ATLAS Search for Dark Matter Produced in Association with a Hadronically Decaying Vector Boson

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on behalf of the ATLAS collaboration

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2nd World Summit on Exploring the Dark Side of the Universe

Guadeloupe, 25 Jun to 29 Jun, 2018

Nanjing University
Academia Sinica

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Introduction

See talk from Mario Martinez:
Overview of DM searches in ATLAS

* Weakly interacting massive particles (WIMPs)
  * can be produced in LHC
  * can be detected by the momentum imbalance of the recoiling SM particles
* Search for dark matter in events with a large missing transverse momentum (MET) and a vector boson, decaying hardronically, in ATLAS detector at LHC
  * DM production in associated with a W/Z boson (mono-V analysis)
  * SM-like Higgs boson decaying into a pair of DM particles (H->invisible analysis)
  * DM production in associated with a potentially new vector boson Z' (mono-Z' analysis, **first time!**)
* Latest result performed with 36.1 fb^{-1} of collision data at centre-of-mass energy of 13 TeV collected by ATLAS detector
  * published on April 2018 ATLAS-CONF-2018-005

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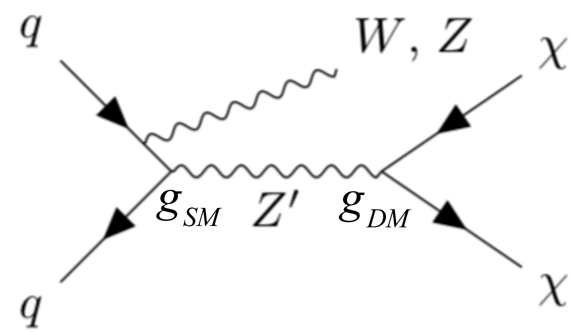
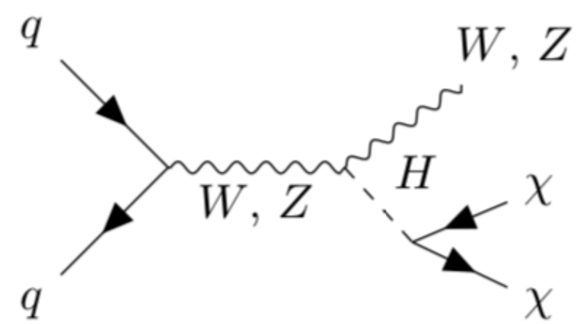
Signal models

* simplified vector-mediator model (mono-V), figure (a)
    * mass m_χ {1 GeV, 1 TeV}, $m_{Z'}$ {10 GeV, 10 TeV}
    * coupling g_{SM} = 0.25, g_{DM} = 1.0
* invisible Higgs boson decays (H->invisible), figure (b)
    * $B_{H\to invisible}$ = 1.0
    * all SM production modes considered
* dark-fermion model and dark-Higgs model (mono-Z'), figure (c) (d)
    * $m_{Z'}$ {50 GeV, 500 GeV}, g_{SM} = 0.1, g_{DM} = 1.0

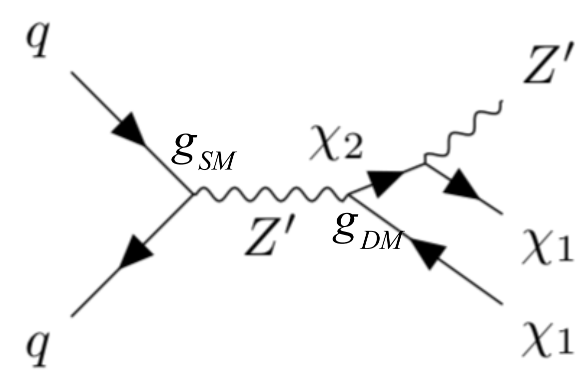
Scenario	Dark-fermion model	Dark-Higgs model
Light dark sector	$m_{\chi_1} = 5$ GeV $m_{\chi_2} = m_{\chi_1} + m_{Z'} + 25$ GeV	$m_\chi = 5$ GeV $m_{h_D} = \begin{cases} m_{Z'} & , m_{Z'} < 125 \text{ GeV} \\ 125 \text{ GeV} & , m_{Z'} > 125 \text{ GeV} \end{cases}$
Heavy dark sector	$m_{\chi_1} = m_{Z'}/2$ $m_{\chi_2} = 2m_{Z'}$	$m_\chi = 5$ GeV $m_{h_D} = \begin{cases} 125 \text{ GeV} & , m_{Z'} < 125 \text{ GeV} \\ m_{Z'} & , m_{Z'} > 125 \text{ GeV} \end{cases}$



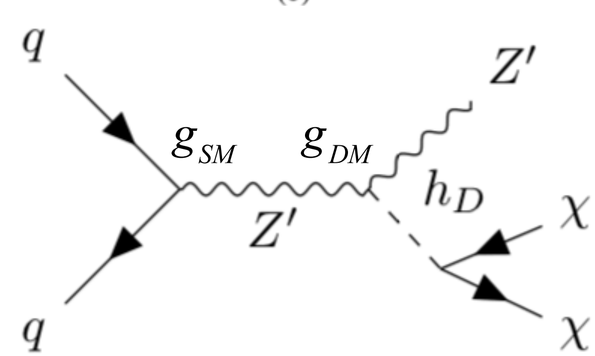
(a)



(b)



(c)

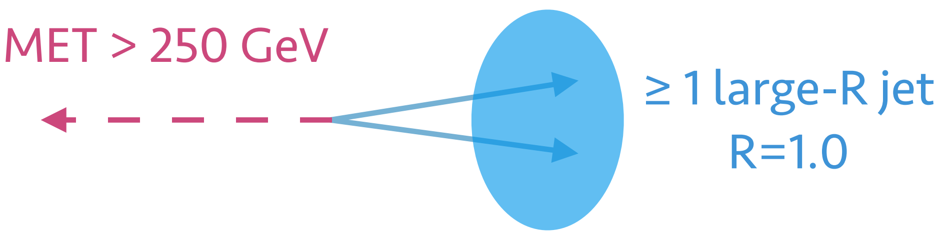


(d)

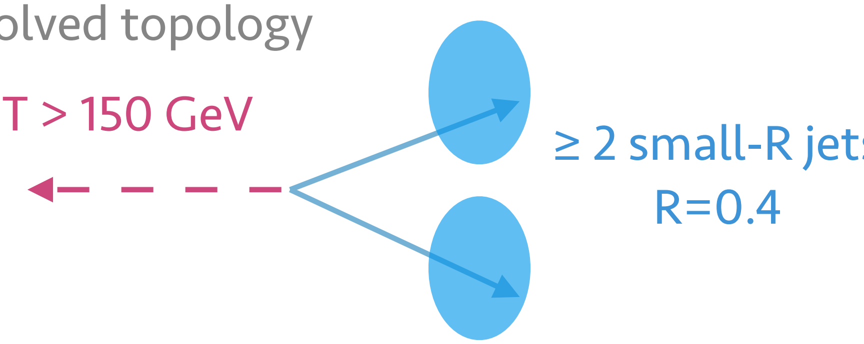
Event selection

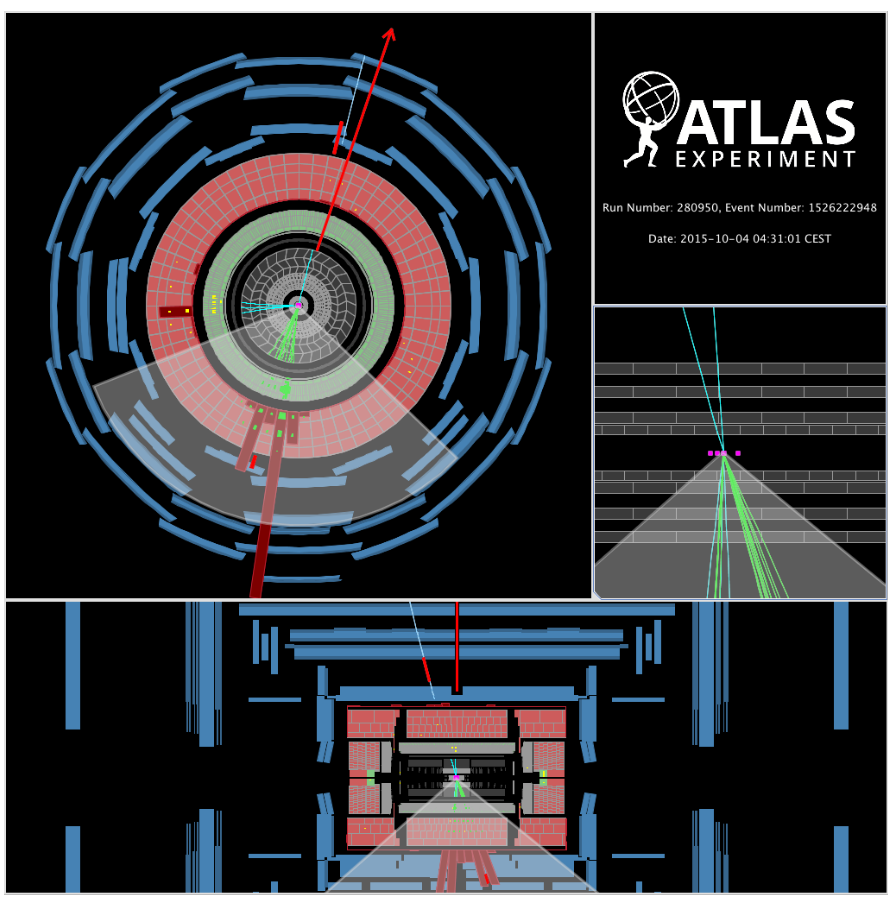
* at least one large-R jet or two small-R jets
* MET above 250 GeV (150 GeV)
* Lepton veto
* Vector boson mass window
* Events categorised into 0/1/2 b-jet region

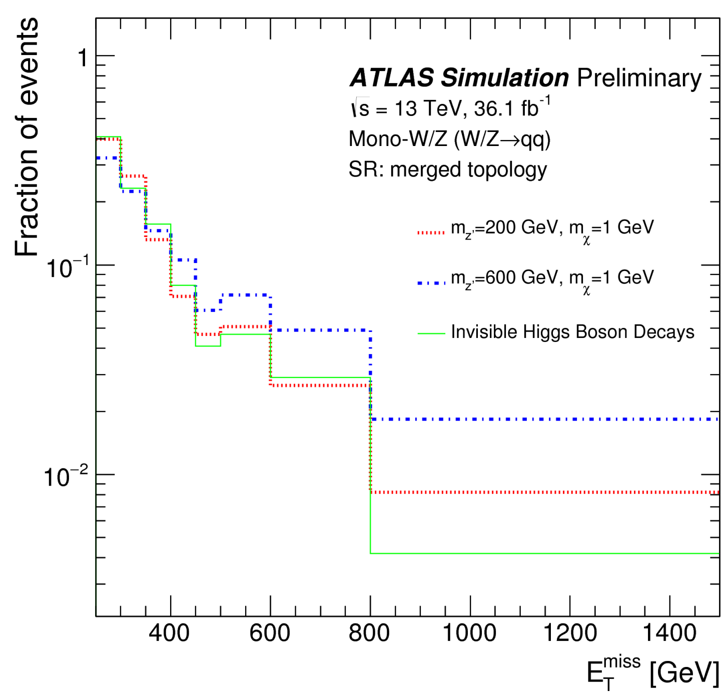
Merged topology

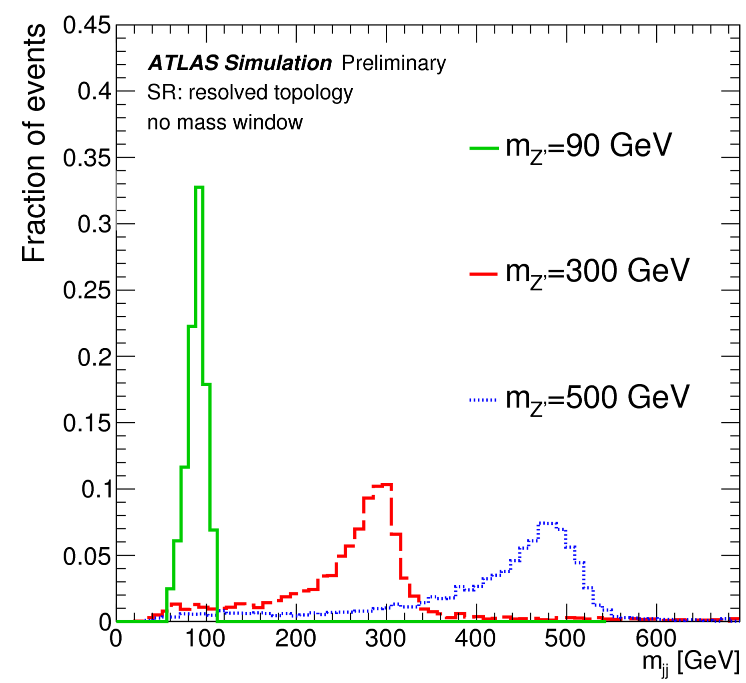


Resolved topology









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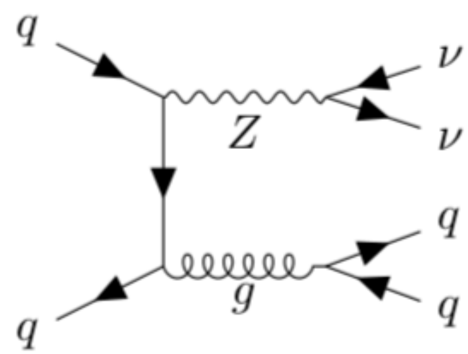
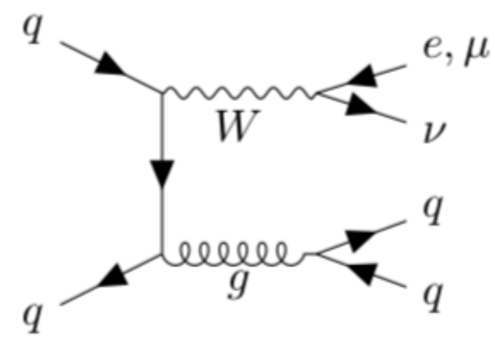
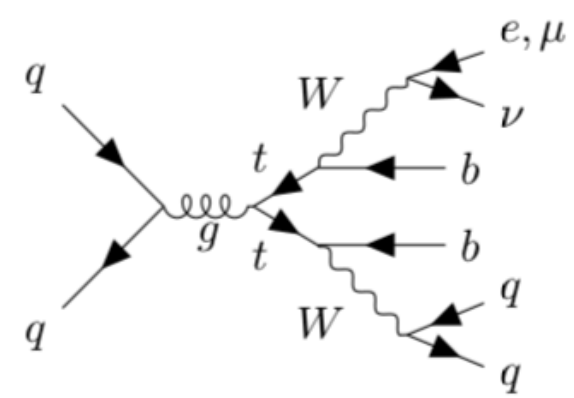
Background estimation

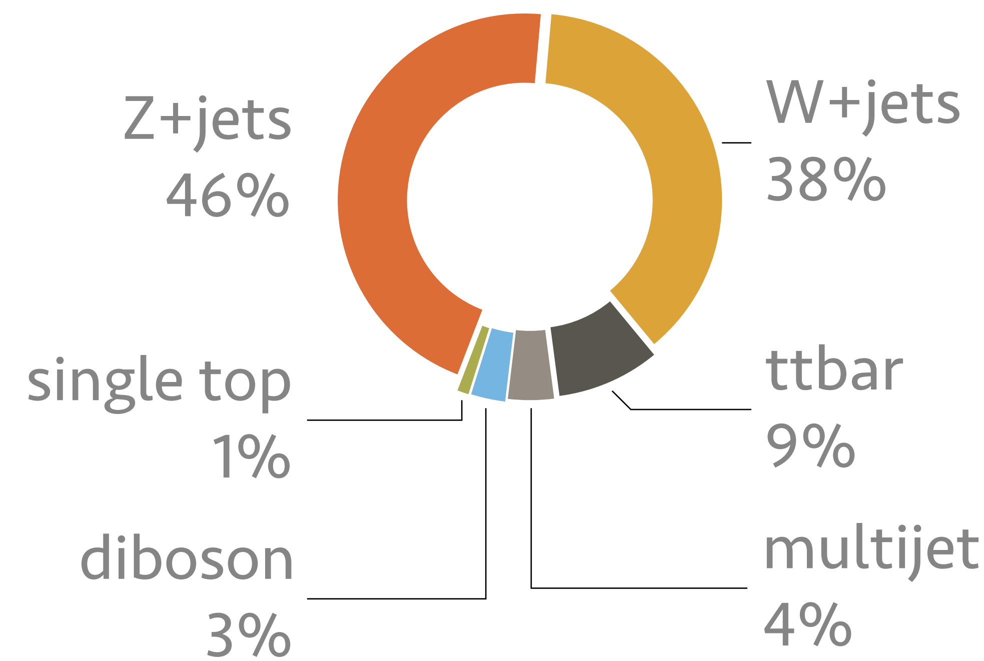
* The dominant background in signal region (SR) are Z(vv)+jets, W(lv)+jets and ttbar







* Control regions (CR) with one or two leptons targeting W(lv)+jets, Z(ll)+jets and ttbar
    * similar selections as in 0-lepton SR
    * ttbar enriched in 1/2 b-jets categories
* Dedicated multijet control region with reverted angular cuts from SR
* Sideband of vector boson mass window in 0-lepton as a validation region for all the background



background contamination
in 0-lepton SR

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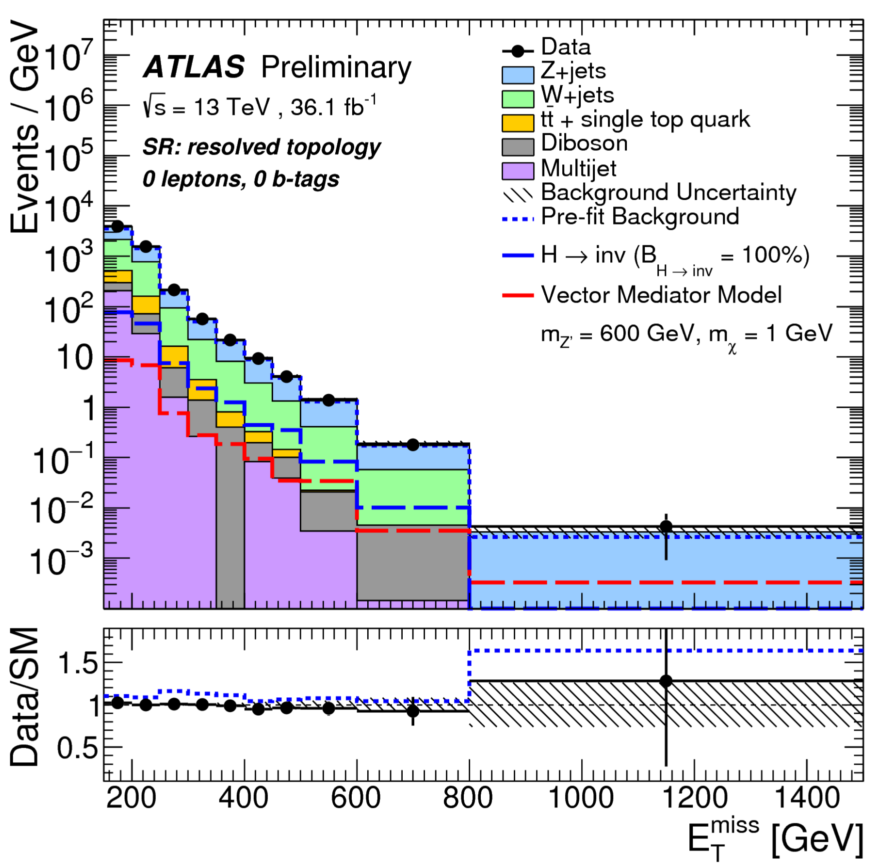
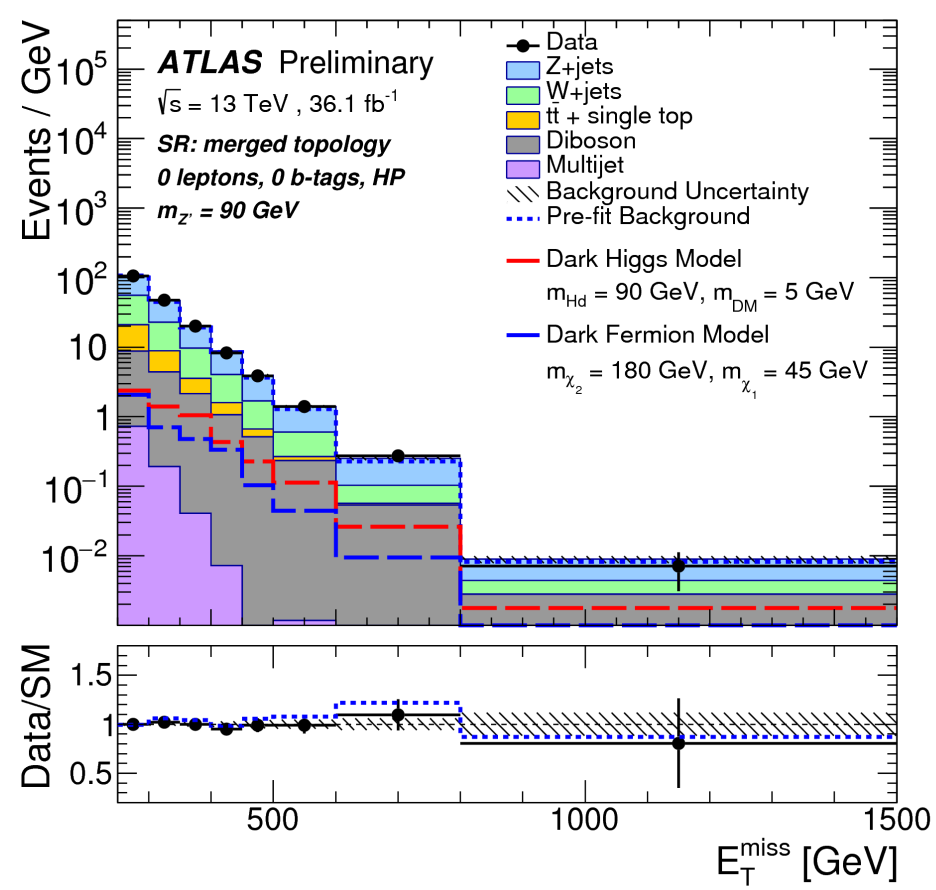
Statistical analysis

- A profile likelihood fit to the data on the discriminate variable MET is performed to interpret the observation of the search
  - signal strength μ as the parameter of interest
  - background normalisation and systematics uncertainties as nuisance parameters





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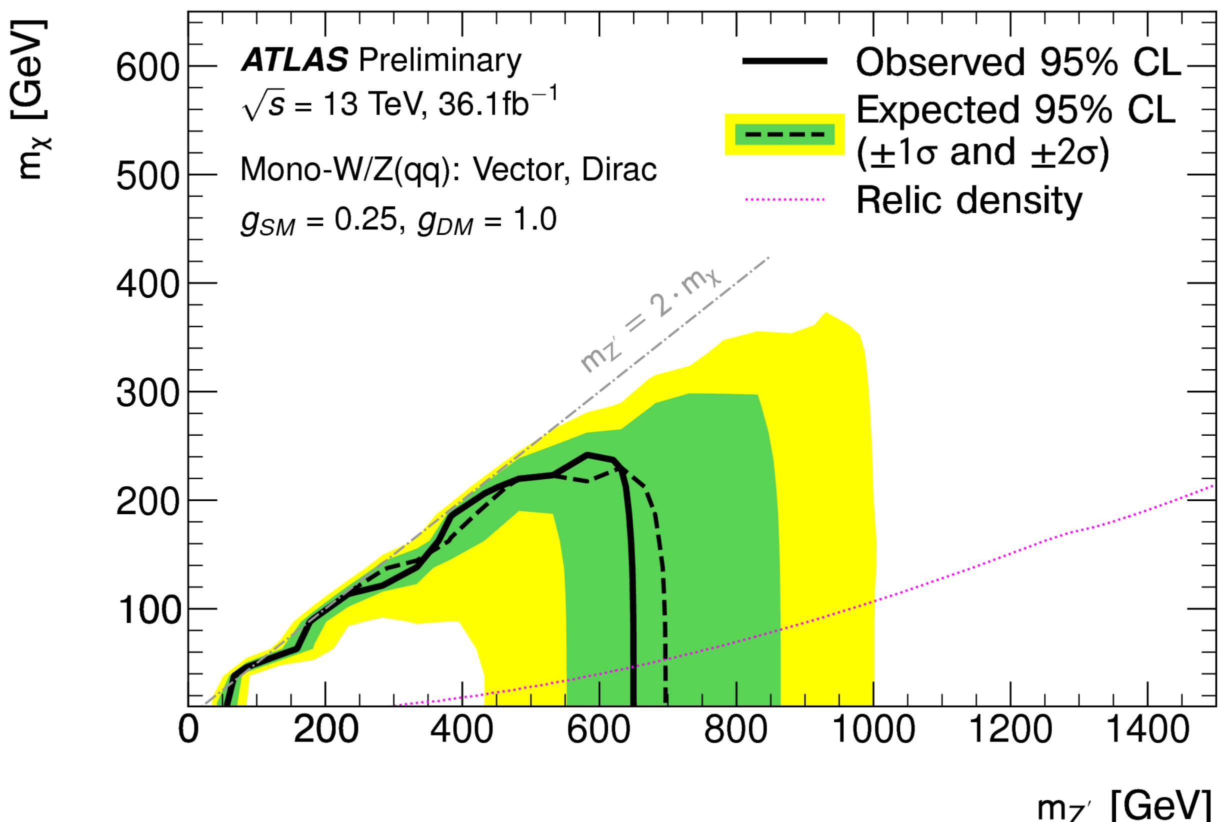
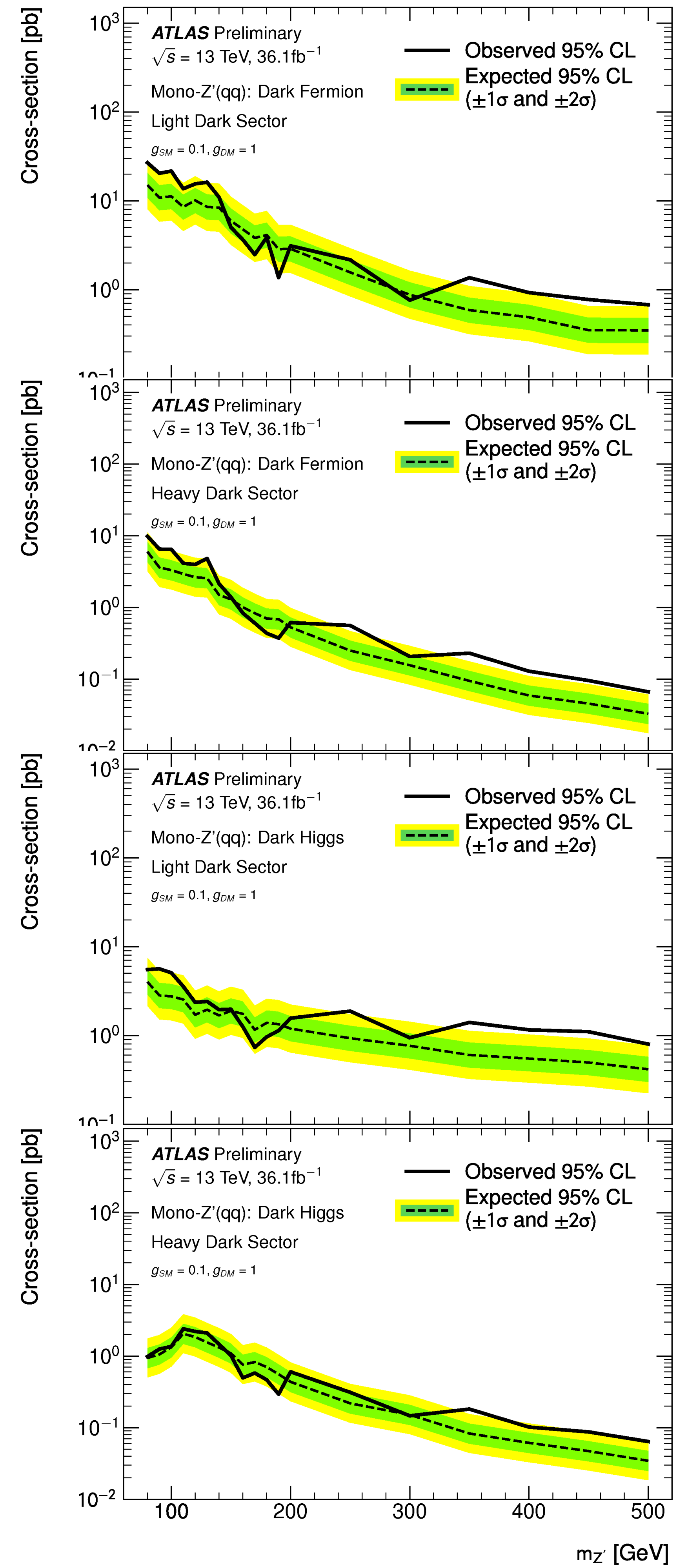
Result

* No significant excess over the SM prediction observed
* Set limit on signal strength μ at 95% CLs for each signal model and interpreted them into limit on:
  * DM and mediator mass for mono-V model
  * branching ratio of H->invisible decay
  * cross section for mono-Z' model

	observed	expected	+ 1σ	- 1σ
limit on BR(H->inv)	0.83	0.58	0.81	0.42





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Summary

* A search of dark matter has been performed in events with hadronically decaying vector boson and large MET in ATLAS detector

* Results are in agreement with SM and translated into exclusion limits on DM-pair production

* For simplified vector-mediator model

    * mediator mass $m_{Z'}$ of up to 650 GeV are excluded for dark matter mass m_χ of up to 250 GeV

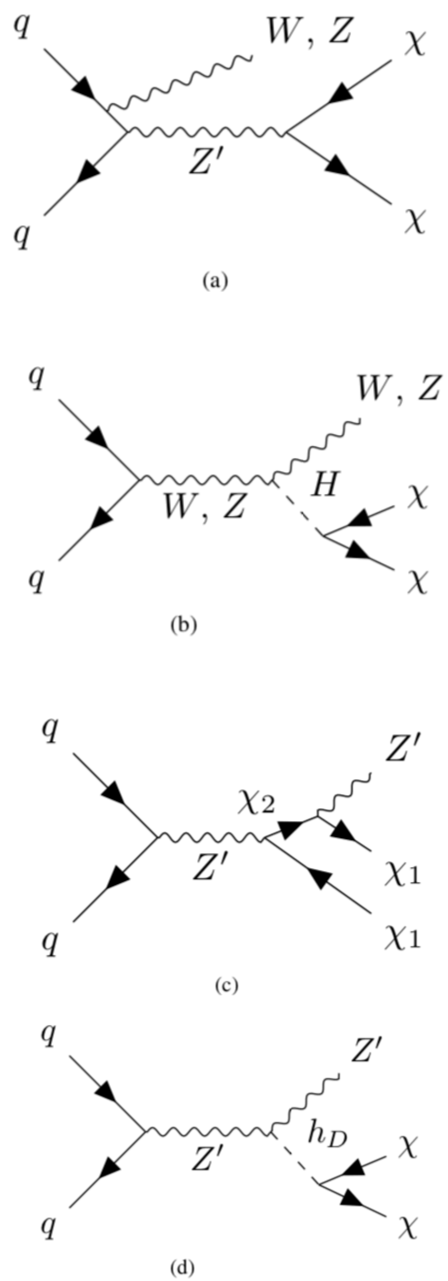
* For invisible Higgs boson decays

    * upper limit of 0.83 is set on branching ratio $B_{H\text{->invisible}}$

* For dark-fermion and dark-Higgs model

    * cross section exclusion for dark-fermion and dark-Higgs model are set in light and heavy dark sector scenario

Xsec. Exlusion. for 80<mZ'<500 GeV	light dark sector scenario	heavy dark sector scenario
dark-fermion	0.68 - 27 pb	0.066 - 9.8 pb
dark-Higgs	0.80 - 5.5 pb	0.064 - 2.4 pb



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Thank you!

Publications

* ATLAS Run1
  * 2013, mono-W/Z arXiv:1309.4017
  * 2015, H->invisible arXiv:1504.04324
* ATLAS Run2
  * 2016, mono-W/Z arXiv:1608.02372
  * 2018, mono-W/Z, H->invisible and mono-Z' ATLAS-CONF-2018-005

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Event Selection

	Merged topology					Resolved topology		
General requirements								
E_T^{miss}	> 250 GeV					> 150 GeV		
Jets, leptons	$\geq 1J$, 0ℓ					$\geq 2j$, 0ℓ		
b-jets	no b-tagged track jets outside of J					≤ 2 b-tagged small-R jets		
Multijet suppression	$\Delta\phi(\vec{E}_T^{miss}, J \text{ or } jj) > 120^o$ $\min_{i\in\{1,2,3\}}\left[\Delta\phi(\vec{E}_T^{miss}, j_i)\right] > 20^o$ $p_T^{miss} > 30$ GeV or ≥ 2 b-jets $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{miss}) < 90^o$							
Signal properties						$p_T^{j_1} > 45$ GeV $\sum p_T^{j_i} > 120$ (150) GeV for 2 (≥ 3) jets		
Mono-W/Z signal regions								
	$0b$ **HP**	$0b$ **LP**	$1b$ **HP**	$1b$ **LP**	$2b$	$0b$	$1b$	$2b$
ΔR_{jj}	-	-	-	-	-	< 1.4	< 1.4	< 1.25
$D_2^{(\beta=1)}$ p_T^J-dep.	pass	fail	pass	fail	-	-	-	-
Mass requirement (GeV)	m_J W/Z tagger requirement				m_J [75, 100]	m_{jj} [65, 105]		m_{jj} [65, 100]
Mono-Z' signal regions								
	$0b$ **HP**	$0b$ **LP**	$1b$ **HP**	$1b$ **LP**	$2b$	$0b$	$1b$	$2b$
$D_2^{(\beta=1)}$ <1.2	pass	fail	pass	fail	-	-	-	-
Mass requirement (GeV)	For $m_{Z'} < 100$ GeV: $[0.85m_{Z'}, m_{Z'} + 10]$		$[0.75m_{Z'}, m_{Z'} + 10]$			For $m_{Z'} < 200$ GeV: $[0.85m_{Z'}, m_{Z'} + 10]$	$[0.75m_{Z'}, m_{Z'} + 10]$	
	For $m_{Z'} \geq 100$ GeV: no merged-topology selection applied					For $m_{Z'} \geq 200$ GeV: $[0.85m_{Z'}, m_{Z'} + 20]$	$[0.80m_{Z'}, m_{Z'} + 20]$	

Yields - W/Z

Process	Merged topology 0b-HP	Merged topology 0b-LP	Merged topology 1b-HP	Merged topology 1b-LP	Merged topology 2b
Vector-mediator model,					
m_χ =1 GeV, $m_{Z'}$ =200 GeV	814 ± 48	759 ± 45	96 ± 18	99 ± 16	49.5 ± 4.3
m_χ =1 GeV, $m_{Z'}$ =600 GeV	280.9 ± 9.0	268.5 ± 8.8	34.7 ± 3.6	33.8 ± 3.1	15.38 ± 0.84
Invisible Higgs boson decays (m_H = 125 GeV, $\mathcal{B}_{H\to\text{inv.}}$ = 100%)					
VH	408.4 ± 2.1	299.3 ± 2.0	52.06 ± 0.85	44.06 ± 0.82	27.35 ± 0.52
ggH	184 ± 19	837 ± 35	11.7 ± 3.8	111 ± 30	12.3 ± 4.2
VBF	29.1 ± 2.5	96.0 ± 4.6	2.43 ± 0.36	5.83 ± 0.43	0.50 ± 0.07
W+jets	3170 ± 140	10120 ± 380	218 ± 28	890 ± 110	91 ± 12
Z+jets	4750 ± 200	15590 ± 590	475 ± 52	1640 ± 180	186 ± 12
$t\bar{t}$	775 ± 48	937 ± 60	629 ± 27	702 ± 34	50 ± 11
Single top-quark	159 ± 12	197 ± 13	89.7 ± 6.7	125.5 ± 8.7	16.1 ± 1.7
Diboson	770 ± 110	960 ± 140	88 ± 14	115 ± 18	54 ± 10
Multijet	12 ± 35	49 ± 140	3.7 ± 3.3	15 ± 13	9.3 ± 9.4
Total background	9642 ± 87	27850 ± 150	1502 ± 31	3490 ± 52	407 ± 15
Data	9627	27856	1502	3525	414

Process	Resolved topology 0b	Resolved topology 1b	Resolved topology 2b
Vector-mediator model,			
m_χ =1 GeV, $m_{Z'}$ =200 GeV	5050 ± 130	342 ± 29	136.7 ± 6.0
m_χ =1 GeV, $m_{Z'}$ =600 GeV	840 ± 16	59.9 ± 4.6	27.86 ± 0.94
Invisible Higgs boson decays (m_H = 125 GeV, $\mathcal{B}_{H\to\text{inv.}}$ = 100%)			
VH	2129.6 ± 6.4	171.7 ± 2.2	104.7 ± 1.2
ggH	4111 ± 78	178 ± 16	37 ± 11
VBF	514 ± 12	19.8 ± 2.3	2.33 ± 0.72
W+jets	117500 ± 4600	5000 ± 680	598 ± 98
Z+jets	135400 ± 5600	7710 ± 780	1219 ± 67
$t\bar{t}$	13800 ± 780	12070 ± 420	2046 ± 70
Single top-quark	2360 ± 140	1148 ± 71	222 ± 14
Diboson	6880 ± 950	514 ± 71	228 ± 34
Multijet	11900 ± 2300	1130 ± 370	290 ± 150
Total background	287770 ± 570	27580 ± 170	4601 ± 90
Data	287722	27586	4642

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Yields - Z' (90GeV)

Process	Merged topology 0b-HP	0b-LP	1b-HP	1b-LP	2b
Dark fermion, light sector	286 ± 54	125 ± 36	53 ± 23	26 ± 16	52 ± 23
Dark fermion, heavy sector	165 ± 18	71 ± 12	30.9 ± 7.7	18.6 ± 6.0	36.3 ± 8.4
Dark Higgs, light sector	253 ± 25	82 ± 14	37.7 ± 9.6	19.1 ± 6.9	45 ± 11
Dark Higgs, heavy sector	224 ± 14	75.9 ± 8.4	37.5 ± 5.9	21.2 ± 4.4	49.5 ± 6.8
W+jets	2960 ± 170	5180 ± 280	342 ± 52	680 ± 100	120 ± 120
Z+jets	4720 ± 190	7990 ± 310	628 ± 69	1280 ± 140	265 ± 22
$t\bar{t}$	780 ± 110	440 ± 59	646 ± 59	434 ± 49	59 ± 19
Single top-quark	161 ± 15	113 ± 14	93 ± 10	94.1 ± 8.9	17.8 ± 2.8
Diboson	830 ± 130	575 ± 95	129 ± 23	107 ± 18	61 ± 11
Multijet	48 ± 41	21 ± 66	1.2 ± 1.0	5.4 ± 5.1	0.52 ± 0.51
Total background	9498 ± 96	14310 ± 120	1840 ± 37	2600 ± 46	523 ± 19
Data	9516	14282	1845	2628	534

Process	Resolved topology 0b	1b	2b
Dark fermion, light sector	2060 ± 150	264 ± 52	228 ± 55
Dark fermion, heavy sector	976 ± 44	121 ± 15	164 ± 18
Dark Higgs, light sector	1206 ± 54	135 ± 18	197 ± 22
Dark Higgs, heavy sector	953 ± 30	112 ± 10	146 ± 12
W+jets	78400 ± 3400	4400 ± 690	1030 ± 190
Z+jets	91700 ± 3800	6970 ± 690	2140 ± 210
$t\bar{t}$	11170 ± 920	10590 ± 530	7760 ± 230
Single top-quark	1200 ± 170	1006 ± 74	602 ± 40
Diboson	6080 ± 930	514 ± 80	337 ± 55
Multijet	14700 ± 2500	1280 ± 540	540 ± 270
Total background	203990 ± 480	24770 ± 220	12400 ± 110
Data	203991	24783	12406

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Yields - Z’ (350GeV)

Process	Resolved topology $0b$	$1b$	$2b$
Dark fermion, light sector	655 ± 14	104.2 ± 5.8	89.5 ± 5.3
Dark fermion, heavy sector	70.79 ± 0.79	12.45 ± 0.33	9.04 ± 0.28
Dark Higgs, light sector	639 ± 13	96.7 ± 4.9	72.3 ± 4.3
Dark Higgs, heavy sector	118.9 ± 1.4	19.62 ± 0.58	14.24 ± 0.50
W+jets	68300 ± 4300	4270 ± 1100	115 ± 84
Z+jets	72200 ± 3000	7230 ± 800	1160 ± 110
$t\bar{t}$	3900 ± 460	10320 ± 720	4920 ± 140
Single top-quark	752 ± 69	1530 ± 110	466 ± 35
Diboson	2000 ± 340	282 ± 47	14.6 ± 2.8
Multijet	17100 ± 2300	7870 ± 390	880 ± 140
Total background	164310 ± 650	31520 ± 250	7567 ± 85
Data	164386	31465	7597

Uncertainties

* Two parts of uncertainties are considered: data statistical uncertainty (5-21%) and systematic uncertainties (21-45%)
* Systematic uncertainties further contain experimental uncertainties and modelling uncertainties
    * large-R jet (9-23%), small-R jet (3-13%)
    * MET and MET trigger (1-4%)
    * b-tagging (2-11%), leptons (4-15%), luminosity (3-4%)
    * signal modeling (7-20%)
    * background modelling (0.3-15%)
    * MC statistical uncertainty (10-20%)
* The impact of uncertainties varies with different signals and analysis categories

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Systematics impact on signal strength

Source of uncertainty	Uncertainty on μ =1 [%] Vector mediator, $m_{Z'}$ = 200 GeV	Vector mediator, $m_{Z'}$ = 600 GeV	$H \rightarrow$invisible ($\mathcal{B}_{H\rightarrow\text{inv.}} = 100\%$)	Dark fermion, $m_{Z'}$ = 90 GeV	Dark fermion, $m_{Z'}$ = 300 GeV
Large-R jets	9	20	17	23	-
Small-R jets	3	8	7	13	6
Electrons	4	9	6	7	8
Muons	6	7	7	15	14
$E_{\mathrm{T}}^{\mathrm{miss}}$	1	4	3	4	3
b-tagging (track jets)	4	4	4	8	-
b-tagging (small-R jets)	2	4	2	5	11
Luminosity	3	4	3	4	4
Multijet normalization	7	11	11	13	11
Diboson normalization	5	11	6	3	1
Z+jets normalization	5	9	4	15	12
W+jets normalization	3	4	2	8	7
$t\bar{t}$ normalization	3	1	0.3	8	6
Signal modeling	7	9	20	-	-
V+jets modeling	4	10	4	7	13
$t\bar{t}$ modeling	2	4	3	10	8
V+jets flavor composition	1	3	3	4	3
Diboson modeling	1	2	2	1	0.3
Background MC stat.	10	18	14	20	19
Total syst.	21	40	38	45	42
Data stat.	7	21	5	14	18
Total	22	45	39	47	47

Profile likelihood fit

SR plus CR

observed event

expected signal and background

Gaussian function for constraint on nuisance parameter

$$\mathcal{L}(\mu, \boldsymbol{\theta}) = \prod_{j}^{N_{\text{categories}}} \prod_{i}^{N_{\text{bins}}} P\left(N_{ij} \mid \mu S_{ij}(\boldsymbol{\theta}) + B_{ij}(\boldsymbol{\theta})\right) \prod_{k}^{N_{\text{nuisance}}} \mathcal{G}(\theta_k)$$

Poisson distribution

signal strength

nuisance parameters for background normalisation and systematic uncertainties

Model independent interpretation

* A generic CLs upper limit on the allowed visible cross-section σ_{vis} of potential W+DM and Z+DM production are also performed with W/Z final state

$$\sigma_{\text{vis, W+DM}}(E_T^{\text{miss}}) \equiv \sigma_{\text{W+DM}}(E_T^{\text{miss}}) \times \mathcal{B}_{W\to q'q} \times (A\times\varepsilon)(E_T^{\text{miss}}) \quad \text{for } W+\text{DM events},$$
$$\sigma_{\text{vis, Z+DM}}(E_T^{\text{miss}}) \equiv \sigma_{\text{Z+DM}}(E_T^{\text{miss}}) \times \mathcal{B}_{Z\to q\bar{q}} \times (A\times\varepsilon)(E_T^{\text{miss}}) \quad \text{for } Z+\text{DM events},$$

* Selection similar to SR but with inclusive b-jet multiplicity and no separation in W/Z mass window

* The exclusion upper limit on σ_{vis} thus apply to any processes which have a generic back-to-back topology with W/Z boson recoiling against MET from weak interacting particles

E_T^{miss} range [GeV]	Upper limit at 95% CL [fb] σ_{vis}^{obs}	σ_{vis}^{exp}	-1σ	$+1\sigma$	$A\times\varepsilon$
	W+DM, $W\to q'q$				
[150, 200)	750	650	470	910	20%
[200, 250)	185	163	117	226	20%
[250, 300)	43	50	36	69	30%
[300, 400)	41	36	26	50	45%
[400, 600)	9.7	12.6	9.1	17.6	55%
[600, 1500)	5.1	3.1	2.2	4.3	55%

E_T^{miss} range [GeV]	Upper limit at 95% CL [fb] σ_{vis}^{obs}	σ_{vis}^{exp}	-1σ	$+1\sigma$	$A\times\varepsilon$
	Z+DM, $Z\to q\bar{q}$				
[150, 200)	313	225	162	314	20%
[200, 250)	69	60	43	83	20%
[250, 300)	39	29	21	40	30%
[300, 400)	31.1	18.5	13.3	25.7	45%
[400, 600)	9.2	9.1	6.5	12.6	50%
[600, 1500)	3.0	2.6	1.9	3.6	55%

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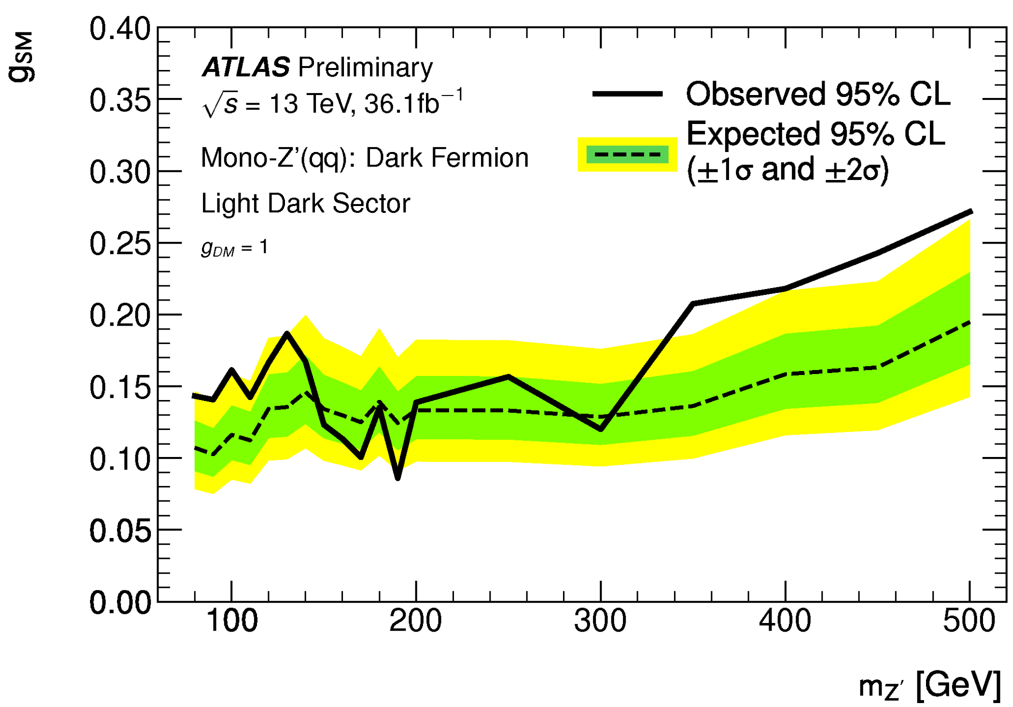
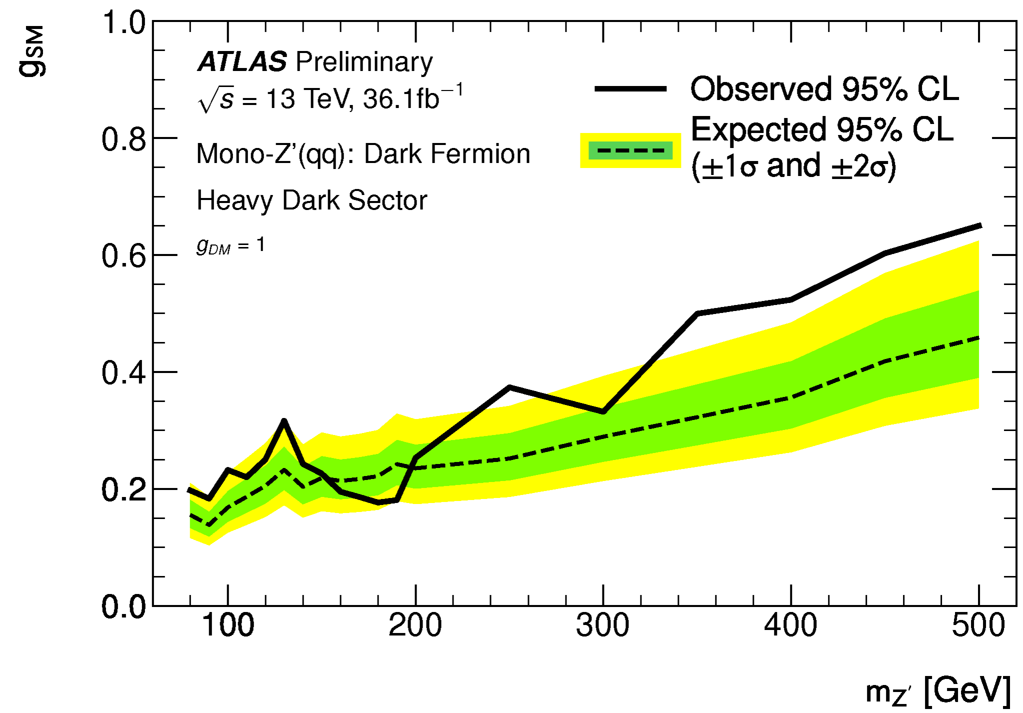
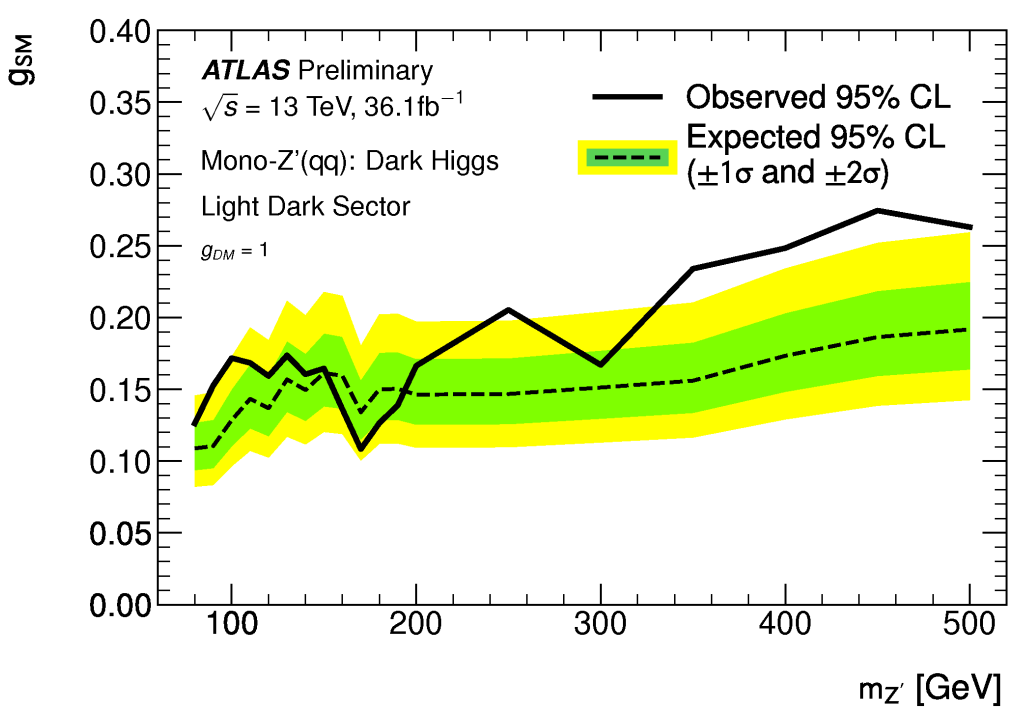
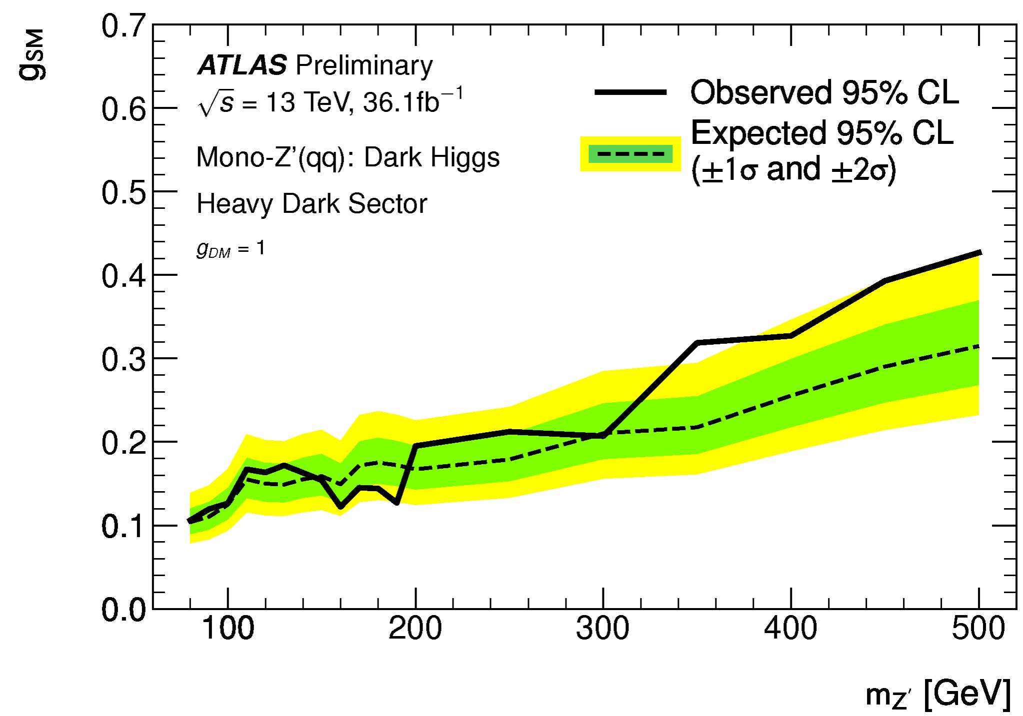
Upper limit on g_{SM} in mono-Z'

* Upper limit on the coupling g_{SM} in mono-Z' models is also performed, assuming g_{DM}=1









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