Higgs and the Dark Sector Searches at ATLAS and CMS

Efe Yiğitbaşı on behalf of ATLAS and CMS collaborations

22 October 2024 Extended Scalar Sectors From All Angles, CERN







The Higgs and the Dark Sectors

- The Higgs discovery at the LHC is one the most important developments of the past years in particle physics. ۲
 - First elementary scalar particle, offers unique windows to new physics searches
- Studying Higgs boson and its properties is extremely important ۲



Efe Yiğitbaşı



22/10/2024

Dark Sectors

- Overwhelming evidence for Dark Matter from astrophysics & cosmology •
 - No evidence from particle physics: **Particle nature is still a mystery!** •
- DM can be a particle from a larger "dark sector" of SM singlets •
 - With a "portal" between SM & DS via mediators •





Dark Sectors

ullet

Can be split into **simplified** and **extended** dark sector models



Efe Yiğitbaşı

A huge list of models with dark sectors within reach of the LHC experiments

•

•

Simplified models:

- Minimal set of parameters
- One DM + one mediator

Extended DS:

- A family of SM singlets that communicate with the SM thorough possible portals
- Rich structures in DS, rich phenomenology for experiments

A lot of results from ATLAS & CMS covering different models in the recent years. I will only cover a select few.







In SM: $\mathscr{B}(H_{125} \rightarrow \text{inv})$ is 0.1%

- Can be larger in BSM models with Higgs coupling to Dark Sectors.
- Latest combination results from ATLAS and CMS for Run 1 + Run 2
- Combining ggF, VBF, VH, ttH production modes
- Sensitivity is mostly driven by VBF channel



$H \rightarrow invisible$







- The upper limits can be interpreted in context of Higgs portal models to dark sectors
 - Translates into limits on m_{DM} and DM-nucleon cross sections for comparison to other DM experiments.
- ATLAS & CMS are more competitive in low DM mass phase space •



$H \rightarrow invisible$





Massless Dark Photons



JHEP 08 (2024) 153

- VBF and ZH channel results are combined under SM Higgs assumption
- Observed $\mathscr{B}(H_{125} \to \gamma \gamma_d)$ is 1.3%

•

- ggF and VBF results are combined under BSM Higgs hypothesis •
 - Assuming $\mathscr{B}(H_{BSM} \to \gamma \gamma_d) = 5 \%$, observed exclusion of $m_H < 1.6 \text{ TeV}$



Efe Yiğitbaşı

Massless Dark Photons





- a new U(1)'
- **Resolved** and **boosted** categories based on E_T^{miss}
- 1μ and 2l CRs to constrain the backgrounds



Efe Yiğitbaşı



ATLAS EXOT-2020-26



Efe Yiğitbaşı

Dark Higgs

CMS search for $X + p_T^{miss}$ for a massive dark Higgs boson (s) with $s \to W^+W^-$, and a new U(1)'Targets $m_s > 160 \text{ GeV}$

Both $WW \rightarrow 2l2\nu$ and $WW \rightarrow l\nu qq$ are considered using single and double lepton triggers

 $WW \rightarrow 2l2\nu$: m_{ll} and transverse mass of l_{min} + p_T^{miss} system $m_T^{l_{min}, p_T^{miss}}$

 $WW \rightarrow l\nu qq$: BDT discriminator using 13 kinematic features

Results are interpreted for a similar benchmark scenario to ATLAS with different m_{γ} values

For $m_{\gamma} = 200 \text{ GeV}$, $m_{Z'} < 2.2 \text{ TeV}$ is excluded for $m_s = 160 \text{ GeV}$









tt +

g



2

Events / Bin

Bkg.

Data

- CMS search for $t\bar{t} + p_T^{miss}$ for simplified models with scalar and pseudo-scalar portals
- Yukawa-like couplings to SM quarks with top couplings favored
- Considering all hadronic, semi-leptonic, and dileptonic channels
- Both $t\bar{t} + p_T^{miss}$ and $t + p_T^{miss}$ are probed
- All hadronic and semi-leptonic: p_T^{miss} discriminator
- dileptonic: NN based discriminator using kinematic variables
- Scalar (pseudo-scalar) masses are excluded below 280 (290) GeV

•

•

miss



Scalar and Pseudo-Scalar Mediators

- final state excluding mediator masses up to 400 GeV



•



DarkSide-50 QF MIGE

m.,<8 GeV: PRL 130 (2023) 02180

Expected

Observed

 $b\overline{b}+E_{T}^{miss}$ 0L, (1) JHEP 05 (2021) 093 $Jet+E_{T}^{miss}$, (2) PRD 103 (2021) 112006 $tW + E_{T}^{miss} 0L - 1L, (3)$ EPJC 83 (2023) 603 $tj + E_{\tau}^{miss}$ 1L, (3) EPJC 81 (2021) 860 $tW+E_{T}^{miss}$ 2L, (3) EPJC 81 (2021) 860 $t\bar{t}H/A \rightarrow 4$ -top, (4) HEP 07 (2023) 203 $t\bar{t}+E_T^{miss}, (3)$ EPJC 83 (2023) 503 JHEP 03 (2024) 139 (2) DM-monojet

2HDM+a Signatures: $b\bar{b} + p_T^{miss}$

- CMS search for $b\bar{b} + p_T^{miss}$ motivated by 2HDM+a models
 - A/a b coupling is enhanced for large $tan(\beta)$
- 1b or 2b signal regions with large p_T^{miss} and CRs to constrain Z + jets, W + jets, and $t\bar{t}$ backgrounds
- . 1*b* SR: p_T^{miss} (or $U = |\vec{p}_T^{miss} + \sum \vec{p}_T^{\ell}|$ for CRs) as discriminator

$$2b$$
 SR: $\cos \Theta^* = | \tanh\left(\frac{\eta_{j1} - \eta_{j2}}{2}\right) |$ as discriminator

• For a 2HDM+a model, $m_a < 260$ GeV is excluded at high $tan(\beta)$ phase space





2HDM Signatures: $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$

- ATLAS search for a heavy scalar (H) or pseudo-scalar (A) in $t\bar{t}t\bar{t}$ final state
 - For $m_{H/A} > 500$ GeV and $\tan \beta \sim 1$ dominant decay is $t\bar{t}$
- 1L channel: One lepton (*e* or μ) and >7 jets
- 2LOS channel: Two opposite charge leptons and >5 jets
- Channels further split into categories based on # of b-tagged jets
- Signal and background classification using GNNs parametrised in $m_{H/A}$
- Results are combined with a previous search with 2 same-sign leptons (2LSS) or multi leptons (ML) channels for a 2HDM model setting upper limits on the cross-sections as a function of $m_{H/A}$



Efe Yiğitbaşı







ATLAS EXOT-2022-13



2HDM Signatures: $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$

- ATLAS search for a heavy scalar (H) or pseudo-scalar (A) in $t\bar{t}t\bar{t}$ final state
 - For $m_{H/A} > 500$ GeV and $\tan \beta \sim 1$ dominant decay is $t\bar{t}$
- 1L channel: One lepton (*e* or μ) and >7 jets
- 2LOS channel: Two opposite charge leptons and >5 jets
- Channels further split into categories based on # of b-tagged jets
- Signal and background classification using GNNs parametrised in $m_{H/A}$
- Results are combined with a previous search with 2 same-sign leptons (2LSS) or multi leptons (ML) channels for a 2HDM model setting upper limits on the cross-sections as a function of $m_{H/A}$











- Structure of DS can lead to new and rich phenomenology •
- Very weak couplings to SM and low masses, compressed ٠ spectra:
 - Long-lived particles (LLPs)
- Unconventional detector signatures and unusual • backgrounds
 - Dedicated strategies for triggering, reconstruction, and background estimation are often necessary

LLPs in Dark Sectors





Displaced Vertices

- ATLAS search for hadronically decaying neutral LLPs leading to displaced vertices (DV)
 - Higgs portal (w/ VH and VBF production): $H \rightarrow ss \rightarrow q\bar{q}q\bar{q}$ •
 - ALP coupling to W/Z or up-type quarks
- Displaced and prompt jets are identified with a **BDT classifier using jet level features**. Selected displaced jets are associated to reconstructed DVs
- Higgs portal benchmark limits are stronger than previous results by **up to a factor of 20**
 - Driven by improvements in large-impact parameter track reconstruction, addition of 1-lepton and VBF regions, and inclusion of $n_{DV} = 1$ SR.
- For $H \rightarrow ss \rightarrow 4b$ BR > 1% are excluded for $m_s = 55$ GeV and $6 < c\tau_s < 68$ mm
- $\mathscr{B}(H \to ss \to 4c) > 10\%$ excluded for $m_s = 5$ GeV and $3 < c\tau_s < 20$ mm







Displaced Calorimeter Jets



ATLAS search for hadronically decaying neutral LLPs leading to displaced jets in calorimeter

- Hidden Sector (w/ VH and ggF production): $\Phi \rightarrow ss \rightarrow q\bar{q}q\bar{q}$
- ALP coupling to W/Z
- Long-lived massive dark photon Z_d
- Neutral LLPs decaying after electromagnetic calorimeter \rightarrow High hadronic to electromagnetic energy ratio (CalRatio)
- CalRatio + 2 jets, CalRatio + W, CalRatio + Z channels using CalRatio, single lepton, and dilepton triggers
- Jet level NN classifier to distinguish signal-like displaced jets from backgrounds
- **Event level NN and BDTs** are trained to separate signal and background events
- Hidden Sector model limits exclude $\mathscr{B}(\Phi \to ss) > 1\%$ for $30 < c\tau_s < 450$ cm improving previous limits by a factor of 3.
 - Extends sensitivity to longer lifetimes compared to displaced vertices search



 ℓ/ν



Emerging jets

- CMS search for emerging jets (EJ) in models with long-lived dark hadrons decaying to SM particles
 - Multiple displaced vertices in a jet
- Yukawa-like coupling between heavy mediator, dark quarks, and SM quarks
 - **Unflavored**: only couplings to down quark
 - **Flavor-aligned**: Universal coupling to d/s/b
- Cut based and GNN based EJ tagging used for both model-agnostic and model specific results
- Selecting events with high H_T , at least 4 jets with at least 2 EJ
- . Unflavored: $m_{X_{dark}} < 1950$ GeV excluded for $c\tau_{\pi_{dark}} \approx 100$ mm and $m_{\pi_{dark}} = 10$ GeV
- . Flavor-aligned: $m_{X_{dark}} < 1850$ GeV excluded for $c\tau_{\pi_{dark}} \approx 500$ mm and $m_{\pi_{dark}} = 10$ GeV



JHEP 07 (2024) 142



Muon showers

- CMS Run 2 search for particle showers by LLP decays in muon systems in models with both $H \rightarrow SS$ and $H \to \Psi \Psi$
- Using muon detectors as sampling calorimeters, ٠
- Trigger on p_T^{muss} , and form clusters of hits in drift tubes (barrel) and cathode strip chambers (endcap) •
- Number of hits in a cluster is used to discriminate signal and background ٠
- Lower level of backgrounds compared to displaced vertex searches and equal sensitivity to different m_{LLP}
- Results are complementary with emerging jets search



Efe Yiğitbaşı



1750

2000

1500

20

2250 2500

m_∲ [GeV]





- CMS early Run 3 result for displaced jets using new trigger and reconstruction techniques
 - New displaced jet triggers: factor 5-10 gain in efficiency compared to Run 2
 - New displaced vertex reconstruction and GNN based LLP taggers
- Displaced dijet GNN score is used to define the signal region
- Limits are set on $H \to SS$ with $S \to b\bar{b}$, $S \to d\bar{d}$, and $S \to \tau\tau$
 - First displaced τ_h exclusion for decay lengths smaller than ≈ 1 m
 - Order of magnitude better results than CMS Run 2 combination with $\sim 1/4$ of the data



Efe Yiğitbaşı

Displaced Jets in Tracker







Displaced Dimuons

CMS early Run 3 result for displaced dimuons from LLP decays using new triggers

- Improved trigger efficiency up to a factor of 4 compared to Run 2
- Using a combination of tracker+muon system and muon system only muons
- Sensitivity to a wide range of LLP $c\tau$
- Results are interpreted for HAHM and RPV SUSY models
 - **Run 3 limits are already better than Run 2 limits** with $\sim 1/3$ of the data for large $c\tau$











$H \rightarrow LLP$ Summary Plots

- A lot of different searches in ATLAS and CMS targeting $H \rightarrow LLP$ signatures
 - Selection of the most sensitive results from Run 2 and early Run 3 are shown in summary plots spanning a large range of lifetimes
 - More Run 3 results will follow!



Efe Yiğitbaşı





Eur. Phys. J. C 82 (2022) 2

 $B(X \rightarrow \mu\mu) = 0.13, m_y = 40 \text{ GeV}$ JHEP 04 (2022) 062 **Displaced dimuon**

 $B(X \rightarrow \mu\mu) = 0.13, m_{y} = 40 \text{ GeV}$ arXiv:2402.14491

- Z + displaced jets $X \rightarrow bb, m_{\gamma} = 55 \text{ GeV}$ JHEP 03 (2022) 160
- Displaced jets
- $X \rightarrow dd, m_{\sim} = 55 \text{ GeV}$ Phys. Rev. D 104 (2021) 1
- $X \rightarrow \tau \tau$, m_v = 55 GeV
- $X \rightarrow bb, m_{\gamma} = 55 \text{ GeV}$
- Eur. Phys. J. C 83 (2023) 933
- 95% CL Upper Limit **Displaced leptons** $B(X \rightarrow ee) = B(X \rightarrow \mu\mu) = 0.5$ $m_{x} = 30.0 \text{ GeV}$ Eur. Phys. J. C 82 (2022) 2 Dimuon scouting $B(X \rightarrow \mu\mu) = 0.14, m_{y} = 20 \text{ GeV}$ JHEP 04 (2022) 062 Displaced dimuon $B(X \rightarrow \mu\mu) = 0.14, m_{y} = 20 \text{ GeV}$ arXiv:2402.14491 Z + displaced jets $X \rightarrow bb, m_{y} = 15 \text{ GeV}$ JHEP 03 (2022) 160 Displaced jets $X \rightarrow dd, \, m_{\!\scriptscriptstyle \nabla} = 15 \; GeV$ Phys. Rev. D 104 (2021) 1 MS Clusters
- $X \rightarrow \tau \tau$, m_x = 15 GeV arXiv:2402.01898
- MS Clusters
- arXiv:2402.01898
- Eur. Phys. J. C 83 (2023) 933



CMS





Summary & Outlook

- Extensive search program at the LHC to investigate Higgs properties and dark sectors ٠
- Impressive results, including combination results, using full Run 2 dataset from ATLAS and CMS exclude huge amounts of BSM parameter space
- **Innovative strategies in Run 3** to substantially increase sensitivity to unconventional final state signatures
 - extensive use of ML methods
- Early Run 3 results already show the impact of new developments, improving on Run 2 results with a fraction of the dataset
- Many more searches are in progress with the Run 3 dataset •
 - **Exciting new results are expected**
- HL-LHC era is around the corner with significant improvements in detectors and trigger systems • Significantly improved sensitivities to unconventional final states

Exciting developments in triggering, reconstruction, and analysis techniques making



BACKUP

Dark Sector Summary





LLP Summary Plots

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

ATLAS Preliminary

Status: March 2023

St	atus: March 2023				$\int \mathcal{L} dt = (32.8 - 139) \text{ fb}^{-1}$	\sqrt{s} = 13 TeV	Overview of CMS long-lived particle searches	
	Model	Signature ∫£ d	lt [fb ⁻¹]	Lifetime limit		Reference	CMS Preliminary	,
	RPV ${ ilde t} o \mu q$	displaced vtx + muon 13	36 t̃ lifetime	0.003-	6.0 m $m(\tilde{t}) = 1.4 \text{ TeV}$	2003.11956	UDD, $\ddot{g} \rightarrow tbs$, $m_d = 2500 \text{ GeV}$ \ddot{g} 2104.13474 (jets with displaced vertices) 0.0006-0.09 m	
	RPV ${ ilde \chi}^0_1 o eev/e\mu v/\mu\mu v$	v displaced lepton pair 32.	2.8 $\tilde{\chi}_1^0$ lifetime	0.003-1.0 m	$m(ilde{q}){=}$ 1.6 TeV, $m(ilde{\chi}^0_1){=}$ 1.3 TeV	1907.10037	UDD, $\ddot{g} \rightarrow tbs$, $m_{d} = 2500 \text{ GeV}$ \ddot{g} 2012.01581 (Displaced jets) 0.003-1 m UDD, $\ddot{t} \rightarrow dd$, $m_{\tilde{t}} = 1600 \text{ GeV}$ \ddot{t} 2104.13474 (Jets with displaced vertices) 0.00035-0.08 m	
	$RPV{ ilde\chi}^0_1 o qqq$	displaced vtx + jets 13	39 $ ilde{\chi}_1^0$ lifetime	0.001	135-9.0 m $m({ ilde \chi}_1^0){=}$ 1.0 TeV	2301.13866	UDD, $t \rightarrow dd$, $m_{\tilde{t}} = 1600 \text{ GeV}$ UDD, $t \rightarrow dd$, $m_{\tilde{t}} = 1600 \text{ GeV}$ UDD, $t \rightarrow dd$, $m_{\tilde{t}} = 1600 \text{ GeV}$ UDD, $t \rightarrow dd$, $m_{\tilde{t}} = 1600 \text{ GeV}$ UDD, $t \rightarrow dd$, $m_{\tilde{t}} = 1600 \text{ GeV}$ UDD, $t \rightarrow dd$, $m_{\tilde{t}} = 1600 \text{ GeV}$ UDD, $t \rightarrow dd$, $m_{\tilde{t}} = 1600 \text{ GeV}$ UDD, $t \rightarrow dd$, $m_{\tilde{t}} = 1600 \text{ GeV}$ UDD, $t \rightarrow dd$, $m_{\tilde{t}} = 1600 \text{ GeV}$ UDD, $t \rightarrow dd$, $m_{\tilde{t}} = 1600 \text{ GeV}$ UDD, $t \rightarrow dd$, $m_{\tilde{t}} = 1600 \text{ GeV}$ UDD, $t \rightarrow dd$, $m_{\tilde{t}} = 1600 \text{ GeV}$ UDD, $t \rightarrow dd$, $m_{\tilde{t}} = 1600 \text{ GeV}$	
	$\operatorname{GGM} \tilde{\chi}_1^0 \to Z \tilde{G}$	displaced dimuon 32.	.9 $ ilde{\chi}_1^0$ lifetime		0.029-18.0 m $m(\tilde{g}) = 1.1 \text{ TeV}, m(\tilde{\chi}_1^0) = 1.0 \text{ TeV}$	1808.03057	Column Column	
	GMSB	non-pointing or delayed γ 13	39 $ ilde{\chi}_1^0$ lifetime	0.24-2.4 m	$m({ ilde\chi}_1^0,{ ilde G})$ = 60, 20 GeV, ${\mathcal B}_{\mathcal H}$ = 2%	2209.01029	LQD, $t \rightarrow bl$, $m_{\ell} = 1600 \text{ GeV}$ t 2012.01581 (Displaced jets) 0.005-0.24 m	
	GMSB $\tilde{\ell} \to \ell \tilde{G}$	displaced lepton 13	39 $\tilde{\ell}$ lifetime	6-750 mm	$m(ilde{\ell}){=}$ 600 GeV	2011.07812	GMSB, $\ddot{g} \rightarrow g\ddot{G}$, $m_{\ddot{g}} = 2450 \text{ GeV}$ \ddot{g} 2012.01581 (Displaced jets) 0.006-0.55 m GMSB, $\ddot{g} \rightarrow q\ddot{G}$, $m_{\ddot{g}} = 2100 \text{ GeV}$ \ddot{g} 1906.06441 (Delayed jet + MET) 0.32-34 m	
USγ	GMSB $\tilde{\tau} \rightarrow \tau \tilde{G}$	displaced lepton 13	39 $\tilde{\tau}$ lifetime	9-270 mm	$m(ilde{\ell}){=}$ 200 GeV	2011.07812	Split SUSY, $\vec{g} \to q \bar{q} \chi_1^0$, $m_{\vec{g}} = 2500 \text{ GeV}$ Split SUSY, $\vec{g} \to q \bar{q} \chi_2^0$, $m_{\vec{g}} = 1300 \text{ GeV}$ Split SUSY, $\vec{g} \to q \bar{q} \chi_2^0$, $m_{\vec{g}} = 1300 \text{ GeV}$	
S	AMSB $pp \rightarrow \tilde{\chi}_1^{\pm} \tilde{\chi}_1^0, \tilde{\chi}_1^+ \tilde{\chi}$	$\overline{1}$ disappearing track 13	36 $\tilde{\chi}_1^{\pm}$ lifetime	0.06-3.06 m	$m(ilde{\chi}_1^{\pm}){=}$ 650 GeV	2201.02472	Split SUSY (HSCP), $f_{\bar{o}\sigma} = 0.1$, $m_{\bar{o}} = 1600$ GeV \ddot{g} CMS-PAS-EXO-16-036 (dE/dx)	
	AMSB $pp ightarrow { ilde\chi}_1^\pm { ilde\chi}_1^0, { ilde\chi}_1^\pm { ilde\chi}$	$\overline{1}$ large pixel dE/dx 13	39 $\tilde{\chi}_1^{\pm}$ lifetime	0.3-30.0 m	$m({ ilde \chi}_1^{\pm}){=}$ 600 GeV	2205.06013	$\mathbf{CMS-PAS-EXO-16-036} (\mathbf{dE/dx + TOF})$ $\mathbf{CMS-PAS-EXO-16-036} (\mathbf{dE/dx + TOF})$ $\mathbf{Stopped \ \tilde{t}, \ \tilde{t} \to t\chi_1^0, \ m_{\tilde{t}} = 700 \ \text{GeV} \qquad \qquad$	60
	Stealth SUSY	2 MS vertices 36.	5.1 Š lifetime	0.1-519 m	$\mathcal{B}(\tilde{g} ightarrow \tilde{S}g) = 0.1, \ m(\tilde{g}) = 500 \ \mathrm{GeV}$	1811.07370	Stopped $\ddot{g}, \ddot{g} \rightarrow q \ddot{q} \chi_{1}^{0}, f_{\bar{g}g} = 0.1, m_{\bar{g}} = 1300 \text{ GeV}$ Stopped $\ddot{g}, \ddot{g} \rightarrow q \ddot{q} \chi_{2}^{0} (\mu \mu \chi_{1}^{0}), f_{\bar{g}g} = 0.1, m_{\bar{g}} = 940 \text{ GeV}$ \ddot{g} 1801.00359 (Delayed jet) 1801.00359 (Delayed jet)	5 600
	Split SUSY	large pixel dE/dx 13	39 ĝ lifetime	> 0.45 m	$m(ilde{g}){=}$ 1.8 TeV, $m(ilde{\chi}_1^0){=}$ 100 GeV	2205.06013	AMSB, $\chi^{\pm} \rightarrow \chi_1^0 \pi^{\pm}$, $m_{\chi^{\pm}} = 700 \text{ GeV}$ χ^{\pm} $\tilde{\sigma} \rightarrow \sigma \tilde{\sigma} \gamma^0 \tau^{\pm}$, $m_{\chi^{\pm}} = 700 \text{ GeV}$ $\tilde{\sigma} \rightarrow \sigma \tilde{\sigma} \gamma^0 \tau^{\pm}$, $m_{\chi^{\pm}} = 1500 \text{ GeV}$, $m_{\chi^{\pm}} = 1575 \text{ GeV}$, $m_{\chi^{\pm}} = 1500 \text{ GeV}$	
	Split SUSY	displaced vtx + $E_{\rm T}^{\rm miss}$ 32.	.8 ĝ lifetime		0.03-13.2 m $m(\tilde{g}) = 1.8$ TeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1710.04901	$\vec{q} \rightarrow q_{X_1}^{\alpha} \text{ or } q'_{X_1}^{\pm}, \chi_1^{\pm} \rightarrow \chi_1^{\alpha} q'_{X_1} \gamma_{X_1}^{\alpha} q'_{X_1} \gamma_{X_1} \gamma_{X_1} \gamma_{X_1}^{\alpha} q'_{X_1} \gamma_{X_1} \gamma_{X_1$	
	Split SUSY	0ℓ , 2 – 6 jets + $E_{\rm T}^{\rm miss}$ 36.	5.1 <mark>ĝ lifetime</mark>	0.0-2.1 m	$m(ilde{g}){=}$ 1.8 TeV, $m(ilde{\chi}_1^0){=}$ 100 GeV	ATLAS-CONF-2018-003	$\frac{t \rightarrow t \chi_1^0 \text{ or } b \chi_1^{\pm}, \chi_1^{\pm} \rightarrow \chi_1^{\circ} \pi^{\pm}, m_{\tilde{t}} = 1100 \text{ GeV}, m_{\chi_1^0} = 1000 \text{ GeV} \qquad \chi_1^{\pm}}{600 \text{ GeV}} \qquad 1909.03460 (Disappearing tracks + jets with M_{T2})} \qquad 0.25-9 \text{ m}}{2212.06695 (Trackless jets + MET)} \qquad 0.04-12 \text{ m}}$	
_		0 MO vertices 10	20 - lifetime	0.21.70.4 m	m(a) = 25 CaV	0000 00507	GMSB, $\chi_1^0 \rightarrow H\ddot{G}(50\%)/Z\ddot{G}(50\%), m_{\chi_1^0} = 300 \text{ GeV}$ χ_1^0 2212.06695 (Trackless jets + MET) 0.05-24 m GMSB, SPSB, $\chi_1^0 \rightarrow \chi_1^0, m_{\chi_1^0} = 400 \text{ GeV}$ χ_1^0 1909.06166 (Delayed $\chi(\chi)$) 0.2-6 m	
	$H \rightarrow s s$	2 INS Vertices 13	s lifetime	0.31-72.4 m	m(s) = 35 GeV	2203.00587	GMSB, co-NLSP, $\vec{i} \rightarrow l\vec{G}$, $m_{\vec{i}} = 270 \text{ GeV}$ \vec{i} 2110.04809 (Displaced leptons) 5e-05-2.65 m	
%0	$H \rightarrow s s$	2 IOW-EIVIF trackless jets 13	s litetime	0.19-	m(s) = 35 GeV	2203.01009	$H \rightarrow Z_D Z_D(0.1\%), Z_D \rightarrow \mu \mu, m_H = 125 \text{ GeV}, m_X = 20 \text{ GeV}$ X 2205.08582 (Displaced dimuon) 5e-05-5 m	
=	$VH \text{ with } H \to ss \to bbb$	$2\ell + 2$ displ. vertices 13	s lifetime	4-85 mm	m(s) = 35 GeV	2107.06092	$H \rightarrow Z_D Z_D(0.1\%), Z_D \rightarrow \mu \mu (15.7\%), m_H = 125 \text{ GeV}, m_X = 5 \text{ GeV} \chi \\ H \rightarrow XX(10\%), X \rightarrow ee, m_H = 125 \text{ GeV}, m_X = 20 \text{ GeV} \chi \\ 1411.6977 \text{ (Displaced dielectron)} \\ 0.0001-0.25 \text{ m} \\ 0.00012-25 \text{ m} \\ $	
s BH	FRVZ $H \rightarrow 2\gamma_d + X$	2μ -jets 13	$\gamma_{\rm d}$ lifetime	0.654-939 mm	$m(\gamma_d) = 400 \text{ MeV}$	2206.12181	$H \rightarrow XX(0.03\%), X \rightarrow ll, m_H = 125 \text{ GeV}, m_X = 30 \text{ GeV}$ $H \rightarrow XX(10\%), X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 125 \text{ GeV}, m_X = 125 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 125 \text{ GeV}, m_X = 125 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 125 \text{ GeV}, m_X = 125 \text{ GeV}, m_X = 125 \text{ GeV}$ $X \rightarrow bh, m_X = 125 \text{ GeV}, m_X = 125 \text{ GeV},$	
ligge	FRVZ $H \rightarrow 4\gamma_d + X$	2μ -jets 13	39 $\gamma_{\rm d}$ lifetime	2.7-534 mm	$m(\gamma_d) = 400 \text{ MeV}$	2206.12181	$H \to XX(10\%), X \to bb, m_H = 125 \text{ GeV}, m_X = 40 \text{ GeV} \qquad \chi$ $H \to XX(10\%), X \to bb, m_H = 125 \text{ GeV}, m_X = 40 \text{ GeV} \qquad \chi$ $2110.13218 (Displaced jets + Z) \qquad 0.004 - 0.248 \text{ m}$	
-	$H \rightarrow Z_d Z_d$	displaced dimuon 32.	2.9 Z _d lifetime	0.009-24.0 m	$m(Z_d) = 40 \text{ GeV}$	1808.03057	Image: Hardware in the system of the system in the sys	
	$H \rightarrow ZZ_d$	2 e, μ + low-EMF trackless jet 36.	5.1 Z _d lifetime	0.21-5.	.2 m $m(Z_d) = 10 \text{ GeV}$	1811.02542	^O ark QCD, mx _{stark} = 1500 GeV, m _{mark} = 10 GeV, agonstic dark QCD, mx _{stark} = 1500 GeV, m _{mark} = 10 GeV, GNN 2403.01556 (Emerging jet + jet) 2403.01556 (Emerging jet + jet) (0.003-0.3 m) (0.003-0.3 m) (0.0 m) (0.003-0.3	
<u>ـ</u>	$\Phi(200 \text{ GeV}) \rightarrow ss$	low-EMF trk-less jets, MS vtx 36	s.1 s lifetime	0.41-51.5 m	$\sigma imes \mathcal{B} =$ 1 pb, $m(s) =$ 50 GeV	1902.03094	$H \rightarrow XX(10\%), X \rightarrow b\bar{b}, m_H = 125 \text{ GeV}, m_X = 40 \text{ GeV}$ X CMS-PAS-EXO-23-013 (Displaced Jets Run3) 0.0005-2.5 m	
cala	$\Phi(600 \text{ GeV}) \rightarrow ss$	low-EMF trk-less jets, MS vtx 36	s.1 s lifetime	0.04-21.5 m	$\sigma imes \mathcal{B} =$ 1 pb, $m(s) =$ 50 GeV	1902.03094	$H \rightarrow XX(10\%), X \rightarrow aa, m_{H} = 125 \text{ GeV}, m_{X} = 40 \text{ GeV} \qquad \chi \qquad CMS-PAS-EXO-23-013 (Displaced jets Run3) \qquad 0.0005-2.5 \text{ m}$	
Ś	$\Phi(1 \text{ TeV}) \rightarrow ss$	low-EMF trk-less jets, MS vtx 36	s.1 s lifetime	0.06-52.4 m	$\sigma imes \mathcal{B}{=}$ 1 pb, $m(s){=}$ 150 GeV	1902.03094	10^{-7} 10^{-5} 10^{-3} 10^{-1} 10^{1} 10^{3}	
_	$W \to N\ell, N \to \ell\ell\nu$	displaced vtx ($\mu\mu$, μe , ee) + μ 13	39 N lifetime	0.74-42 mm	m(N) = 6 GeV, Dirac	2204.11988	ст [m] Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.	
	$W \to N\ell, N \to \ell\ell\nu$	displaced vtx ($\mu\mu$, μe , ee) + μ 13	39 N lifetime	3.1-33 mm	m(N) = 6 GeV. Majorana	2204.11988		
NL	$W \to N\ell, N \to \ell\ell\gamma$	displaced vtx ($\mu u.\mu e. ee$) + e 13	39 N lifetime	0.49-81 mm	m(N) = 6 GeV. Dirac	2204 11988		
Т	$W \to N\ell, N \to \ell\ell\gamma$	displaced vtx ($\mu\mu$, μe , ee) + e 13	39 N lifetime	0.39-51 mm	m(N) = 6 GeV. Majorana	2204.11988		
	,							
	-		(0.01 0.01 1	¹⁰ 100 c τ [m]			
		$\sqrt{s} = 13 \text{ TeV}$ $\sqrt{s} = 13 \text{ TeV}$	/ I .	record records records records				
*Or	lv a selection of the a	available lifetime limits is sh	0.001	0.01 0.1 1 1() 100			
01	.,				au [ns]			





 $\sqrt{s} = 13 \text{ TeV}$





2HDM+a Summary Plots



2HDM+*a*, Dirac DM, sin θ = 0.35, tan β = 1, g_{γ} = 1, m_A = m_H = $m_{H\pm}$ = 1.2 TeV

ATL-PHYS-PUB-2024-010





CMS EXO-23-005



