Exotics at ATLAS (Dark sectors, ALPs, LLPs…)

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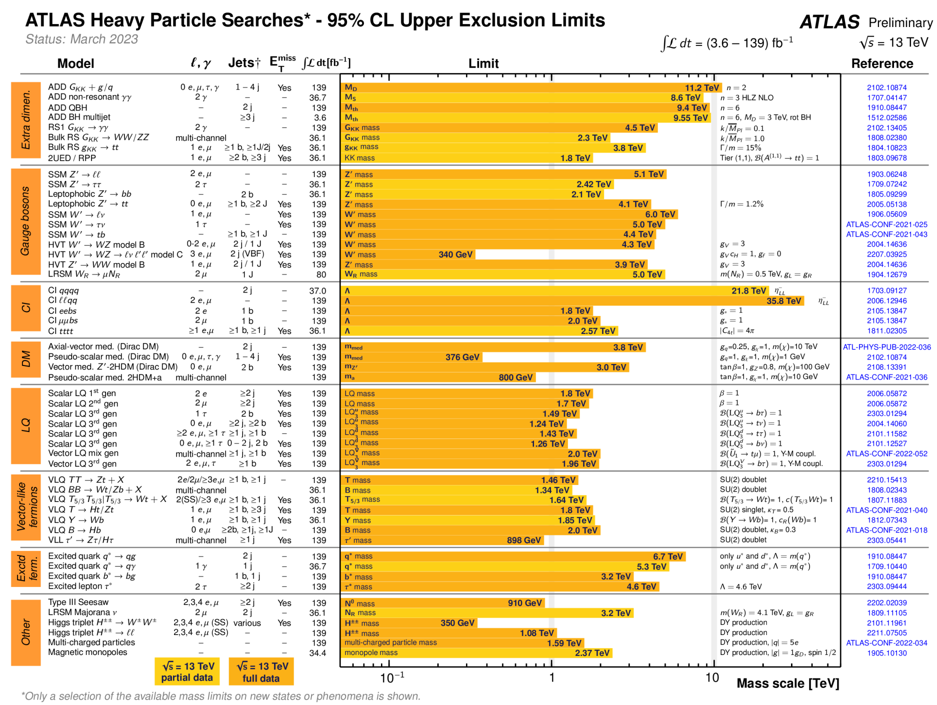
Overview of SUSY searches at ATLAS already given by Joaquin on Monday

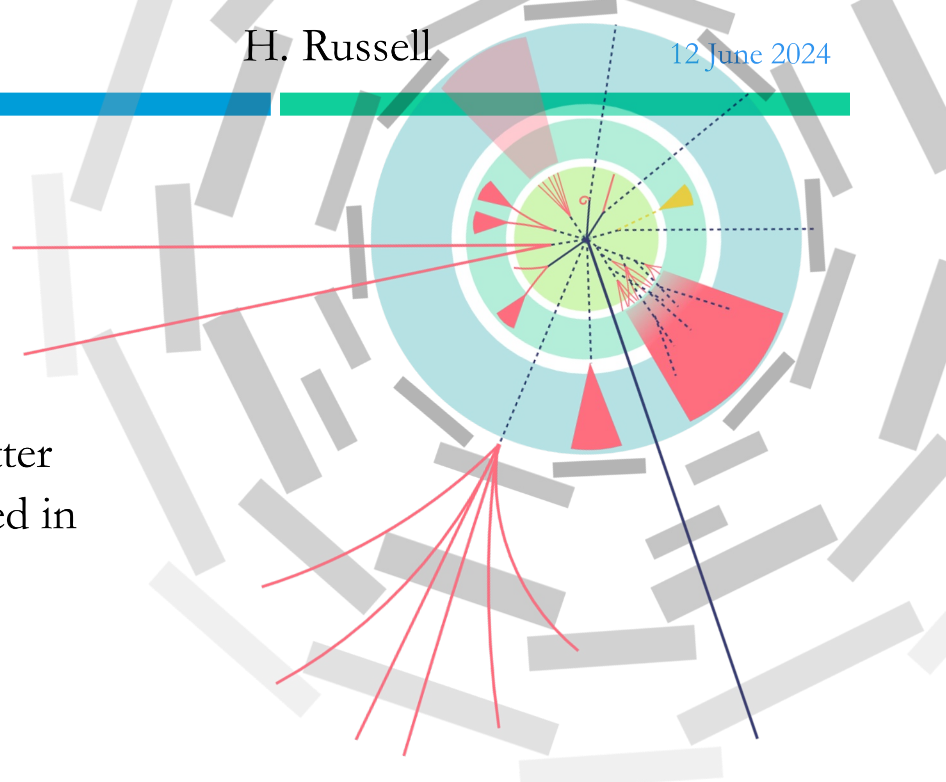
This talk will focus on recent results from the Exotics physics program at ATLAS

More results presented in Maura's, Simon's, and Alexander's talks

The Exotics program is extremely active and diverse!

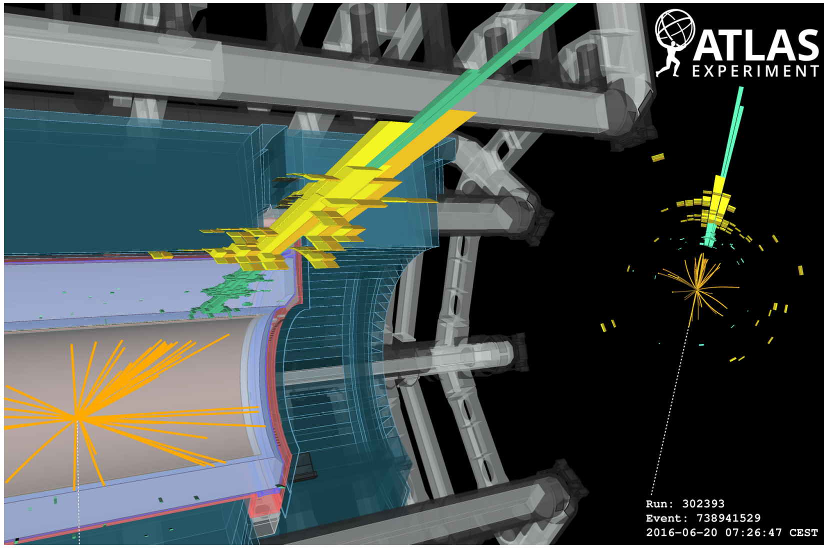
- Signature-driven
- Targeting a wide range of BSM theories
- Searches for dark matter particles, hidden-sector particles, new vector resonances, leptoquarks, vector-like quarks…
- Aim to provide model-independent limits and use simplified models to maximize reinterpretability





BSM searches can have extremely wide variety of final states, therefore develop a wide variety of strategies and techniques

MET+X: often defines searches for dark-matter candidates; X refers to visible particles produced in interaction, used to measure p_T imbalance



Displaced objects: long-lived particles (LLPs) can have wildly different signatures depending on decay mode and where the decay happens in the detector! Often rely on dedicated triggers and reconstruction algorithms

Today I'll highlight some recent results involving dark sectors, ALPs, and LLPs!

For a more thorough overview, please take a look at the Exotics Report and the complete list of recent exotics results.

Combination and summary of ATLAS dark matter searches interpreted in a 2HDM with a pseudo-scalar mediator

2306.00641

BENCHMARK MODEL

2HDM+a: SM scalar sector extended with an additional complex doublet, with an additional pseudo-scalar mediating the interaction between ordinary and dark matter

6 scenarios identified to systematically probe variations of 5 free parameters

SM Higgs sector extended with 5 additional scalar states:
- Scalar H
- Pseudo-scalar A
- Charged Higgs bosons H+/-
- Pseudo-scalar mediator a

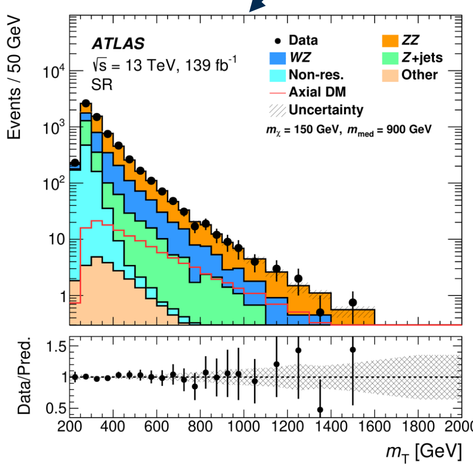
χ is fermionic DM particle

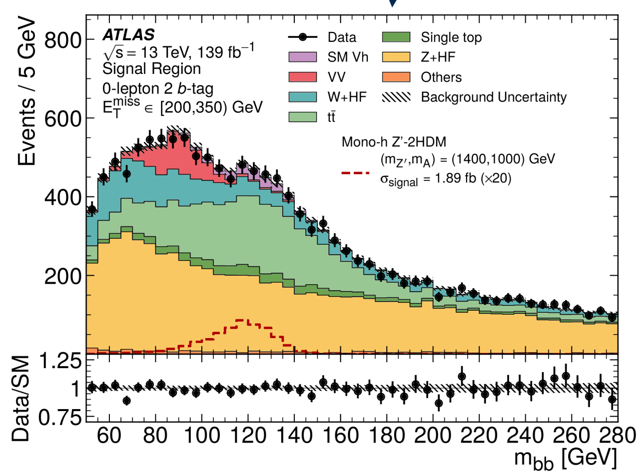
Scenario		Fixed parameter values					Varied parameters
		$\sin\theta$	m_A [GeV]	m_a [GeV]	m_χ [GeV]	$\tan\beta$	
1	a	0.35	–	–	10	1.0	(m_a, m_A)
	b	0.70	–	–	10	1.0	
2	a	0.35	–	250	10	–	$(m_A, \tan\beta)$
	b	0.70	–	250	10	–	
3	a	0.35	600	–	10	–	$(m_a, \tan\beta)$
	b	0.70	600	–	10	–	
4	a	–	600	200	10	1.0	$\sin\theta$
	b	–	1000	350	10	1.0	
5		0.35	1000	400	–	1.0	m_χ
6		0.35	1200	–	–	1.0	(m_a, m_χ)

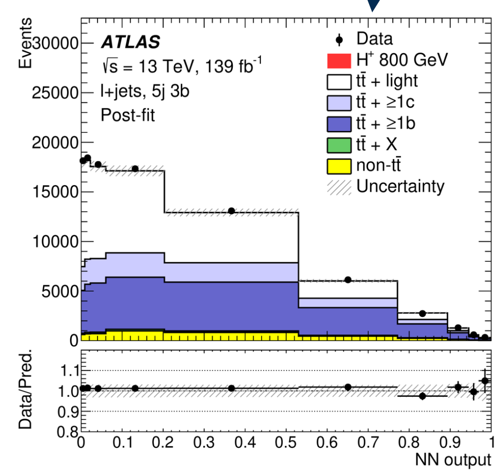
Summary of 18 analyses, each targeting a subset of the 6 scenarios presented above. The 3 most sensitive results are combined: MET+Z($\ell\ell$), MET+h($b\bar{b}$), tb H+-(tb)

STRATEGY

	MET + Z(ℓℓ)	MET + h(bb)	tb H+-(tb)
Trigger	single μ and single e	MET	single μ and single e
Features of signal topology	MET>90 GeV Same flavor, opposite sign lepton pairs in Z mass window	MET>150 GeV Resolved regime: 2 b-jets with R=0.4 Merged regime: 2 b-jets within large R=1.0 jet	At least 5 jets, at least 3 of which are b-jets



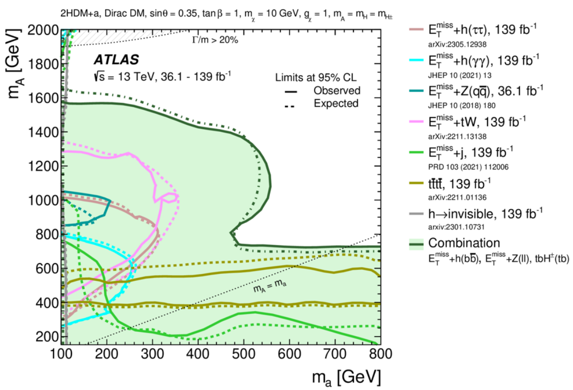




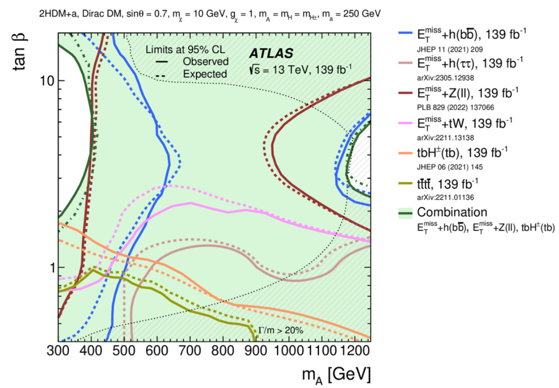
No overlap between analysis signal regions

RESULTS

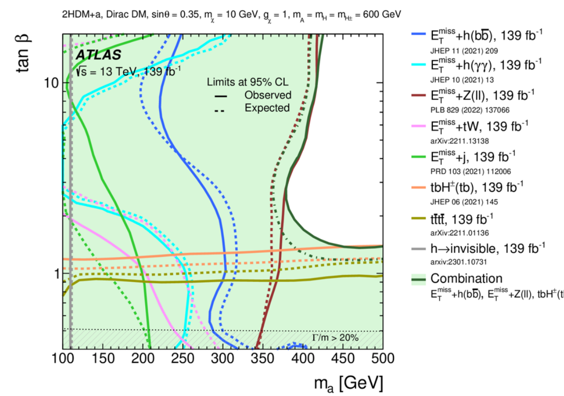
Scenario 1a



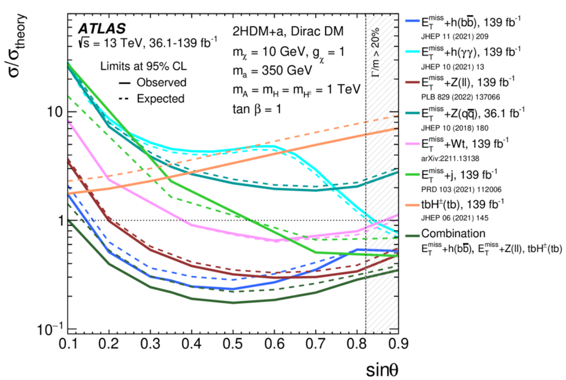
Scenario 2b



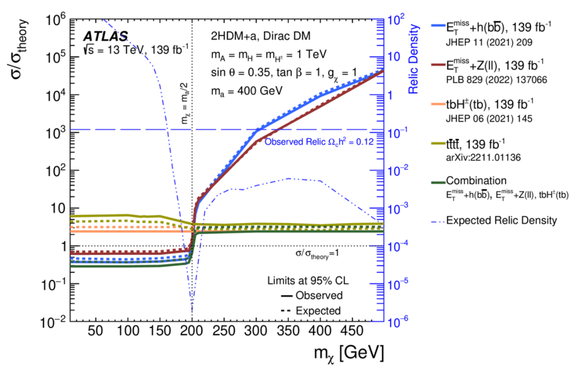
Scenario 3a



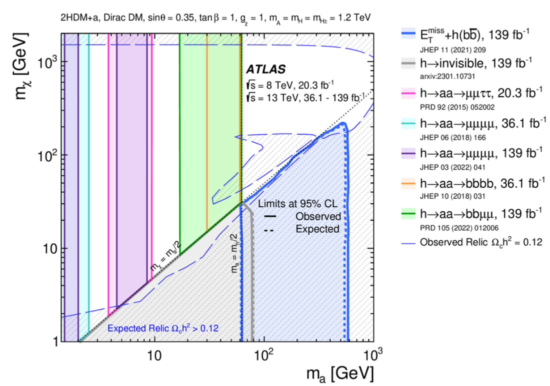
Scenario 4b



Scenario 5



Scenario 6



For scenario 1a with m_a=150 GeV, values of m_A between 250 GeV and 1.55 TeV are excluded

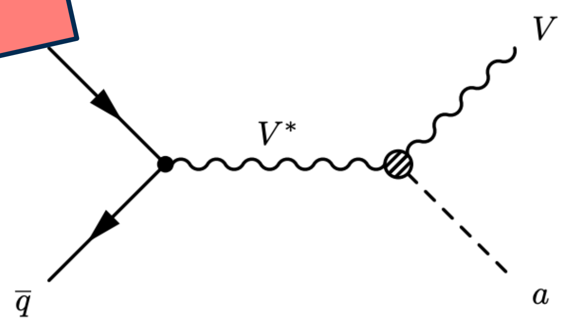
For scenario 3a with $\tan\beta$=10, values of m_a are excluded up to ~400 GeV

Search for dark matter particles in events with a hadronically decaying vector boson and missing transverse momentum

2406.01272

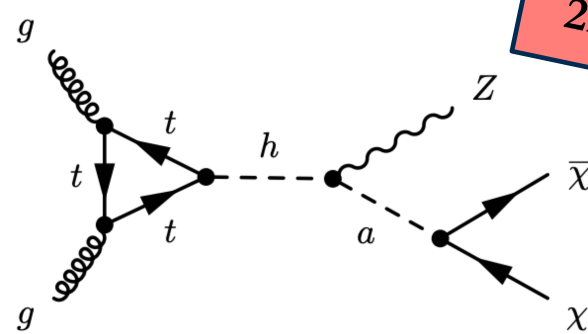
BENCHMARK MODELS

Photophobic ALP



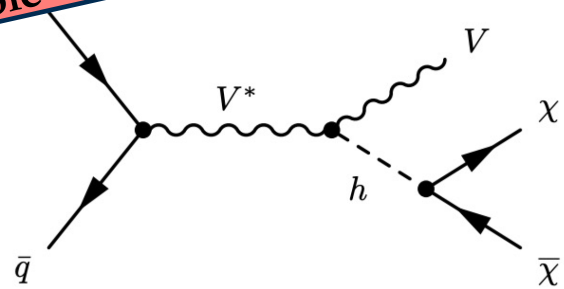
ALP a in association with V boson

2HDM+a



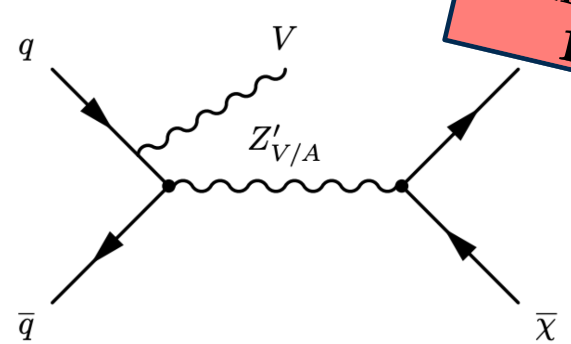
MET+Z decaying hadronically

Higgs to invisible



h produced in association with V, decaying into χ

Simplified DM



χ pair-production with mediator $Z'_{V/A}$

STRATEGY

Search is split into 2 regimes based on the boost of the V boson in the final state

	Merged	**Resolved**
Preselection	Data cleaning Primary vertex with at least two tracks with $p_T > 500$ MeV No τ-leptons $p^{miss}_{T,\ell} > 30$ GeV $\min_i(\Delta\phi(\boldsymbol{E}^{miss}_{T,\ell}, j_i)) > 20°$ $\Delta\phi(\boldsymbol{E}^{miss}_{T,\ell}, \boldsymbol{p}^{miss}_{T,\ell}) < 90°$	(same as Merged)
$\Delta\phi(\boldsymbol{E}^{miss}_{T,\ell}, V)$	$\Delta\phi(\boldsymbol{E}^{miss}_{T,\ell}, J_1) > 120°$	$\Delta\phi(\boldsymbol{E}^{miss}_{T,\ell}, j_1 j_2) > 120°$
$E^{miss}_{T,\ell}$	> 250 GeV	> 200 GeV
Jets	$\geq 1J$; $\leq 4j$ $p_T^{J_1} > 200$ GeV b-tagged track jet veto outside J_1	$\geq 2j$; $\leq 4j$ $p_T^{j_1} > 45$ GeV $\sum_i p_T^{j_i} \geq 120\,(150)$ GeV for $2j$ ($\geq 3j$)
V-tag	**High purity:** mass and substructure **Low purity:** mass and inverted substructure	$\Delta\phi(j_1, j_2) < 140°$; $\Delta R(j_1, j_2) < 1.4$ $m_{j_1 j_2} \in [65, 105]$ GeV

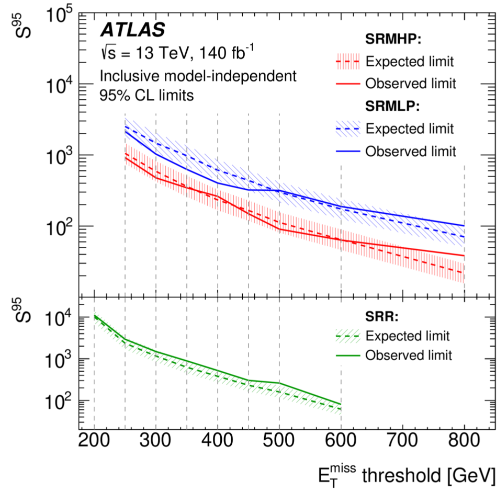
	SR	CR2mu	CR2el	CR1mu0b	CR1mu1b	SR	CR2mu	CR2el	CR1mu0b	CR1mu1b
Trigger	E_T^{miss}	E_T^{miss}	Electron	E_T^{miss}	E_T^{miss}	E_T^{miss}	E_T^{miss}	Electron	E_T^{miss}	E_T^{miss}
e	0	0	2	0	0	0	0	2	0	0
μ	0	2	0	1	1	0	2	0	1	1
$\mathcal{S}$	>8	-	-	-	-	>8	-	-	-	-
$m_{\ell\ell}$ [GeV]	-	$\in [66, 116]$	$\in [66, 116]$	-	-	-	$\in [66, 116]$	$\in [66, 116]$	-	-
$m^T_{\mu\nu}$ [GeV]	-	-	-	$\in [30, 100]$	$\in [30, 100]$	-	-	-	$\in [30, 100]$	$\in [30, 100]$
$n_{b\in J}$	-	-	-	0	≥ 1	-	-	-	-	-
n_b	-	-	-	-	-	-	-	-	0	≥ 1

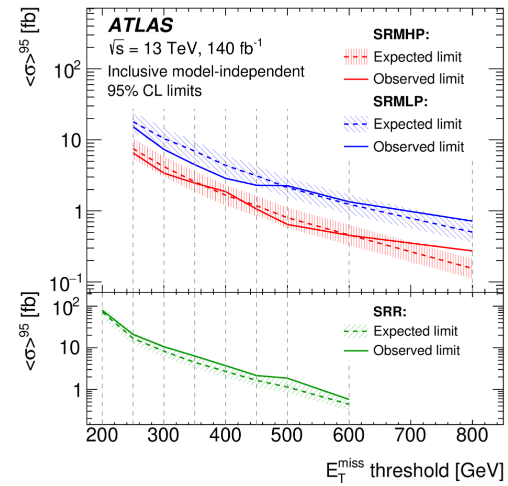
Each signal region has 2 corresponding control regions to estimate Z+jets, and 2 CRs to estimate W+jets and ttbar background processes

RESULTS

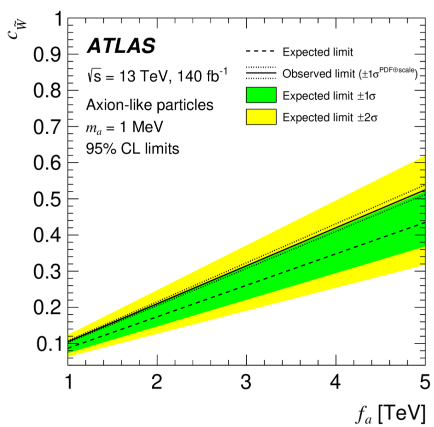
No excess observed

Model independent limits set on visible cross-section, in addition to model-dependent limits

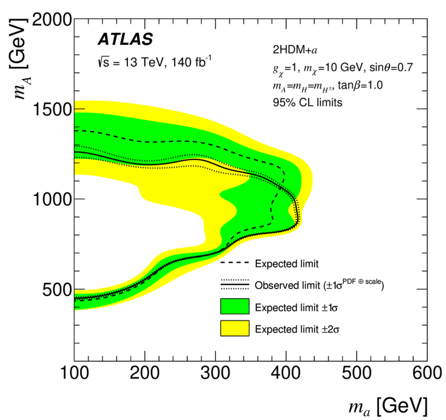




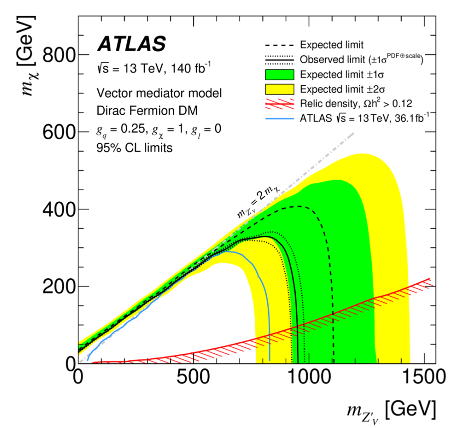
ALPs



2HDM+a, scenario 1



Simplified DM



H to invisible

Limits on $B_{h\to inv.}$	Expected limit	Observed limit
Merged topology	$0.34^{+0.14}_{-0.09}$	0.38
Resolved topology	$0.54^{+0.23}_{-0.15}$	0.71
Combined	$0.31^{+0.13}_{-0.09}$	0.34

Search for high-mass resonances in final states with a τ-lepton and missing transverse momentum

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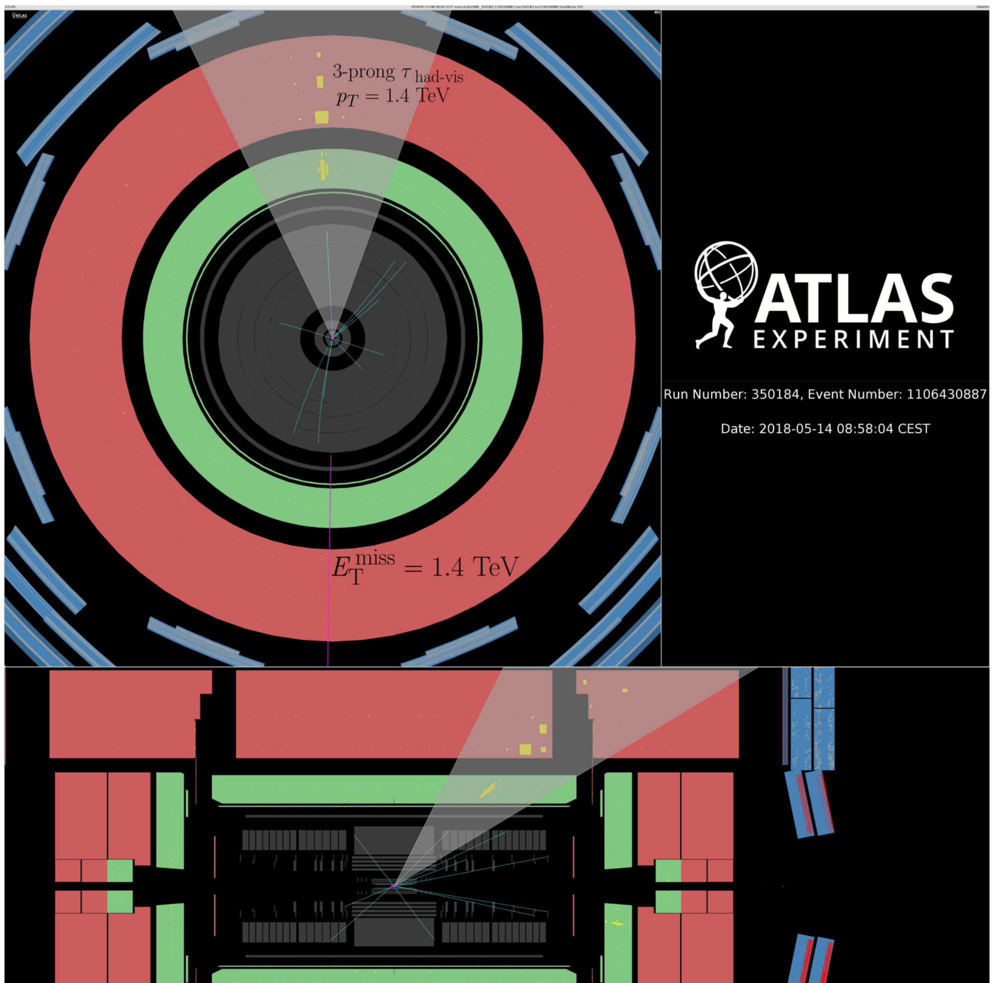
BENCHMARK MODELS



Targeting theories that predict the existance of **additional heavy vector gauge bosons**

In this search: $W' \to \tau\nu$

Interpreted in terms of

- **Sequential SM**: flavor-universal benchmark that assumes the W' and Z' couplings are identical to SM W and Z
- **NUGIM**: can exhibit different couplings for the three lepton generations, where non-universality of W' couplings to SM fermions is parametrized by angle parameter θ_{NU}

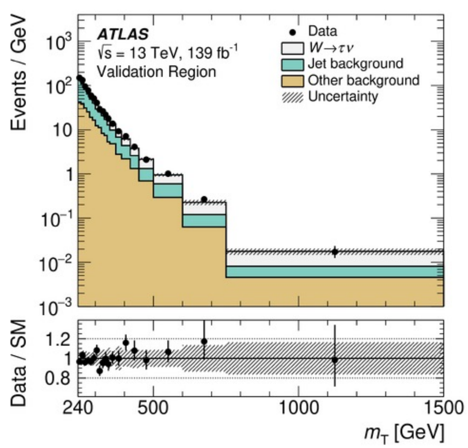
STRATEGY

Hadronic τ-lepton decays are identified with an RNN based on calorimeter shower shape and tracking information. Non-jet backgrounds estimated with MC simulation

Misidentification of jets as τ-lepton candidates is not well modeled by simulation

CRs defined to estimate in a data-driven way

Transfer factor derived from CR2/CR3 and applied to CR1 to get expected background in SR



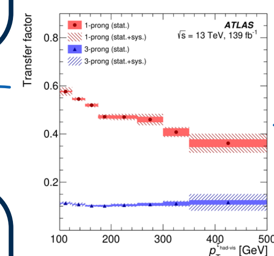
SR

τ passes Loose ID

CR2

dijet enriched

τ passes Loose ID



CR1

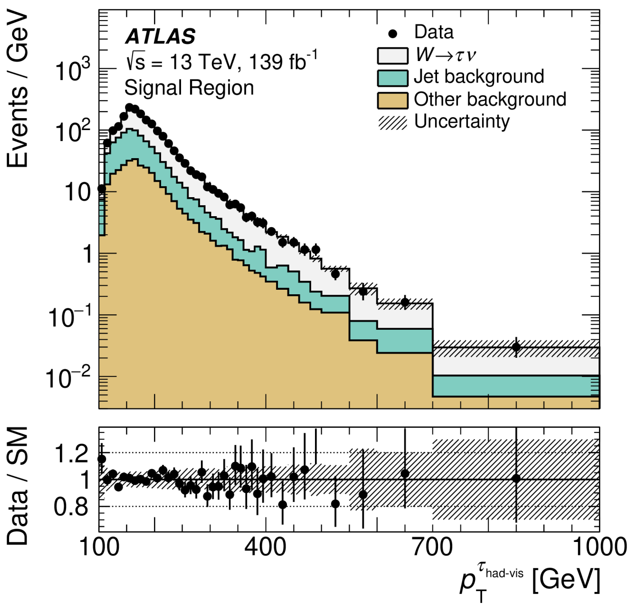
τ fails Loose, passes VeryLoose ID

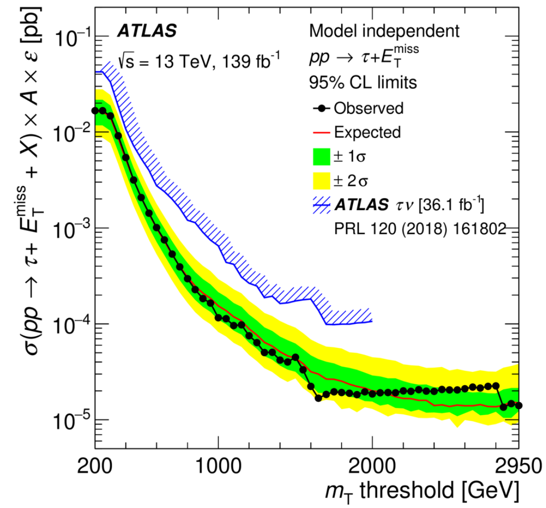
CR3

dijet enriched

τ fails Loose, passes VeryLoose ID

RESULTS



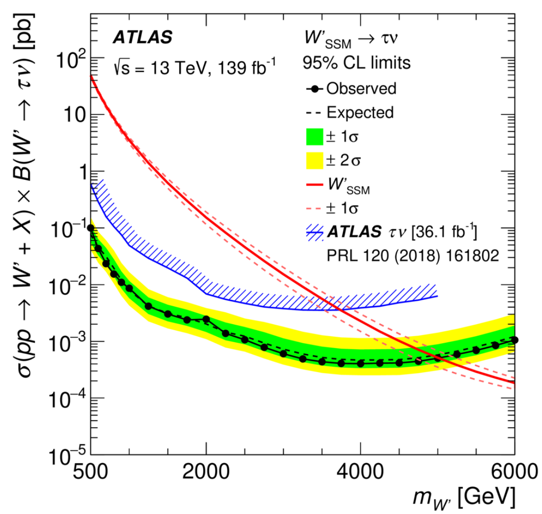


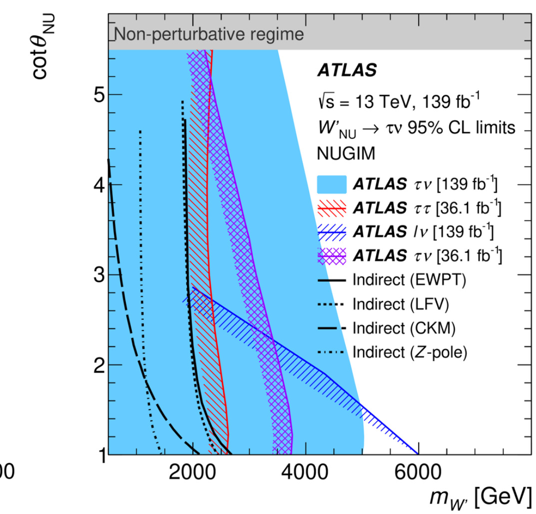
Visible cross-sections larger than 17 fb for m_T^{thresh}=0.2 TeV and 0.014 fb for m_T^{thresh}=2.95 TeV excluded

5x improvement over previous visible cross section limits >1.5 TeV!

No excess observed

Model-independent limits provided on visible cross section, as well as limits on SSM and NUGIM models



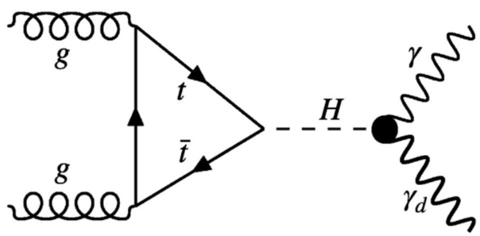


Combination of searches for a Higgs boson decaying into a photon and a massless dark photon

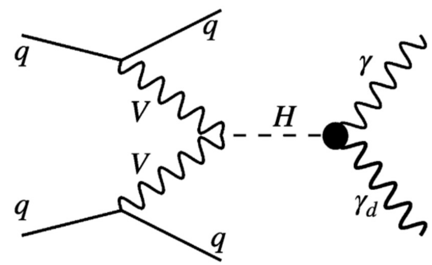
2406.01656

BENCHMARK MODELS

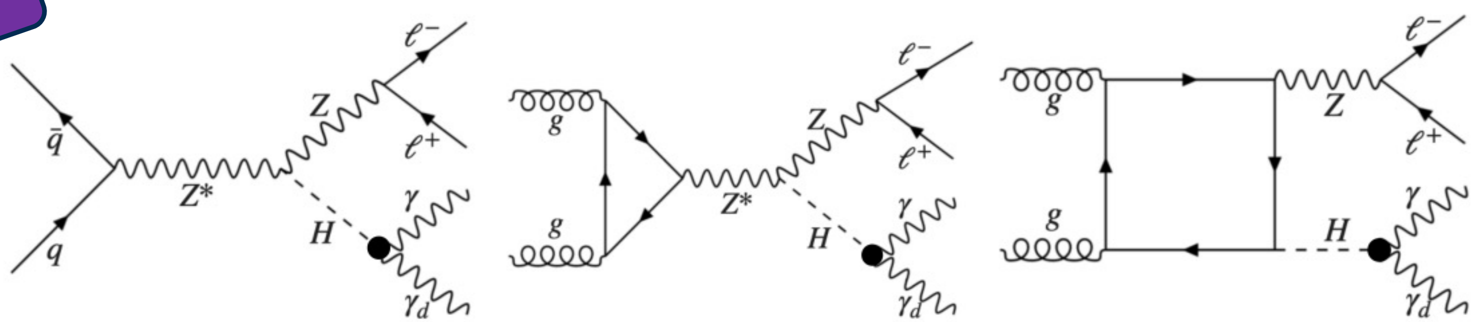
ggF



VBF



ZH



ZH and **VBF** used in combination for SM Higgs assumption

ggF and **VBF** used in combination for additional BSM Higgs hypotheses

STRATEGY

Searches defined by final-state signatures targeting production modes

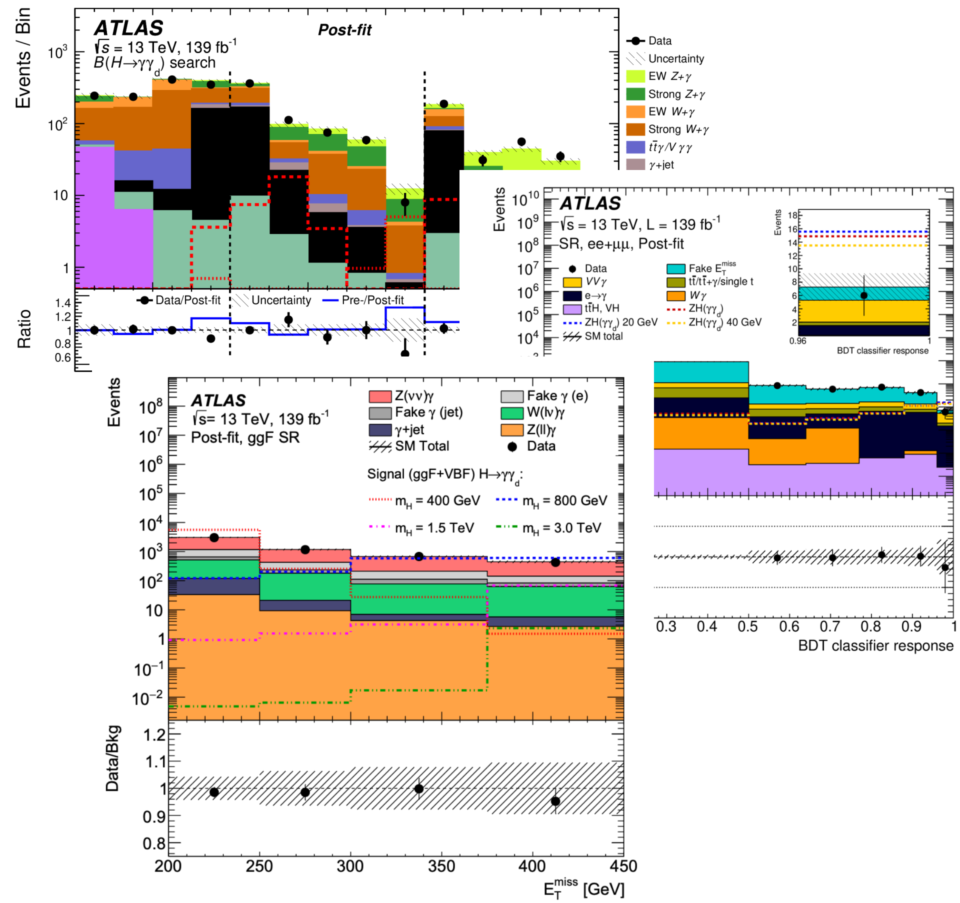
1. γ + MET + VBF jets (VBF channel)
- MET trigger, 2 VBF jets
- 10 SRs defined by m_{jj} and m_{T}

For combination:
- ggF contribution included using RECAST
- Additional signal samples generated to align with masses probed in ggF analysis

2. γ + MET + $Z(\ell\ell)$ (ZH channel)
- Lepton trigger
- BDT classifier used to discriminate signal and background

3. γ + MET (ggF channel)
- Photon trigger
- RECAST from mono-γ search (2011.05259)

For combination:
- VBF contribution also included

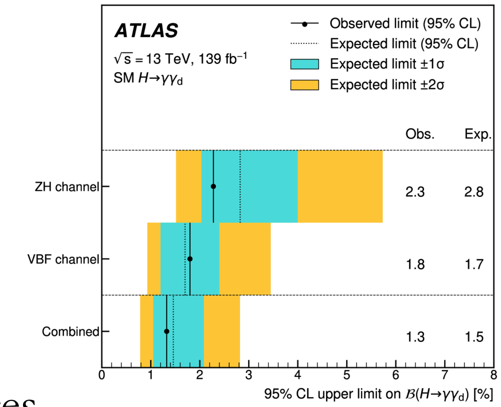


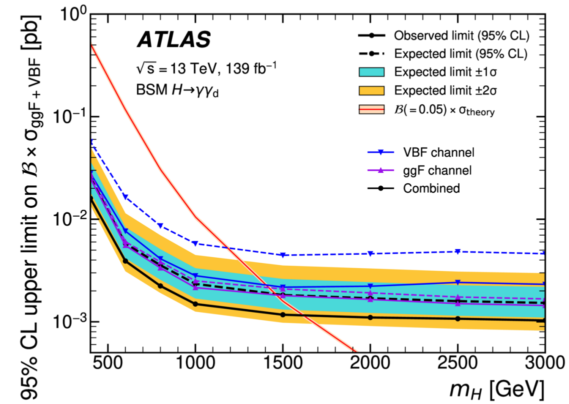
The 3 SRs were found to have negligible overlap, therefore treated as statistically independent

RESULTS

No excess observed

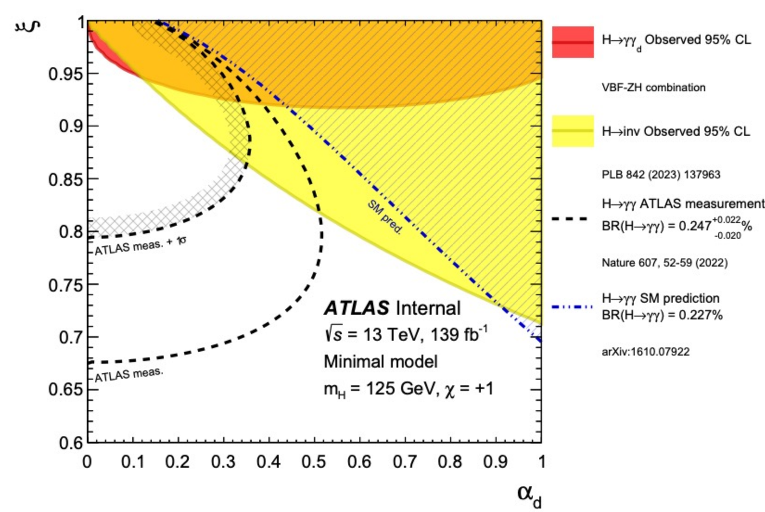
Observed limit on $H \to \gamma\gamma_d$ set to **1.3%**





The observed 95% CL limit on the cross-section times BR ranges from 16 fb for $m_H = 400$ GeV to 1.0 fb for $m_H = 3$ TeV

Assuming $BR(H_{BSM} \to \gamma\gamma_d)$ of 5%, masses of H_{BSM} below around **1600 GeV** are excluded.

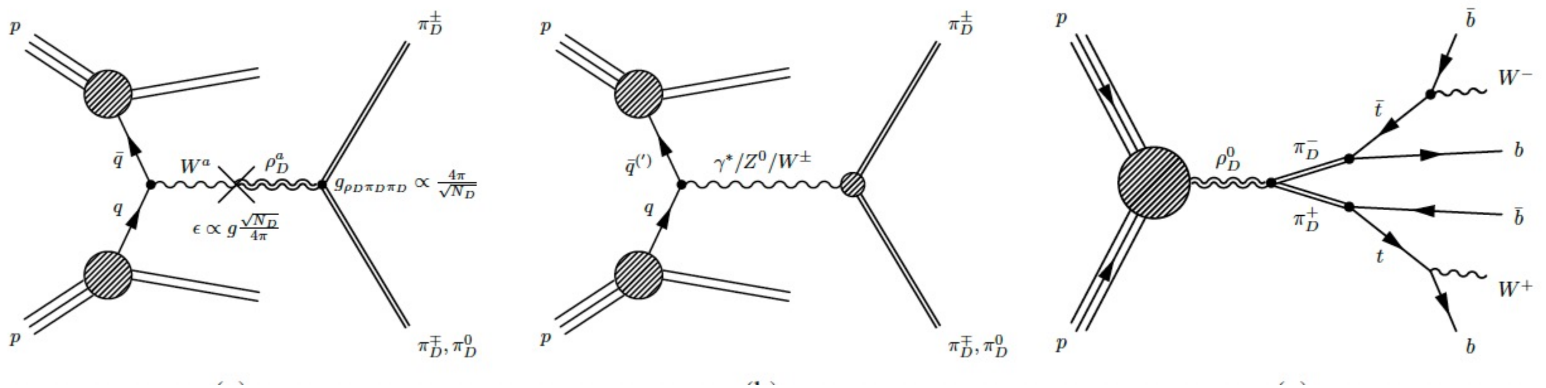


Most stringent constraints on Higgs decaying to photon+dark photon to date!

ZH+VBF results also interpreted in terms of a minimal DM model featuring a generic messenger sector coupling to both U(1) and $U(1)_d$ sectors

Search for dark mesons decaying to top and bottom quarks

BENCHMARK MODELS



2405.20061

Extension of the SM by a new dark sector:

- Strongly coupled and confining
- Conserving SU(2) dark flavor symmetry
- Dark mesons are the composites of dark vector-like fermions
- Dark mesons interact with EW sector and Higgs boson

Analysis target: Pair production of dark mesons resonantly through dark rho or through Drell-Yan, **decaying into ttbb or tttb**

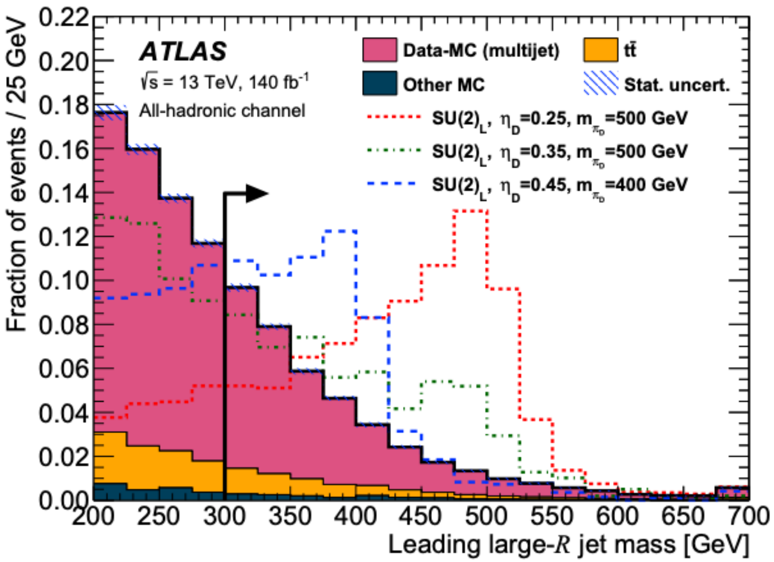
STRATEGY

1. Hadronic channel
   - 8-10 jets, at least 4 of which are b-jets
   - H_T trigger with threshold 850-1000 GeV, depending on data-taking period
   - Main background from multijets estimated in ABCD plane

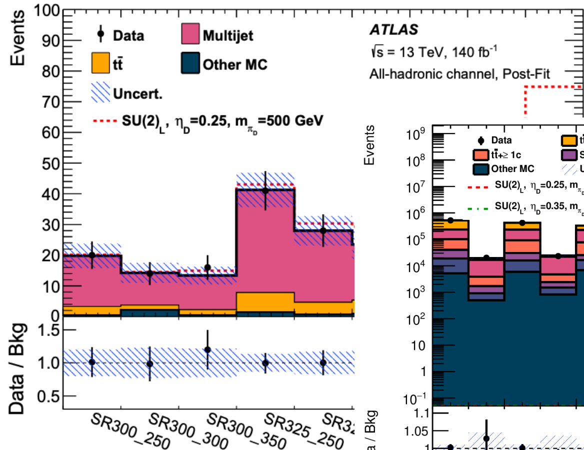
2. 1-lepton channel
   - Exactly 1 muon or electron in the event, in addition to jets
   - Single-lepton triggers with threshold 20-26 GeV, depending on data-taking period
   - Main background from $t\bar{t}$+HF estimated with MC simulation

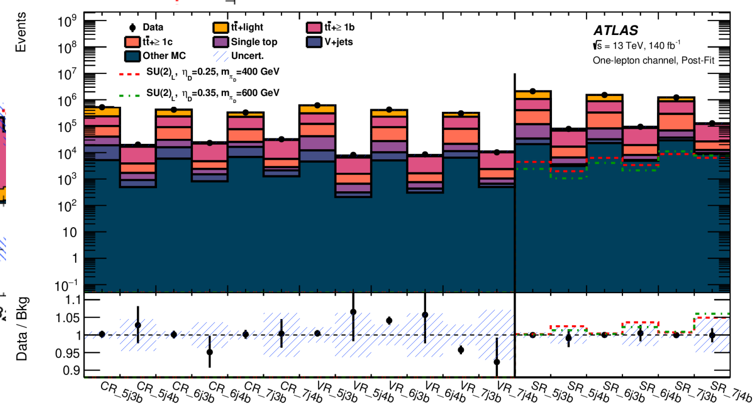
To fully contain dark meson decay products, jets are reclustered into large-R jets with radius R=1.2

Fully hadronic large-R jets: J^{had}
Large-R jets containing 1 lepton: J^{lep}



RESULTS



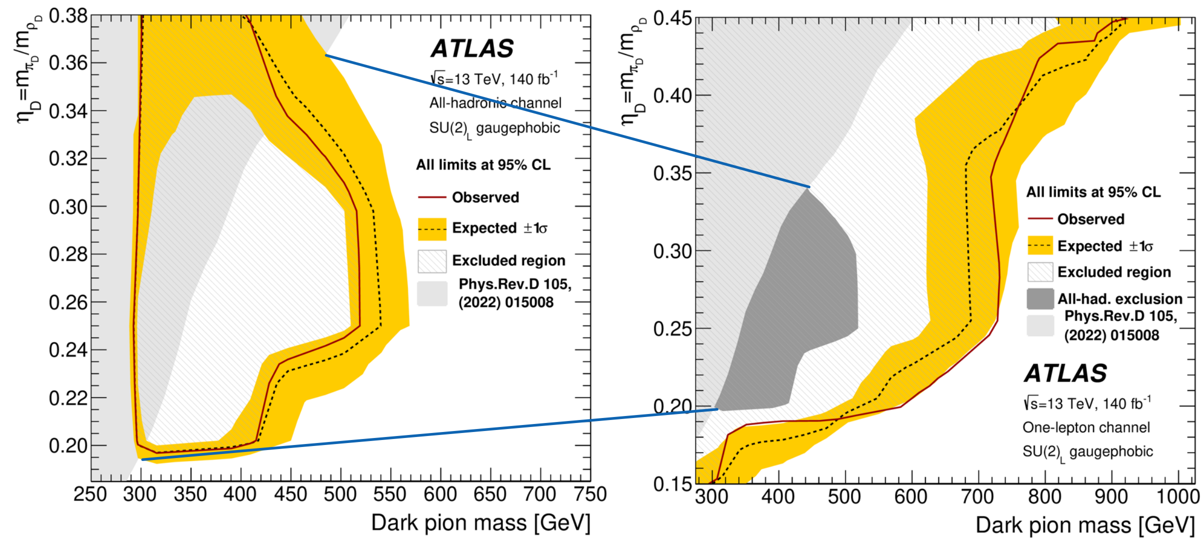


All-hadronic channel:
Fit performed in SR, where bins are split by large-R jet mass

One-lepton channel:
$m_{J,\text{had}} + m_{J,\text{lep}}$ distribution fit simultaneously in 6 SRs and 6 CRs

No excess observed

For m_{π_D}/m_{ρ_D}=0.45,
m_{π_D}< 940 GeV excluded
For m_{π_D}/m_{ρ_D}=0.25,
m_{π_D}< 740 GeV excluded



One-lepton channel shows significantly higher sensitivity than all-hadronic channel

Search for light, long-lived particles using displaced vertices

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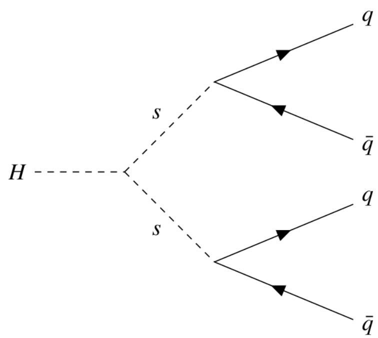
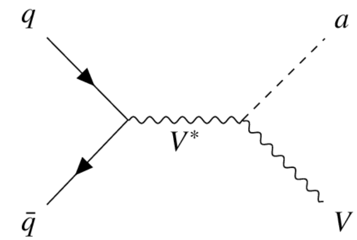
BENCHMARK MODELS

Higgs portal



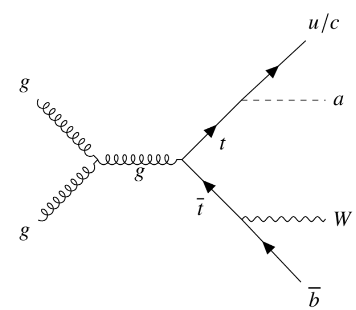
H mediates interactions with dark sector through coupling to neutral scalar *s*

ALP model #1



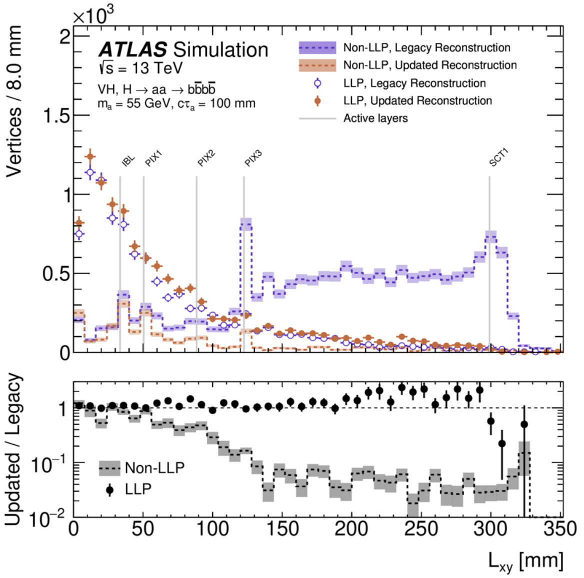
photophobic *a* couples to W/Z bosons

ALP model #2



photophobic *a* couples to up-type quarks

STRATEGY



Displaced vertices are reconstructed from a combination of prompt and displaced tracks

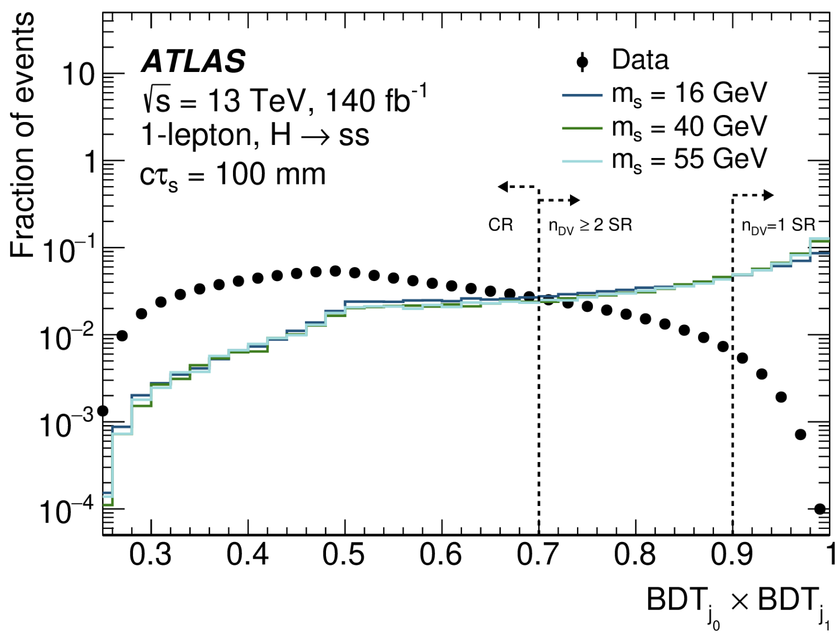
This is the first result using the updated large-radius tracking (LRT) reconstruction algorithm

- Maintains signal efficiency while reducing fake reconstruction by a factor of 20

Displaced jets are distinguished from prompt jets using a per-jet BDT

Events must have at least 2 jets with BDT score>0.5

Event-level discriminant computed by taking product of jet BDT scores



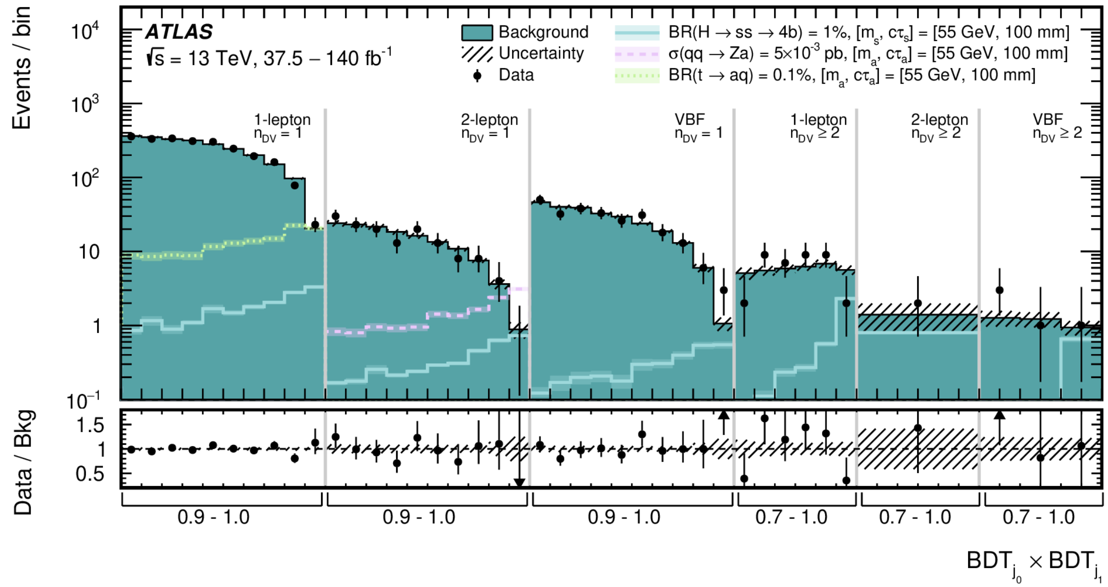
RESULTS

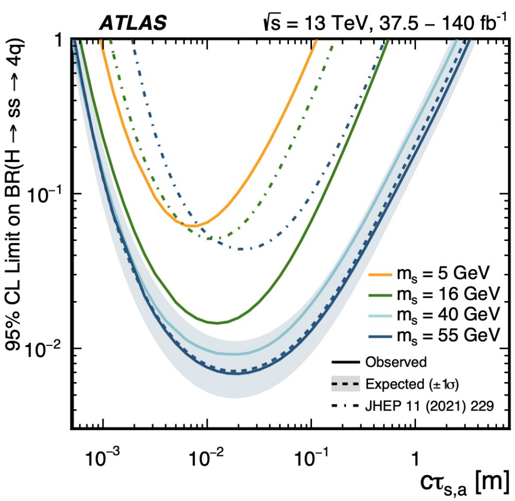
SRs are divided by Higgs production mode and vertex multiplicity

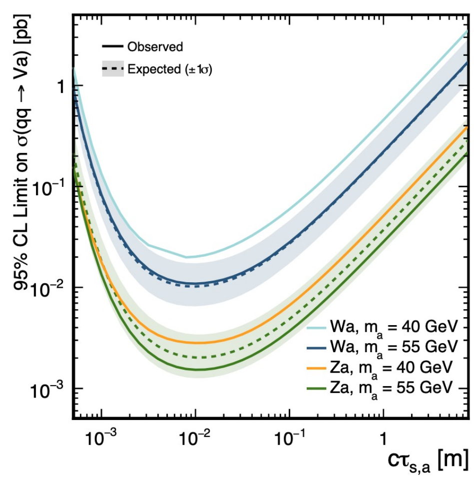
Higgs portal: all 6 are fit simultaneously

ALP Za model: only 2-lepton nDV=1 considered

ALP t->qq(Za) model: only 1-lepton nDV=1 considered







No excess observed

Provides 10-100x improvement over previous ATLAS results for Higgs portal with the same dataset!

First LLP results for the $V' \rightarrow Va$ and $t\bar{t}$, $t \rightarrow aq$ ALP models

Summary

- Highlighting a few very recent Exotics results
  - Summary/combination of 2HDM+a dark matter searches
  - Search for DM with hadronically-decaying vector boson + MET
  - Search for high-masses resonances with τ + MET
  - Combination of searches for Higgs boson to a photon+dark photon
  - Search for dark mesons decaying to t, b quarks
  - Search for LLPs decaying to hadronic jets in the inner detector

- Signature-driven analyses interpreted in terms of benchmark models, often simplified models, in addition to providing model-independent limits

- Developments in analysis techniques allow for significant improvements in sensitivity even with the same dataset

- Lots more to come, especially with Run 3!

Thank you!

BACKUP

Search for dark mesons decaying to top and bottom quarks

Event preselection:

Variable	All-hadronic channel	One-lepton channel
N_{lep}(baseline)	0	1
N_{lep}(signal)	-	1
$N_{jets}(R = 0.4)$	≥ 6	≥ 5
$N_{jets}(R = 1.2)$	≥ 2	-
$N_{b\text{-jets}}$	≥ 3	≥ 3
H_T	≥ 1150 GeV	≥ 300 GeV

SR event selection:

	Tag	Variable	Tag selection	Anti-tag selection
Both large-R jets		$m_{bb}/p_{T,bb}$	> 0.25	> 0.25
Leading large-R jet	bb_1	$\Delta R\,(j, b_2)$	< 1.0	≥ 1.0
Sub-leading large-R jet	bb_2	$\Delta R\,(j, b_2)$	< 1.0	≥ 1.0
Leading large-R jet	$\pi_{D,1}$	$m_{\text{jet,R=1.2}}$	[300 – 325 GeV, 325 – 400 GeV, > 400 GeV]	≤ 300 GeV
Sub-leading large-R jet	$\pi_{D,2}$	$m_{\text{jet,R=1.2}}$	[250 – 300 GeV, 300 – 350 GeV, > 350 GeV]	≤ 250 GeV

Combination and summary of ATLAS dark matter searches interpreted in a 2HDM with a pseudo-scalar mediator

14 free parameters in 2HDM+a model:

- Masses of $m_A, m_H, m_{H^\pm}, m_a, m_\chi$
- Yukawa coupling strength between mediator and DM particle, g_χ
- EW vacuum expectation value, VEV
- Ratio of the VEVs of the two Higgs doublets, $\tan\beta$
- Mixing angles of CP-even (α) and CP-odd (θ) weak eigenstates
- Quartic coupling of the pure 2HDM potential term (λ_3)
- Quartic couplings of the potential terms connecting the doublet (λ_{P1}) and singlet fields (λ_{P2})

Assumptions made for 2HDM+a scenarios:

$$m_A = m_H = m_{H^\pm}$$

$$\lambda_{P1} = \lambda_{P2} = \lambda_3 = 3$$

$$g_\chi = 1$$

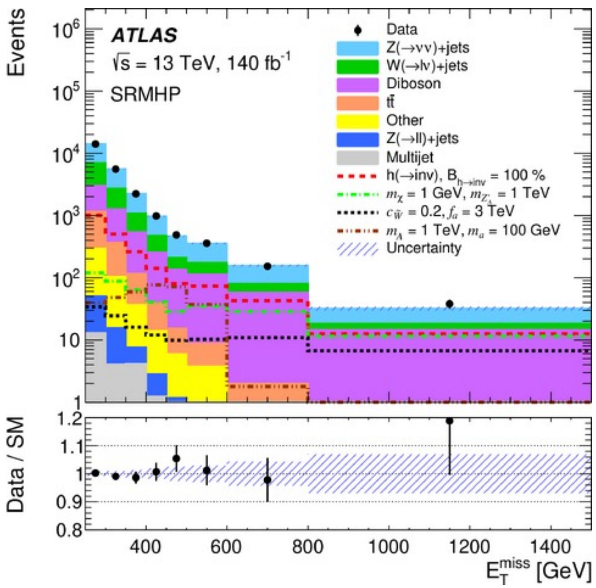
$$\sin(\beta - \alpha) = 1$$

Combination and summary of ATLAS dark matter searches interpreted in a 2HDM with a pseudo-scalar mediator

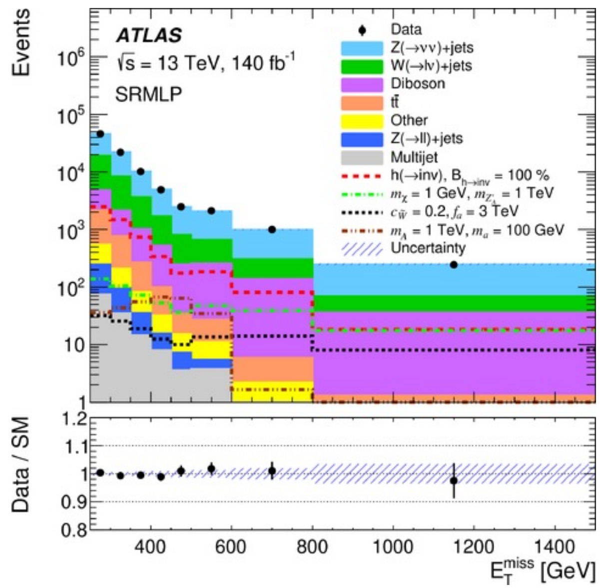
Analysis/Scenario	1a	1b	2a	2b	3a	3b	4a	4b	5	6
$E_T^{miss} + Z(\ell\ell)$ [74]	x	x	x	x	x	x	x	x	x	
$E_T^{miss} + h(b\bar{b})$ [75]	x	x	x	x	x	x	x	x	x	x
$E_T^{miss} + h(\gamma\gamma)$ [84]	x	x			x	x	x	x		
$E_T^{miss} + h(\tau\tau)$ [78]	x			x						
$E_T^{miss} + tW$ [77]	x	x	x	x	x	x	x	x		
$E_T^{miss} + j$ [45]	x	x			x	x	x	x		
$h \to$ invisible [86]	x	x			x					x
$E_T^{miss} + Z(q\bar{q})$ [126]	x						x	x		
$E_T^{miss} + b\bar{b}$ [127]							x	x		
$E_T^{miss} + t\bar{t}$ [127, 128]							x	x		
$t\bar{t}t\bar{t}$ [85]	x	x	x	x	x	x	x	x	x	
$tbH^{\pm}(tb)$ [76]	x	x	x	x	x	x	x	x	x	
$h \to aa \to f\bar{f}f'\bar{f}'$ [79–83]										x

Search for dark matter particles in events with a hadronically decaying vector boson and missing transverse momentum

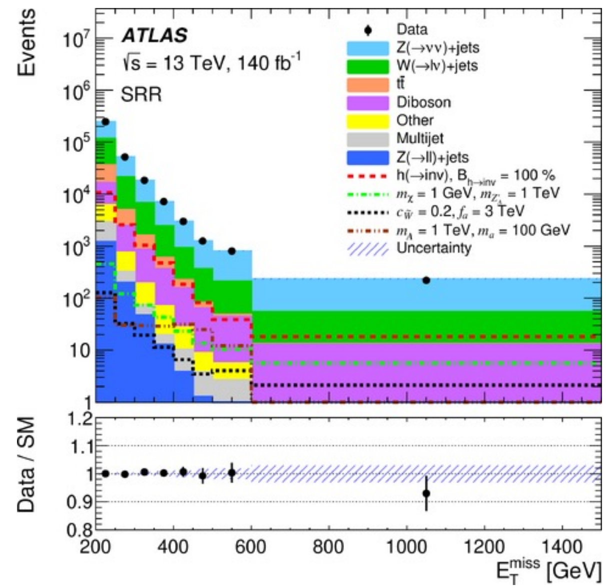
Merged, High Purity



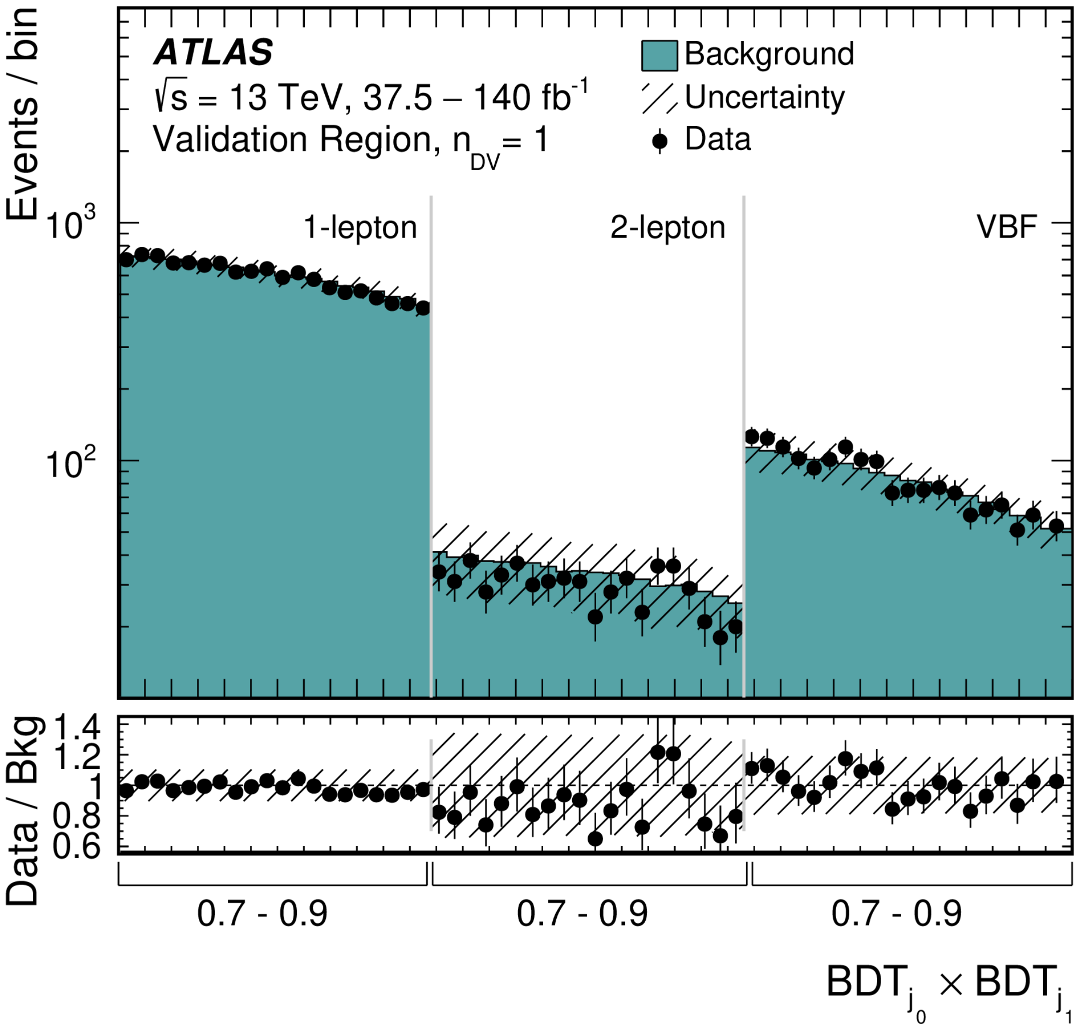
Merged, Low Purity



Resolved



Search for light, long-lived particles using displaced vertices



Search for light, long-lived particles using displaced vertices

	Excluded range of $c\tau_s$ (mm)			
$BR(H \rightarrow ss \rightarrow 4b/4c)$	m_s = 55 GeV	m_s = 40 GeV	m_s = 16 GeV	m_s = 5 GeV
1%	5.7 – 67.9	9.1 – 33.4	–	–
5%	1.8 – 361.2	1.6 – 254.2	2.2 – 80.3	–
10%	1.1 – 626.8	1.2 – 447.5	1.5 – 133.3	3.1 – 19.5
20%	0.8 – 1070.0	0.9 – 761.9	1.1 – 210.2	1.9 – 37.0

	Excluded range of $c\tau_s$ (mm)			
$BR(H \rightarrow ss \rightarrow 4u)$	m_s = 55 GeV	m_s = 40 GeV	m_s = 16 GeV	m_s = 5 GeV
1%	4.4 – 107.4	4.5 – 80.9	7.5 – 19.8	–
5%	1.6 – 398.6	1.4 – 329.2	1.8 – 104.7	5.6 – 8.5
10%	1.2 – 651.9	1.1 – 547.2	1.3 – 168.4	2.4 – 23.3
20%	0.9 – 1076.0	0.8 – 928.5	1.0 – 263.4	1.5 – 42.2