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The hidden side of scalar-triplets models with spontaneous CP violation

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BERNARDO GONÇALVES

In collaboration with P.M. Ferreira and F.R. Joaquim

Spontaneous CP violation in scalar-triplet models

Spontaneous CP violation in scalar-triplet models

WHY?

Motivation

Type-II seesaw mechanism

Scalar triplet extensions of the Standard Model

Possible connections with leptonic CP violation

Under which conditions can spontaneous CP violation (SCPV) arise in scalar-triplet models?

Spontaneous CP violation in the STM

In the scalar-triplet model (STM):

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Spontaneous CP violation in the STM

In the scalar-triplet model (STM):

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad + \quad Y = 2 \text{ scalar triplet } \Delta$$

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$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad + \quad \Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

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$$\downarrow$$

$$\begin{aligned} V_S = {} & m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + (\mu\Phi^T i\tau_2\Delta^\dagger\Phi + \mathrm{H.c.}) \\ & + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda[\mathrm{Tr}(\Delta^\dagger\Delta)]^2 + \tilde{\lambda}\mathrm{Tr}[(\Delta^\dagger\Delta)^2] + \lambda'(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \hat{\lambda}\Phi^\dagger\Delta\Delta^\dagger\Phi \end{aligned}$$

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$$V_S = m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + (\mu\Phi^T i\tau_2\Delta^\dagger\Phi + \mathrm{H.c.})$$
$$+ \lambda_1(\Phi^\dagger\Phi)^2 + \lambda[\mathrm{Tr}(\Delta^\dagger\Delta)]^2 + \tilde{\lambda}\mathrm{Tr}[(\Delta^\dagger\Delta)^2] + \lambda'(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \hat{\lambda}\Phi^\dagger\Delta\Delta^\dagger\Phi$$

$$\langle\phi^0\rangle = \frac{v}{\sqrt{2}}, \quad \langle\delta^0\rangle = \frac{ue^{i\theta}}{\sqrt{2}}$$

Minimisation equations →

$$\boxed{\mu\, vu \sin\theta = 0}$$

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↓

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Minimisation equations →

$$\boxed{\mu\, vu\sin\theta = 0}$$

NO SCPV

Spontaneous CP violation in scalar-triplet models

But what about in the two-scalar-triplet model (2STM)?

Spontaneous CP violation in the 2STM

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$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad + \quad Y = 2 \text{ scalar triplets } \Delta_{1,2}$$

Spontaneous CP violation in the 2STM

In the two-scalar-triplet model (2STM):

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Spontaneous CP violation in the 2STM

In the two-scalar-triplet model (2STM):

$$V = \boxed{V_{\mathrm{U(1)}}} + V_{\mathrm{SB}}$$

↓ U(1)-symmetric

$$\Phi \to e^{i\alpha}\Phi$$
$$\Delta_{1,2} \to e^{i\alpha_{1,2}}\Delta_{1,2}$$

Spontaneous CP violation in the 2STM

In the two-scalar-triplet model (2STM):

$$V = V_{\mathrm{U}(1)} + \boxed{V_{\mathrm{SB}}}$$

$$V_{\mathrm{SB}} = M_{12}^2[\mathrm{Tr}(\Delta_1^\dagger \Delta_2) + \mathrm{Tr}(\Delta_2^\dagger \Delta_1)] + (\mu_1 \Phi^T \mathrm{i}\tau_2 \Delta_1^\dagger \Phi + \mu_2 \Phi^T \mathrm{i}\tau_2 \Delta_2^\dagger \Phi + \mathrm{H.c.})$$

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$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad , \quad \langle \Delta_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ u_1 e^{i\theta_1} & 0 \end{pmatrix} \quad , \quad \langle \Delta_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ u_2 e^{i\theta_2} & 0 \end{pmatrix}$$

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Minimisation equations

$$u_1 = u\, c_\beta$$
$$u_2 = u\, s_\beta$$

$$\boxed{uv\left(\mu_1 c_\beta s_{\theta_1} + \mu_2 s_\beta s_{\theta_2}\right) = 0}$$

$$\theta_1 \neq \theta_2$$

Spontaneous CP violation in the 2STM

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$$\boxed{uv\left(\mu_1 c_\beta s_{\theta_1} + \mu_2 s_\beta s_{\theta_2}\right) = 0}$$

SCPV is possible!

Spontaneous CP violation in the 2STM

In the two-scalar-triplet model (2STM):

$(\alpha, \beta) = e, \mu, \tau$

$$\mathcal{L}_{\text{Yuk}} = \mathbf{Y}^{\Delta_1}_{\alpha\beta}\, L^T_\alpha \mathcal{C}^\dagger i\tau_2 \Delta_1\, L_\beta + \mathbf{Y}^{\Delta_2}_{\alpha\beta}\, L^T_\alpha \mathcal{C}^\dagger i\tau_2 \Delta_2\, L_\beta \text{H.c.}$$

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SSB ↓

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$$m_\nu = \frac{1}{2} \left(\mathbf{Y}^{\Delta_1} u_1 e^{i\theta_1} + \mathbf{Y}^{\Delta_2} u_2 e^{i\theta_2} \right)$$

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CP violation can be communicated to the fermion sector

Spontaneous CP violation in the 2STM

And what about the scalar mass spectrum in the 2STM?

Scalar mass spectrum in the 2STM

Mass spectrum		CP-Conserving	CP-Violating
Neutral	h_1^0	Massless – Goldstone boson	
	h_2^0		
	h_3^0		
	h_4^0		
	h_5^0		
	h_6^0		
Singly-charged	H_1^+	Massless – Goldstone boson	
	H_2^+		
	H_3^+		
Doubly-charged	H_1^{++}		
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Scalar mass spectrum in the 2STM

Using results from **matrix theory**, it is possible to find analytical results, exact or up to a good approximation, regarding the eigenvalues of the squared mass matrices

Scalar mass spectrum in the 2STM

$$m^2_{h^0_{2,3}} \leq \frac{u^2}{2}\left[\Lambda_3 + \Lambda_5 + (\Lambda_3 - \Lambda_5)c_{2\beta} \pm \sqrt{\left[\Lambda_3 + \Lambda_5 + (\Lambda_3 - \Lambda_5)c_{2\beta}\right]^2 + \left(\Lambda_4^2 - 4\Lambda_3\Lambda_5\right)s^2_{2\beta}}\right]$$

Exact upper bound!

Λ_i → combinations of quartic parameters

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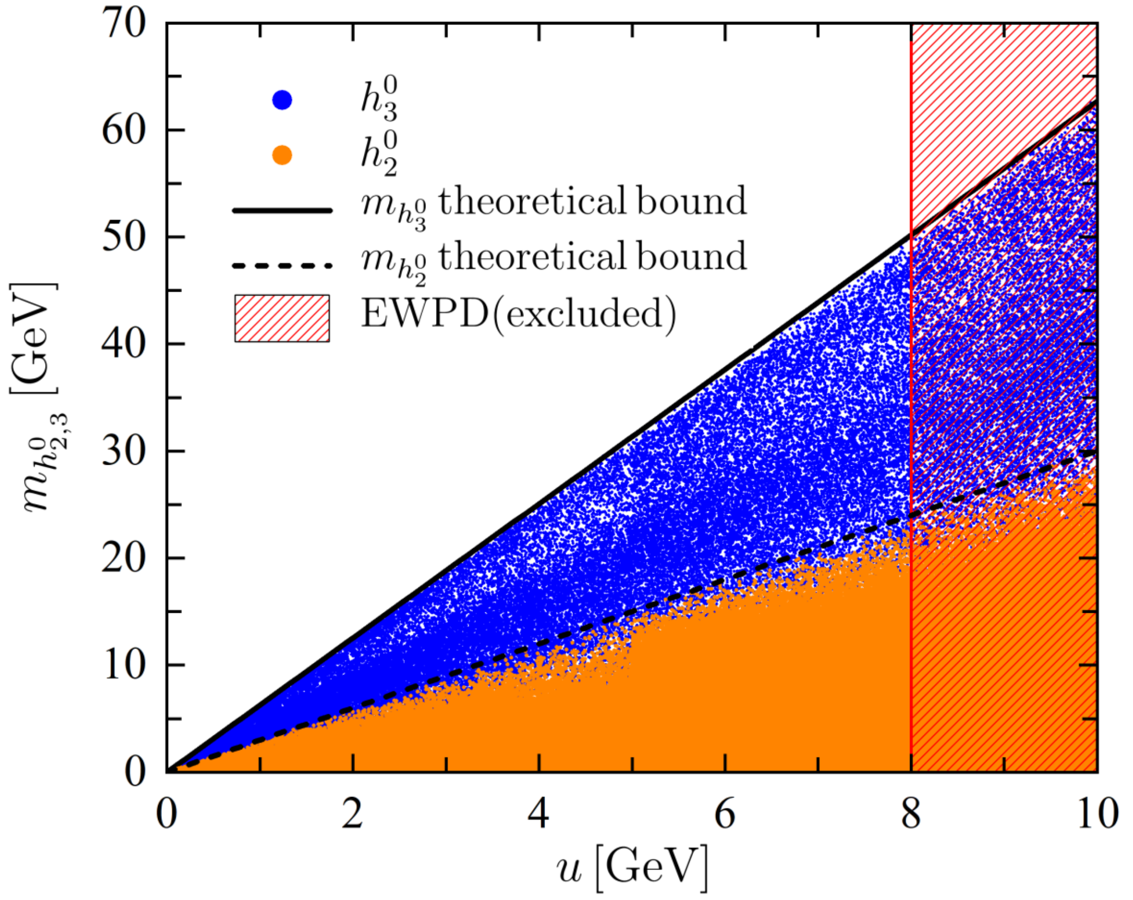

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Scalar mass spectrum in the 2STM

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Doubly-charged	H_1^{++}	Decoupled	
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Scalar mass spectrum in the 2STM

$$m^2_{h^0_5} \simeq m^2_{h^0_6} \simeq -\frac{s_{\theta_2}}{s_{\theta_1-\theta_2}} \left[f_1(\beta,\theta_1,\theta_2) + f_2(\beta)\right] M^2_\Delta$$

$$M^2_\Delta \equiv \frac{\mu_1\, v^2}{\sqrt{2}u}$$

Scalar mass spectrum in the 2STM

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Scalar mass spectrum in the 2STM

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	h_6^0		
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	H_3^+	Decoupled	
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Scalar mass spectrum in the 2STM

$$m_{H_2^+}^2 \simeq \frac{m_{H_1^{++}}^2}{2} \simeq -\frac{1}{4}\frac{\hat{\lambda}_1 f_1(\beta,\theta_1,\theta_2)+\hat{\lambda}_2 f_2(\beta)}{f_1(\beta,\theta_1,\theta_2)+f_2(\beta)}v^2$$

Scalar mass spectrum in the 2STM

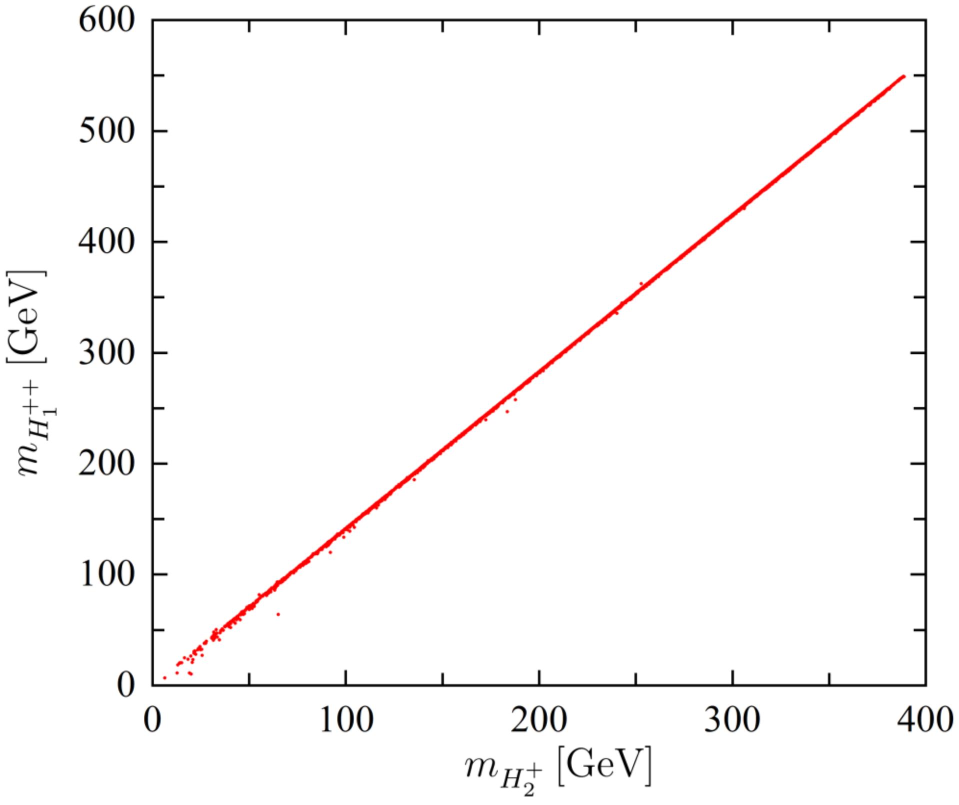
$$m^2_{H_2^+} \simeq \frac{m^2_{H_1^{++}}}{2} \simeq -\frac{1}{4}\frac{\hat{\lambda}_1 f_1(\beta,\theta_1,\theta_2) + \hat{\lambda}_2 f_2(\beta)}{f_1(\beta,\theta_1,\theta_2) + f_2(\beta)} v^2$$

$$m_{H_2^+} \lesssim \sqrt{\max\left(-\widehat{\lambda}_1/4, -\widehat{\lambda}_2/4\right)}\, v \simeq 390\,\mathrm{GeV}$$

$$m_{H_1^{++}} \lesssim \sqrt{\max\left(-\widehat{\lambda}_1/2, -\widehat{\lambda}_2/2\right)}\, v \simeq 550\,\mathrm{GeV}$$

Scalar mass spectrum in the 2STM

$$m^2_{H_2^+} \simeq \frac{m^2_{H_1^{++}}}{2} \simeq -\frac{1}{4}\frac{\hat{\lambda}_1 f_1(\beta,\theta_1,\theta_2)+\hat{\lambda}_2 f_2(\beta)}{f_1(\beta,\theta_1,\theta_2)+f_2(\beta)}v^2$$



$$m_{H_2^+} \lesssim 390\,\text{GeV}$$

$$m_{H_1^{++}} \lesssim 550\,\text{GeV}$$

Scalar mass spectrum in the 2STM

$$m^2_{H_3^+} \simeq m^2_{H_2^{++}} \simeq -\frac{s_{\theta_2}}{s_{\theta_1-\theta_2}} \left[f_1(\beta,\theta_1,\theta_2) + f_2(\beta)\right] M^2_\Delta$$

Scalar mass spectrum in the 2STM

$$m^2_{H_3^+} \simeq m^2_{H_2^{++}} \simeq -\frac{s_{\theta_2}}{s_{\theta_1-\theta_2}} \left[f_1(\beta,\theta_1,\theta_2) + f_2(\beta)\right] M_\Delta^2$$

REMINDER

$$m^2_{h_5^0} \simeq m^2_{h_6^0} \simeq -\frac{s_{\theta_2}}{s_{\theta_1-\theta_2}} \left[f_1(\beta,\theta_1,\theta_2) + f_2(\beta)\right] M_\Delta^2$$

$$M_\Delta^2 \equiv \frac{\mu_1 v^2}{\sqrt{2}u}$$

Scalar mass spectrum in the 2STM

<table>
<tr><th colspan="2">Mass spectrum</th><th>CP-Conserving</th><th>CP-Violating</th></tr>
<tr><td rowspan="6">Neutral</td><td>h_1^0</td><td colspan="2">Massless – Goldstone boson</td></tr>
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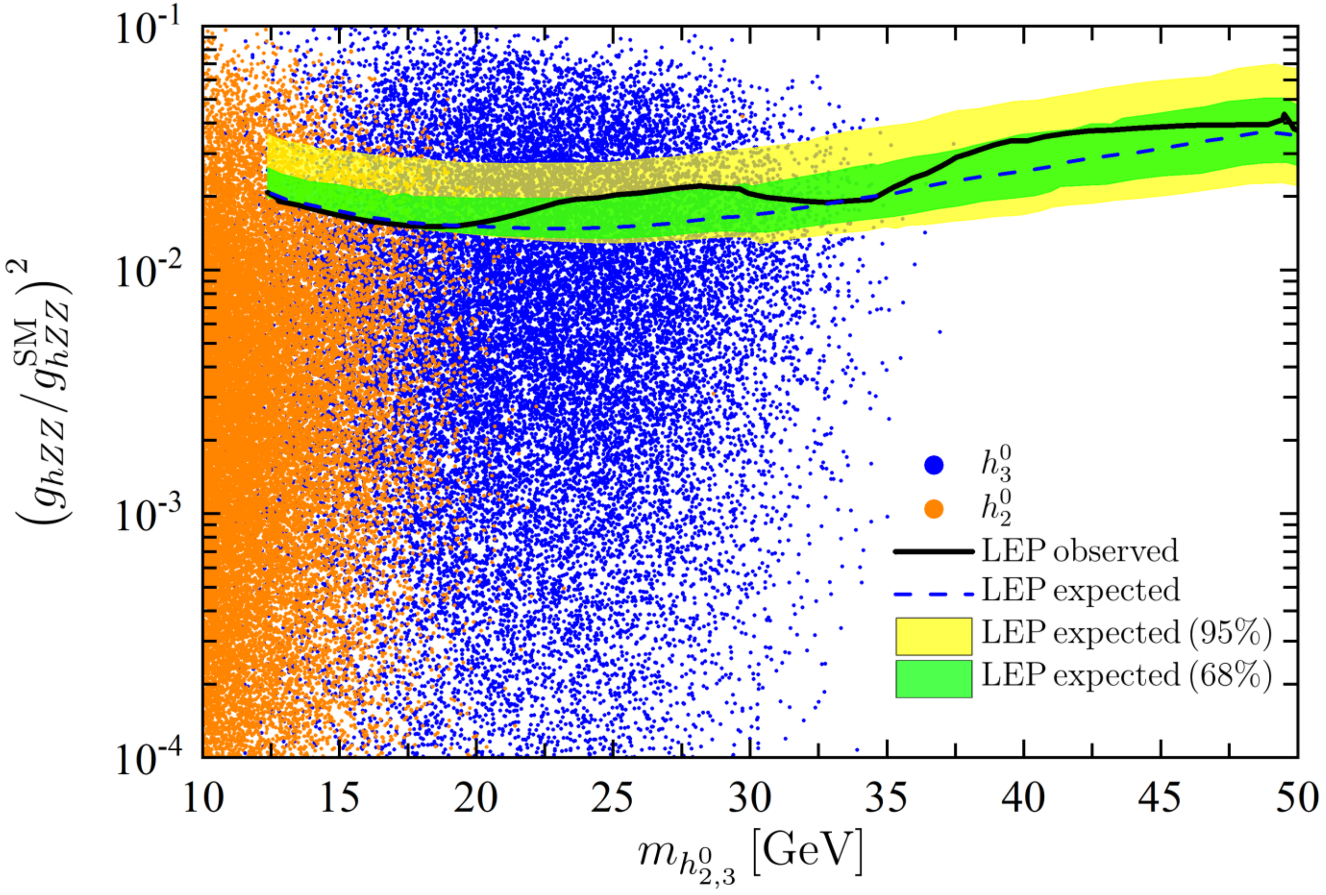
	h_5^0	Decoupled	Decoupled
	h_6^0		
Singly-charged	H_1^+	Massless – Goldstone boson	
	H_2^+	Decoupled	Electroweak
	H_3^+	Decoupled	Decoupled
Doubly-charged	H_1^{++}	Decoupled	Electroweak
	H_2^{++}	Decoupled	Decoupled

Scalar mass spectrum in the 2STM

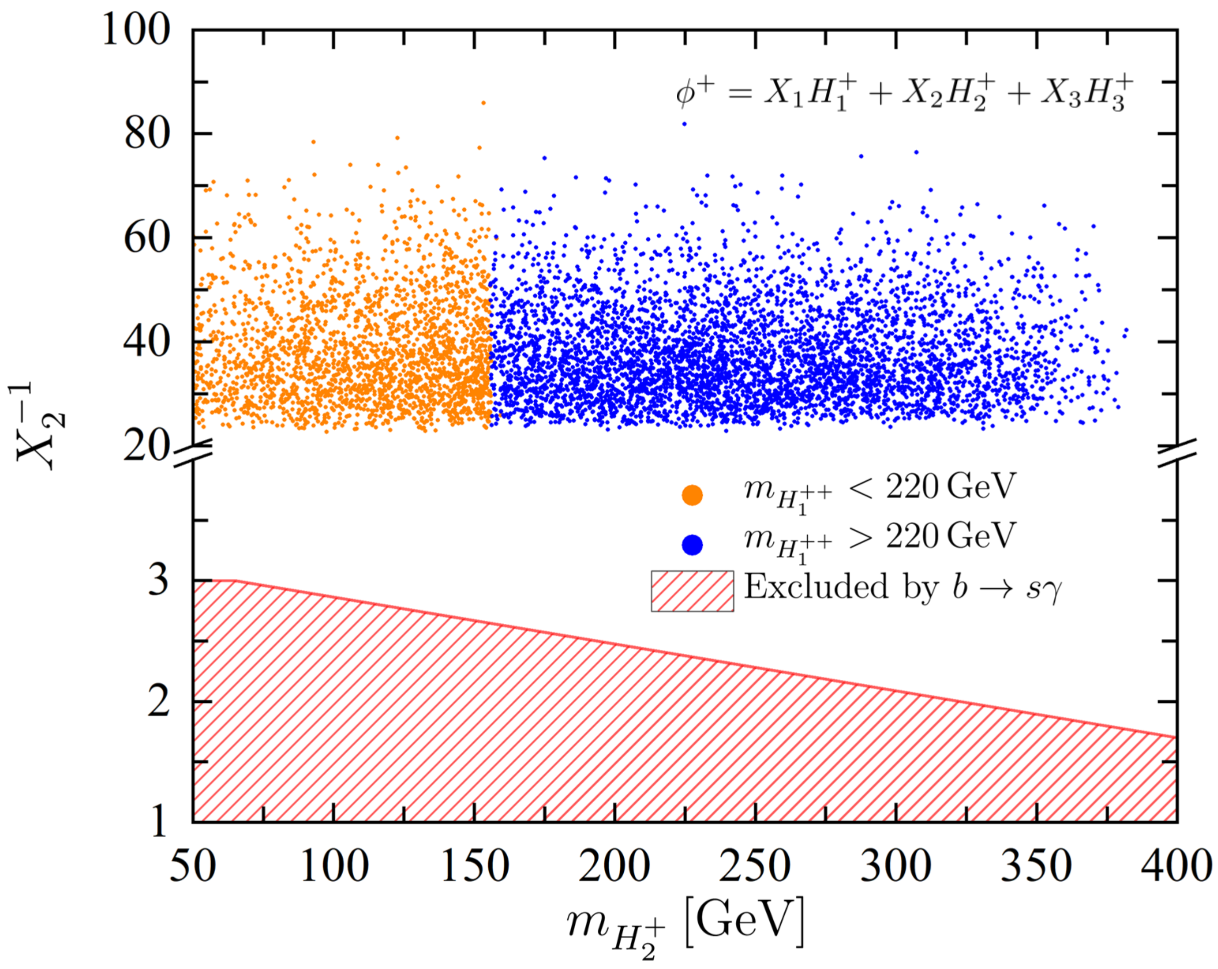
Could such scalars have evaded detection?

Scalar mass spectrum in the 2STM

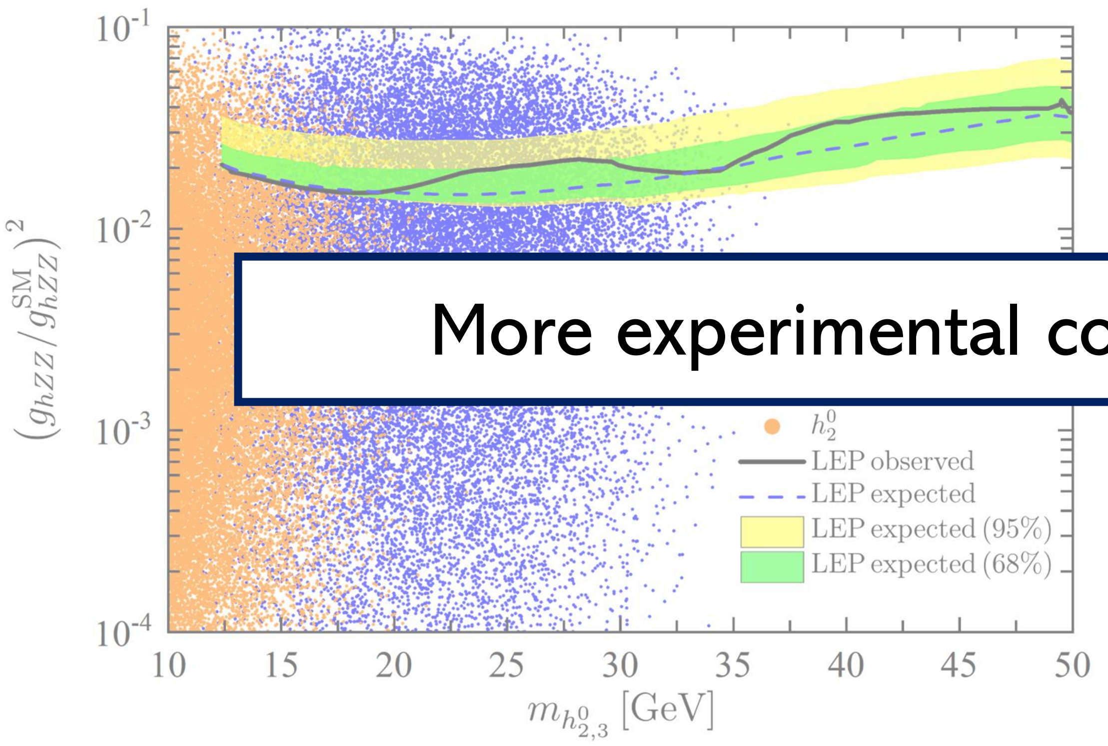


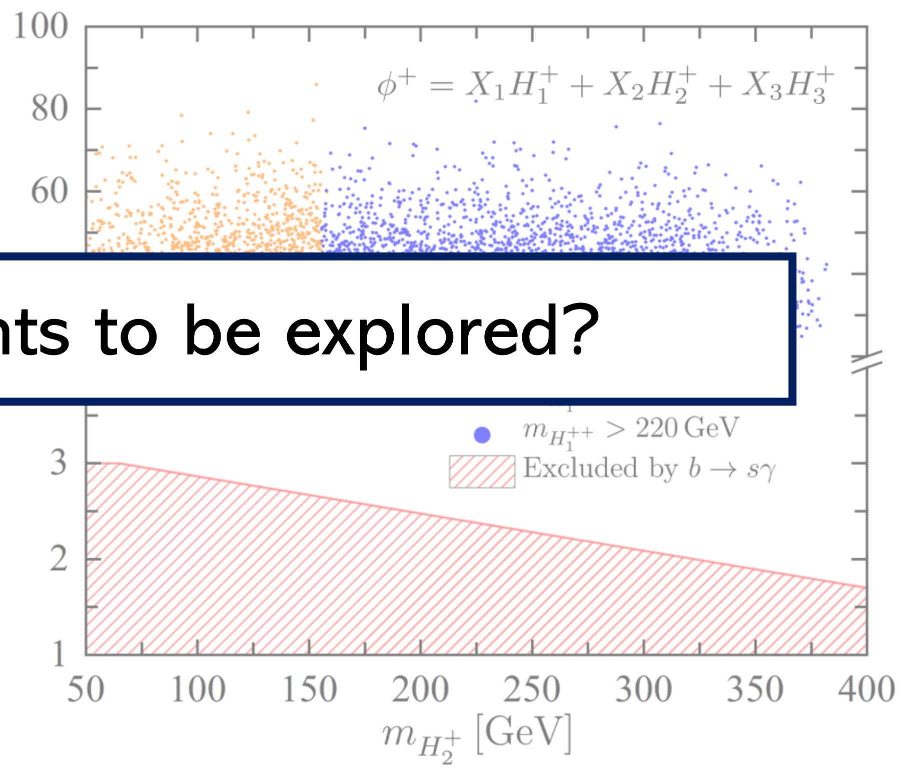
Scalar mass spectrum in the 2STM

$$-\mathcal{L}_{H_2^{\pm}} = \frac{\sqrt{2}\,V_{ud}^{\text{CKM}}}{v} X_2 H_2^+ \overline{u}\,(m_d P_R - m_u P_L)\, d + \text{H.c.}$$



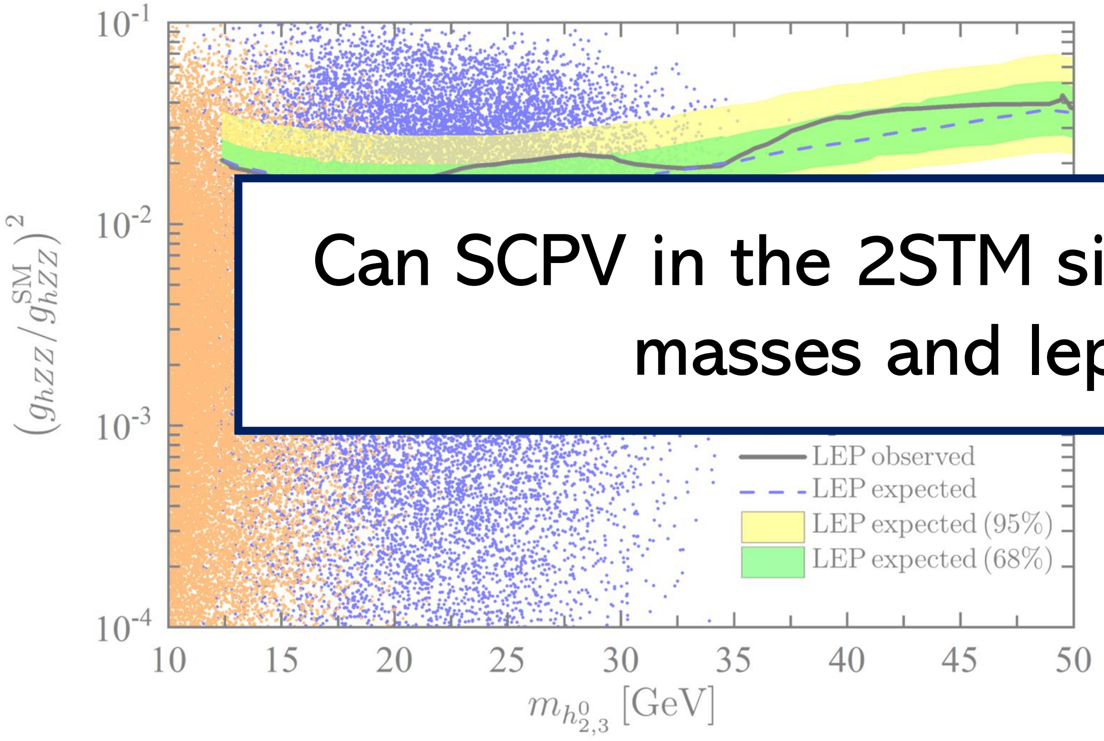
Scalar mass spectrum in the 2STM

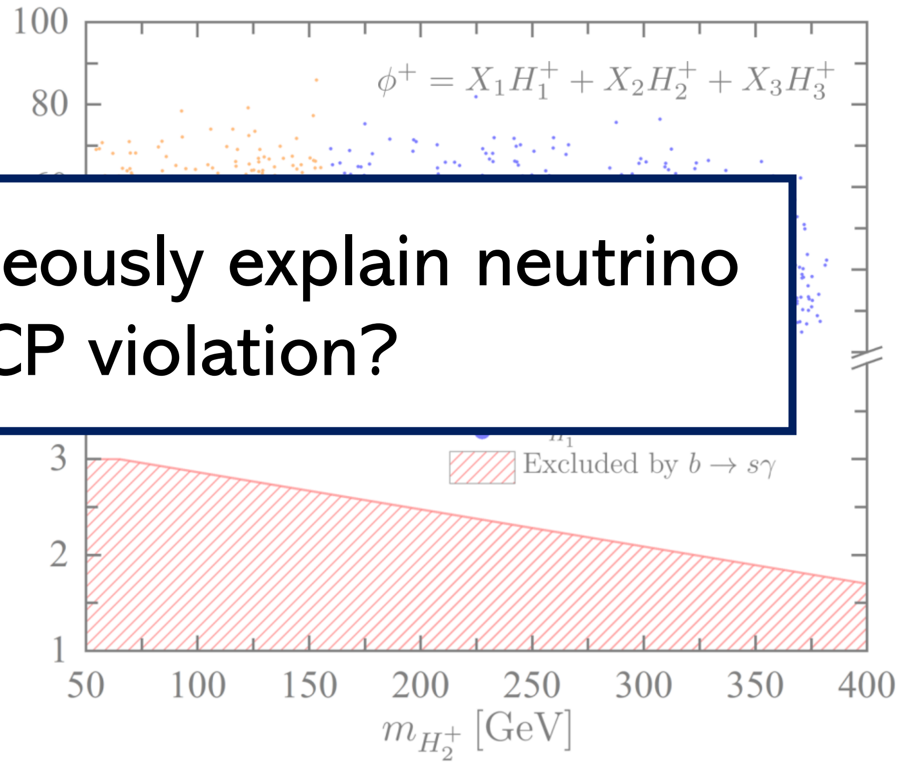




More experimental constraints to be explored?

Scalar mass spectrum in the 2STM





Can SCPV in the 2STM simultaneously explain neutrino masses and leptonic CP violation?

TAKE-HOME MESSAGE

WHEN SCPV OCCURS, THE 2STM HAS NO DECOUPLING LIMIT

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Thank you!