Search for dark matter produced in association with bottom or top quarks with the ATLAS detector

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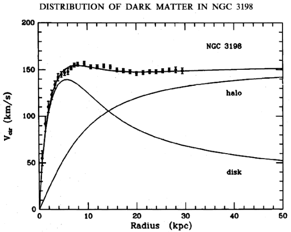
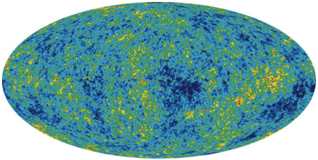
Introduction

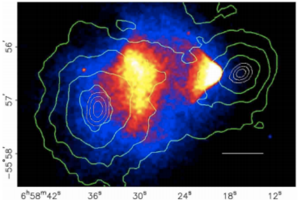
- I will present the results of a search for dark matter produced in association with bottom or top quarks with the ATLAS detector detailing:
    - Motivation
    - Signal models & characteristic signatures
    - Backgrounds & background estimation strategy
    - Signal region results
    - Limits and interpretation
    - Current status of the analysis
    - Ongoing improvements
    - Summary and Conclusions

Motivation

- evidence for dark matter (DM):
    - Galactic Rotation Curves
    - Cosmic Microwave Background
    - Galactic Clusters
    - Bullet Cluster ← **cannot** be explained by modified gravity
    - etc...
- **Weakly interacting massive particles (WIMPs) are possible DM candidates**
- can then search for WIMP pair production in pp collisions

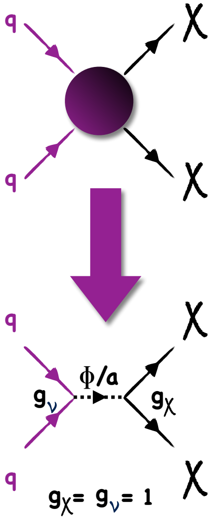






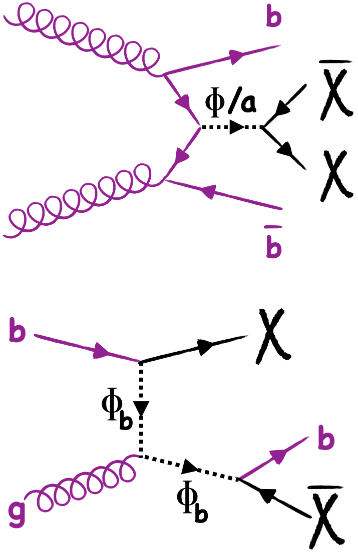
Theoretical Motivation

- Proposed simplified benchmark models assume existence of SM-DM mediator.
  - replacing effective field theories used in Run 1
- assume minimal flavour violation $\rightarrow$ interaction between new neutral spin-0 state and SM $\propto$ fermion masses via Yukawa-type couplings
- large production of colour neutral mediators :
  - through loop induced gluon fusion
  - **in a association with heavy flavour quarks**
- search for DM in association with b and t quarks
- define:
  - SM $\leftrightarrow$ DM-mediator coupling $= g_\nu$
  - DM-mediator $\leftrightarrow$ DM coupling $= g_\chi$
- set $g_\nu = g_\chi = g$
- set $g = 1$



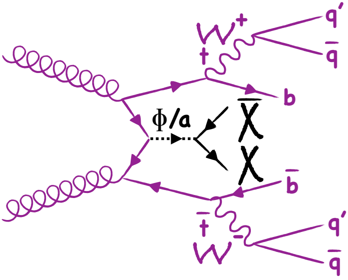
$b\bar{b}$ Signatures

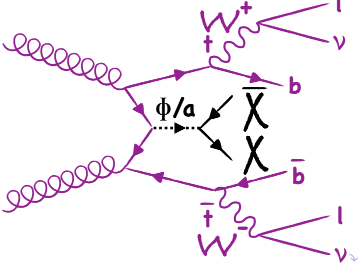
- signatures:
  - $b\bar{b}$ with associated production of dark matter scalar/pseudoscalar mediator ϕ/a (DM$b\bar{b}$)
  - colour charged scalar mediator decaying into a b-quark and a DM candidate (b-FDM)
- signatures characterised by:
  - high missing transverse momentum (MET)
  - b-jets (1 or 2 at leading order)



$t\bar{t}$ Signatures

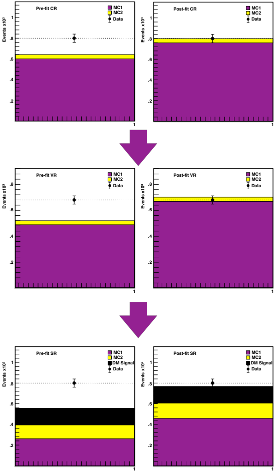
- signatures:
  - $t\bar{t}$ with associated production of dark matter scalar/pseudoscalar mediator ϕ/a where the t-quarks decay:
    - fully hadronically (DM$t\bar{t}0l$)
    - fully leptonically (DM$t\bar{t}2l$)
- signatures characterised by:
  - high missing transverse momentum (MET)
  - b-jet multiplicity (at least 2 at leading order)
  - leptons (DM$t\bar{t}2l$ only)





Analysis Strategy

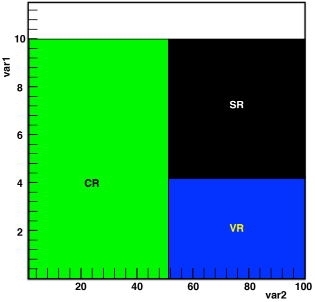
- define signal regions which are regions of phase-space that are expected to be high in signal with as little background contamination as possible
- use a combination of Monte Carlo (MC) simulated data and a strategy of ‘control regions’ and ‘validation regions’ to estimate and validate background contributions in signal regions
- use MC simulated data to estimate the contribution of DM signal in signal regions
- place limits on DM↔SM couplings based on the difference between the observed data and MC simulated data



Background Estimation Strategy

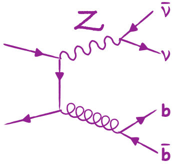
- define a control region (CR) per background that is:
  - kinematically similar to the signal region (SR)
  - orthogonal to SR
  - dominant in a particular background
- then fit the background to the data in that CR
- define a scale factor as μ_{bkg} required to match the data to the background in this control region

- define a validation region (VR) per background that is:
  - also kinematically similar to SR
  - closer to SR than CR
  - orthogonal to both CR and SR
- apply μ_{bkg} in VR as test
- apply in SR
- this can then be done for several CRs simultaneously to estimate several backgrounds in SR
- main advantage of CR strategy is to reduce the impact of systematic uncertainties in SRs



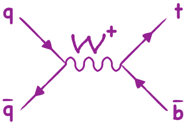
Backgrounds

- Z+jets :



  - dominant for: DM$b\bar{b}$ and b-FDM

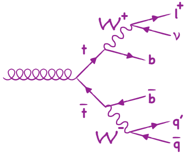
- t :



  - subsubdominant for: DM$b\bar{b}$ and b-FDM

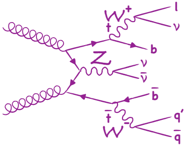
- fakes (from jets, leptons produced in hadron decays and photon conversion): subsubdominant for DM$t\bar{t}2l$

- $t\bar{t}$:



  - dominant for DM$t\bar{t}0l$ and DM$t\bar{t}2l$
  - subdominant for: DM$b\bar{b}$ and b-FDM

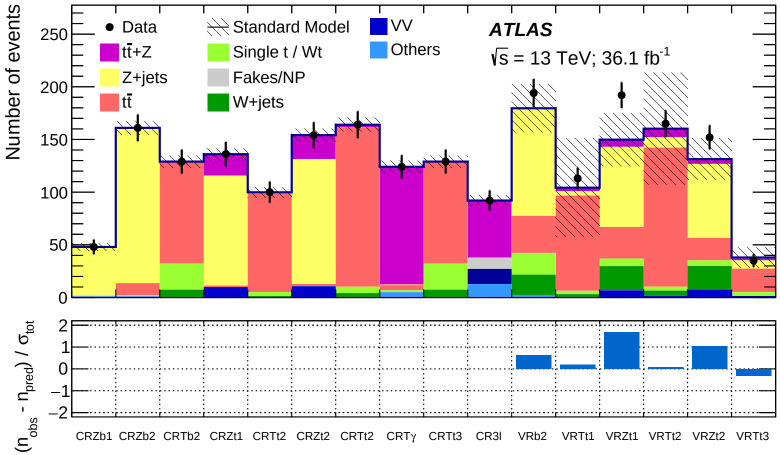
- $t\bar{t}Z$:



  - subdominant for DM$t\bar{t}0l$ and DM$t\bar{t}2l$

Control & Validation Region Post-fit Results

- all VRs yield data consistent with MC within at least 2σ (mostly $< 1\sigma$)



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DM$b\bar{b}$ & b-FDM Results

- SRb1 signal region optimised for b-FDM
- SRb2 signal region optimised for DM$b\bar{b}$
- data compatible with predictions
- excesses seen, but always within 1.3σ
- first ATLAS Results on $b\bar{b}+\phi/a$!
- errors in table are statistical+systematic

	SRb1	SRb2-bin1	SRb2-bin2	SRb2-bin3	SRb2-bin4
Observed	19	88	88	90	82
Total background (fit)	16.9 ± 3.3	77 ± 13	72 ± 11	76 ± 13	66.4 ± 9.1
Z/γ^*+ jets	14.2 ± 3.1	39.7 ± 6.3	44.4 ± 6.6	53.3 ± 9.9	55.6 ± 8.6
$t\bar{t}$	$0.58^{+0.60}_{-0.58}$	17.8 ± 6.5	13.8 ± 5.5	14.0 ± 4.7	7.0 ± 2.9
Single top quark	$0.25^{+0.42}_{-0.25}$	14.7 ± 5.8	10.2 ± 3.7	5.5 ± 3.1	2.6 ± 1.7
Others	2.0 ± 1.1	5.2 ± 3.4	$3.4^{+1.7}_{-1.6}$	2.7 ± 1.1	1.3 ± 1.0
Z/γ^*+ jets (pre-fit)	12.1	30.6	34.2	41.1	42.8
$t\bar{t}$ (pre-fit)	-	27.1	21.1	21.4	10.6
Signal benchmarks					
$m(\phi,\chi) = (20, 1)$ GeV, $g = 1$		0.238 ± 0.085	0.262 ± 0.079	0.320 ± 0.082	0.277 ± 0.080
$m(a,\chi) = (20, 1)$ GeV, $g = 1$		0.256 ± 0.065	0.199 ± 0.060	0.308 ± 0.085	0.267 ± 0.067
$m(\phi_b,\chi) = (1000, 35)$ GeV	18.6 ± 3.8				

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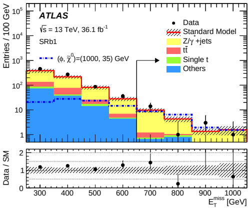

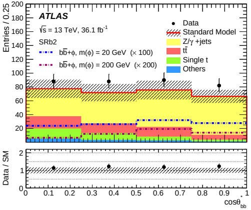

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DM$t\bar{t}0l$ & DM$t\bar{t}2l$ Results

- SRt1 & SRt2 signal regions optimised for low high mediator mass DM$t\bar{t}0l$ models respectively
- SRt3 signal region optimised for DM$t\bar{t}2l$
- excesses seen again, but always within 1.3σ
- errors in table are statistical+systematic

	SRt1	SRt2	SRt3
Observed	23	24	18
Total background (fit)	20.5 ± 5.8	20.4 ± 2.9	15.2 ± 4.3
$t\bar{t}$	7.0 ± 3.9	3.1 ± 1.3	4.5 ± 2.5
$t\bar{t}+Z$	4.3 ± 1.1	6.9 ± 1.4	4.4 ± 1.9
W+jets	3.3 ± 2.6	1.28 ± 0.50	incl. in Fakes/NP
Wt	incl. in Others	incl. in Others	$0.33^{+0.53}_{-0.33}$
Z/γ^*+ jets	3.7 ± 1.4	6.2 ± 1.1	incl. in Others
VV	incl. in Others	incl. in Others	0.61 ± 0.25
Fakes/NP	-	-	2.7 ± 1.3
Others	2.2 ± 1.2	3.00 ± 1.6	2.69 ± 0.93
$t\bar{t}$ (pre-fit)	6.1	2.8	4.0
$t\bar{t}+Z$ (pre-fit)	3.53	5.6	5.6
Z/γ^*+ jets (pre-fit)	3.2	5.72	-
Signal benchmarks			
$m(\phi, \chi)$ = (20, 1) GeV, g = 1	9.3 ± 1.6	12.8 ± 1.9	21.0 ± 2.3
$m(a, \chi)$ = (20, 1) GeV, g = 1	7.6 ± 1.5	12.1 ± 1.8	14.1 ± 1.6
$m(\phi, \chi)$ = (100, 1) GeV, g = 1	6.5 ± 1.3	10.1 ± 1.5	11.5 ± 1.5
$m(a, \chi)$ = (100, 1) GeV, g = 1	6.2 ± 1.2	11.5 ± 2.0	11.9 ± 1.5

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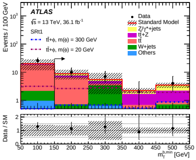

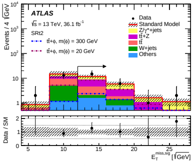

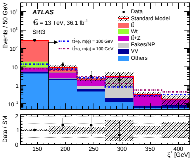

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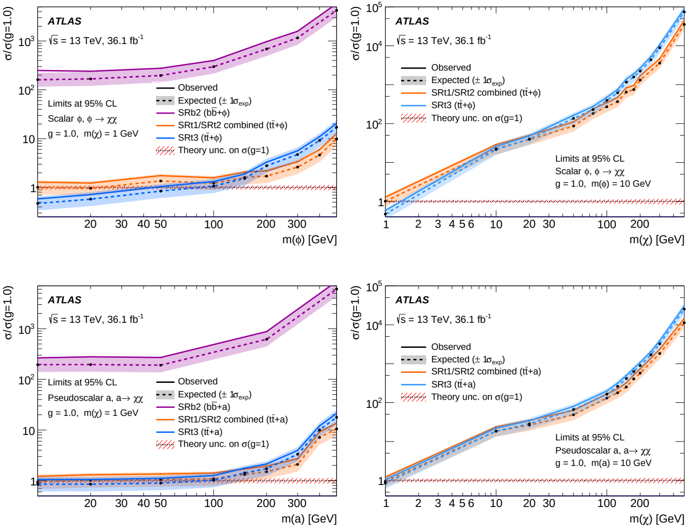
Limits

- most stringent limits on $t\bar{t} + \phi/a$
- limits for on shell $t\bar{t} + \phi/a$ decays constant for $m_\phi < 100$ GeV
- SRT3 excludes excludes $g = 1$ for scalar mediator masses < 50 GeV
- for bottom-like signal regions, limits set of ∼300x production x-sec for mediator mass between 10 and 50 GeV



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Limits

- model-independent limits on production x-sec of colour-neutral scalar mediator particles converted to limit on spin-independent DM-nucleon scattering
- the results can then be compared with the results from direct-detection experiments
- **SRt3 places the most stringent limit and so is used here**

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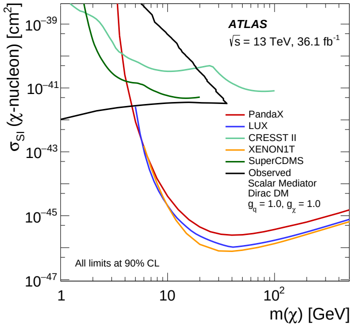

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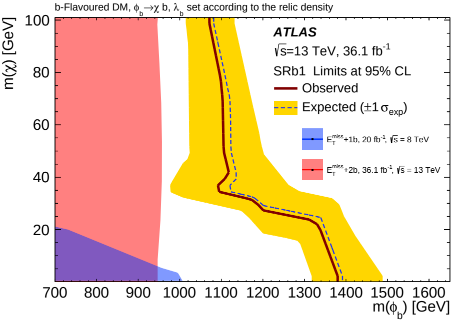

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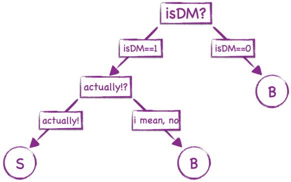
- results for b-FDM only
- sensitivity highly dependent on λ_b, which is set according to relic density constraint
- for a DM particle of $\sim$ 35 GeV, as suggested by Fermi-LAT Collaboration, mediator masses below 1.1 TeV are excluded at 95% CL

Current Status

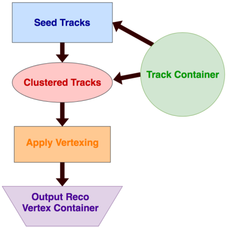
- DM$b\bar{b}$ and ‘sbottom’ (supersymmetric partner to the bottom quark) signals both have leading order final states containing 2 b-jets and E_T^{miss} and so are performed in the same framework under ‘bbMET’
- DM$t\bar{t}$ and ‘stop’ (supersymmetric partner to the top quark) signals both have leading order final states containing at least 2 b-jets and E_T^{miss} therefore:
  - DM$t\bar{t}0l$ and stop 0l are performed in the same framework $=>$ ttMET0l
  - DM$t\bar{t}2l$ and stop 2l are performed in the same framework $=>$ ttMET2l
- b-FDM models have fallen out of favour due constraints placed by astrophysical observations
- currently in R&D stage of full Run2 ($\sim 150\ \text{fb}^{-1}$) bbMET paper

Ongoing Improvements

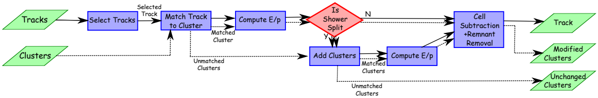
- BDTs
  - improve background discrimination in signal regions



- increased luminosity
  - $36 fb^{-1} \rightarrow 139 fb^{-1}$
- soft b-tagging
  - improve sensitivity in regions with a small mass splitting
  - b-tagging on track jets
  - secondary Vertex Tagging



- Particle flow Jets
  - improved energy resolution
  - lower fake rate



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Conclusions

- limits placed on dark-matter pair production in association with bottom or top quarks
- results interpreted in framework of simplified models of spin-0 mediators to the dark sector decaying into pairs of DM particles
- no significant excesses observed
- mediator masses between 10 and 50 GeV excluded at 95% CL
- 300 times the nominal x-sec limit placed for scalar and pseudoscalar mediator masses between 10 and 50 GeV in bottom-quark final states
- b-FDM constraints exclude $m_\phi < 1.1$ TeV for $m_\chi = 35$ GeV

Backup

- $\Delta\phi(j, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$ = $\Delta\phi$ between missing energy and any jet
- H_{T3} = scalar sum of jet momenta excluding leading and subleading jets
- δ^{+} = $|\Delta\phi(j, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) + \Delta\phi_{bb} - \pi|$
- δ^{-} = $\Delta\phi(j, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) - \Delta\phi_{bb}$
- $m_{R=0.8}^{jet\ 1,2}$ = mass of leading and subleading jet with R=0.8
- $m_{R=1.2}^{jet\ 1,2}$ = mass of leading and subleading jet with R=1.2
- $m_{\mathrm{T}}^{b,mathrmmin}$ = transverse mass of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and b jet with smallest ΔR to it
- $m_{\mathrm{T}}^{b,mathrmmax}$ = transverse mass of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and b jet with largest ΔR to it
- ΔR_{bb} = angular distance between the 2 b jets
- m_{T2}^{ll} = ”stransverse mass”. kinematic variable with an endpoint at the W-boson mass. Link
- $cos^{*}(bb)$ =$|tanh(\frac{\Delta\eta_{bb}}{2})|$

Control Region Definitions

- CRTb2, CRTt1 and CRTt2:
  - to estimate $t\bar{t}$
  - tight 1 lepton regions in SRb2, SRt1 and SRt2
- CRZt1, CRZt2, CRZb1 and CRZb2:
  - to estimate $Z \to \nu\nu$ in all SRs
  - 2 same flavour opposite sign leptons with invariant mass $\sim Z$ mass
- CRγ and CR3l (SRT3)
  - to estimate $t\bar{t}Z(\to \nu\nu)$ in SRt1, SRT2 and SRT3
  - CRγ requires $p_{T\gamma} > m_Z$ to imitate $t\bar{t}Z(\to \nu\nu)$
  - CR3l maker use of $Z \to l^+l^-$ and semi-leptonic $t\bar{t}$

Observable	CRZb1	CRZb2	CRZt1	CRZt2	CRTb2	CRTt1	CRTt2	CRTt3	CRγ	CR3ℓ
Trigger	1ℓ	1ℓ	1ℓ		1ℓ	$E_{\mathrm{T}}^{\mathrm{miss}}$		2ℓ	1γ	2ℓ
$\mathcal{N}_j$	≥ 2	2–3	≥ 4		2–3	≥ 3		≥ 1	≥ 4	≥ 3 or ≥ 4
$\mathcal{N}_b$	≥ 1	≥ 2	≥ 2		≥ 2	≥ 2		≥ 1	≥ 2	≥ 2 or $= 1$
$\mathcal{N}_\ell^{\mathrm{T}}$	$= 2$ (SFOS)		$= 2$ (SFOS)		$= 1$	$= 1$		-	$= 1$	-
$\mathcal{N}_\ell^{\mathrm{M}}$	-	-	-		-	-		$= 2$ (OS)	-	3 (1 SFOS)
$\mathcal{N}_\tau$	-	-	0		-	0		-	-	-
$\mathcal{N}_\gamma$	-	-	-		-	-		$= 1$	-	-
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	< 120	< 60	< 50		> 180	> 250		-	-	-
$E_{\mathrm{T},\ell\ell}^{\mathrm{miss}}$ [GeV]	> 300	> 120	> 160		-	-		-	-	> 80
$p_{\mathrm{T}}(\gamma)$ [GeV]	-	-	-		-	0		-	> 150	-
$p_{\mathrm{T}}(\ell_1), p_{\mathrm{T}}(\ell_2)$ [GeV]	$> 30, > 25$	$> 30, > 25$	$> 28, > 28$		$> 30, -$	$> 28, -$		$> 25, 20$	> 28	$> 25, > 20$
Multi-jet rejection specific	as SR		no			as SR			no	as SR
m_{T} [GeV]	-	-	-		> 30	[30–100]		-	-	> 30
$\Delta R_{b\ell}^{\min}$ [rad]	-	-	-		-	< 1.0	< 1.5	-	-	-
$\|m_{\ell\ell} - m_Z\|$ [GeV]	< 20	< 30	< 5		-	-		as SR	-	< 10
$\Delta\phi(\mathrm{j}, \vec{p}_{\mathrm{T},\ell\ell}^{\mathrm{miss}})$ [rad]	> 0.6	-	-		-	-		-	-	-
$H_{\mathrm{T}}^{\mathrm{ratio}}$	-	> 0	-		as SR	-		-	-	-
$\delta_{\ell\ell}^-, \delta_{\ell\ell}^+$ [rad]	-	$< 1, < 0.5$	-		as SR	-		-	-	-
$m_{\mathrm{R=SR}}^{\mathrm{jet}\ 0}$ [GeV]	-	-	> 60	> 60	-	> 60	> 140	-	-	-
$m_{\mathrm{R=SR}}^{\mathrm{jet}\ 1}$ [GeV]	-	-	-		-	> 60	> 80	-	-	-
$m_{\mathrm{T}}^{b,\min}$ [GeV]	-	-	-		-	> 100		-	-	-
$m_{\mathrm{T}}^{b,\max}$ [GeV]	-	-	-		-	-		-	-	-
$m_{\mathrm{T},\ell\ell}^{b,\min}$ [GeV]	-	-	-	> 100	-	-		-	-	-
$m_{\mathrm{T},\ell\ell}^{b,\max}$ [GeV]	-	-	> 100	-	-	-		-	-	-
ΔR_{bb}	-	-	0		-	1.5		-	-	-
$E_{\mathrm{T},\ell\ell}^{\mathrm{miss,\ sig}}$ [$\sqrt{GeV}$]	-	-	-	> 6	-	-		-	-	-
ξ^+ [GeV]	-	-	-		-	-		< 150	-	-
$m_{b2\ell}^{\min}$ [GeV]	-	-	-		-	-		< 170	-	-
$\xi_{\ell\ell}^+$ [GeV]	-	-	-		-	-		-	-	> 120
$m_{2b\ell}^{\min}$ [GeV]	-	-	-		-	-		-	-	< 170

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Validation Region Definitions

- SRb2 backgrounds validated in VRb2
- SRt1 and SRt2:
  - top background estimated in VRTt1 and VRTt2
  - Z background estimated in VRZt1 and VRZt2
- SRt3 top background validated in SRT3

Observable	VRb2	VRZt1	VRZt2	VRTt1	VRTt2	VRTt3
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}}$		$E_{\mathrm{T}}^{\mathrm{miss}}$		$2\mu \Vert 2e \Vert 1e1\mu$
$\mathcal{N}_j$	2–3	≥ 4		≥ 4		≥ 1
$\mathcal{N}_b$	≥ 2	≥ 2		≥ 2		≥ 1
$\mathcal{N}_\ell$	as SR					
τ multiplicity	-	-		0		-
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 180	> 250		> 300		-
$p_{\mathrm{T}}(j_1, j_2)$ [GeV]	$> 150, > 20$	$> 80, > 80$		$> 80, > 80$		> 30,-
$p_{\mathrm{T}}(j_3, j_4)$ [GeV]	< 60,-	$> 40, > 40$		$> 40, > 40$		-
$p_{\mathrm{T}}(bj_1)$ [GeV]	> 150	> 20		> 20		> 30
$p_{\mathrm{T}}(\ell_1, \ell_2)$ [GeV]	-	-		-		$> 25, 20$
Multi-jet rejection	as SR					
$\vert m_{\ell\ell}^{\mathrm{SF}} - m_Z \vert$ [GeV]	-	-		-		> 20
δ^-, δ^+ [rad]	$< 0, > 0.5$	-		-		-
$m_{\mathrm{R=SR}}^{\mathrm{jet}\ 0}$ [GeV]	-	< 80	< 140	> 80	> 140	-
$m_{\mathrm{R=SR}}^{\mathrm{jet}\ 1}$ [GeV]	-	-		> 40	> 50	-
$m_{\mathrm{T}}^{b,\mathrm{min}}$ [GeV]	-	> 150		$(80, 150)$	$(100, 200)$	-
$m_{\mathrm{T}}^{b,\mathrm{max}}$ [GeV]	-	> 250	-	> 200	-	-
ΔR_{bb}	-	< 1.5		> 0.8	> 1.0	-
$E_{\mathrm{T}}^{\mathrm{miss,\ sig}}$ $[\sqrt{GeV}]$	-	> 12	-	-	> 10	-
ξ^+, $m_{b2\ell}^{\mathrm{min}}$, $m_{\mathrm{T2}}^{\ell\ell}$ [GeV]	-	-		-		as SR
$\Delta\phi_{\mathrm{boost}}$ [rad]	-	-		-		> 1.5

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DM$b\bar{b}$ & b-FDM Definitions

- some common requirements:
  - passes $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
  - minimum requirement on $\Delta\phi(j, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$ to reduce multi-jet contamination
  - at least 1 b-tagged jet
- SRb1 signal region optimised for b-FDM models require:
  - very high $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement
  - upper limit on scalar sum of jet momenta excluding leading and subleading jets (H_{T3}) required to reduce $t\bar{t}$ background.
- SRb2 signal region optimised for DM$b\bar{b}$ models require:
  - at least 2 b-tagged jets
  - 2 or 3 jets only and $\frac{p_{\mathrm{T}}(j_1)}{H_{\mathrm{T}}} = H_{\mathrm{T}}^{\mathrm{ratio}} < 100$ to reduce $t\bar{t}$ background
  - δ^+ & δ^- take advantage of azimuthal separations between $\Delta\phi(bb)$ and $\Delta\phi(j, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$ to discriminate signal from irreducible $Z(\nu\bar{\nu}) + b\bar{b}$ background

Observable	SRb1	SRb2
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	
$\mathcal{N}_j$	≥ 2	2 or 3
$\mathcal{N}_b^{\mathrm{T}}$	≥ 1	≥ 2
$\mathcal{N}_\ell^{\mathrm{B}}$	0	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 650	> 180
$p_{\mathrm{T}}(bj_1)$ [GeV]	> 160	> 150
$p_{\mathrm{T}}(j_1)$ [GeV]	> 160	> 150
$p_{\mathrm{T}}(j_2)$ [GeV]	> 160	> 20
$p_{\mathrm{T}}(j_3)$ [GeV]	-	< 60
H_{T3} [GeV]	< 100	-
$H_{\mathrm{T}}^{\mathrm{ratio}}$	-	> 0.75
δ^- [rad]	-	< 0
δ^+ [rad]	-	< 0.5
Multi-jet rejection specific		
$\Delta\phi(\mathrm{j}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$ [rad]	> 0.6	> 0.4

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DM$t\bar{t}0l$ & DM$t\bar{t}2l$ Definitions

- SRt1 & SRt2 signal regions optimised for low mediator mass ($m_{\phi/a} < 100$ GeV) and high mediator mass ($100 \text{ GeV} < m_{\phi/a} < 250$ GeV) DM$t\bar{t}0l$ models respectively and require:
  - passes $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
  - at least 4 jets, 2 of which of b-jets
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 300$ GeV
  - several requirements on composite jet/$E_{\mathrm{T}}^{\mathrm{miss}}$ variables to reduce multi-jet contamination
  - cuts on $m_{R=0.8}^{jet\ 1,2}$, $m_{R=1.2}^{jet\ 1,2}$, $m_{\mathrm{T}}^{b,\min}$, $m_{\mathrm{T}}^{b,\max}$ and ΔR_{bb} discriminate DM signal from background (variables defined in backup)
- SRt3 signal region optimised for DM$t\bar{t}2l$ models require:
  - 2 opposite sign leptons
  - at least 1 b-tagged jet
  - 'stransverse mass' (m_{T2}^{ll}) used as main background discriminant. This is a kinematic variable with an endpoint at the W-boson mass and so can be used to classify events with 2 Ws (Link)

Observable	SRt1	SRt2	SRt3
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$		2ℓ
$\mathcal{N}_j$	≥ 4		≥ 1
$\mathcal{N}_b^{\mathrm{M}}$	≥ 2		≥ 1
$\mathcal{N}_\ell^{\mathrm{B}}$	0		-
$\mathcal{N}_\ell^{\mathrm{M}}$	-		2 OS
$\mathcal{N}_\tau$	0		-
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 300		-
$p_{\mathrm{T}}(bj_1)$ [GeV]	> 20		> 30
$p_{\mathrm{T}}(j_1, j_2)$ [GeV]	$> 80, 80$		> 30
$p_{\mathrm{T}}(j_3, j_4)$ [GeV]	$> 40, 40$		-
$p_{\mathrm{T}}(\ell_1, \ell_2)$ [GeV]	-		$> 25, 20$
$m_{\ell\ell}$ [GeV]	-		> 20
$\lvert m_{\ell\ell}^{\mathrm{SF}} - m_Z \rvert$ [GeV]	-		> 20
$m_{\mathrm{R}=0.8}^{\mathrm{jet}\ 1,2}$ [GeV]	$> 80, 80$	-	-
$m_{\mathrm{R}=1.2}^{\mathrm{jet}\ 1,2}$ [GeV]	-	$> 140, 80$	-
$m_{\mathrm{T}}^{b,\min}$ [GeV]	> 150	> 200	-
$m_{\mathrm{T}}^{b,\max}$ [GeV]	> 250	-	-
ΔR_{bb}	> 1.5	> 1.5	-
$E_{\mathrm{T}}^{\mathrm{miss,\ sig}}$ [$\sqrt{GeV}$]	-	> 12	-
$\Delta\phi_{\mathrm{boost}}$ [rad]	-		< 0.8
$m_{b2\ell}^{\min}$ [GeV]	-		< 170
ξ^+ [GeV]	-		> 170
$m_{\mathrm{T2}}^{\ell\ell}$ [GeV]	-		> 100
Multi-jet rejection specific			
$\Delta\phi(\mathrm{j}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$ [rad]	> 0.4		-
$E_{\mathrm{T}}^{\mathrm{miss,track}}$ [GeV]	> 30		-
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss,track}})$ [rad]	$< \pi/3$		-

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