

IDM

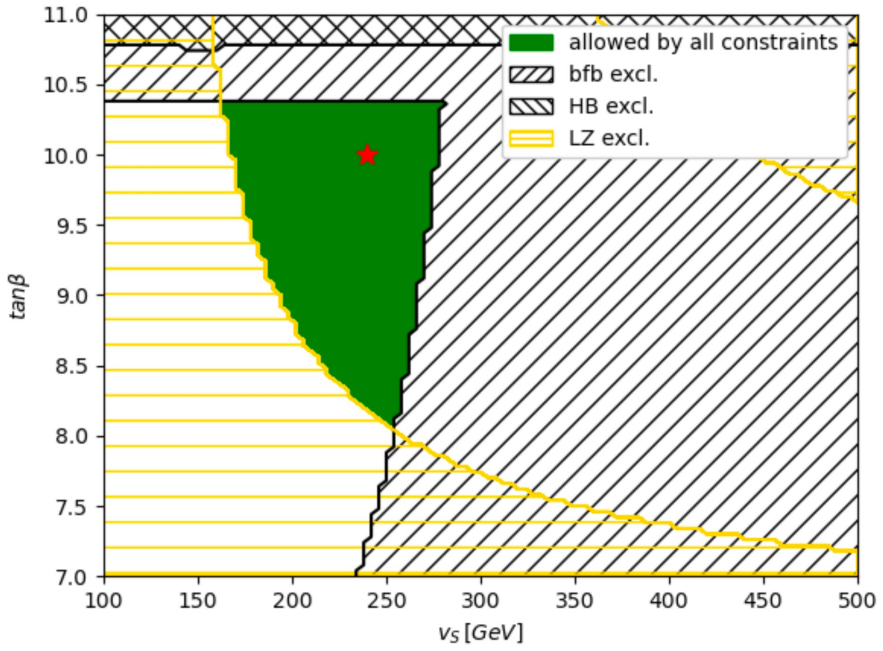
$$\widetilde{R}_{Z\gamma} = \frac{\Gamma(h \to Z\gamma)^{\mathrm{IDM}}}{\Gamma(h \to Z\gamma)^{\mathrm{SM}}} \approx 2$$

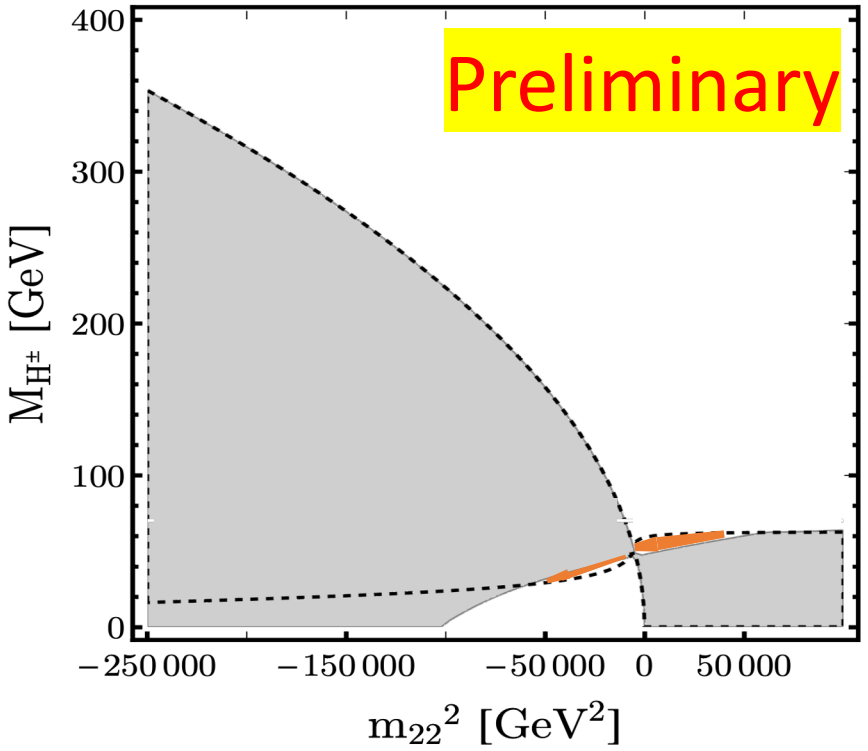
$$\widetilde{R}_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)^{\mathrm{IDM}}}{\Gamma(h \to \gamma\gamma)^{\mathrm{SM}}}$$



Summary

- Various BSM Higgs sector → DM → various collider pheno

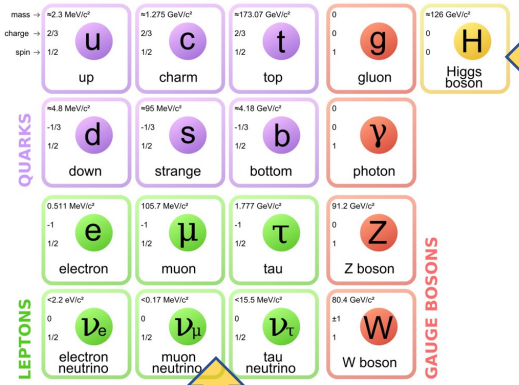




Thanks !

backup

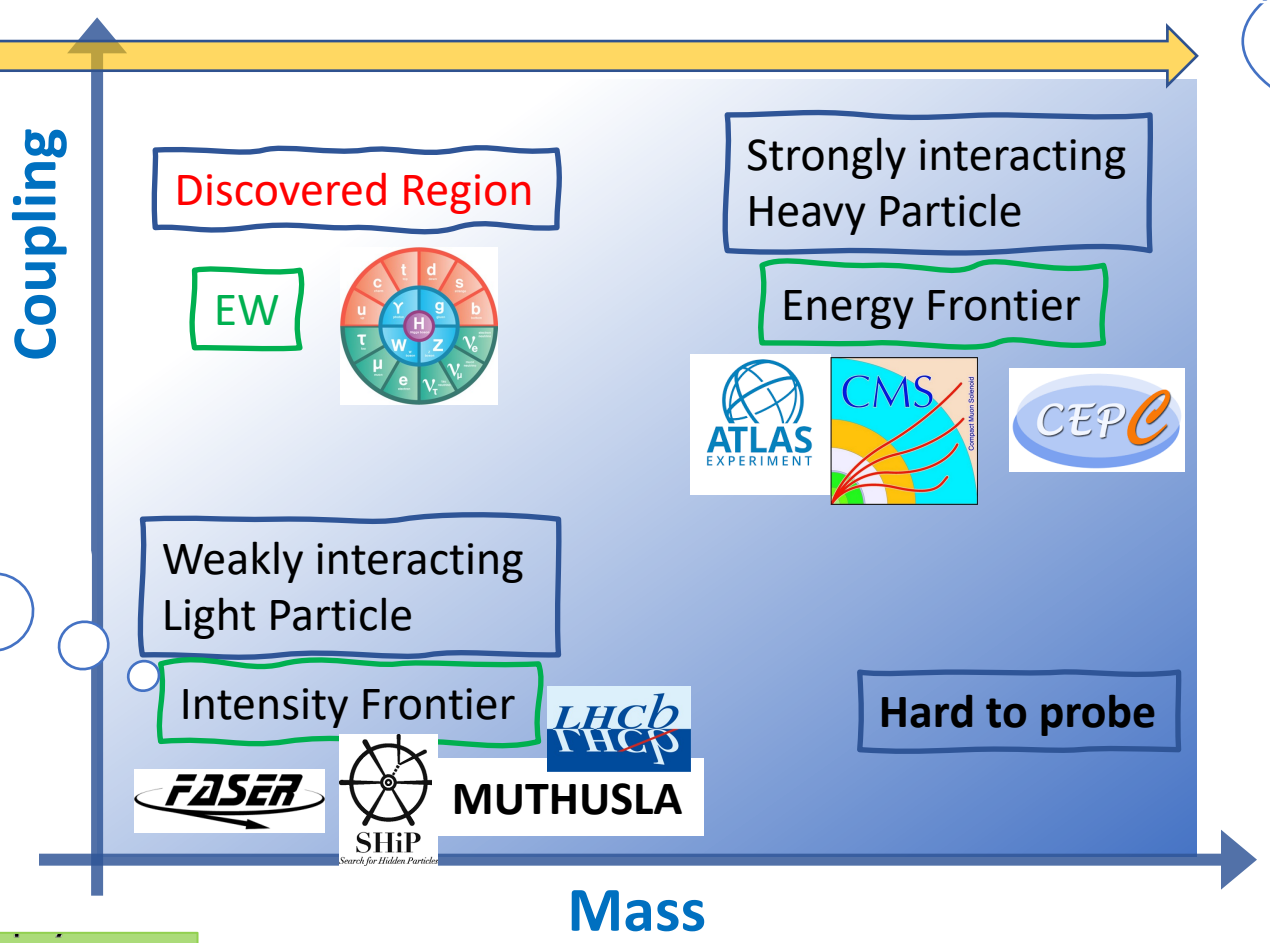
Summary



$WIMP, Dark\ Photon$ ..

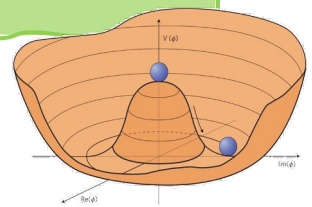
- Naturalness
- Muon g-2
- B anomaly
- ...

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu\mu)}{\mathrm{BR}(B \to K^{(*)}ee)}$$



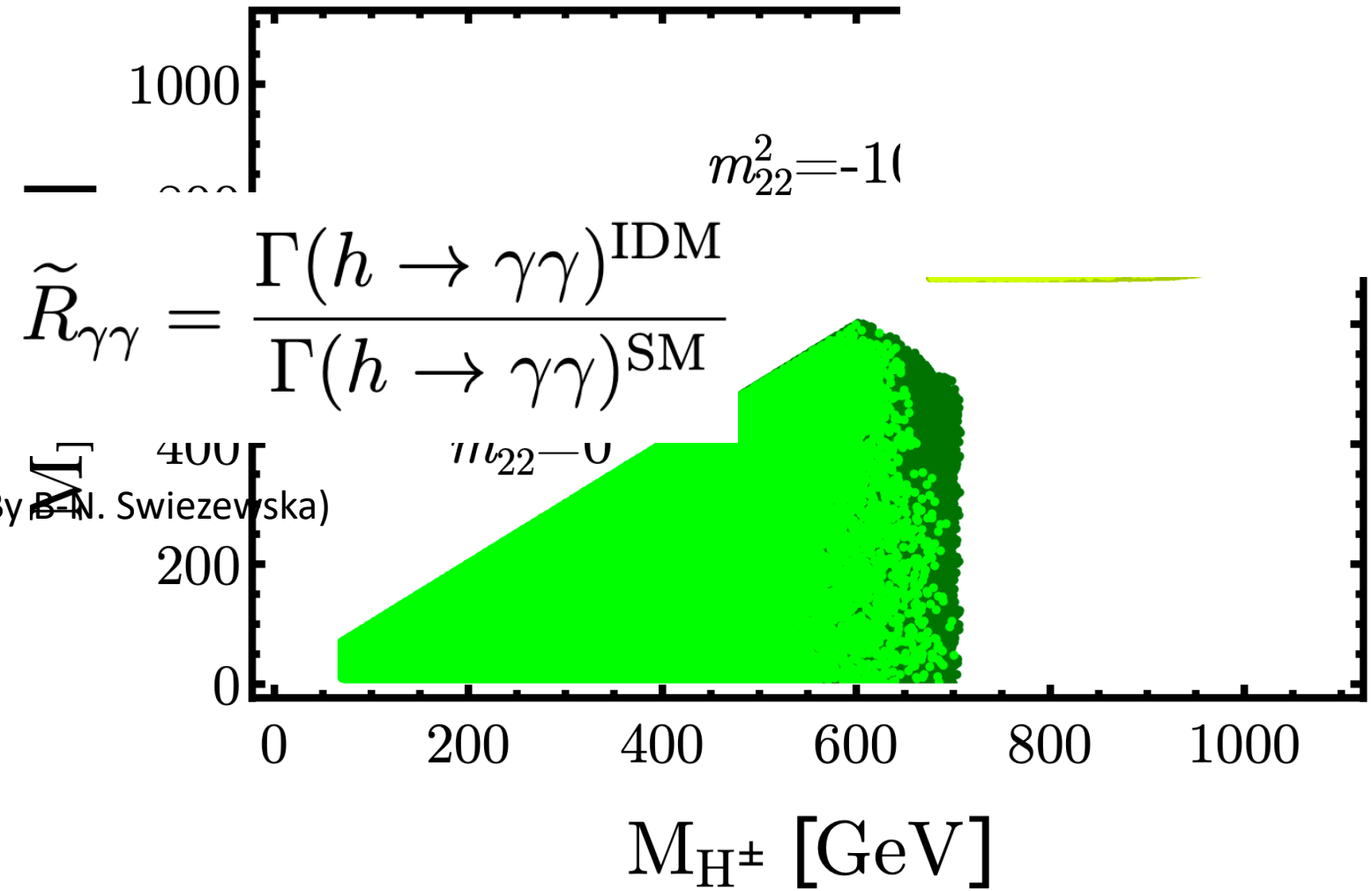
$DM, Dark\ Photon$ ...

- Naturalness
- Muon g-2
- Phase transition
- ...



$$\Gamma(h \to \gamma\gamma)^{\rm IDM} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \Big| \underbrace{\frac{4}{3} A_{1/2}\left(\frac{4M_t^2}{M_h^2}\right) + A_1\left(\frac{4M_W^2}{M_h^2}\right)}_{\mathcal{M}^{\rm SM}} + \underbrace{\frac{2M_{H^\pm}^2 + m_{22}^2}{2M_{H^\pm}^2} A_0\left(\frac{4M_{H^\pm}^2}{M_h^2}\right)}_{\delta\mathcal{M}^{\rm IDM}} \Big|^2,$$

$$\widetilde{R}_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)^{\rm IDM}}{\Gamma(h \to \gamma\gamma)^{\rm SM}}$$

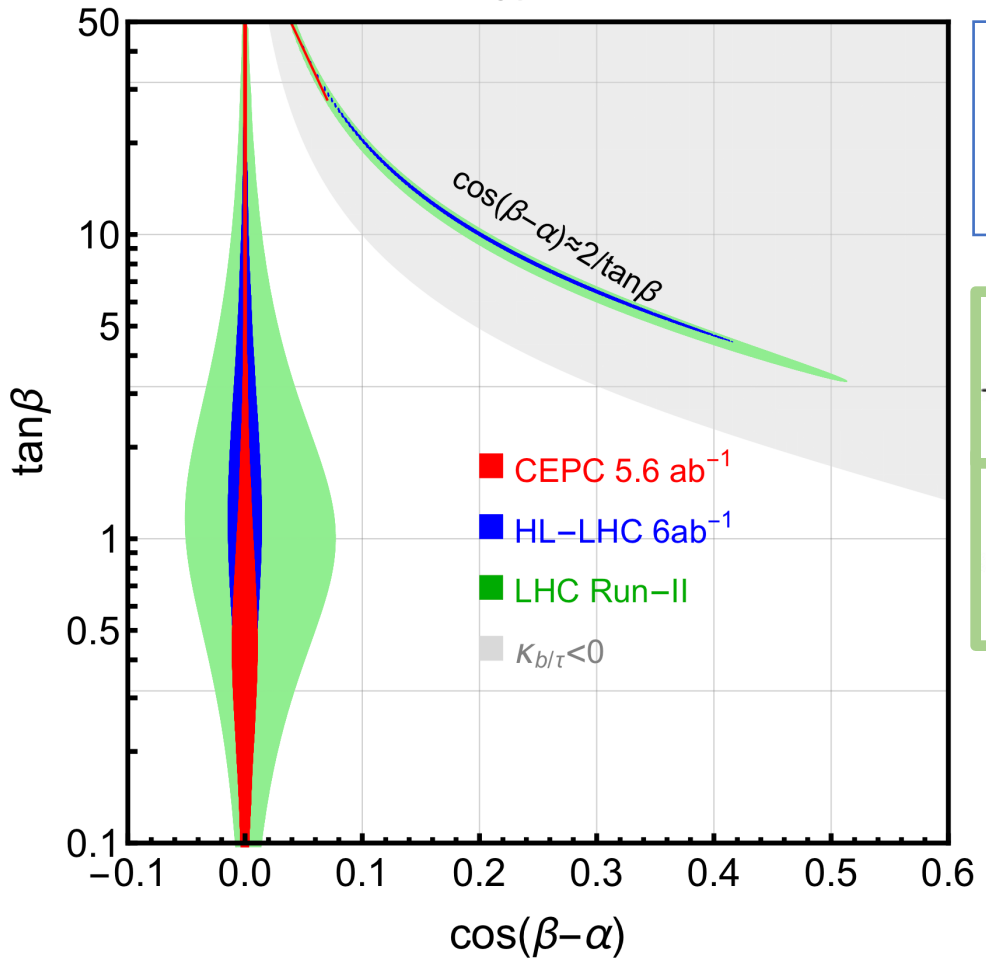


By B-N. Swiezewska)

2HDM: Tree Level

Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

2HDM Type-II



Alignment limit :

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

$g(2HDM)=g(SM)$

1910.06269

WS

$$-\frac{\sin\beta}{\cos\alpha}-1=-\frac{1}{2}\cos^2(\beta-\alpha)-\cos(\beta-\alpha)\times\tan\beta$$

$$\frac{\cos\alpha}{\sin\beta}-1=-\frac{1}{2}\cos^2(\beta-\alpha)+\frac{\cos(\beta-\alpha)}{\tan\beta}$$

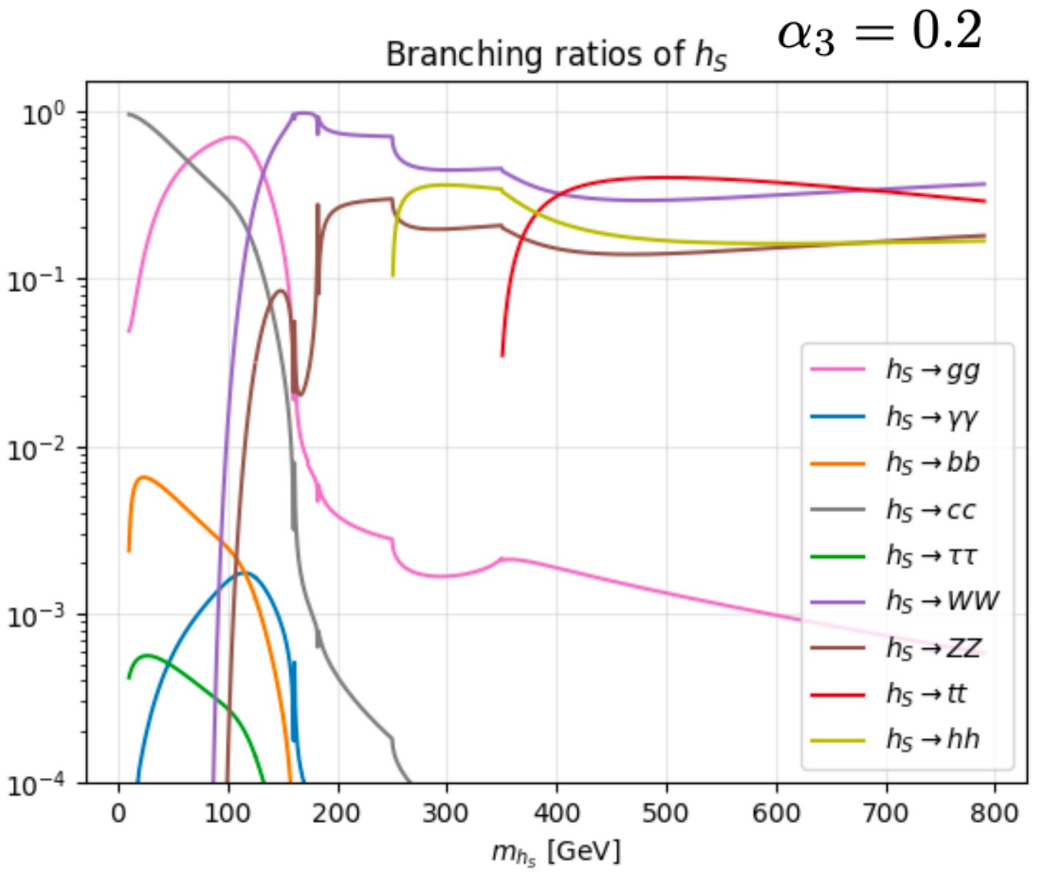
m_{h_1}	m_{h_2}	m_{h_3}	m_A	m_{A_S}
95 GeV	125.09 GeV	900 GeV	900 GeV	325.86 GeV
$m_{H^\pm}$	$m_S'^2$	δ'_{14}	δ'_{25}	$\tan(\beta)$
900 GeV	-4.809×10^4 GeV^2	-9.6958	0.2475	10
v_S	c_{h_1bb}	c_{h_1tt}	$alignm$	$\tilde{\mu}^2$
239.86 GeV	0.2096	0.4192	0.9998	8.128×10^5 GeV^2

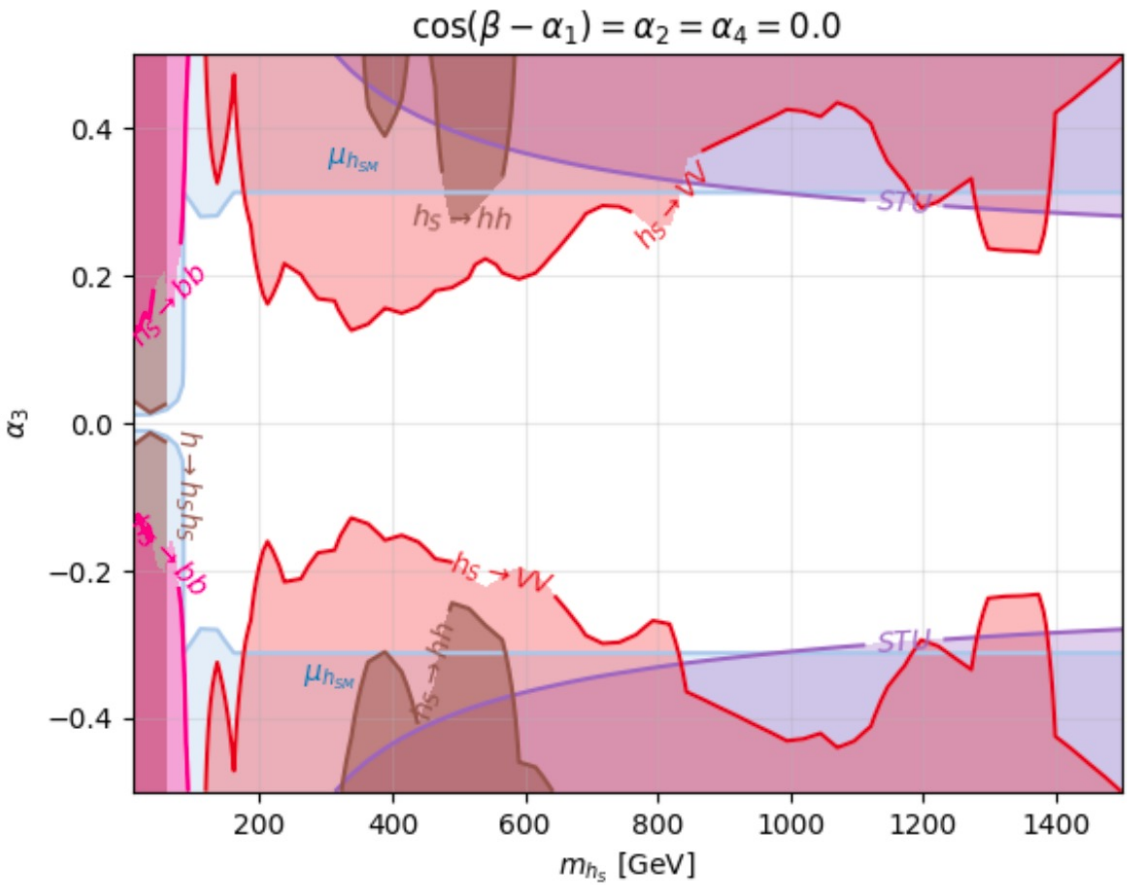
Table 3. The benchmark point **BP1** in the mass basis.

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \rho_i + i\eta_i) \end{pmatrix}$$

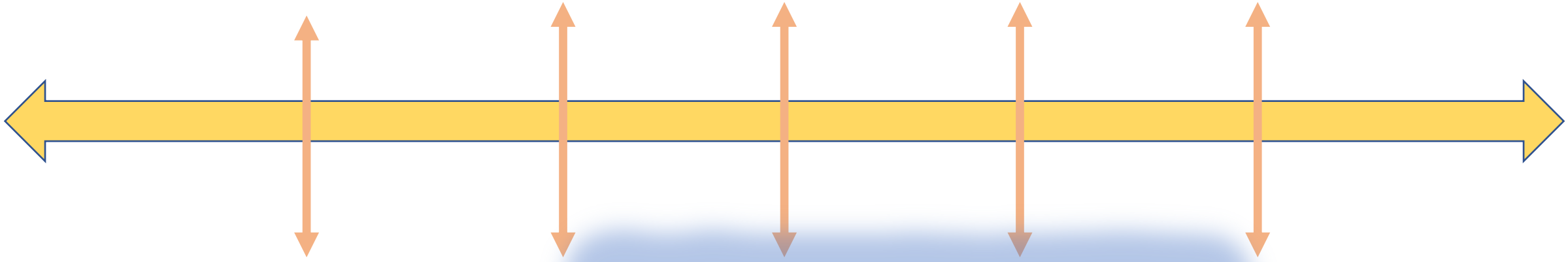
$$S = \frac{1}{\sqrt{2}}(v_S + \rho_S + iA_S)$$

2HDM+singlet:h_S





Scenarios



- $m_{h_S} < 0.1$ GeV
- 0.1 GeV$< m_{h_S} <$ 10 GeV
- 10 GeV $< m_{h_S} <$ 62.5 GeV
- 62.5 GeV $< m_{h_S} <$ 1 TeV
- 1 TeV $< m_{h_S} <$ 10TeV
- 10 TeV $< m_{h_S}$

Mass hierarchy

LHC era