Constraints on spin-0 dark matter mediators and invisible Higgs decays

using ATLAS 13 TeV pp collision data

with two top quarks and missing energy in the final state

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OKC BSM meeting, 19 January 2023

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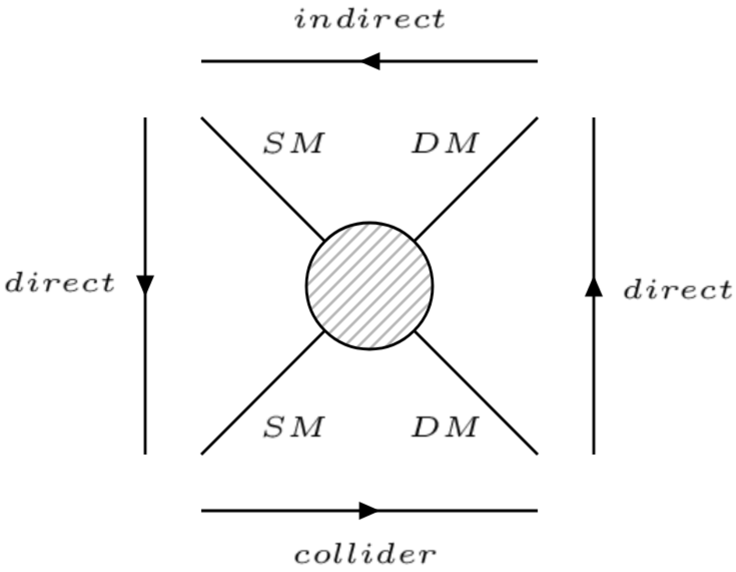
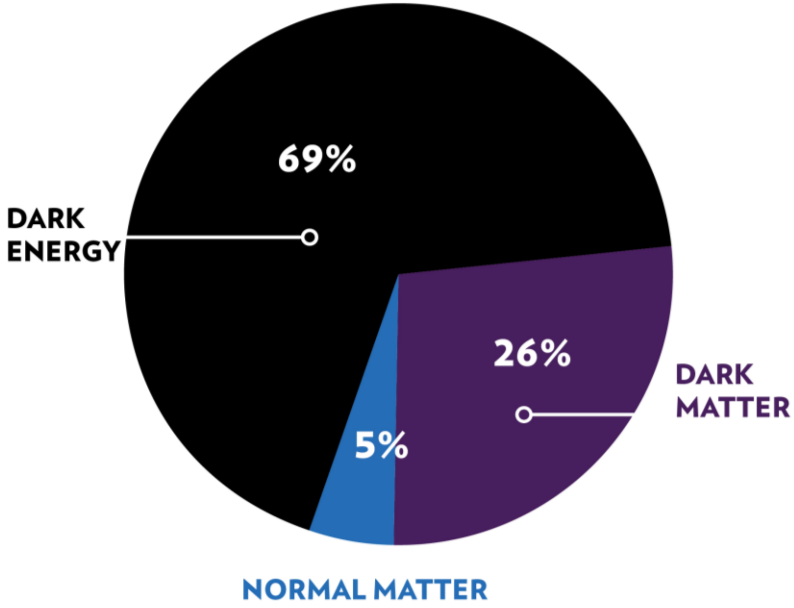
ATLAS EXPERIMENT

Dark Matter

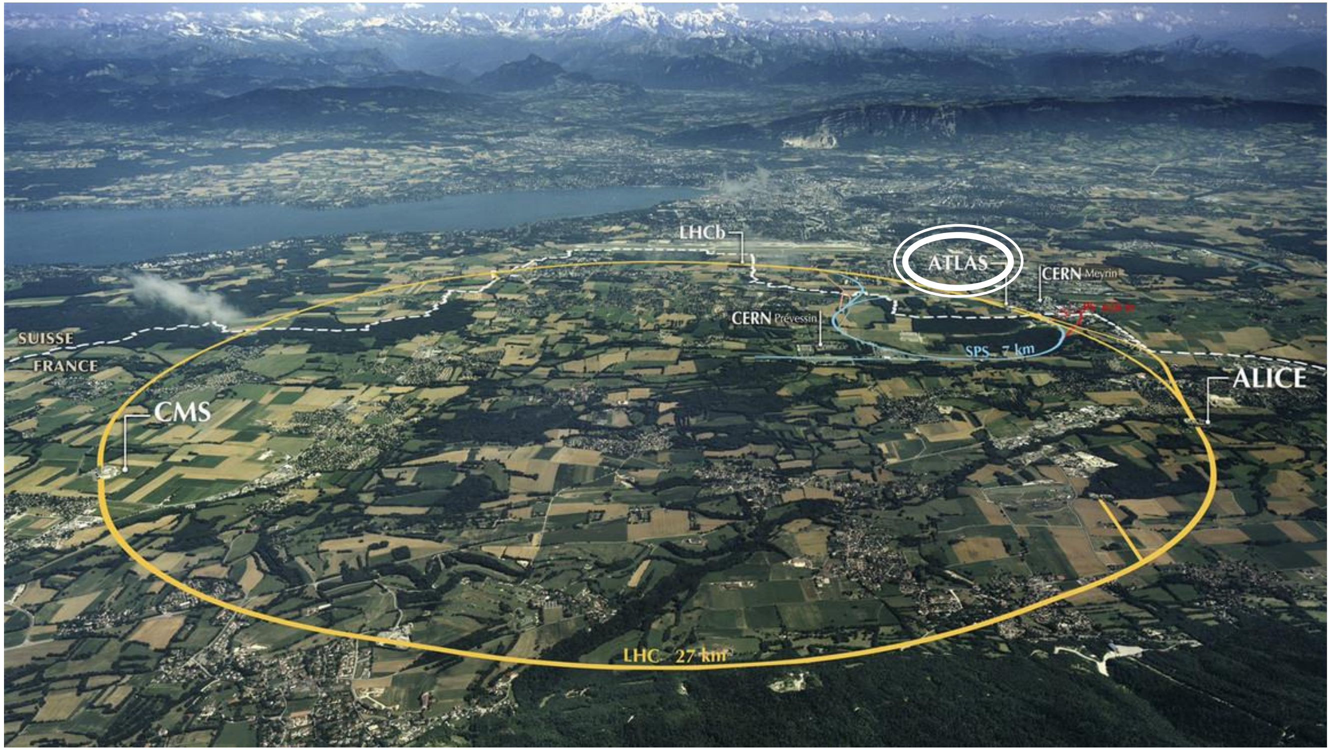
- Dark Matter (DM)
  - existence confirmed by many astrophysical measurements
  - **weakly interacting massive particles**
    - arise naturally in many BSM extensions





Search for Dark Matter in ATLAS

- ATLAS - one of the two multi-purpose experiments at the Large Hadron Collider



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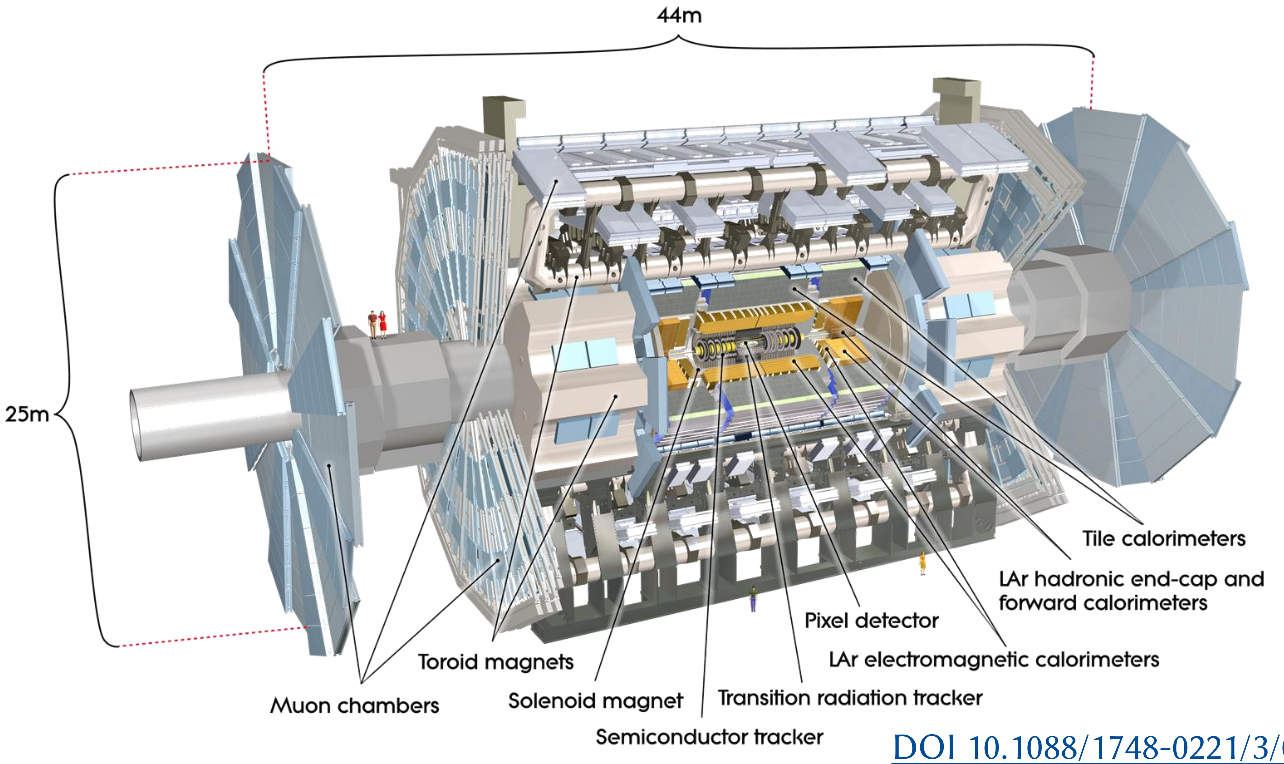

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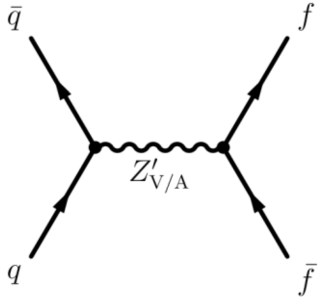
Search for Dark Matter in ATLAS

- DM resonance search
  - look for **distinctive resonances** in visible decay
  - sensitivity (almost) **independent of DM mass**



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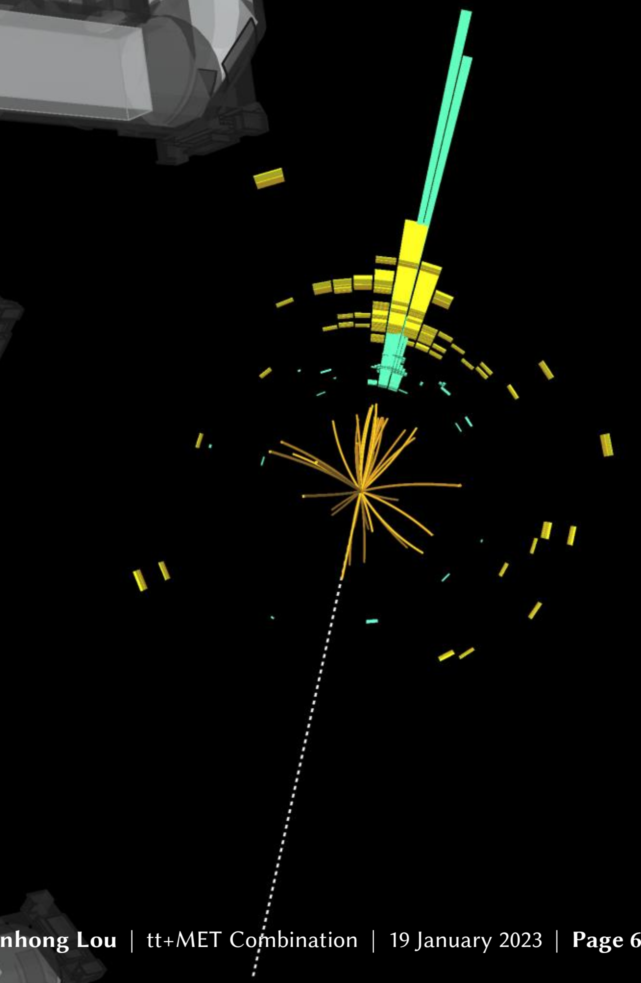
- MET+X search
  - MET – missing transverse energy
    - momentum conservation in the transverse plane
    - MET ~ **total p_T of invisible particles**



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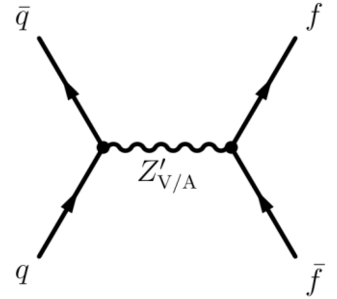
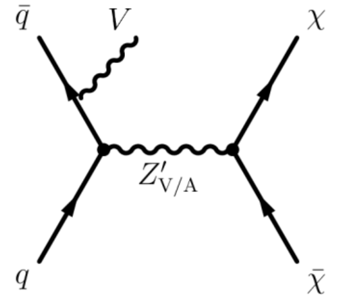


- MET+X search
  - MET – missing transverse energy
    - momentum conservation in the transverse plane
    - MET ~ **total p_T of invisible particles**
  - X – recoiled SM particles
    - e.g. W/Z boson, Higgs boson, photon, jet(s), or top quark(s)
  - best sensitivity at **low DM mass** region (on-shell production)



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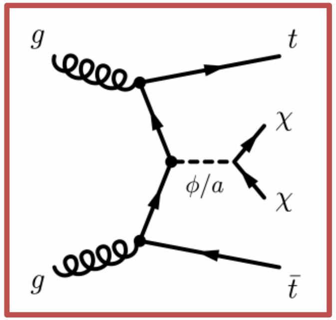
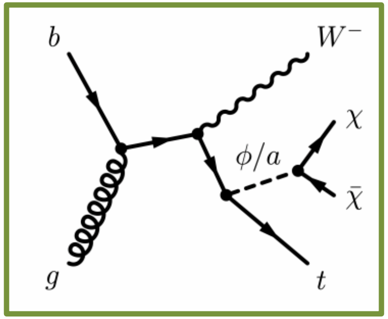
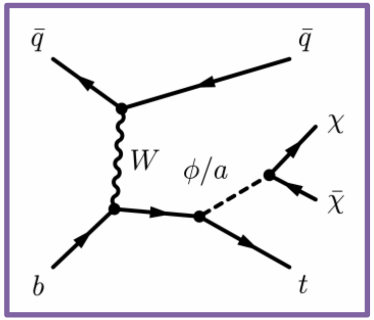
ATLAS EXPERIMENT

The Signals

- Simplified dark matter (DM) models with a spin-0 mediator particle
  - scalar (ϕ) or pseudoscalar (a)
  - Yukawa-type couplings, $g_q = g_\chi = 1$
  - three production modes:
    - **DM+tt** (primary)
    - **DM+tW**
    - **DM+tj**







for pseudo-scalar,
greatly suppressed at non-relativistic limit
~ O(10^{-12}) in direct detection

DM-nucleon scattering XS

$$\tilde{\sigma}_n^{\mathrm{SD}} = \frac{9}{16\pi}\boxed{\frac{q^4}{m_{\mathrm{DM}}^2 m_{\mathrm{N}}^2}}\frac{g_{nna}^2\, g_{\mathrm{DM}}^2\, \mu_n^2}{m_a^4}$$

1401.6458

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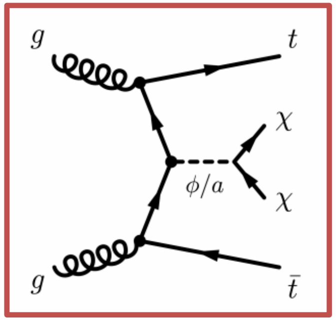

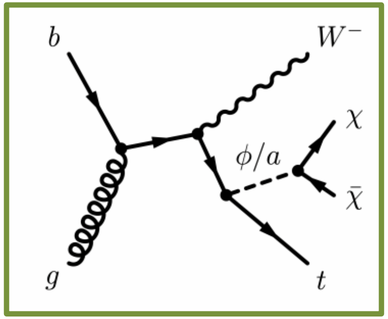

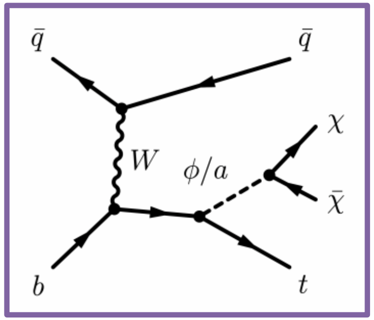

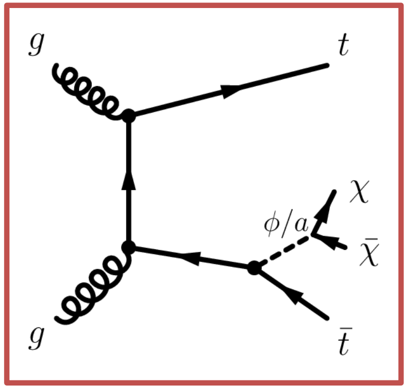

enhanced at small x,
leading to a cross section one order of magnitude larger for $m_{med} < m_t$

$$f_{t\to\phi}(x) = \frac{g_t^2}{(4\pi)^2}\left[\boxed{\frac{4(1-x)}{x}} + x\ln\left(\frac{s}{m_t^2}\right)\right],$$

$$f_{t\to a}(x) = \frac{g_t^2}{(4\pi)^2}\left[x\ln\left(\frac{s}{m_t^2}\right)\right],$$

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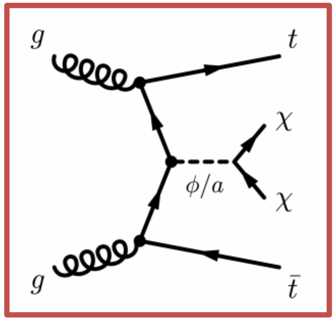
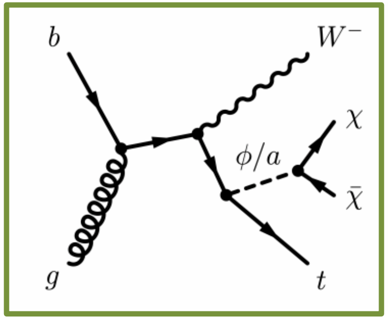
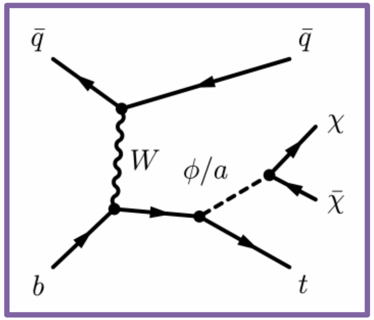
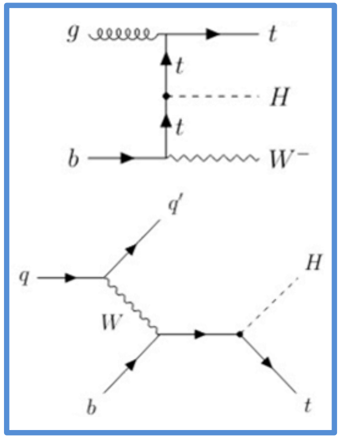
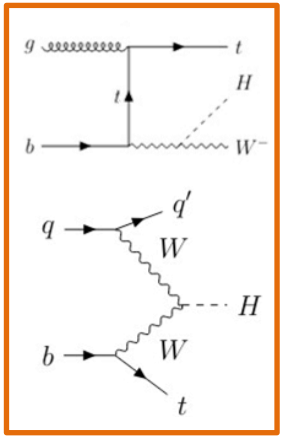






- Invisible Higgs decays
  - special case: ttH (125) production ~ DM+tt, m_ϕ = 125 GeV
  - unlike DM, tWH and tjH production not included
    - destructive interference between **top-** / **W-radiated** Higgs





signal	tWH LO	DM+tW $m(\phi,\chi)$ = (100, 1) GeV	DM+tW $m(\phi,\chi)$ = (150, 1) GeV
cross section [fb]	16.4	60.1	36.2
signal	tjH LO	DM+tj $m(\phi,\chi)$ = (100, 1) GeV	DM+tj $m(\phi,\chi)$ = (150, 1) GeV
cross section [fb]	60.2	290	141

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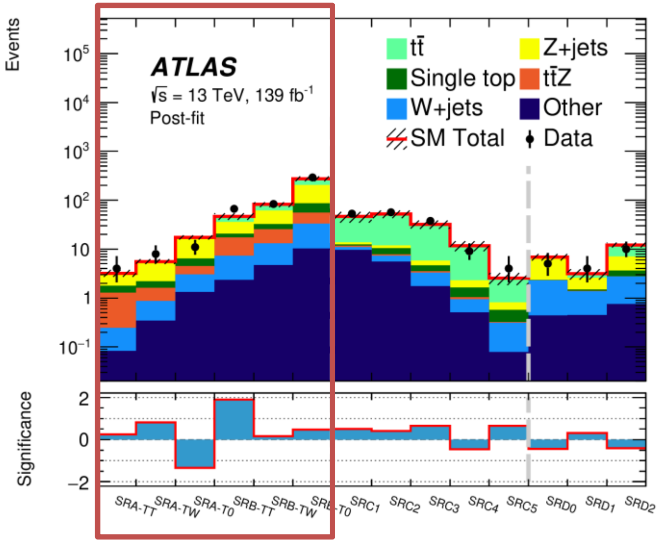
Experimental Signatures

- Common: presence of at least one b-tagged jet and E_T^{miss} / E_T^{miss} significance ($\mathcal{S}$)

- Three analysis channels based on light lepton multiplicity
  - **tt0L**
    - consists of tt0L-high and tt0L-low
    - tt0L-high: no leptons (e, μ, τ), E_T^{miss} trigger, ≥ 2 b-jets, large $\mathcal{S}$, high top mass
    - tt0L-low: no leptons (e, μ, τ), E_T^{miss} trigger + b-jet trigger, ≥ 2 b-jets, lower E_T^{miss} / $\mathcal{S}$
  - **tt1L**
    - exactly one lepton (e, μ), E_T^{miss} trigger, ≥ 2 b-jets, large $\mathcal{S}$, high top mass
  - **tt2L**
    - exactly two opposite-charge leptons (e, μ), dilepton trigger, ≥ 1 b-jets

The tt0L-high Analysis

- Previous publication (stop search)
  - SRA, SRB optimised for 2-body decays
  - SRC (3-body) and SRD (4-body) not considered for DM interpretation

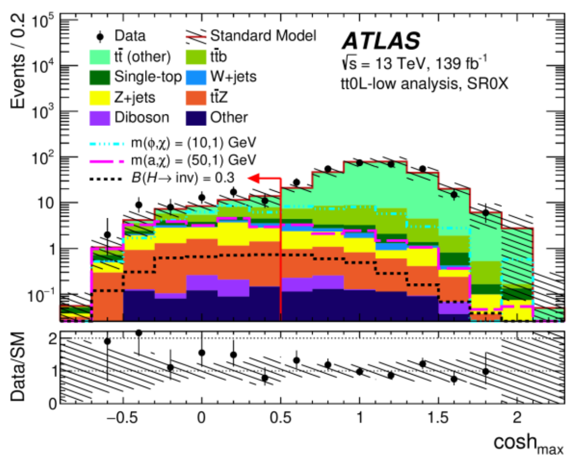


SRA + SRB

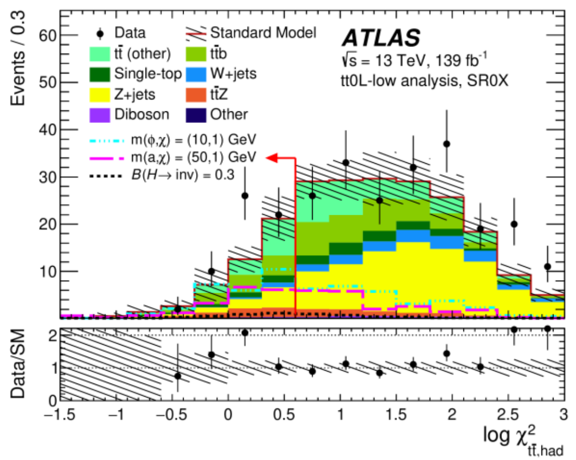
Variable/SR	SRA-TT	SRA-TW	SRA-T0	SRB-TT	SRB-TW	SRB-T0
Trigger	E_T^{miss}					
E_T^{miss}	> 250 GeV					
N_ℓ	exactly 0					
N_j	≥ 4					
$p_{T,2}$	> 80 GeV					
$p_{T,4}$	> 40 GeV					
$\left\|\Delta\phi_{min}\left(\mathbf{p}_{T,1-4}, \mathbf{p}_T^{miss}\right)\right\|$	> 0.4					
N_b	≥ 2					
$m_T^{b,min}$	> 200 GeV					
τ-veto	✓					
$m_1^{R=1.2}$	> 120 GeV					
$m_2^{R=1.2}$	> 120 GeV	60–120 GeV	< 60 GeV	> 120 GeV	60–120 GeV	< 60 GeV
$m_1^{R=0.8}$	> 60 GeV			–		
$j_1^{R=1.2}(b)$	✓			–		
$j_2^{R=1.2}(b)$	✓	–				
$\Delta R(b_1, b_2)$	> 1.0	–		> 1.4		
$m_T^{b,max}$	–			> 200 GeV		
$\mathcal{S}$	> 25			> 14		
m_{T2,χ^2}	> 450 GeV			< 450 GeV		

The tt0L-low Analysis

- Newly added for the combination
  - 3 SR bins: SR0X, SRWX and SRTX
  - major backgrounds in SR:
    - tt, tt+b, single-top
    - Z+jets
    - tt+Z



- Main discriminating variables:
  - $\cosh_{max}$
    - reducing backgrounds originating from the semi-leptonic top quark with lost lepton
  - χ_{tt}^{2}
    - reducing backgrounds with no hadronically decaying top quark pair



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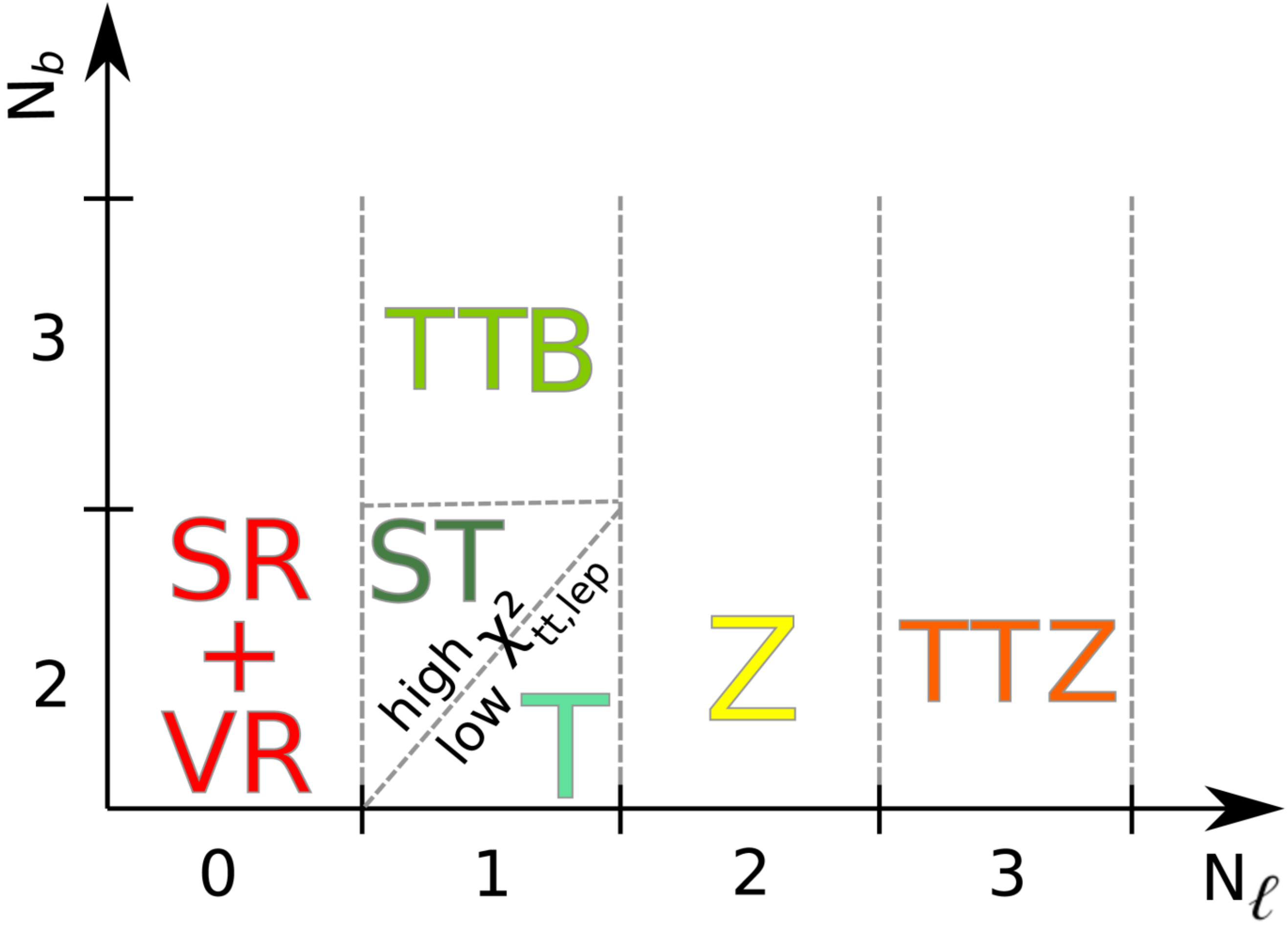
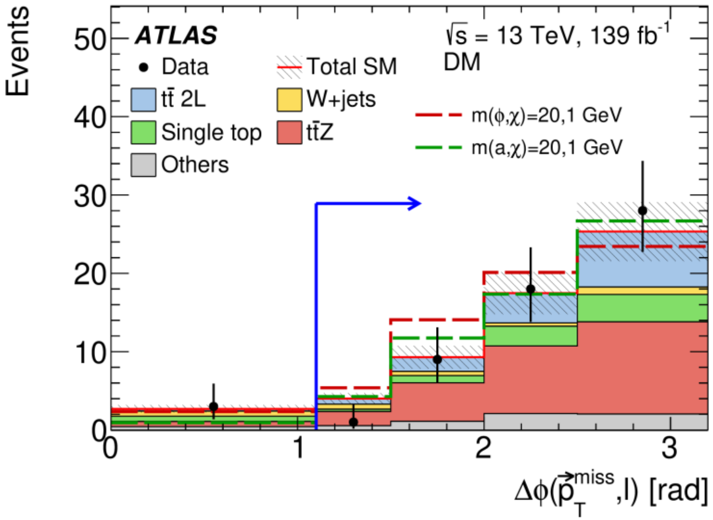
The tt0L-low Analysis



The tt1L Analysis

- Previous publication
  - Dedicated DM SRs
  - spin-0 mediator mass up to approximately 200 GeV excluded at unitary couplings, assuming m_χ = 1 GeV



Selection		DM_scalar	DM_pseudoscalar
Preselection		hard-lepton preselection	
N_{jet}, $N_{b\text{-}jet}$		$\geq (4, 2)$	
Jet p_T	[GeV]	$> (80, 60, 30, 25)$	
b-tagged jet p_T	[GeV]	$> (80, 25)$	
E_T^{miss}	[GeV]	> 230	
$H_{T,sig}^{miss}$		> 15	
m_T	[GeV]	> 180	
Topness		> 8	
$m_{top}^{reclustered}$	[GeV]	> 150	
$\Delta\phi(\text{jet}_i, \vec{p}_T^{miss})$, $i \in [1, 4]$	[rad]	> 0.9	
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	[rad]	> 1.1	> 1.5
Exclusion technique		Based on shape-fit in $\Delta\phi(\vec{p}_T^{miss}, \ell)$	
Bin boundaries in $\Delta\phi(\vec{p}_T^{miss}, \ell)$		$\{1.1, 1.5, 2.0, 2.5, \pi\}$	

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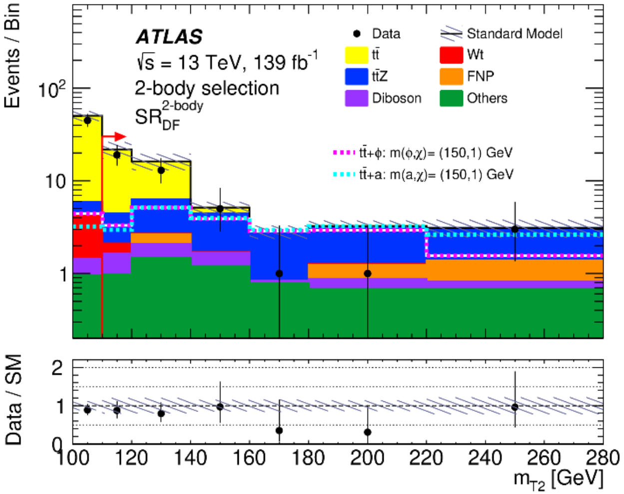
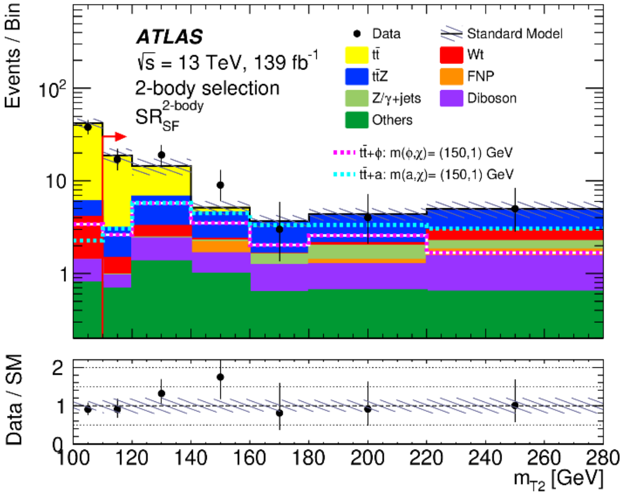
The tt2L Analysis

- Previous publication
  - Dedicated 2-body SRs with DM interpretation
  - scalar (pseudoscalar) mediator mass up to 250 (300) GeV excluded at unitary couplings, assuming m_χ = 1 GeV





	$\mathrm{SR}^{2\text{-body}}$	
Leptons flavour	DF	SF
$p_T(\ell_1)$ [GeV]	> 25	
$p_T(\ell_2)$ [GeV]	> 20	
$m_{\ell\ell}$ [GeV]	> 20	
$\|m_{\ell\ell} - m_Z\|$ [GeV]	–	> 20
$n_{b\text{-jets}}$	≥ 1	
$\Delta\phi_{\text{boost}}$ [rad]	< 1.5	
E_T^{miss} significance	> 12	
$m_{T2}^{\ell\ell}$ [GeV]	> 110	

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Orthogonalisation

- Between tt0L-high and tt0L-low
  - orthogonalization requirements on large-radius jet, E_T^{miss} and $\mathcal{S}$ in tt0L-low SRs
  - CRZAB-T0 removed from tt0L-high
  - orthogonalization requirements on large-radius jets in tt0L-low Z+jets enriched CRs

- Between tt0L, tt1L and tt2L
  - SR non-overlapping by construction thanks to the requirements on lepton multiplicity
  - orthogonality of CRs checked explicitly using EventNumbers
  - exception: tt+Z CR
    - all analyses adopted a similar strategy and constrained the tt+Z (Z⟶νν) process using 3-lepton tt+Z (Z⟶ll) enriched CRs
    - large overlap
  - in the combination, the most inclusive tt+Z CR across all channels (from tt2L) is used

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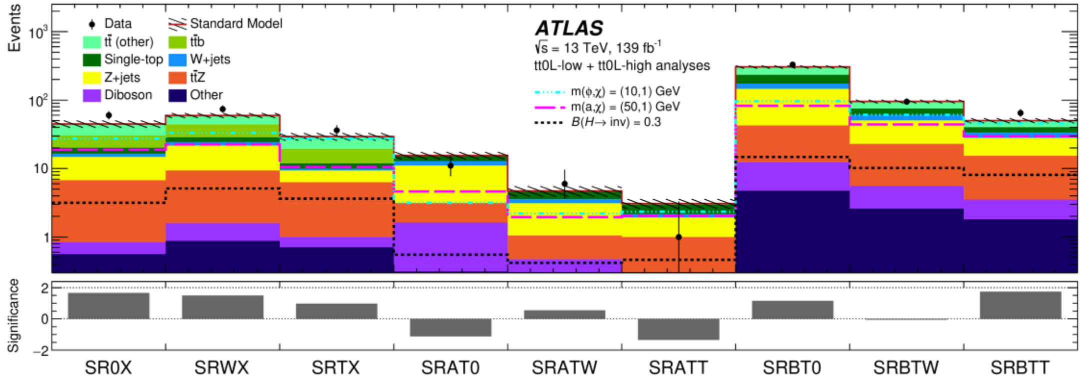
Statistical Combination

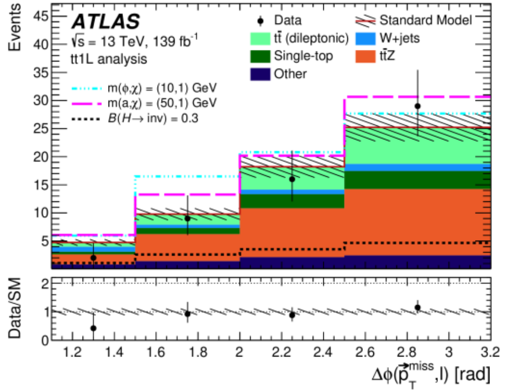
- A profile likelihood fit to
  - tt0L: 3+6 = 9 SR bins
  - tt1L: 4 SR bins
  - tt2L: 6×2 = 12 SR bins
  - … and all CRs

- Correlation strategy
  - fully correlated:
    - experimental uncertainties
    - signal modelling
  - uncorrelated:
    - background modelling

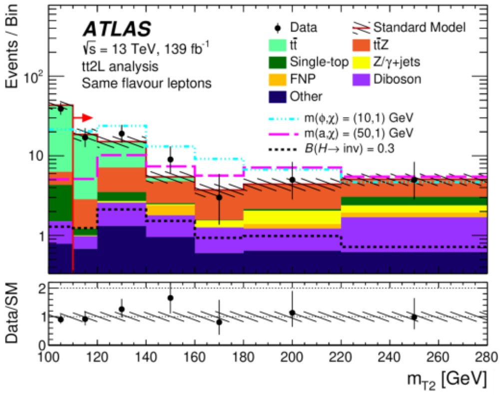


tt0L-low

tt0L-high

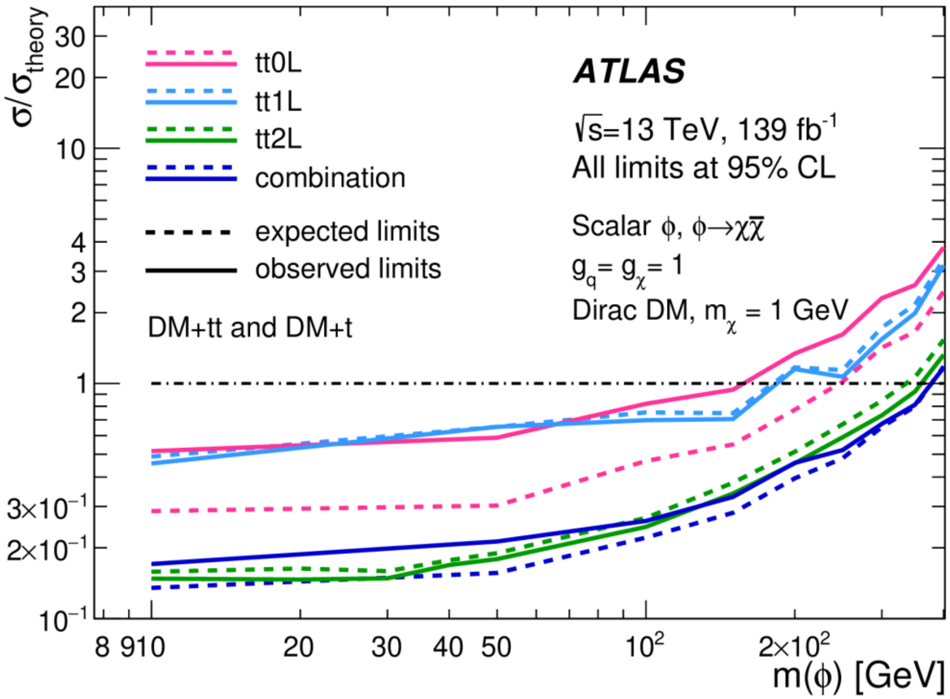


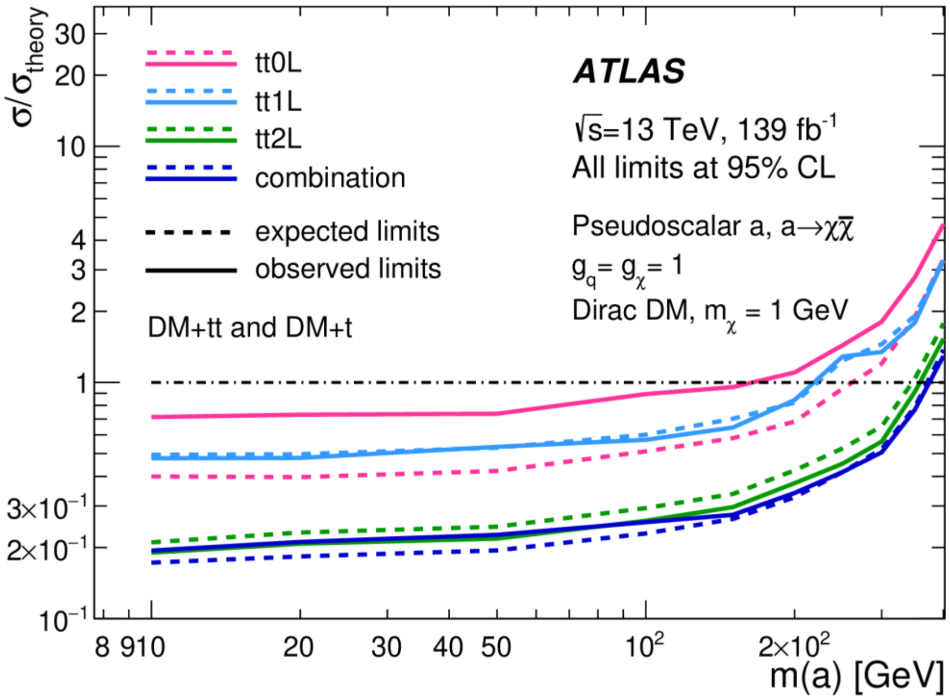
tt1L



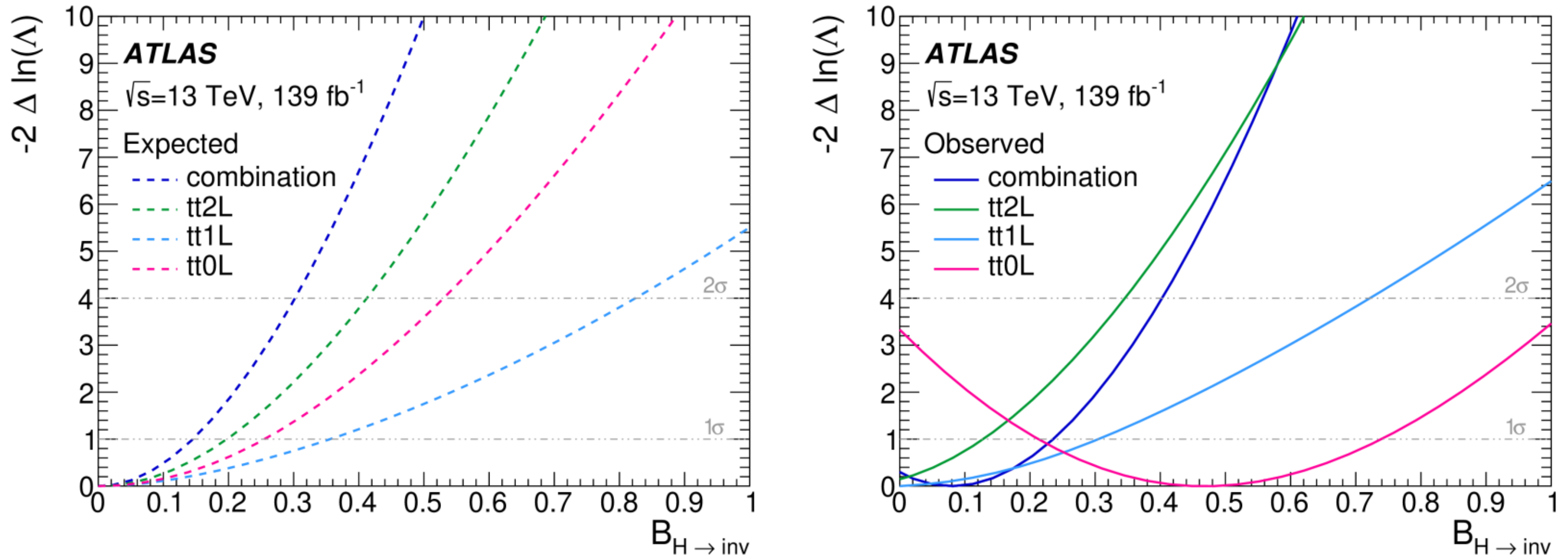
tt2L (same-flavour)

Full Combination Results: Dark Matter





Full Combination Results: Invisible Higgs Decays



Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit	Reference
tt0L	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$	[28], this document
tt1L	$-0.04^{+0.35}_{-0.29}$	0.74	$0.80^{+0.40}_{-0.26}$	[29], this document
tt2L	$-0.08^{+0.20}_{-0.19}$	0.36	$0.40^{+0.18}_{-0.12}$	[30], this document
$t\bar{t}H$ comb.	$0.08^{+0.15}_{-0.15}$	0.38	$0.30^{+0.13}_{-0.09}$	This document

Conclusion

- A combination of three analyses in $tt+E_T^{miss}$ final state has been presented
  - for scalar (pseudoscalar) mediator DM models, the combination extends the excluded mass range by the best of the individual channels by 50 (25) GeV
  - an upper limit on the Higgs boson invisible branching ratio of 0.38 (0.30) is observed (expected)

- Paper accepted by EPJC
  - https://inspirehep.net/literature/2180393
  - https://arxiv.org/abs/2211.05426

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Backup Materials

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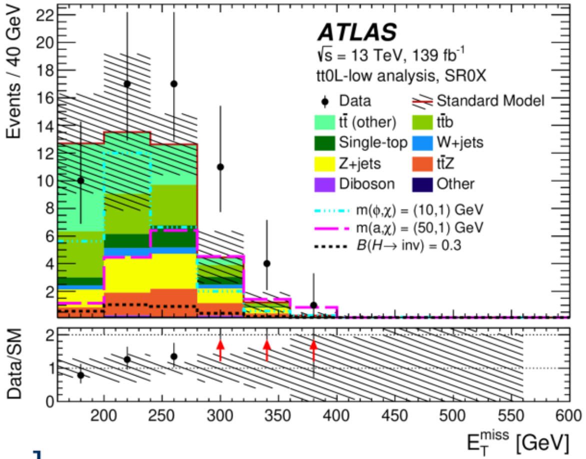
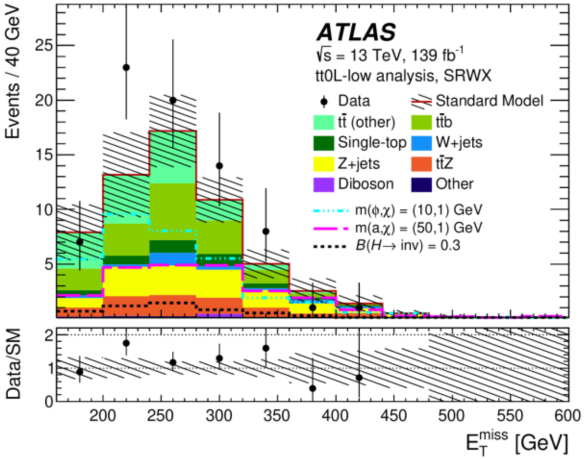
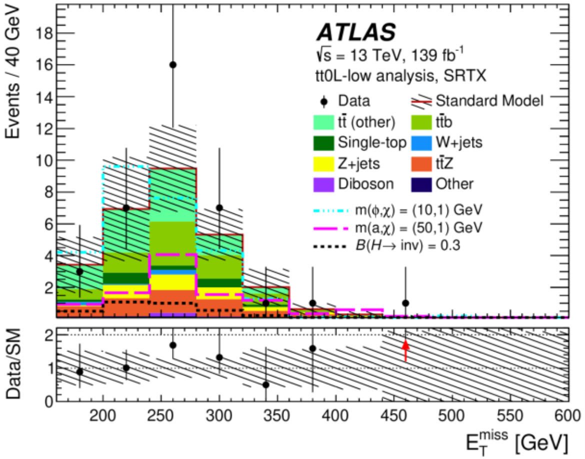
The tt0L-low Analysis: SR Selections

Variables	SR0X	SRWX	SRTX
N_{lepton}	$= 0$		
Orthogonalisation	$E_{\text{T}}^{\text{miss}} < 250$ GeV or $\mathcal{S} < 14$ or $m_{\text{large-radius jet}}^{R=1.2} < 120$ GeV		
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 160 < 250, when passing b-jet triggers		
$\mathcal{S}$	> 10		
$\Delta\phi_{\text{min}}(\boldsymbol{p}_{\text{T},1\text{-}4}, \boldsymbol{p}_{\text{T}}^{\text{miss}})$	> 1.0	> 0.5	
$\Delta R\,(b_1, b_2)$	> 1.2		
$N_{\text{large-radius jet}}$	$= 0$	> 0	
$m_{\text{large-radius jet}}$ [GeV]	—	(40, 130)	≥ 130
ΔR_{min}(large-radius jet, b-tagged jets)	—		< 1.2
$\cosh_{\text{max}}$	< 0.5	< 0.6	< 0.7
$\chi^2_{t\bar{t},\text{ had}}$	< 4	< 6	< 8
$p_{\text{T}}^{t\bar{t}}/E_{\text{T}}^{\text{miss}}$	(0.7, 1.2)	(0.5, 1.2)	







The tt0L-low Analysis: Post-fit SR Yields

Process	SR0X	SRWX	SRTX
Observed data	60	74	36
Expected SM events	45 ± 8	59 ± 6	28 ± 5
$t\bar{t}$ (other)	14 ± 4	15 ± 4	9.4 ± 3.5
$t\bar{t}+b$	10 ± 7	15.0 ± 3.1	7.2 ± 2.8
Single-top	3.8 ± 3.0	4.3 ± 2.6	1.9 ± 1.5
Z+jets	8.0 ± 1.6	12.1 ± 2.3	3.1 ± 0.8
W+jets	1.6 ± 1.1	2.7 ± 2.1	0.6 ± 0.6
$t\bar{t}+Z$	5.9 ± 1.0	7.8 ± 1.3	5.3 ± 1.1
Diboson	0.28 ± 0.20	0.7 ± 0.4	0.30 ± 0.19
Other	0.55 ± 0.15	0.88 ± 0.24	0.70 ± 0.22
Pre-fit $t\bar{t}$	15	17	9.8
Pre-fit $t\bar{t}+b$	7	11.5	5.6
Pre-fit Single-top	7.1	8.2	3.6
Pre-fit Z+jets	6.1	9.2	2.3
Pre-fit $t\bar{t}+Z$	5.9	7.9	5.4
Benchmark signal models			
DM $m(\phi, \chi) = (10, 1)$ GeV	27.4 ± 2.4	33.2 ± 2.2	27.5 ± 2.2
DM $m(a, \chi) = (50, 1)$ GeV	18.8 ± 1.3	22.6 ± 1.5	10.6 ± 1.0
$H \rightarrow$ inv ($\mathcal{B} = 100\%$)	10.52 ± 0.34	17.1 ± 0.4	12.1 ± 0.4

The tt0L-low Analysis: Background Estimation

- Main backgrounds normalised in dedicated CRs
  - **tt, tt+b, single-top**
  - **Z+jets**
  - tt+Z will be constrained in CR_{ttZ} from tt2L analysis
- Estimation validated in the corresponding VRs
  - no lepton, orthogonal to SRs
    - $\cosh_{max}$ / χ_{tt}^2 sidebands
  - background prediction in VRs agrees with data within 1 σ

	Variables	CR0X	CRWX	CRTX
Shared selections	N_{lepton}	$= 1$		
	$E_{\text{T, no lepton}}^{\text{miss}}$ [GeV]	> 160		
	$E_{\text{T}}^{\text{miss}}$ [GeV]	< 250, when passing b-jet triggers		
	$S_{\text{no lepton}}$	> 10		
	$\Delta\phi_{\text{min}}(\boldsymbol{p}_{\text{T},1\text{-}4}, \boldsymbol{p}_{\text{T,no lepton}}^{\text{miss}})$	> 1.0	> 0.5	
	$\Delta R\,(b_1, b_2)$	> 1.2		
	$N_{\text{large-radius jet}}$	$= 0$	> 0	
	$m_{\text{large-radius jet}}$ [GeV]	—	(40, 130)	≥ 130
	ΔR_{min}(large-radius jet, b-tagged jets)	—		< 1.2
	$\cosh_{\text{max, no lepton}}$	< 0.9	< 0.95	< 1.0
	$\chi^2_{t\bar{t},\text{ had}}$	< 10	< 20	< 40
	$p_{\text{T}}^{t\bar{t}} / E_{\text{T, no lepton}}^{\text{miss}}$	(0.7, 1.2)	(0.5, 1.2)	

	Variables	$\text{CR0X}_{t\bar{t}}$	$\text{CRWX}_{t\bar{t}}$	$\text{CRTX}_{t\bar{t}}$
$t\bar{t}$ (other) enriched selections	$\chi^2_{t\bar{t},\text{ lep}}$	< 6		

	Variables	$\text{CR0X}_{t\bar{t}+b}$	$\text{CRWX}_{t\bar{t}+b}$	$\text{CRTX}_{t\bar{t}+b}$
$t\bar{t}$+b enriched selections	$\chi^2_{t\bar{t},\text{ lep}}$	≥ 6		
	$N_{\text{extra } b\text{-tagged jet}}$	≥ 1		

	Variables	$\text{CR0X}_{\text{single-top}}$	$\text{CRWX}_{\text{single-top}}$	$\text{CRTX}_{\text{single-top}}$
Single-top enriched selections	$\chi^2_{t\bar{t},\text{ lep}}$	≥ 30		
	$N_{\text{extra } b\text{-tagged jet}}$	$= 0$		
	$\cosh_{\text{max, no lepton}}$	< 0.5	< 0.6	< 0.7

Variables	$\text{CR0X}_{Z\text{+jets}}$	$\text{CRWX}_{Z\text{+jets}}$	$\text{CRTX}_{Z\text{+jets}}$
N_{lepton}	$= 2$		
Orthogonalisation	$N^{R=1.2}_{\text{large-radius jet}} < 2$ or $m^{R=1.2}_{\text{subleading large-radius jet}} < 60$ GeV		
$E_{\text{T, no lepton}}^{\text{miss}}$ [GeV]	> 160		
$S_{\text{no lepton}}$	> 8		
$\Delta\phi_{\text{min}}(\boldsymbol{p}_{\text{T},1\text{-}4}, \boldsymbol{p}_{\text{T}}^{\text{miss}})$	> 0.5		
$N_{\text{large-radius jet}}$	$= 0$	> 0	
$m_{\text{large-radius jet}}$ [GeV]	—	(40, 130)	≥ 130
$m_{\ell\ell}$ [GeV]	(80, 100)		
$p_{\text{T}}^{\ell\ell}$ [GeV]	> 160		
$\mathcal{S}$	< 5		

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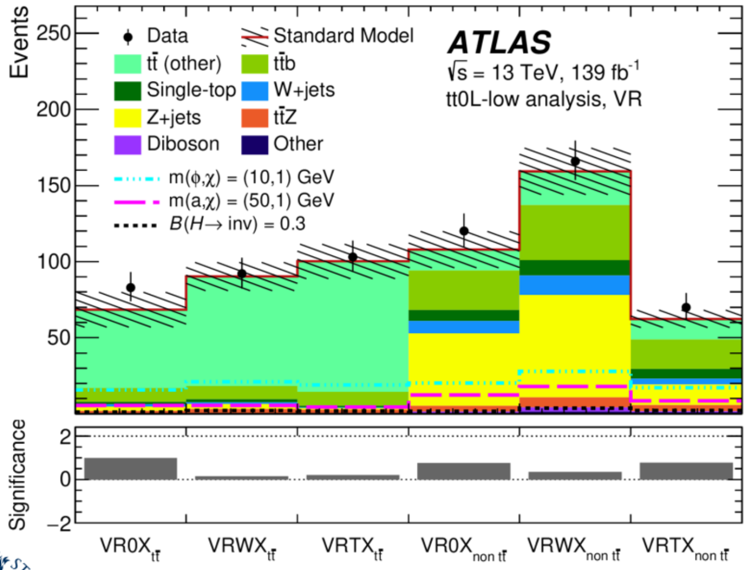
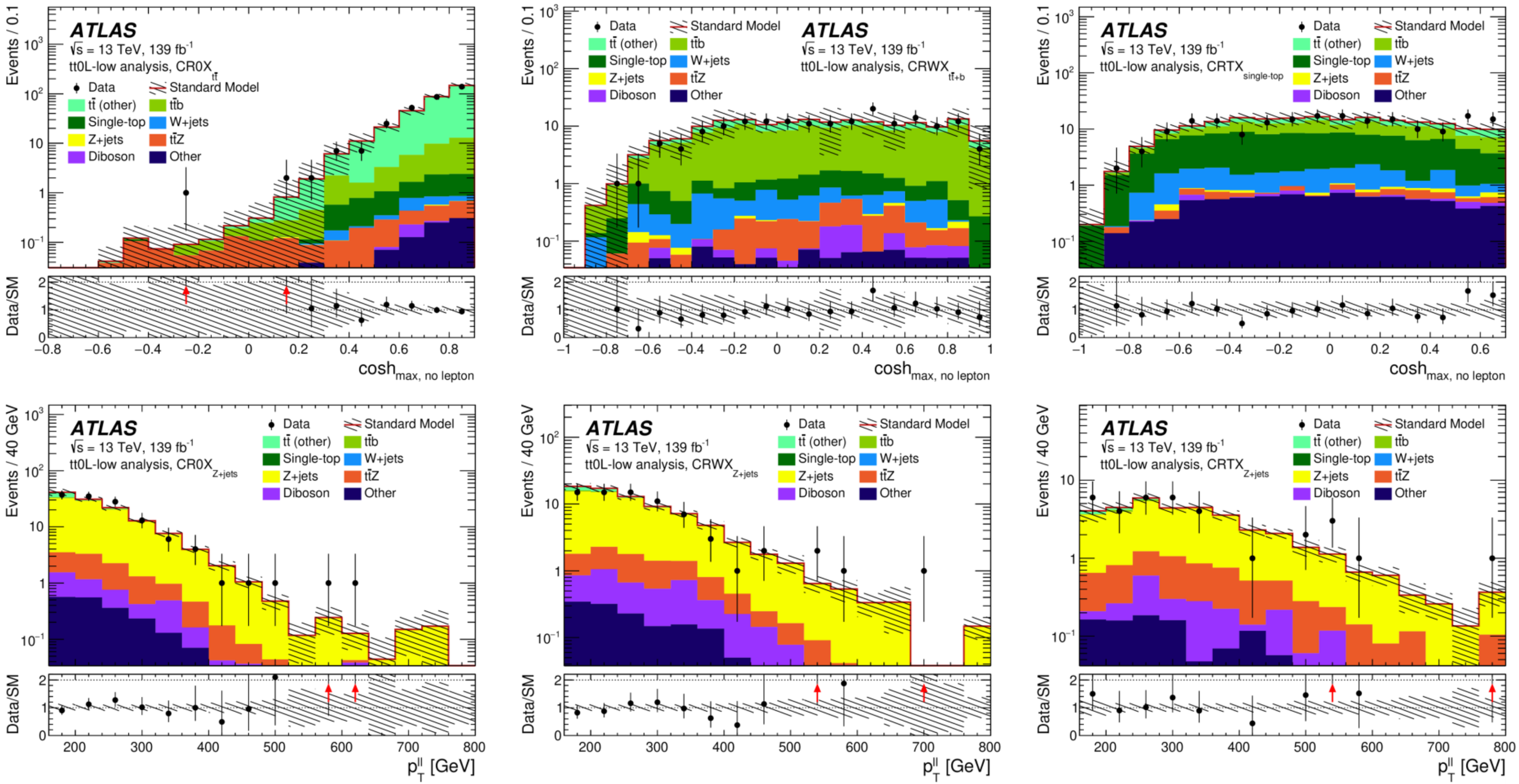
The tt0L-low Analysis: VR Selections

- VRs are not included in the statistical model
  - 3 bins for tt+b, single-top and Z+jets
  - 3 bins for tt (other)

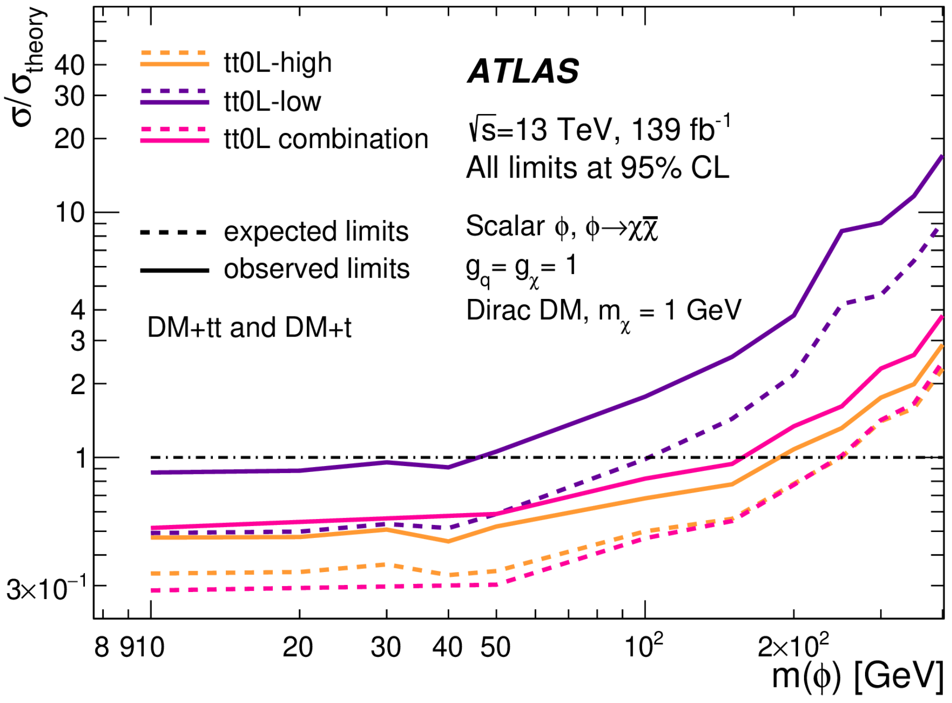


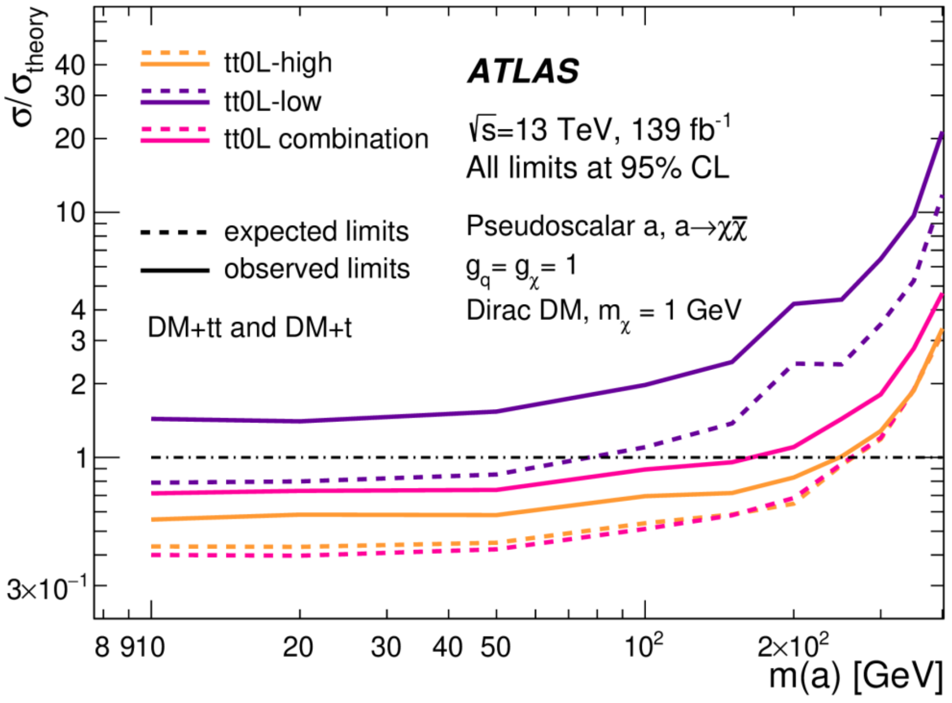
Variables	VR0X$_{t\bar{t}}$	VRWX$_{t\bar{t}}$	VRTX$_{t\bar{t}}$	VR0X$_{\text{non } t\bar{t}}$	VRWX$_{\text{non } t\bar{t}}$	VRTX$_{\text{non } t\bar{t}}$
N_{lepton}	$= 0$					
Orthogonalisation	$E_T^{\text{miss}} < 250$ GeV or $\mathcal{S} < 14$ or $m^{R=1.2}_{\text{large-radius jet}} < 120$ GeV					
E_T^{miss} [GeV]	> 160 < 250, when passing b-jet triggers					
$\mathcal{S}$	> 10					
$\Delta R(b_1, b_2)$	> 1.2			> 2.2	> 1.6	> 1.2
$N_{\text{large-radius jet}}$	$= 0$	> 0		$= 0$	> 0	
$m_{\text{large-radius jet}}$ [GeV]	—	(40, 130)	≥ 130	—	< 130	≥ 130
$\Delta\phi_{\min}(\boldsymbol{p}_{T,1\text{-}4}, \boldsymbol{p}_T^{\text{miss}})$	> 1.0	> 0.5		> 0.5		
$\cosh_{\max}$	(0.5, 0.9)	(0.6, 0.95)	(0.7, 1.0)	< 0.5	< 0.6	< 0.7
$\chi^2_{t\bar{t},\text{had}}$	< 4	< 6	< 8	(4, 999)	(6, 999)	(8, 999)
$p_T^{t\bar{t}} / E_T^{\text{miss}}$	(0.7, 1.2)	(0.5, 1.2)		—		
$\Delta R_{\min}$(large-radius jet, b-tagged jets)	—		< 1.2	—		< 1.2

The tt0L-low Analysis: CR plots

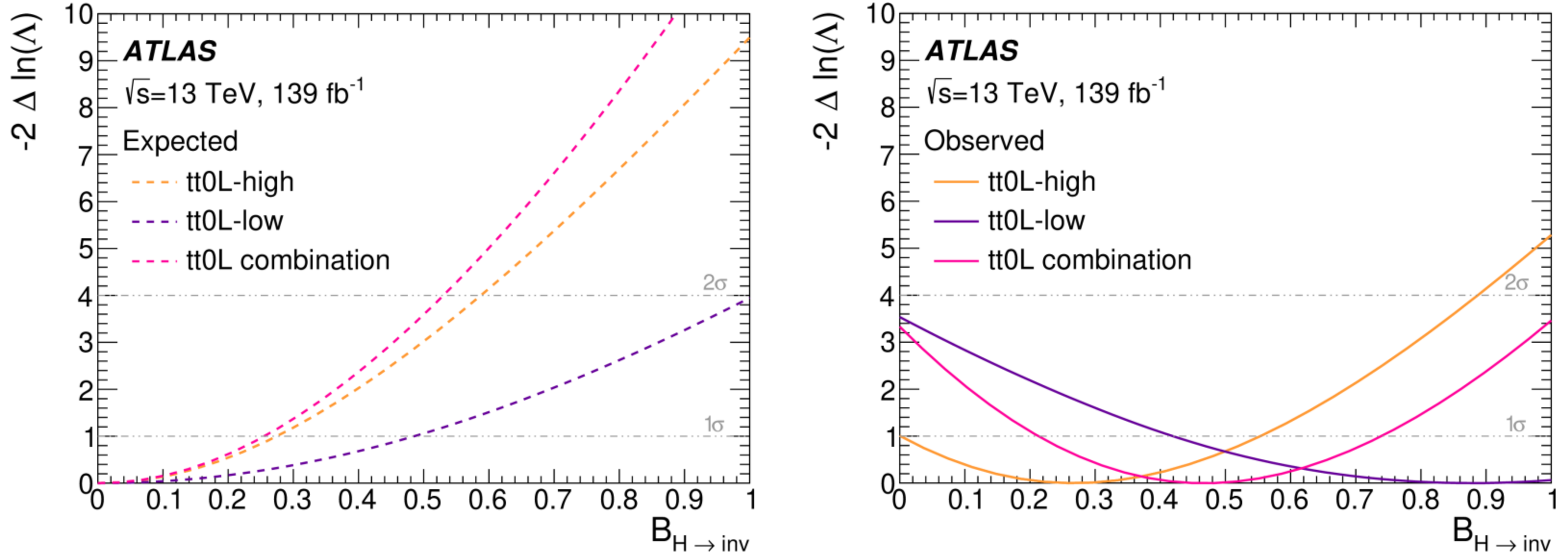


tt0L Combination Results: Dark Matter





tt0L Combination Results: Invisible Higgs Decays



Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit	Reference
tt0L-low	$0.88^{+0.48}_{-0.46}$	1.80	$1.09^{+0.50}_{-0.26}$	this document
tt0L-high	$0.27^{+0.28}_{-0.27}$	0.80	$0.59^{+0.29}_{-0.18}$	[28], this document
tt0L comb.	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$	[28], this document

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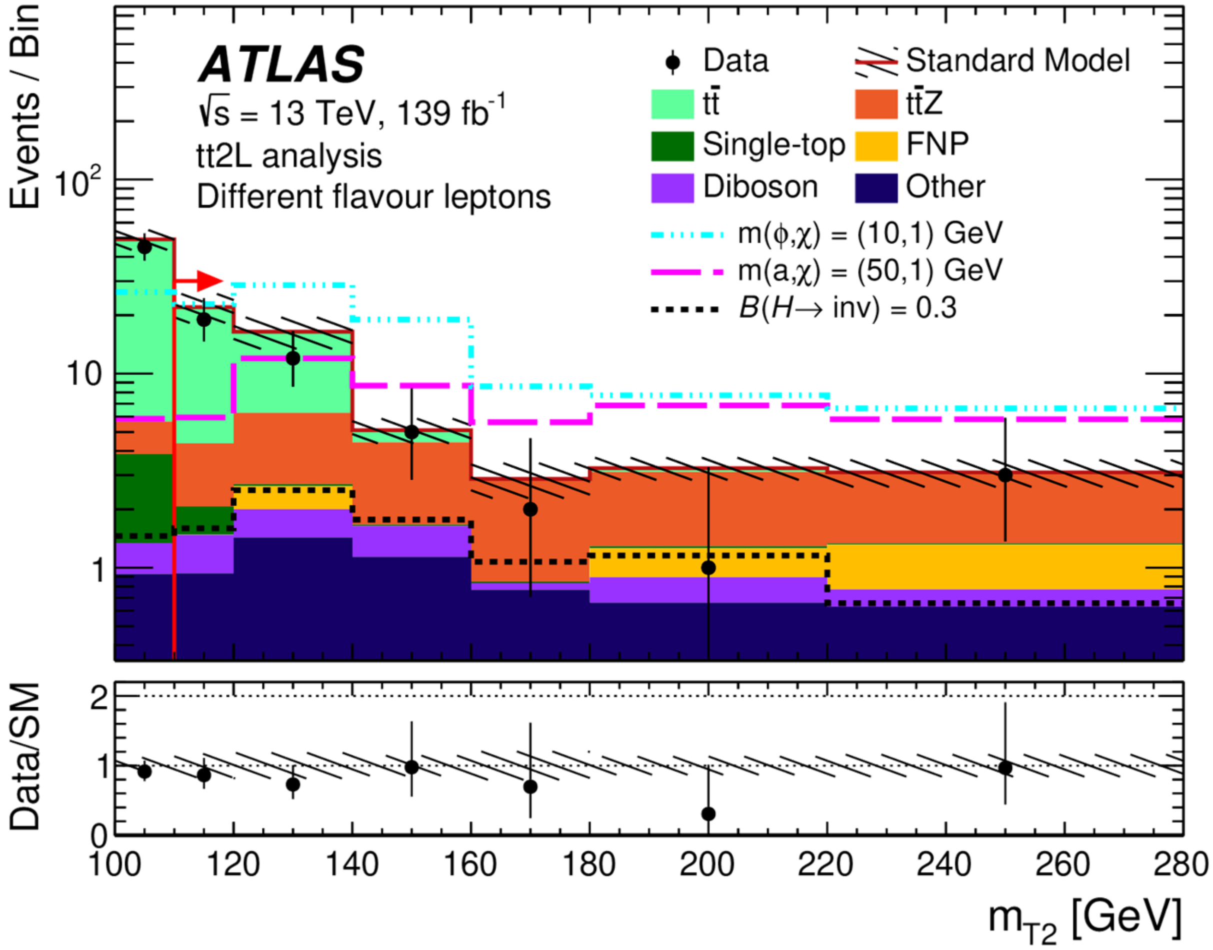
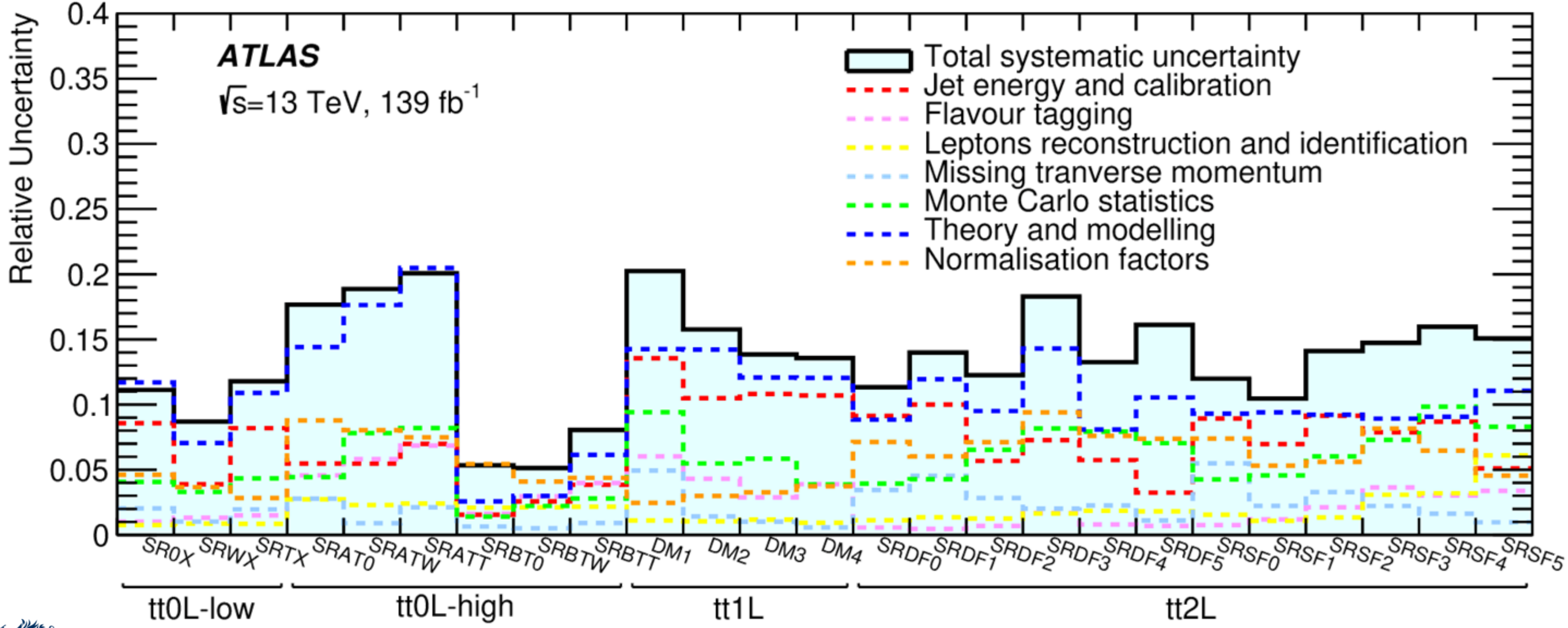
The tt2L Analysis: Additional SR Plot



Impact of Background Systematics



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