Mixed hidden sector-visible sector dark matter and observation of CP odd Higgs at the LHC

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Motivation: Multi-component dark matter

- Under the assumption of R-parity conservation, supersymmetry (SUSY) provides a viable candidate for dark matter: the lightest neutralino (LSP)
- There is no reason why dark matter should be composed of only one component
- For small μ, LSP is higgsino-like, hence it has a small relic density
- To saturate the relic density, at least another component is needed. The second component can belong to the hidden sector
- The smallness of μ brings about a light MSSM Higgs spectrum
- We discuss a hidden $U(1)_X$ extension of MSSM/SUGRA model with gauge kinetic and Stueckelberg mass mixings between $U(1)_Y$ and $U(1)_X$

The model

- To the MSSM/SUGRA we add an extra $U(1)_X$ under which all visible sector particles are neutral
- The extended model contains two vector superfields: B and C associated to $U(1)_Y$ and $U(1)_X$ and one chiral scalar superfield S
- The contents of the superfields

$$B(B_\mu, \lambda_B, D_B), \quad C(C_\mu, \lambda_C, D_C), \quad S(\rho + ia, \chi, F_S)$$

- The matter sector of the model consists of the visible sector chiral superfields Φ_i and hidden sector chiral superfields $\Psi_i = (\phi, f, F_m)$,

$$\mathcal{L}_{\rm m} = \int d^2\theta d^2\bar{\theta} \sum_i \left[\bar{\Phi}_i e^{2g_Y YB + 2g_X XC} \Phi_i + \bar{\Psi}_i e^{2g_Y YB + 2g_X XC} \Psi_i \right]$$

- Visible sector is neutral under $U(1)_X$ while the hidden sector is neutral under $U(1)_Y$, i.e., $X\Phi_i = 0$ and $Y\Psi_i = 0$

- The hidden sector fields f and f' form a Dirac fermion ψ whose mass arises from the term in the superpotential

$$W = W_{\rm MSSM} + M_\psi \Psi\Psi^c$$

- The gauge kinetic energy sector of the model is

$$\mathcal{L}_{\rm gk} = -\frac{1}{4}(B_{\mu\nu}B^{\mu\nu}+C_{\mu\nu}C^{\mu\nu})-i\lambda_B\sigma^\mu\partial_\mu\bar{\lambda}_B-i\lambda_C\sigma^\mu\partial_\mu\bar{\lambda}_C+\frac{1}{2}(D_B^2+D_C^2)$$

- We allow gauge kinetic mixing between $U(1)_X$ and $U(1)_Y$

$$-\frac{\delta}{2}B^{\mu\nu}C_{\mu\nu} - i\delta(\lambda_C\sigma^\mu\partial_\mu\bar{\lambda}_B + \lambda_B\sigma^\mu\partial_\mu\bar{\lambda}_C) + \delta D_B D_C$$

- We rotate into the diagonal basis using the transformation

$$\begin{pmatrix} B^\mu \\ C^\mu \end{pmatrix} = \begin{pmatrix} 1 & -s_\delta \\ 0 & c_\delta \end{pmatrix} \begin{pmatrix} B'^\mu \\ C'^\mu \end{pmatrix},$$

where $c_\delta = 1/(1-\delta^2)^{1/2}$ and $s_\delta = \delta/(1-\delta^2)^{1/2}$

Neutralino mass matrix

- We assume a Stueckelberg mass mixing between the $U(1)_X$ and $U(1)_Y$ sectors

$$\mathcal{L}_{\rm St} = \int d\theta^2 d\bar{\theta}^2 (M_1 C + M_2 B + S + \bar{S})^2,$$

with M_1 and M_2 being input mass parameters

- Rotate $(\lambda_Y, \lambda_3, \tilde{h}_1, \tilde{h}_2, \lambda_X, \psi_S) \longrightarrow (\lambda'_Y, \lambda_3, \tilde{h}_1, \tilde{h}_2, \lambda'_X, \psi_S)$ so that

$$\left(\begin{array}{cccc|cc}
m_1 & 0 & -c_\beta s_W M_Z & s_\beta s_W M_Z & -m_1 s_\delta + M_{XY} c_\delta & M_2 \\
0 & m_2 & c_\beta c_W M_Z & -s_\beta c_W M_Z & 0 & 0 \\
-c_\beta s_W M_Z & c_\beta c_W M_Z & 0 & -\mu & s_\delta c_\beta s_W M_Z & 0 \\
s_\beta s_W M_Z & -s_\beta c_W M_Z & -\mu & 0 & -s_\delta s_\beta s_W M_Z & 0 \\
\hline
-m_1 s_\delta + M_{XY} c_\delta & 0 & s_\delta c_\beta s_W M_Z & -s_\delta s_\beta s_W M_Z & m_X c_\delta^2 + m_1 s_\delta^2 - 2M_{XY} c_\delta s_\delta & M_1 c_\delta - M_2 s_\delta \\
M_2 & 0 & 0 & 0 & M_1 c_\delta - M_2 s_\delta & 0
\end{array}\right)$$

- The input parameters of the $U(1)_X$-extended MSSM/SUGRA with hidden sector matter are taken to be

$$m_0, \quad A_0, \quad m_1, \quad m_2, \quad m_3, \quad \tan\beta, \quad \text{sgn}(\mu), \quad M_1, \quad m_X, \quad M_\psi, \quad B_\psi, \quad \delta, \quad g_X$$

- Scan the parameter space of the model while imposing the Higgs boson mass and relic density constraints
- The hidden and visible sectors communicate via the small gauge kinetic mixing δ and mass mixing $\propto \epsilon = M_2/M_1$
- Choices of g_X and mass of Z' are constrained by experiment with

$$\frac{m_{Z'}}{g_X} \gtrsim 12 \text{ TeV}$$

- The Z boson mass receives a correction due to gauge kinetic and mass mixings such that

$$M_-^2 \simeq M_Z^2 + \frac{\epsilon}{2} g_Y^2 v^2 \frac{s_\delta}{c_\delta} + \frac{1}{4} g_2^2 v^2 \left(\frac{\epsilon}{\kappa}\right)^2$$

The extended MSSM/SUGRA sparticle spectrum

Model	h	$\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm$	$\tilde{\tau}$	$\tilde{\chi}_5^0$	$\tilde{t}$	$\tilde{g}$	A	Ωh^2	$(\Omega h^2)_\chi$	$(\Omega h^2)_\psi$
(a)	123.3	455.9	457.1	8109	1245	6343	8408	305.8	0.124	0.022	0.102
(b)	123.3	322.6	324.9	2115	1008	5898	8195	351.8	0.101	0.012	0.089
(c)	123.1	258.9	262.6	665.6	1015	4565	6855	408.9	0.116	0.009	0.107
(d)	124.0	354.8	356.4	8425	1250	6573	5467	450.8	0.117	0.019	0.098
(e)	123.9	639.5	642.2	1875	851.5	4943	7712	504.2	0.106	0.042	0.064
(f)	124.7	544.3	545.7	4982	1055	4314	5803	547.3	0.125	0.031	0.094
(g)	123.1	212.4	215.3	1906	601.8	4646	6229	604.2	0.118	0.006	0.112
(h)	125.0	289.1	290.5	4426	775.5	6109	8565	650.9	0.121	0.009	0.112
(i)	124.3	510.8	512.9	1627	1276	3077	5292	702.7	0.118	0.028	0.090
(j)	125.0	231.5	233.7	1845	1041	2335	5164	750.3	0.113	0.008	0.105

Table: Display of the SM-like Higgs boson mass, the stau mass, the relevant electroweak gaugino masses, the CP odd Higgs mass and the relic density for the ten benchmarks computed at the electroweak scale. All masses are in GeV.

A. Aboubrahim and P. Nath, PRD **100**, 015042 (2019) [arXiv:1905.04601 [hep-ph]]

- High scale models with DM candidates must satisfy the current DM relic density $\Omega h^2 = 0.1198 \pm 0.0012$ N. Aghanim et al. [Planck Collaboration], arXiv:1807.06209 [astro-ph.CO]
- Model gives two DM candidates: a neutralino LSP, χ, belonging to the visible sector and a Dirac fermion ψ of the hidden sector
- The main processes that enter in the neutralino and Dirac fermion relic abundance are

$$\begin{aligned} \chi\chi &\longleftrightarrow \text{SM SM}, & (\textit{dominant}) \\ \psi\bar{\psi} &\longleftrightarrow \text{SM SM}, & (\textit{subdominant}) \\ \psi\bar{\psi} &\longleftrightarrow \chi\chi\,. & (\textit{negligible}) \end{aligned}$$

- The total relic density can be expressed as

$$\Omega h^2 = (\Omega h^2)_\chi + (\Omega h^2)_\psi \simeq \frac{C_\chi}{\int_0^{x_f^\chi} \langle \sigma v \rangle_{\chi\chi} dx} + \frac{C_\psi}{\int_0^{x_f^\psi} \langle \sigma v \rangle_{\psi\bar{\psi}} dx}$$

E. Aprile et al. [XENON Collaboration], Phys. Rev. Lett. 121, no. 11, 111302 (2018) doi:10.1103/PhysRevLett.121.111302 [arXiv:1805.12562 [astro-ph.CO]]

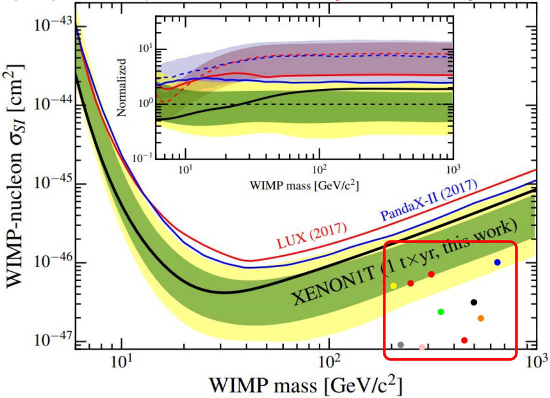


Figure: The SI proton-neutralino cross section exclusion limits as a function of the LSP mass from XENON1T. The ten benchmarks are overlaid on the plot showing them lying below the upper limit (black curve).

- The full CP-conserving Higgs scalar potential in the extended model can be written as

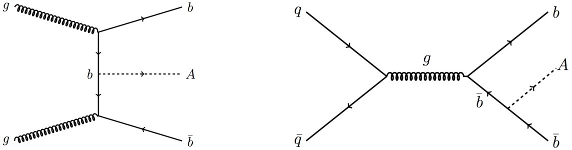
$$V_H = \left[|\mu|^2 + m^2_{H_d} - \frac{1}{2} g_Y \rho M_1 (\epsilon - s_\delta)\right] |H_d|^2 + \left[|\mu|^2 + m^2_{H_u} + \frac{1}{2} g_Y \rho M_1 (\epsilon - s_\delta)\right] |H_u|^2$$
$$- B\epsilon_{ij}(H^i_u H^j_d + \text{h.c.}) + \left(\frac{g^2_Y c^2_\delta + g^2_2}{8}\right)(|H_d|^2 - |H_u|^2)^2 + \frac{1}{2} g^2_2 |H^\dagger_d H_u|^2$$
$$+ \frac{1}{2}(M^2_1 + M^2_2 + m^2_\rho)\rho^2 + \Delta V_{\text{loop}}$$

- The neutral components of the Higgs doublets and the scalar ρ can be expanded around their VEVs so that

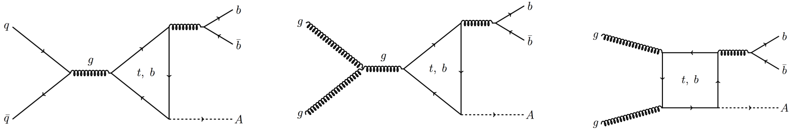
$$H^0_d = \frac{1}{\sqrt{2}}(v_d + \phi_d + i\psi_d), \quad H^0_u = \frac{1}{\sqrt{2}}(v_u + \phi_u + i\psi_u), \quad \rho = v_\rho + \phi_\rho$$

- As a result of EWSB and the Stueckelberg mass growth, the Higgs sector has six degrees of freedom: 3 CP even Higgs, h, H and ρ and one CP odd Higgs A and 2 charged Higgs $H^\pm$

- For $\tan\beta \gtrsim 10$, the H, A Yukawa couplings to bottom quarks and tau leptons are strongly enhanced, hence we study $b\bar{b}A$ production



The leading order (LO) partonic processes $gg \to b\bar{b}A$, $q\bar{q} \to b\bar{b}A$ (4FS)



- Absorbing potential large logarithms to all orders in α_S constitute the 5FS approach: $b\bar{b} \to A$ (zeroth order in α_S)

- Branching ratio of $A \to \tau\tau$ for the ten benchmarks range from ~ 0.09 to 0.123
- Stringent limits are set on the mass of A from ATLAS and CMS especially in the large $\tan\beta$ regime
- All ten benchmarks considered in this analysis are not yet excluded by experiments
- The final states investigated constitute of two hadronically decaying τ's with two b-tagged jets [$p_T(b) > 20$ GeV, $|\eta(b)| < 2.5$ and $p_T(\tau_h) > 15$ GeV]
- We exploit BDTs (`AdaBoost`) to discriminate between signal and background using a set of eight kinematic variables

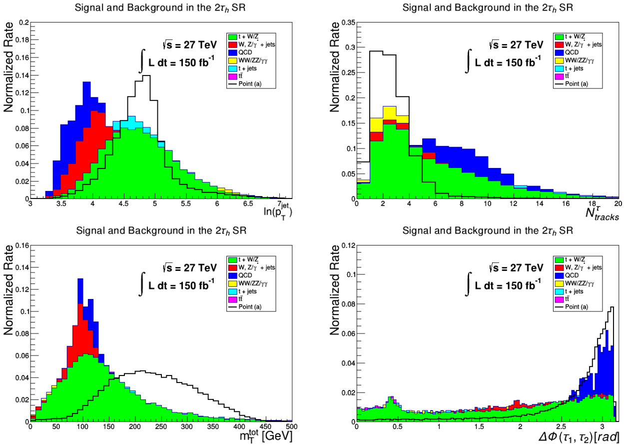


Figure: Distributions normalized to the bin size of four kinematic variables for benchmark (a) at 27 TeV: $\ln(p_T^{\text{jet}})$, N^{τ}_{tracks}, m_T^{tot} and $\Delta\phi(\tau_{h1},\tau_{h2})$ in the $2\tau_h$ signal region (SR).

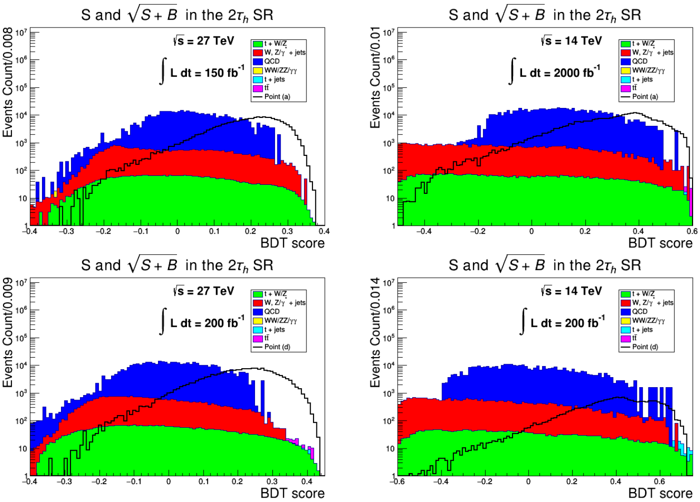
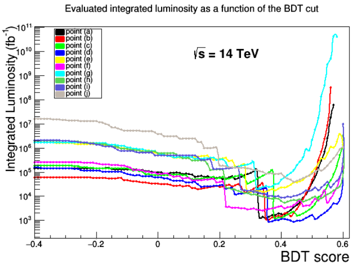
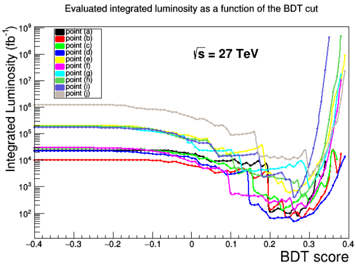


Figure: Distributions in the BDT score for benchmarks (a) and (d)


Evaluated integrated luminosity as a function of the BDT cut
√s = 14 TeV
Integrated Luminosity (fb⁻¹)
BDT score
point (a)
point (b)
point (c)
point (d)
point (e)
point (f)
point (g)
point (h)
point (i)
point (j)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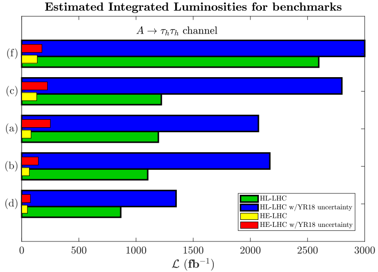
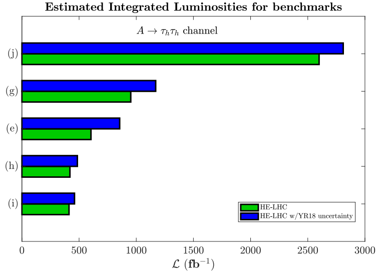
point (j)


Estimated Integrated Luminosities for benchmarks
A → τhτh channel
(f)
(c)
(a)
(b)
(d)
HL-LHC
HL-LHC w/YR18 uncertainty
HE-LHC
HE-LHC w/YR18 uncertainty
ℒ (fb⁻¹)


Estimated Integrated Luminosities for benchmarks
A → τhτh channel
(j)
(g)
(e)
(h)
(i)
HE-LHC
HE-LHC w/YR18 uncertainty
ℒ (fb⁻¹)

Conclusions

- We presented a $U(1)_X$ extension of the MSSM/SUGRA with hidden sector matter
- In this model, DM is made of two components: a neutralino from the visible sector and a Dirac fermion from the hidden sector
- A small μ leads to a higgsino-like neutralino with a small relic abundance. The relic density is saturated due to the Dirac fermion
- Scenarios with small μ support naturalness and lead to light CP odd Higgs with visible signatures at the LHC
- We showed that half the points can be discovered at HL-LHC while all of them are within the reach of HE-LHC with reduced run time

BACKUP SLIDES

- The prototype Stueckelberg Lagrangian couples one abelian vector boson A_μ to one pseudo-scalar σ in the following way

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}(mA_\mu + \partial_\mu\sigma)(mA^\mu + \partial^\mu\sigma)$$

which is gauge invariant if σ transforms together with A_μ according to

$$\delta A_\mu = \partial_\mu\epsilon, \quad \delta\sigma = -m\epsilon$$

- Add a gauge fixing term $\mathcal{L}_{\rm gf} = -\frac{1}{2\xi}(\partial_\mu A^\mu + \xi m\sigma)^2$ so that the total Lagrangian reads

$$\begin{aligned}\mathcal{L} + \mathcal{L}_{\rm int} + \mathcal{L}_{\rm gf} =& -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{m^2}{2}A_\mu A^\mu - \frac{1}{2\xi}(\partial_\mu A^\mu)^2 \\ & -\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \xi\frac{m^2}{2}\sigma^2 + gJ_\mu A^\mu\end{aligned}$$

- We assume a Stueckelberg mass mixing between the $U(1)_X$ and $U(1)_Y$ sectors so that

$$\mathcal{L}_{\rm St} = \int d\theta^2 d\bar{\theta}^2 (M_1 C + M_2 B + S + \bar{S})^2$$

We note that $\mathcal{L}_{\rm St}$ is invariant under $U(1)_Y$ and $U(1)_X$ gauge transformation so that,

$$\delta_Y B = \Lambda_Y + \bar{\Lambda}_Y, \quad \delta_Y S = -M_2 \Lambda_Y,$$
$$\delta_X C = \Lambda_X + \bar{\Lambda}_X, \quad \delta_X S = -M_1 \Lambda_X$$

- In component notation, $\mathcal{L}_{\rm St}$ is

$$\mathcal{L}_{\rm St} = -\frac{1}{2}(M_1 C_\mu + M_2 B_\mu + \partial_\mu a)^2 - \frac{1}{2}(\partial_\mu \rho)^2 - i\chi\sigma^\mu \partial_\mu \bar{\chi} + 2|F|^2$$
$$+ \rho(M_1 D_C + M_2 D_B) + \bar{\chi}(M_1 \bar{\lambda}_C + M_2 \bar{\lambda}_B) + \chi(M_1 \lambda_C + M_2 \lambda_B)$$

In unitary gauge the axion field a is absorbed to generate mass for the $U(1)_X$ gauge boson

- We introduce the Majorana spinors, ψ_S, λ_X and λ_Y so that

$$\psi_S = \begin{pmatrix} \chi_\alpha \\ \bar{\chi}^{\dot{\alpha}} \end{pmatrix}, \quad \lambda_X = \begin{pmatrix} \lambda_{C\alpha} \\ \bar{\lambda}_C^{\dot{\alpha}} \end{pmatrix}, \quad \lambda_Y = \begin{pmatrix} \lambda_{B\alpha} \\ \bar{\lambda}_B^{\dot{\alpha}} \end{pmatrix}$$

- In addition to the above we add a soft SUSY breaking term to the Lagrangian so that

$$\Delta\mathcal{L}_{\rm soft} = -\left(\frac{1}{2}m_X\bar{\lambda}_X\lambda_X + M_{XY}\bar{\lambda}_X\lambda_Y\right) - \frac{1}{2}m_\rho^2\rho^2,$$

  where m_X is mass of the $U(1)_X$ gaugino and M_{XY} is the $U(1)_X$-$U(1)_Y$ mixing mass
- In the unitary gauge, the axion field a is absorbed to generate mass for the $U(1)_X$ gauge boson so that $M_{Z'} \sim M_1$

- After spontaneous electroweak symmetry breaking and the Stueckelberg mass growth the 3×3 mass squared matrix of neutral vector bosons in the basis $(C'_\mu, B'_\mu, A^3_\mu)$ is given by

$$\mathcal{M}_V^2 = \begin{pmatrix} M_1^2\kappa^2 + \frac{1}{4}g_Y^2 v^2 s_\delta^2 & M_1 M_2 \kappa - \frac{1}{4}g_Y^2 v^2 s_\delta & \frac{1}{4}g_Y g_2 v^2 s_\delta \\ M_1 M_2 \kappa - \frac{1}{4}g_Y^2 v^2 s_\delta & M_2^2 + \frac{1}{4}g_Y^2 v^2 & -\frac{1}{4}g_Y g_2 v^2 \\ \frac{1}{4}g_Y g_2 v^2 s_\delta & -\frac{1}{4}g_Y g_2 v^2 & \frac{1}{4}g_2^2 v^2 \end{pmatrix}$$

- The Z boson mass receives a correction due to gauge kinetic and mass mixings. Knowing that $M_2 \ll M_1$ and $s_\delta \ll 1$, we can write M_-^2 as

$$M_-^2 \simeq M_Z^2 + \frac{\epsilon}{2} g_Y^2 v^2 \frac{s_\delta}{c_\delta} + \frac{1}{4} g_2^2 v^2 \left(\frac{\epsilon}{\kappa}\right)^2$$

The 27 TeV collider: HE-LHC

- The High Energy LHC (HE-LHC) is a possible candidate as the next generation *pp* collider at CERN
- Uses the existing LHC ring with 16 T FCC magnets replacing the current 8.3 T ones
- Center-of-mass energy boosted to 27 TeV with a design luminosity $\sim$ 5 times that of the HL-LHC
- This set up necessarily means that a larger part of the parameter space of supersymmetric models beyond the reach of the 14 TeV collider will be probed

The input parameters from the hidden sector and the visible sector (MSSM)

Model	m_0	A_0	m_1	m_2	m_3	μ	M_1	m_X	M_ψ	B_ψ	$\tan\beta$	g_X	δ
(a)	8115	-7477	6785	9115	4021	423	1261	27	627	9283	6	0.06	0.02
(b)	1743	898	4551	2160	4084	301	-1086	27	627	5167	10	0.07	0.02
(c)	1056	-920	1706	3417	3396	243	1059	89	525	2846	10	0.03	0.01
(d)	8424	-2488	6165	3544	2466	330	-1469	473	733	4680	12	0.03	0.01
(e)	2011	-2462	3008	5030	3833	598	875	38	425	3248	9	0.06	0.06
(f)	4637	-4045	7004	5480	2727	511	-1230	372	613	7557	15	0.04	0.04
(g)	819	477	7847	1218	3040	201	820	509	401	3425	12	0.05	0.09
(h)	3881	-2580	7449	4870	4429	268	850	152	419	9199	13	0.08	0.02
(i)	1349	-2722	3938	4420	2558	482	1292	19	636	4235	15	0.07	0.08
(j)	2015	-4435	2695	5399	2470	217	1343	690	670	4587	11	0.03	0.03

Table: Input parameters for the benchmarks used in this analysis. Here $M_{XY} = 0 = B$ at the GUT scale and M_2 is chosen at the GUT scale so that it is nearly vanishing at the electroweak scale. All masses are in GeV.

Model	$\sigma^{\rm 4FS}_{\rm NLO}(pp \to b\bar{b}A)$ 14 TeV	$\sigma^{\rm 4FS}_{\rm NLO}(pp \to b\bar{b}A)$ 27 TeV	$\sigma^{\rm 5FS}_{\rm NNLO}(pp \to A)$ 14 TeV	$\sigma^{\rm 5FS}_{\rm NNLO}(pp \to A)$ 27 TeV	$\sigma^{\rm matched}$ 14 TeV	$\sigma^{\rm matched}$ 27 TeV	$\mu_F = \mu_R$ (4FS only)	$\bar{m}_b$ (4FS only)
(a)	$649.4^{+4.1\%}_{-5.8\%}$	$2388^{+2.1\%}_{-5.4\%}$	$982.0^{+3.8\%}_{-4.2\%}$	$3538^{+4.0\%}_{-4.9\%}$	$881.0^{+3.9\%}_{-4.7\%}$	$3188^{+3.5\%}_{-5.1\%}$	78.5	2.91
(b)	$996.9^{+4.3\%}_{-5.8\%}$	$3926^{+1.9\%}_{-5.0\%}$	$1565^{+3.5\%}_{-3.6\%}$	$5963^{+3.6\%}_{-4.1\%}$	$1400^{+3.7\%}_{-4.3\%}$	$5369^{+3.1\%}_{-4.4\%}$	90.0	2.88
(c)	$521.0^{+4.5\%}_{-6.3\%}$	$2201^{+1.9\%}_{-4.6\%}$	$846.1^{+3.3\%}_{-3.3\%}$	$3440^{+3.4\%}_{-3.7\%}$	$755.4^{+3.6\%}_{-4.2\%}$	$3094^{+3.7\%}_{-3.2\%}$	104.3	2.84
(d)	$497.0^{+5.2\%}_{-7.0\%}$	$2200^{+2.9\%}_{-4.7\%}$	$808.9^{+3.1\%}_{-3.1\%}$	$3442^{+3.2\%}_{-3.3\%}$	$724.2^{+3.7\%}_{-4.1\%}$	$3105^{+3.1\%}_{-3.7\%}$	114.8	2.82
(e)	$165.2^{+5.4\%}_{-7.0\%}$	$777.8^{+3.0\%}_{-4.5\%}$	$277.2^{+3.0\%}_{-2.9\%}$	$1247^{+3.0\%}_{-3.1\%}$	$247.7^{+3.6\%}_{-4.0\%}$	$1123^{+3.0\%}_{-3.5\%}$	128.1	2.79
(f)	$313.2^{+5.0\%}_{-7.5\%}$	$1524^{+2.8\%}_{-4.3\%}$	$530.8^{+2.9\%}_{-2.8\%}$	$2493^{+2.9\%}_{-3.0\%}$	$474.6^{+3.4\%}_{-4.0\%}$	$2243^{+2.9\%}_{-3.3\%}$	138.9	2.77
(g)	$125.1^{+5.1\%}_{-7.8\%}$	$649.6^{+3.4\%}_{-4.7\%}$	$219.6^{+2.8\%}_{-2.7\%}$	$1090^{+2.8\%}_{-2.8\%}$	$195.9^{+3.4\%}_{-4.0\%}$	$979.4^{+2.9\%}_{-3.3\%}$	153.1	2.75
(h)	$93.2^{+5.1\%}_{-8.5\%}$	$555.0^{+3.5\%}_{-4.9\%}$	$182.0^{+2.7\%}_{-2.6\%}$	$944.2^{+2.7\%}_{-2.7\%}$	$160.1^{+3.3\%}_{-4.1\%}$	$848.0^{+2.90\%}_{-3.3\%}$	164.8	2.74
(i)	$92.8^{+5.2\%}_{-8.4\%}$	$529.9^{+3.7\%}_{-5.2\%}$	$164.1^{+2.6\%}_{-2.6\%}$	$892.8^{+2.6\%}_{-2.7\%}$	$146.8^{+3.3\%}_{-4.0\%}$	$804.8^{+2.9\%}_{-3.3\%}$	177.8	2.72
(j)	$35.8^{+5.2\%}_{-8.5\%}$	$213.5^{+3.8\%}_{-5.4\%}$	$65.5^{+2.5\%}_{-2.6\%}$	$371.9^{+2.6\%}_{-2.6\%}$	$58.4^{+3.2\%}_{-4.0\%}$	$334.1^{+2.9\%}_{-3.3\%}$	189.7	2.71

Table: The production cross-sections, in fb, of the CP odd Higgs in the four flavor scheme at NLO (in association with bottom quarks) and in the five flavor scheme at NNLO along with the matched values at $\sqrt{s} = 14$ TeV and $\sqrt{s} = 27$ TeV for the ten benchmarks. The running b-quark mass, in GeV, is also shown evaluated at the factorization and normalization scales, $\mu_F = \mu_R$ (in GeV).

Variables used in training BDTs

1. The total transverse mass of the di-tau system is given by

$$m_T^{\rm tot} = \sqrt{m_T^2(E_T^{\rm miss}, \tau_{h1}) + m_T^2(E_T^{\rm miss}, \tau_{h2}) + m_T^2(\tau_{h1}, \tau_{h2})},$$

   where

$$m_T(i,j) = \sqrt{2p_T^i p_T^j(1-\cos\Delta\phi_{ij})}$$

2. The hadronic di-tau invariant mass, $m_{\tau_h\tau_h}$
3. The angular separation $\Delta\phi(\tau_{h1}, \tau_{h2})$ between the leading and sub-leading hadronic tau jets
4. The number of charged tracks associated with the leading tau, $N^\tau_{\rm tracks}$
5. Due to the presence of b-tagged jets, we use the number of such jets, $N^b_{\rm jet}$, as a discriminating variable.

6. Due to the rich jetty final states, we define the variable $\ln(p_T^{\text{jet}})$ as

$$\ln(p_T^{\text{jet}}) = \begin{cases} \ln(p_T^{\text{jet}_1}) & \text{if} \quad N_{\text{jets}} \geq 1 \\ 0 & \text{if} \quad N_{\text{jets}} = 0 \end{cases} ,$$

where $p_T^{\text{jet}_1}$ is the p_T of the leading jet.

7. The di-jet transverse mass $m_T^{\text{di-jet}}$ of the leading and sub-leading jets
8. The effective mass defined as

$$m_{\text{eff}} = H_T + E_T^{\text{miss}} + p_T(\tau_{h1}) + p_T(\tau_{h2}),$$

where H_T is the sum of the hadronic p_T's in an event, $p_T(\tau_{h1})$ and $p_T(\tau_{h2})$ are the transverse momenta of the leading and sub-leading hadronic taus.

	$\mathcal{L}$ for 5σ discovery in $2\tau_h$ + b-jets	
Model	$\mathcal{L}$ at 14 TeV	$\mathcal{L}$ at 27 TeV
(a)	1221	82
(b)	1102	67
(c)	1195	131
(d)	866	50
(e)	...	604
(f)	2598	136
(g)	...	952
(h)	...	420
(i)	...	412
(j)	...	2599

Table: Comparison between the estimated integrated luminosity ($\mathcal{L}$) in fb^{-1} for a 5σ discovery at 14 TeV and 27 TeV for the CP odd Higgs following the selection criteria and BDT cut.