Top of the tops.

Combining dark matter searches with top quarks with the ATLAS detector

Physics at the Terascale — BSM Physics
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

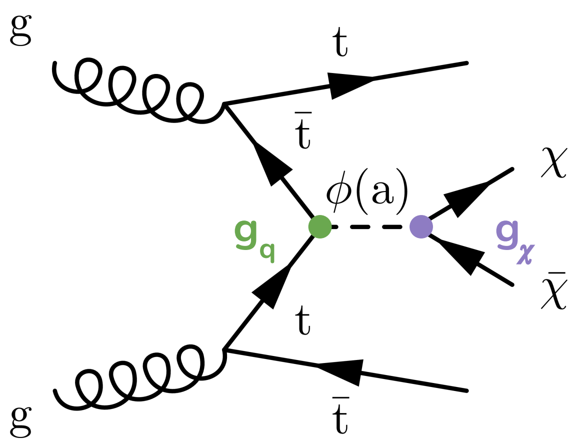
ATLAS EXPERIMENT

DESY.

Introduction.

Theoretical introduction

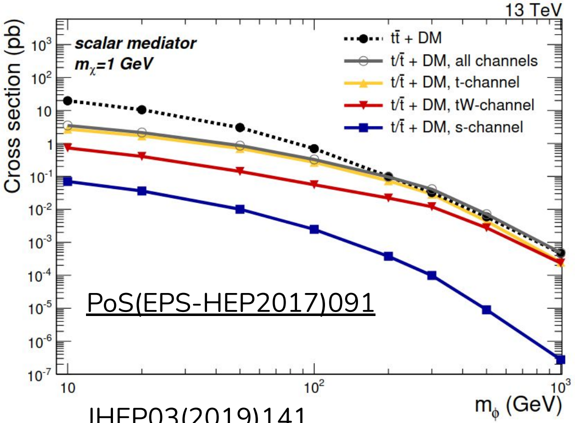
Mediator based dark matter (DM) scenarios



- **Weakly Interactive Massive Particle**
- **Simplified model** → Scalar (**ϕ**) / pseudoscalar (**a**) mediator decaying into dirac fermions DM candidates (**χ**)
- Set of 4 free parameters: **m_χ**, **m_ϕ**, g_χ, g_q
  - With benchmark **$g_\chi = g_q = 1$**
- Yukawa-type couplings are assumed
  - $\propto$ **m_q** → would couple preferentially to the **top** quark

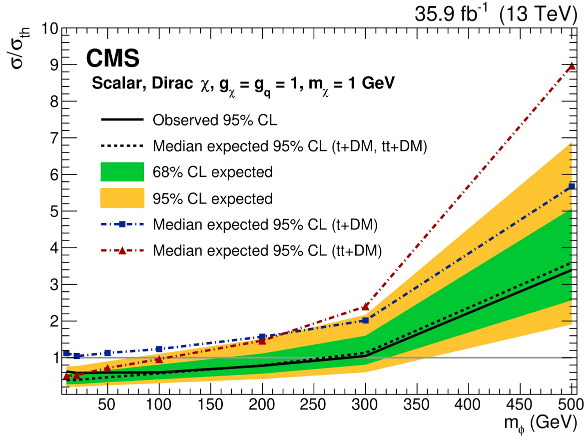
$t\bar{t}+\chi\chi$ and $t/\bar{t}+\chi\chi$

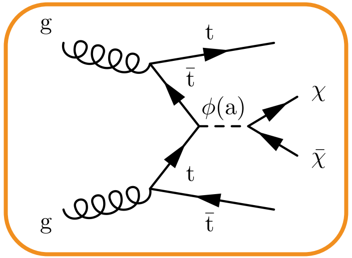
Combination motivation



PoS(EPS-HEP2017)091

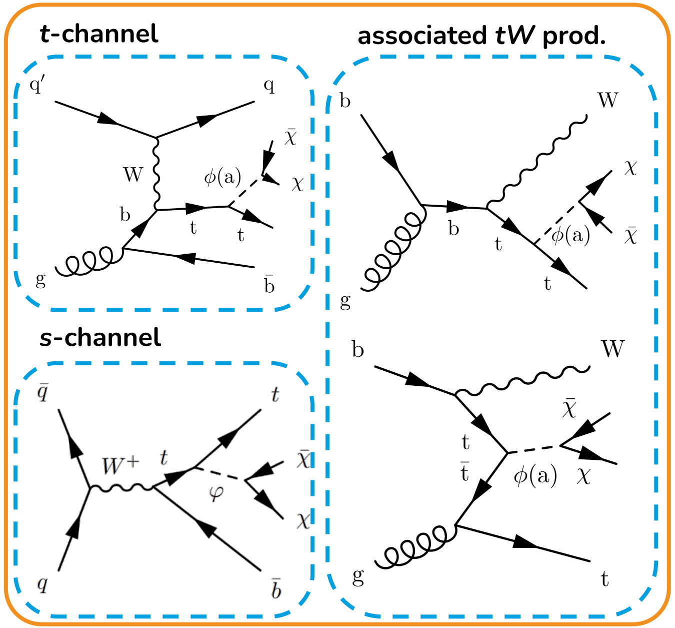
JHEP03(2019)141





$t\bar{t}+\chi\chi$

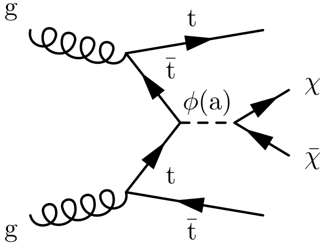
$t+\chi\chi$



- Much attention brought to $t\bar{t}+\chi\chi$
  - **Higher** cross section at **low** mediator masses
- Contribution at high mediator masses from $t+\chi\chi$
  - Lower cross-section but different production modes and kinematics → **overall rates comparable** to $t\bar{t}+\chi\chi$
  - **Combination** could improve sensitivity significantly
- Such combination only studied in CMS so far
  - $m_{\phi/a}$ excluded up to 290/300 GeV

$t\bar{t}+\chi\chi$ and $t/\bar{t}+\chi\chi$

Recent studies in ATLAS



$t\bar{t}+\chi\chi$ in ATLAS

- arXiv:2012.03799
  - 1 lepton final state
  - $m_{\phi/a}$ constrained up to 200 GeV
- arXiv:2102.01444
  - 2 leptons final state
  - $m_{\phi/a}$ constrained up to 250/300 GeV

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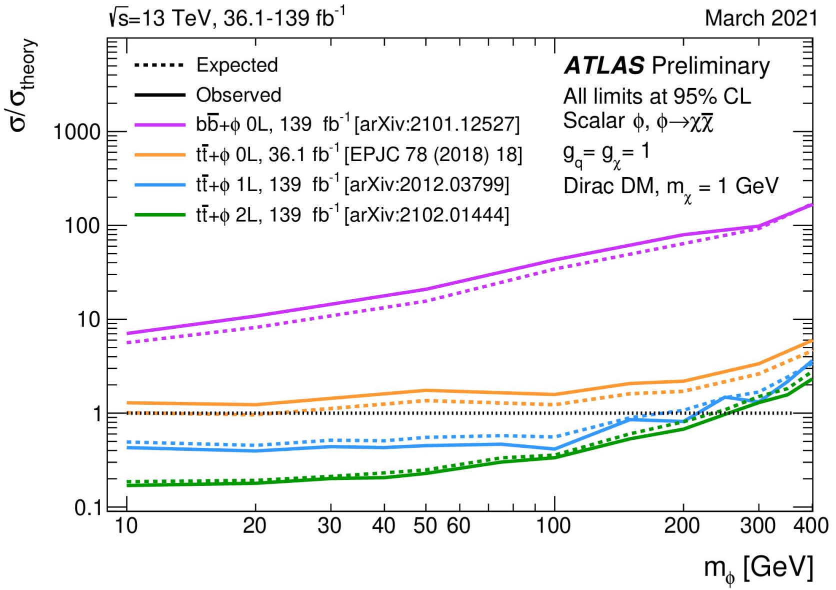

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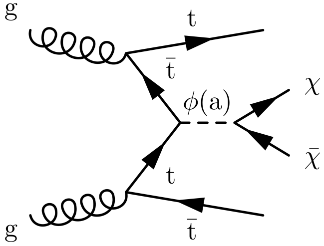

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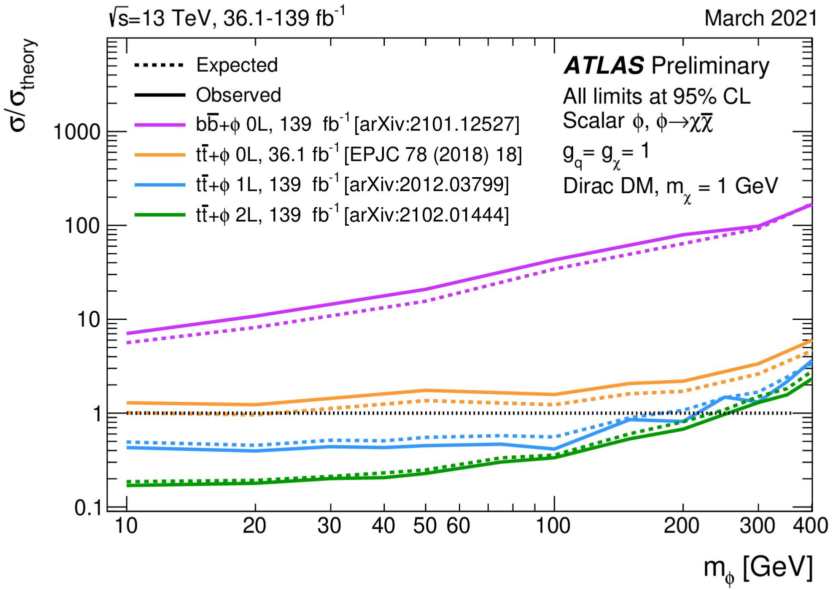
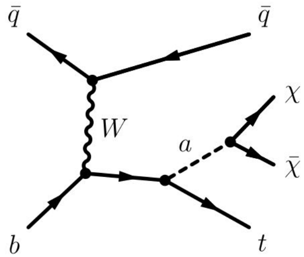
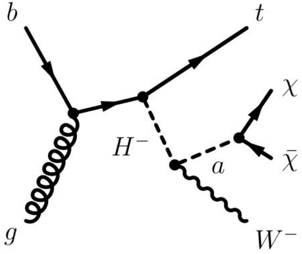




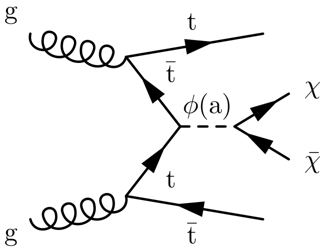


$t+\chi\chi$ in ATLAS

- arXiv:2011.09308
  - *tj/tW+χχ (2HDM+a model)*
  - Mediator mass exclusion between 200-330 GeV

$t\bar{t}+\chi\chi$ and $t/\bar{t}+\chi\chi$

Recent studies in ATLAS



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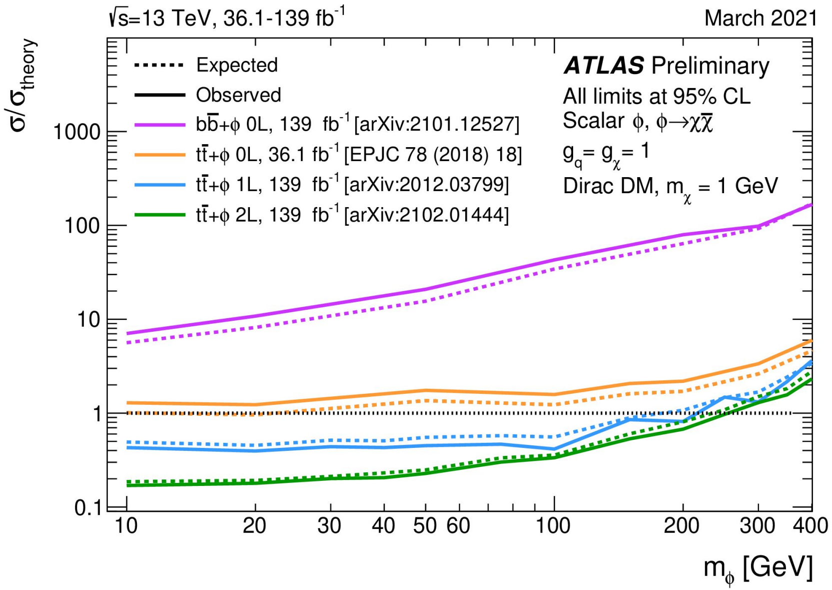
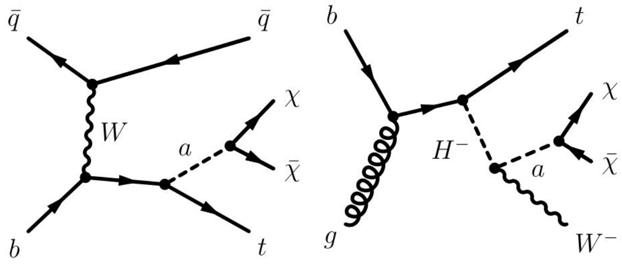




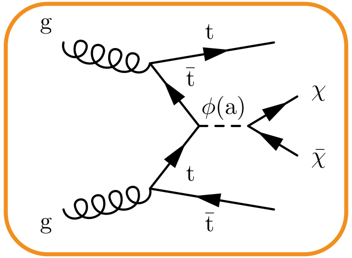
$t+\chi\chi$ in ATLAS

- arXiv:2011.09308
  - $tj/tW+\chi\chi$ (2HDM+a model)
  - Mediator mass exclusion between 200-330 GeV

Combine both analyses results to improve exclusion limits

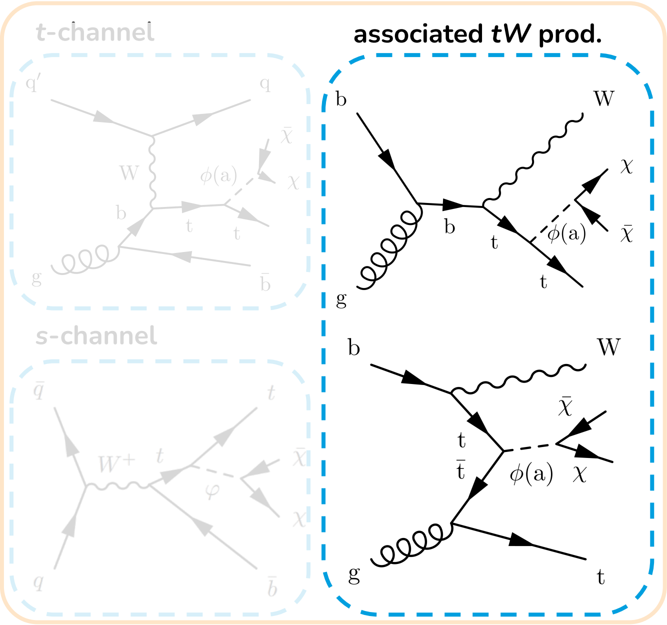
$t\bar{t}+\chi\chi$ and $t/\bar{t}+\chi\chi$

Combination motivation



$t\bar{t}+\chi\chi$

$t+\chi\chi$



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- Such c

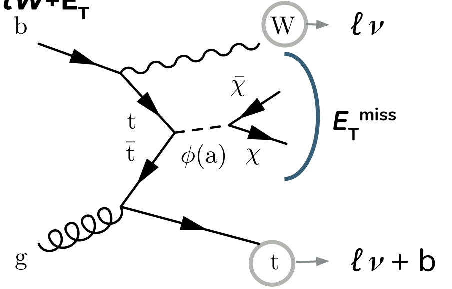
Focus on combining $t\bar{t}+\chi\chi$ and $tW+\chi\chi$ searches in the simplified model

Analysis setup and combination strategy.

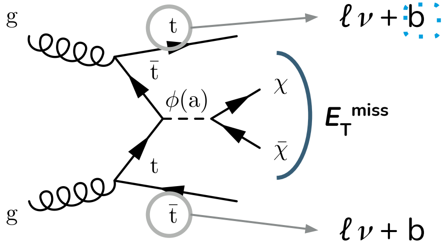
tW+E_T^{miss} & $t\bar{t}$+E_T^{miss} in the two leptons final state

Experimental signatures and dominant backgrounds

tW+E_T^{miss}



$t\bar{t}$+E_T^{miss}



- Considering $t\bar{t}$+$\chi\chi$ and tW+$\chi\chi$ signatures in the simplified model
- **Missing transverse momentum** (E_T^{miss}) is the main signature
- Focus on the **two leptons** final state **(2L)**
  - Requesting 2 leptons
  - Veto on Z-peak for same flavour opposite charge leptons
  - Both request at least one b-jet
  - Stringent selection on E_T^{miss}

tW+E_T^{miss} & $t\bar{t}$+E_T^{miss} in the two leptons final state

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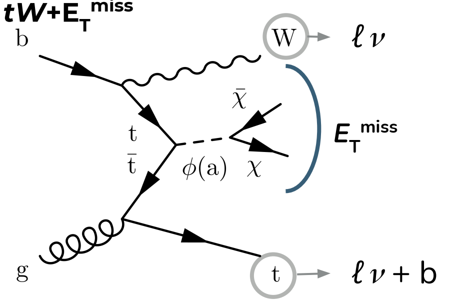
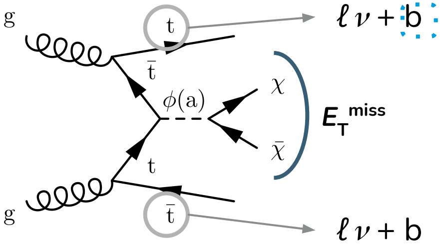


$t\bar{t}$+E_T^{miss}



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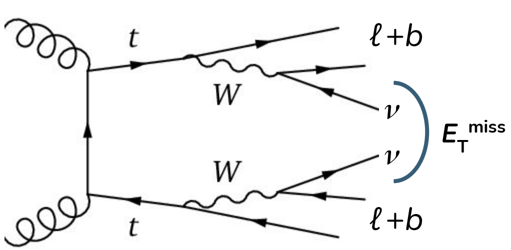
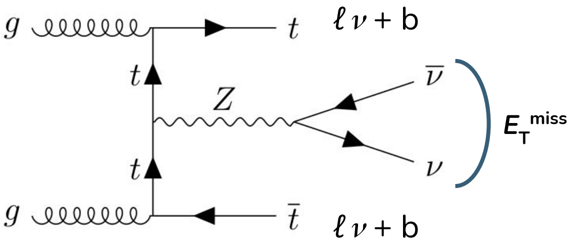
- Focus on the **two leptons** final state **(2L)**
  - Requesting 2 leptons
  - Veto on Z-peak for same flavour opposite charge leptons
  - Both request at least one b-jet
  - Stringent selection on E_T^{miss}
- The dominant backgrounds are the same: $\boldsymbol{t\bar{t}}$ & $\boldsymbol{t\bar{t}Z\nu\nu}$
  - Similar background estimation strategy



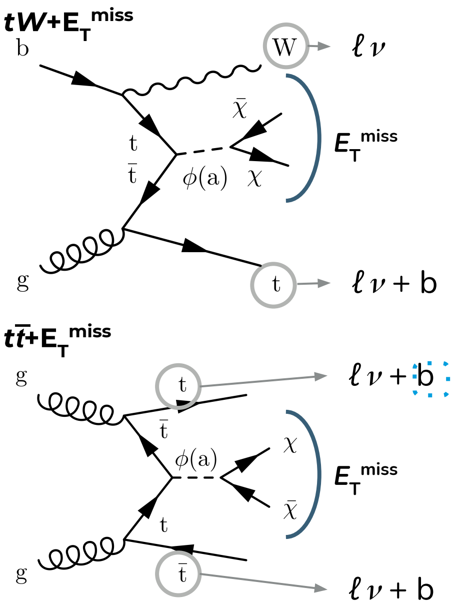


Signal regions definition

$tW+\chi\chi \rightarrow$ (DM)tW
$t\bar{t}+\chi\chi \rightarrow$ (DM)$t\bar{t}$

	tW-SR
n_{ℓ}	=2 (OS)
$m_{\ell\ell}$ [GeV]	$\notin$ [71,111]
n_{jet}	≥1
$n_{b\text{-jet}}$	≥1
$m_{b\ell}^{\text{min}}$ [GeV]	<170
$m_{b\ell}^{\text{t}}$ [GeV]	>150
m_{T2} [GeV]	>130
$\Delta\phi_{min}$ [rad]	>1.1
$E_{\text{T}}^{\text{miss}}$ [GeV]	>200

	$t\bar{t}$-SR	
Leptons flavour	Diff	Same
$m_{\ell\ell}$ [GeV]	>20	
$\|m_{\ell\ell}-m_Z\|$ [GeV]	—	>20
$n_{b\text{-jets}}$	≥1	
m_{T2} [GeV]	>110	
$\Delta\phi_{boost}$ [rad]	<1.5	
$E_{\text{T}}^{\text{miss}}$ significance	>12	



- Requesting 2 leptons
- Veto on Z-peak for same flavour opposite charge leptons
- Both request at least one b-jet
- Stringent selection on E_T^{miss}
- Single tW-SR
- Inclusive tt-SRs for exclusion fit
  - m_{T2}: [110,120],[120,140],[140,160],[160,180],[180,220],[180,∞)
  - Same and Different Flavour events (SRSF,SRDF)
- Multiple **discriminating variables** to define signal enriched regions

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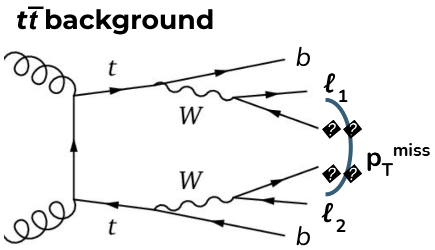

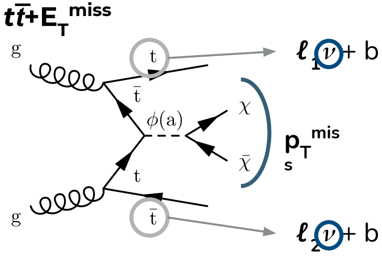

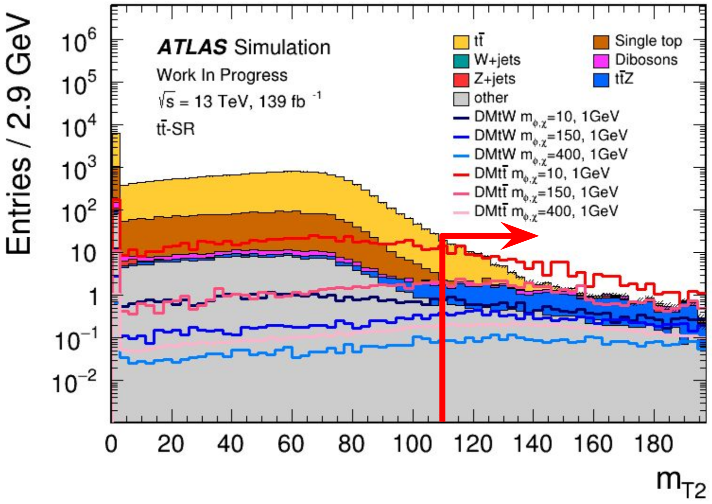

$$m_{\rm T2}(\mathbf{p}_{\rm T}^{l_1},\mathbf{p}_{\rm T}^{l_2},\mathbf{p}_{\rm T}^{\rm miss}) = \min_{\mathbf{p}_{\rm T,1}^{\rm miss}+\mathbf{p}_{\rm T,2}^{\rm miss}=\mathbf{p}_{\rm T}^{\rm miss}} \left[\max\left(m_{\rm T}(\mathbf{p}_{\rm T}^{l_1},\mathbf{p}_{\rm T,1}^{\rm miss}), m_{\rm T}(\mathbf{p}_{\rm T}^{l_2},\mathbf{p}_{\rm T,2}^{\rm miss})\right)\right]$$

- Stransverse mass $\boldsymbol{m_{\rm T2}}$: discrimination against pair-produced particles (e.g. $t\bar{t}$) decaying to **visible** + **invisible** particles
- For backgrounds → endpoint ~ $\boldsymbol{m_{\rm W}}$
- **Higher** endpoint for **signal** (e.g. $t\bar{t}/tW+\chi\chi$)

Orthogonalization strategy

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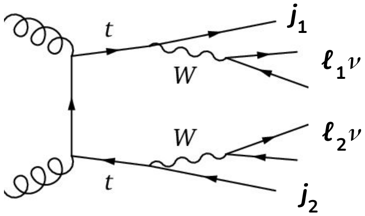
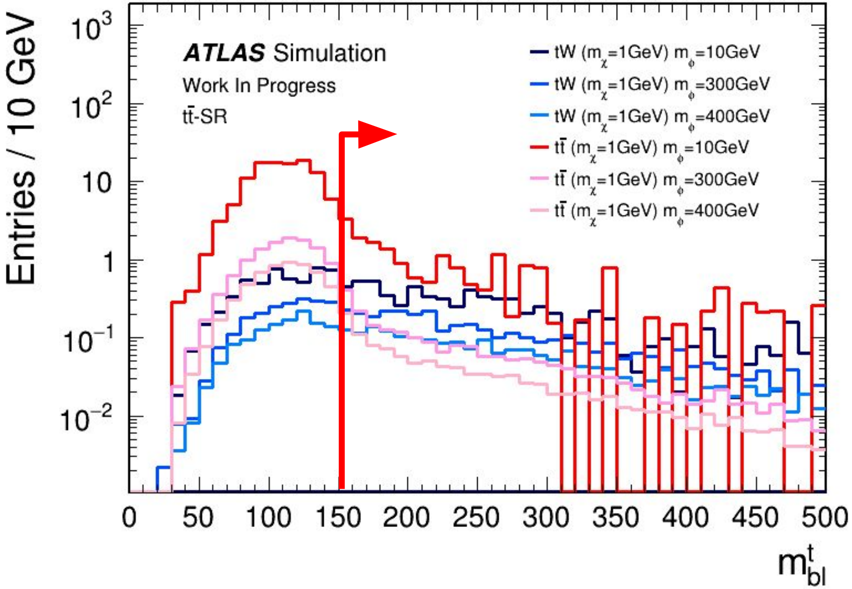
E_T^{miss} significance	>12	

→ Find proper parameter(s) requirement(s) to avoid double counting of events





$$m_{bl}^{t} = \min(\max(m_{l_1 j_1}, m_{l_2 j_2}), \max(m_{l_1 j_2}, m_{l_2 j_1}))$$

With j_1,j_2 → jets with highest *b*-tag weight

- $\mathbf{m^t_{bl}}$ → discriminate against events containing 2 leptonic top decays
- Applying m^t_{bl} > 150 GeV *tW*-SR reduces $t\bar{t}$, $t\bar{t}V$, $t\bar{t}+\chi\chi$ contributions

Orthogonalization strategy

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	$t\bar{t}$-SR ortho	
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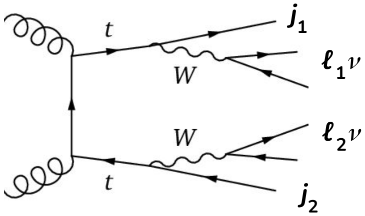

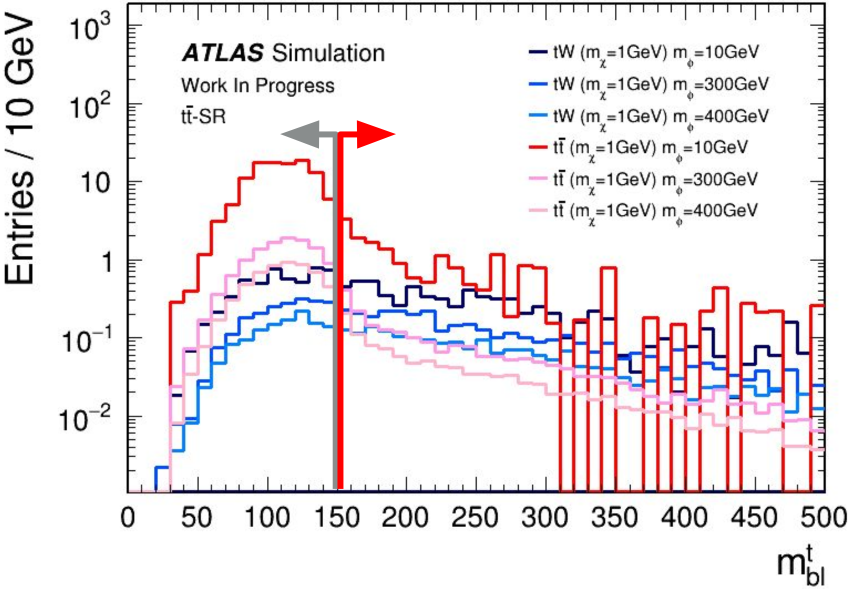

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With j_1, j_2 → jets with highest b-tag weight

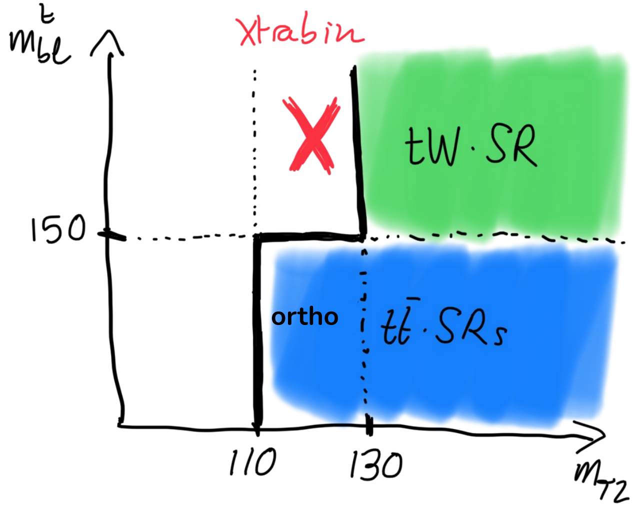
- $\boldsymbol{m^t_{bl}}$ → discriminate against events containing 2 leptonic top decays
- Applying m^t_{bl} > 150 GeV tW-SR reduces $t\bar{t}$, $t\bar{t}V$, $t\bar{t}+\chi\chi$ contributions
- m^t_{bl} < 150 GeV in $t\bar{t}$-SR could make the two analyses **orthogonal**

Orthogonalization strategy

Extending the binning

	tW-SR	
n_ℓ $m_{\ell\ell}$ [GeV]	=2 (OS) $\notin$ [71,111]	
n_{jet} $n_{b\text{-jet}}$	≥ 1 ≥ 1	
$m_{b\ell}^{\text{min}}$ [GeV] $m_{b\ell}^{\text{t}}$ [GeV]	<170 >150	
m_{T2} [GeV]	**$\in$[110,130]**	**>130**
$\Delta\phi_{min}$ [rad] E_T^{miss} [GeV]	>1.1 >200	

	$t\bar{t}$-SR	
Leptons flavour	Diff	Same
$m_{\ell\ell}$ [GeV]	>20	
$\lvert m_{\ell\ell}-m_Z\rvert$ [GeV]	—	>20
$n_{b\text{-jets}}$	≥ 1	
$m_{b\ell}^{\text{t}}$ [GeV]	<150	
m_{T2} [GeV]	**>110**	
$\Delta\phi_{boost}$ [rad] E_T^{miss} significance	<1.5 >12	



- Orthogonalized through $\boldsymbol{m^{t}_{bl}}$
- Lowest m_{T2} cut is different
  - in tW-SR add xtra bin $\boldsymbol{m_{T2} \in [110,130]}$ **GeV** to get in more signal → improve exclusion fit

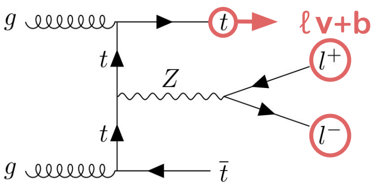
Control region definition

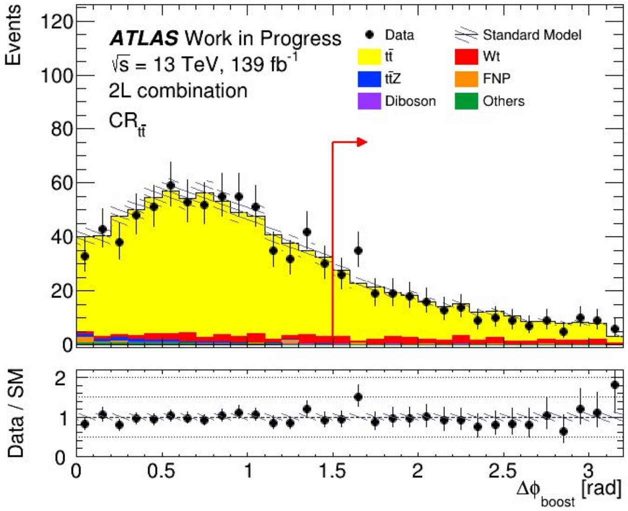
$t\bar{t}$ and $t\bar{t}Z$ backgrounds

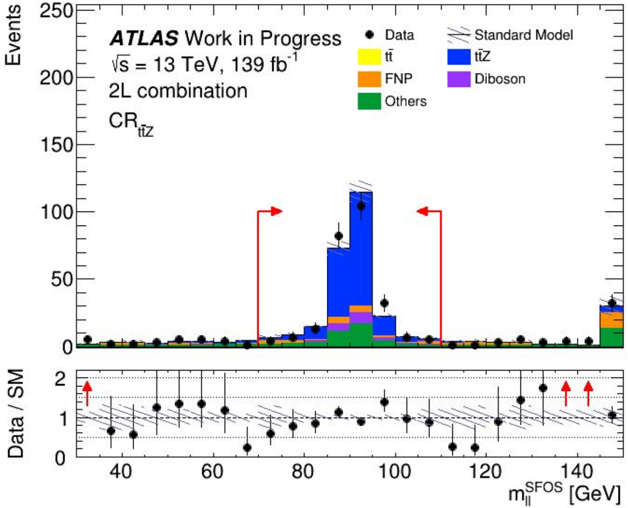
	CR($t\bar{t}$)
n_ℓ	2
Leptons flavour	Different
$m_{\ell\ell}$ [GeV]	>20
$n_{b\text{-jets}}$	≥1
$\Delta\phi_{boost}$ [rad]	≥1.5
E_T^{miss} significance	>8
m_{T2} [GeV]	[100,120]

	CR($t\bar{t}Z$)
n_ℓ	3
Leptons flavour	≥1 SFOS
$\lvert m_{\ell\ell}-m_Z\rvert$ [GeV]	<20 (≥1 SFOS)
$n_{b\text{-jets}}$	≥2 with n_{jets}≥3
E_T^{miss} corr. [GeV]	>140

- $t\bar{t}$ and $ttZ\nu\nu$ dominant backgrounds in both analyses
- Define background-enriched regions for better estimation
- **common CRs**
- In CR($t\bar{t}$)
  - Inverted SR cut on $\Delta\phi_{boost}$
  - looser cuts on $\boldsymbol{m_{T2}}$
- In CR(ttZ)
  - ttZ→4ℓ low statistical power
  - "trick" defining a CR for ttZ→3ℓ (with Z→ℓℓ)
  - Define "corrected" variables using p_T of leptons from the Z in the E_T^{miss} derivation

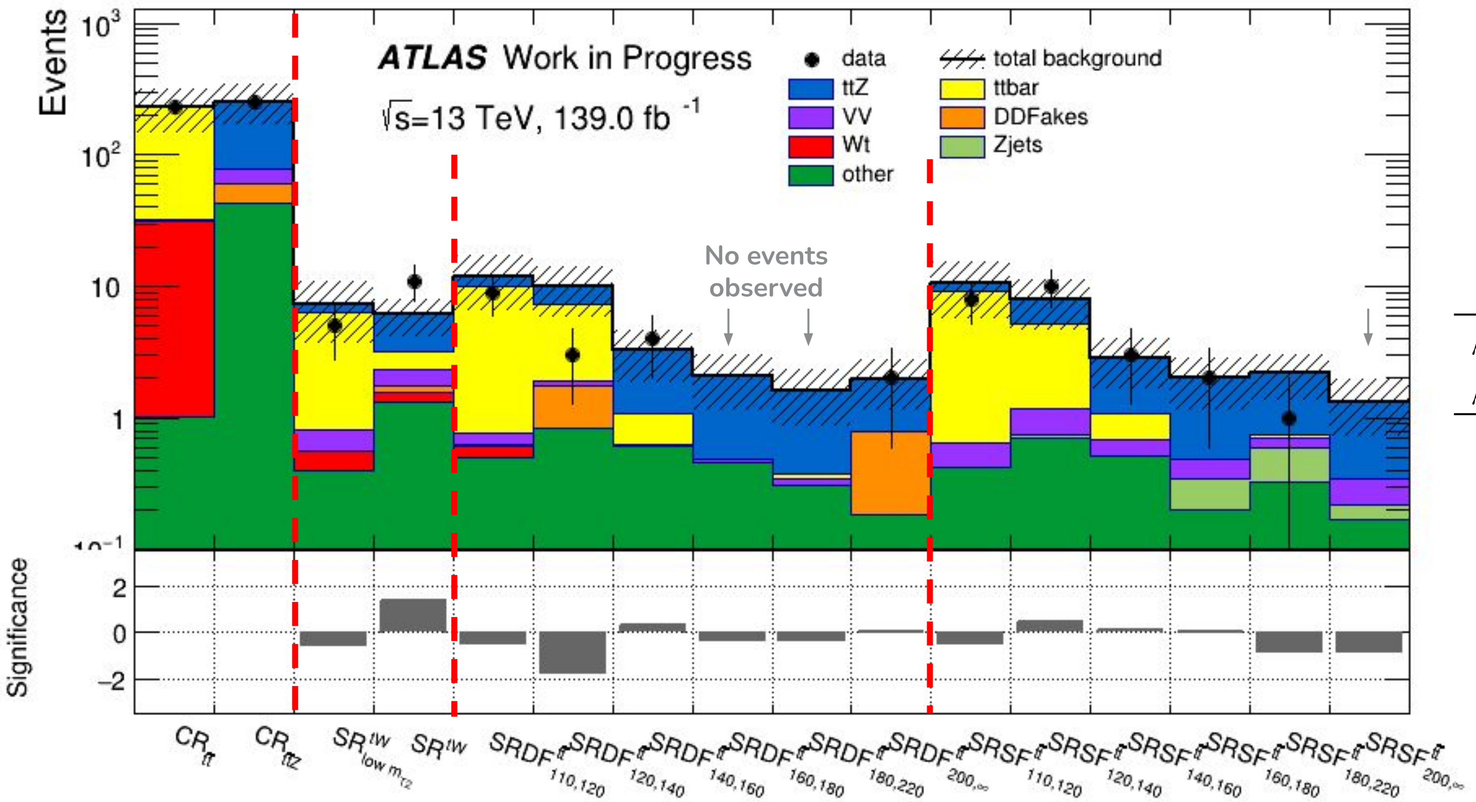






Results.

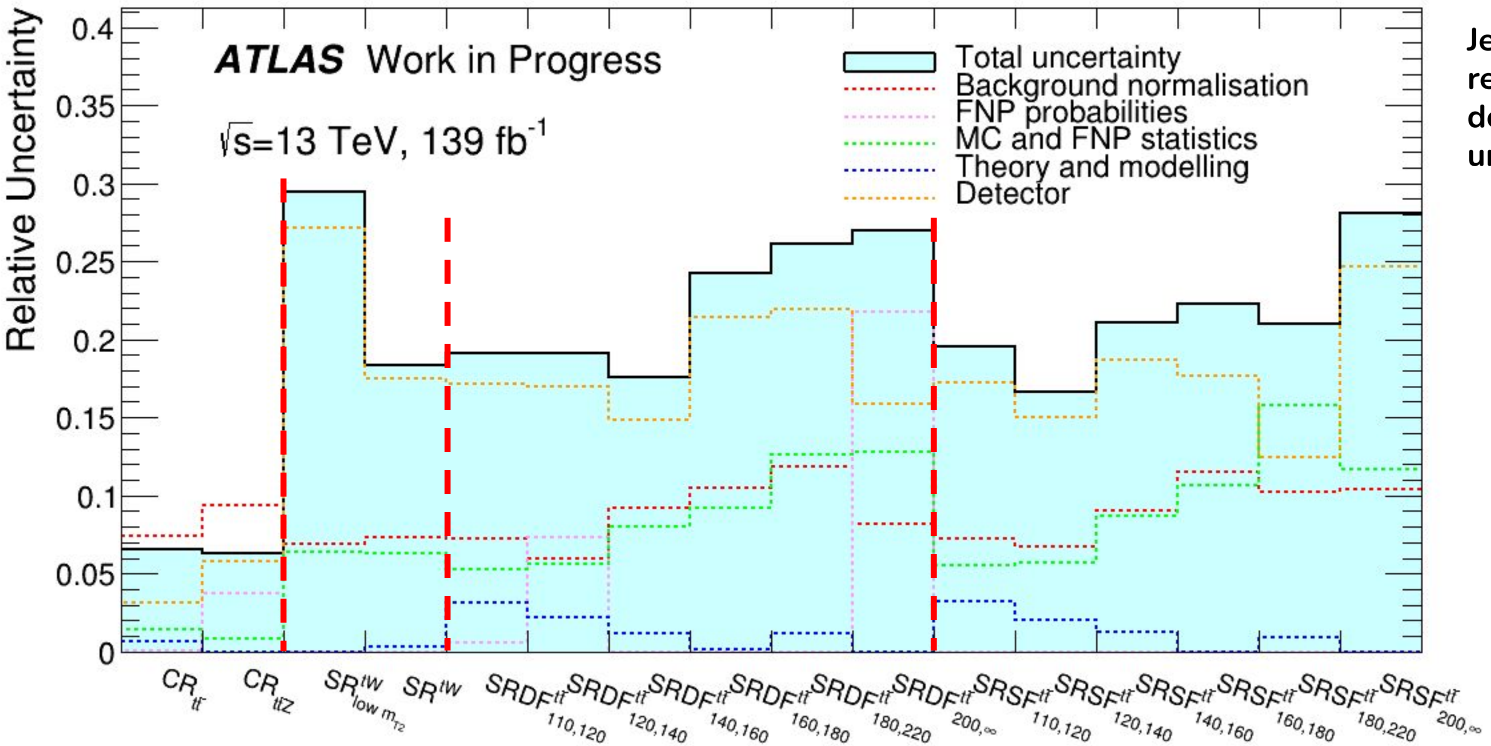
Validation pull plot



μ_{tt}	0.89 ± 0.08
μ_{ttZ}	1.06 ± 0.16

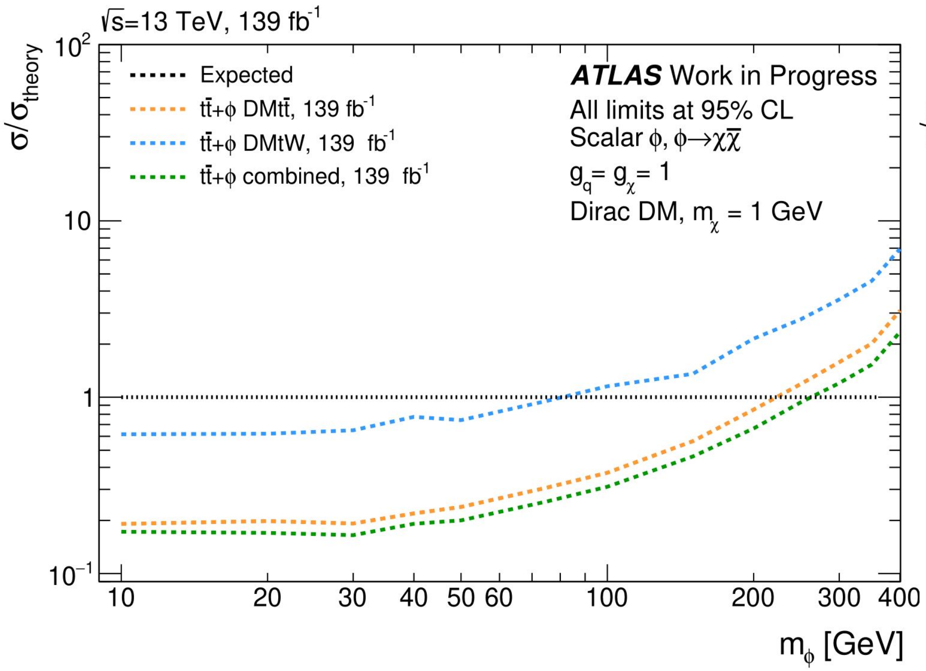
Uncertainties breakdown

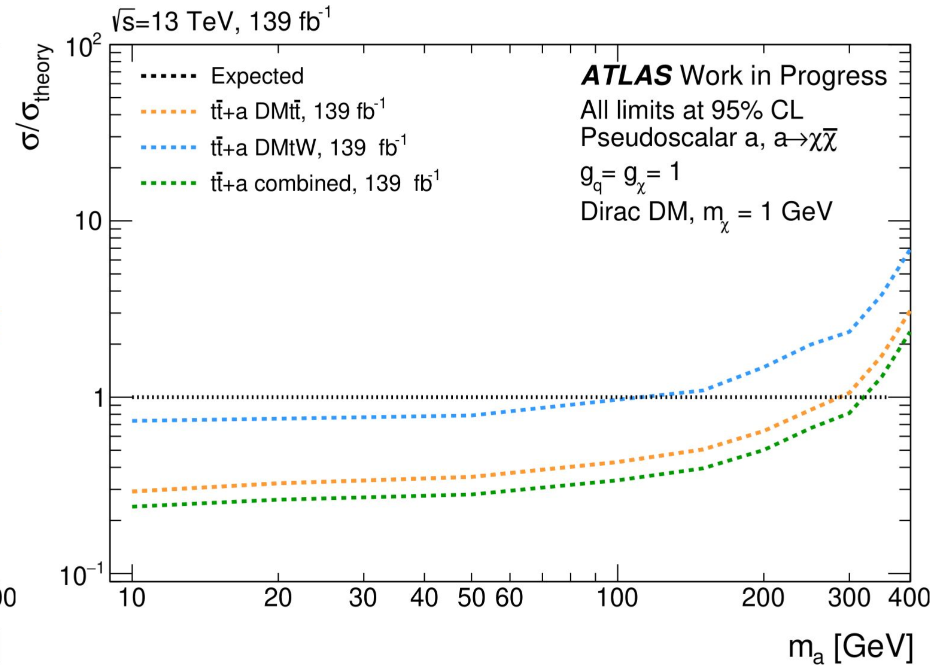
FNP = fake and non-prompt leptons



Jet energy resolution/scale dominating uncertainties

Exclusion plots in combined and separated analyses



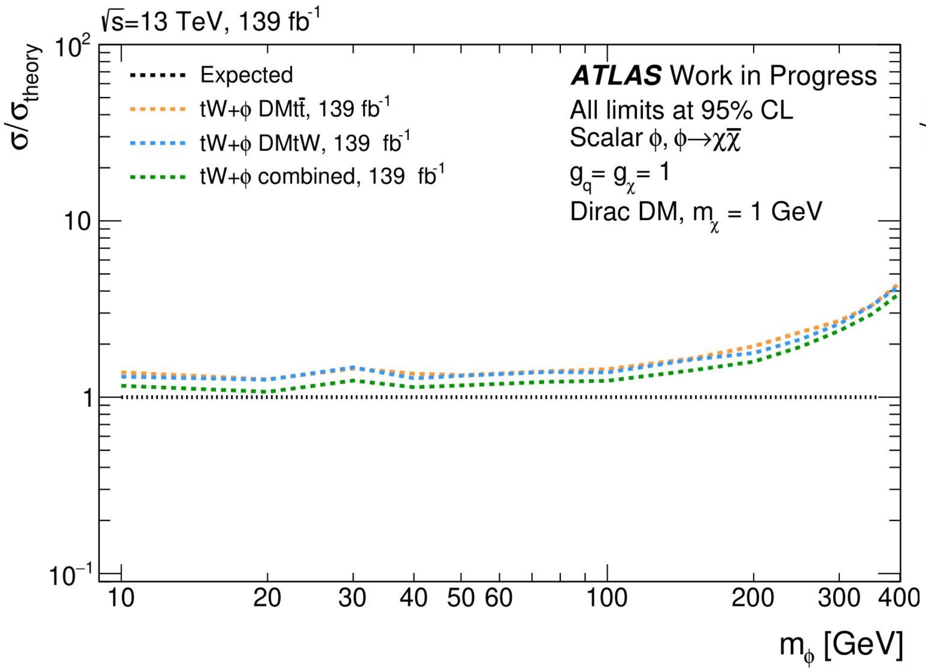


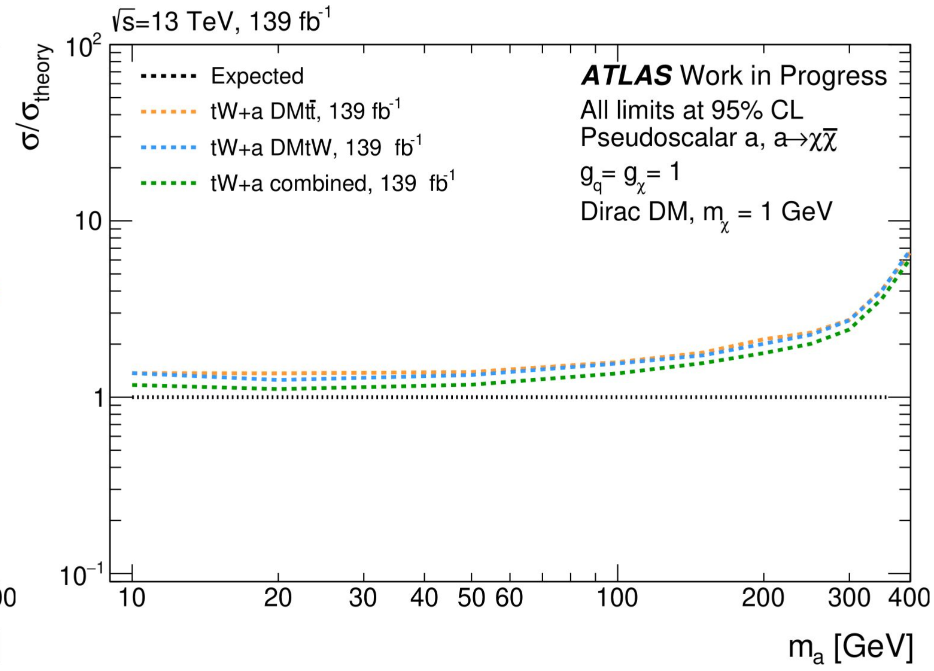
$t\bar{t}$+DM signal in DMtW analysis

$t\bar{t}$+DM signal in DM$t\bar{t}$ analysis

$t\bar{t}$+DM signal in combined analyses

Exclusion plots in combined and separated analyses



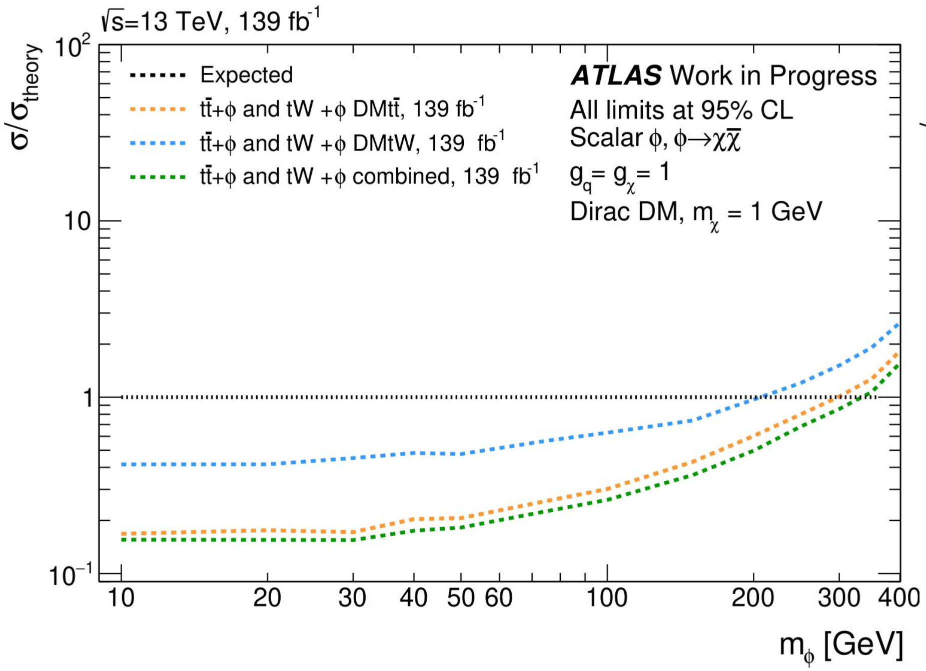


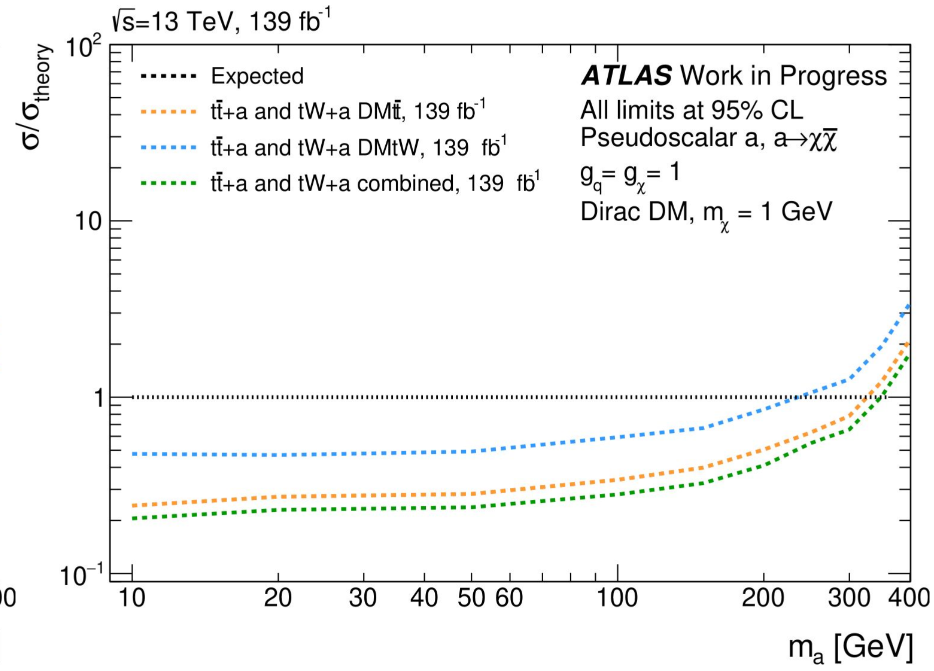
tW+DM signal in DM*tW* analysis

tW+DM signal in DM$t\bar{t}$ analysis

tW+DM signal in combined analyses

Exclusion plots in combined and separated analyses





$t\bar{t}$+DM and tW+DM signals in DMtW analysis

$t\bar{t}$+DM and tW+DM signals in DM$t\bar{t}$ analysis

$t\bar{t}$+DM and tW+DM signals in combined analyses

Summary and outlook

- Combination of $t\bar{t}+\chi\chi$ and $tW+\chi\chi$ searches to improve the sensitivity to DM simplified models
  - Focus on 2L final state
- Defined strategy for the combination setup
- Improvement of the exclusion limit in combined searches for higher mediator masses as expected
- New mass constraints expected up to 350 GeV for both scalar and pseudoscalar mediator

Thank you!

Backup.

Bkg and signal samples, ntuples production

- Samples (Full lumi: mc16a/d/e) - detailed table in DMtt2L paper:

Physics process	Generator
DM signals	MADGRAPH+PYTHIA8
$t\bar{t}$	POWHEG+PYTHIA8
$t\bar{t}V$ ($V = W, Z$)	MADGRAPH+PYTHIA8
Wt	POWHEG+PYTHIA8
$Z(\to\ell\ell)$+jets	SHERPA 2.2.1
Diboson VV ($V = W, Z$)	SHERPA 2.2.1/2
Triboson VVV ($V = W, Z$)	SHERPA 2.2.2
ttH	POWHEG+PYTHIA8
Other ($t\bar{t}WW$, $t\bar{t}WZ$, tZ, $t\bar{t}t\bar{t}$, $t\bar{t}t$)	MADGRAPH+PYTHIA8

- Producing signals+backgrounds ntuples using `DAOD_SUSY2` derivation samples with ***harmonized*** config file
  - `AnalysisBase 21.2.129`
- Following DMtt2L definitions
- *Fake/misidentified leptons* estimated from data-driven Fake Factor method

Object definitions

Harmonized for combination

Need to select same type of objects while remaining specific to each analysis

In particular…

- Same kinematic baseline lepton definition
- Same jets/b-tagging definition
- Same jets uncertainties definition

DM+tW	DM+tt
Electron baseline	
pt>4.5 GeV, η<2.47	
ID: LooseAndBLayerLLH	
Electron	
pt>4.5 GeV, η<2.47	
Iso:FCLoose IsoHighPt:FCLoose ID: TightLLH	Iso: Gradient IsoHighPt:Gradient ID:MediumLLH
Muon Baseline	
pt>4 GeV, η<2.7	
ID: Medium	
Muon	
pt>4 GeV, η<2.7 ID: Medium	
Iso: Loose_FixedRad IsoHighPt: Loose_VarRad	Iso: Loose_VarRad IsoHighPt: Loose_VarRad
Jet	
pt>20 GeV	
η<4.5	η<2.8
EMTopoAntikt4 jets JVT_WP: Medium	
JvtPtMax: 120 GeV	JvtPtMax: 60 GeV
Btagger: MV2c10 Btag WP: Continuous UncertConfig:rel21/Summer2019/R4_CategoryReduction_FullJER.config	
Forward Jet	
true	false
OR	
MuBJet: true	MuBJet: false

Systematics uncertainties

Experimental

- Electrons
  - energy scale, energy resolution (config: 1NP_v1)
  - reconstruction efficiency, identification efficiency, isolation efficiency (config: TOTAL);
- Muons
  - momentum scale, momentum resolution, sagitta correction,
  - reconstruction efficiency, isolation efficiency, track-to-vertex association efficiency;
- Jets
  - energy scale, energy resolution (config: rel21/Summer2019/R4_CategoryReduction_FullJER, to allow combination with other analyses)
- Flavour tagging
  - offline b-jet, c-jet, light-flavor, τ jet tagging efficiencies (config: pseudo-continuous, eigenvectors)
  - online w.r.t offline b-jet tagging efficiencies
- Pileup modeling
  - JVT efficiency, fJVT efficiency
  - pileup reweighting SF
- E_T^{miss}
  - Soft term scale, and perp/para resolution
- Luminosity
  - 1.7% for full Run 2

Systematic uncertainties

Theoretical

For ttbar:

- **Radiation(ISR)** - Weights systematics
- **Radiation(FSR)** - Weights systematics
- **Hard-scatter** - Compare Powheg+Pythia8 versus aMcAtNlo+Pythia8 (TRUTH)
- **Parton showering** - Compare Powheg+Pythia8 versus Powheg+Herwig7 (TRUTH)

For Wt:

- **Wt-ttbar interference** - Diagram Removal (DR) Versus Diagram Substraction (DS)

For ttZ:

- **Hard-scatter** - Compare aMC@NLO+Pythia8 versus Sherpa (TRUTH)
  Check if scale variation unc cover difference between aMC@NLO+Pythia8 versus Sherpa.
- **Parton showering** - Compare aMC@NLO+Pythia8 versus aMC@NLO+Herwig7 (TRUTH)
- **Scale variations** - Renormalisation/Factorisation uncertainties (Weights systematics)
- **Radiation uncertainties** - Use the Pythia8 Tune variations (TRUTH)

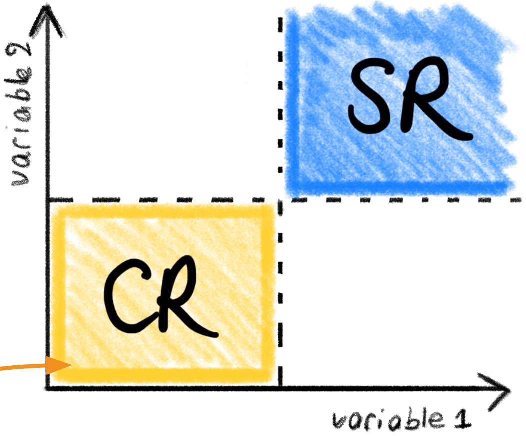
Multi-bosons (VV) :

- **Scale variations** (Weights systematics)
- **QKKM and CKM** for Multi-bosons (TRUTH)
- **Heavy Flavour (HF) Fragmentation** - 30% on the number of events having at least 1 b-quark and 1 b-tagged jet (only for ¾ -body selection where we extrapolate from a 0 b-tagged jet region)

Combination strategy

Signal and Control Regions and how to orthogonalize them

- **Signal enriched** region(s) → signal region(s) (SR)
- Estimate **background processes** contaminating the SR(s) → define control region(s) (CR)
    - designed to have a high purity for dedicated dominant background + free of signal contamination
- ***Orthogonal*** between each other
    - Avoids counting same events twice → can be used in **combined statistical likelihood**



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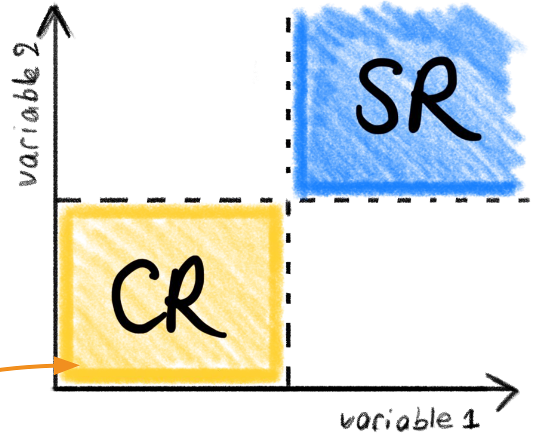
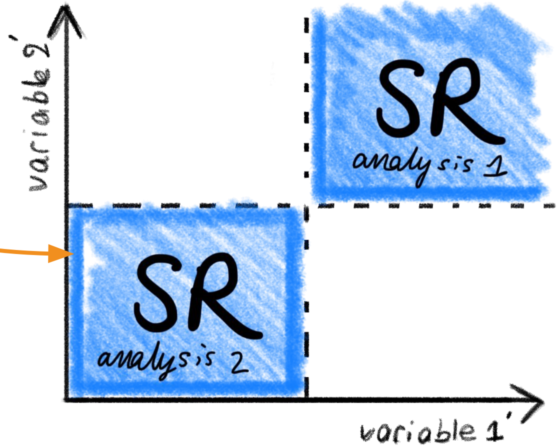


- Regions definition is done **independently** by the two analyses
- For combination look for orthogonality between each analysis regions when possible
    - Find/modify discriminant variables cuts to make the regions ***orthogonal*** → statistical combination
    - Define common analysis region otherwise



Same idea for CRs...

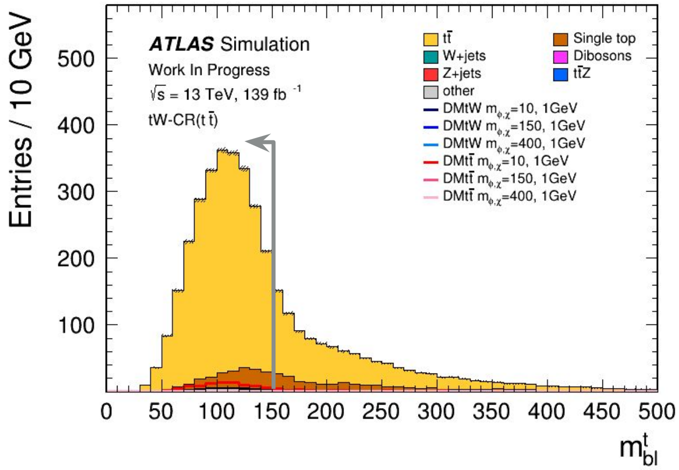
Control region definition

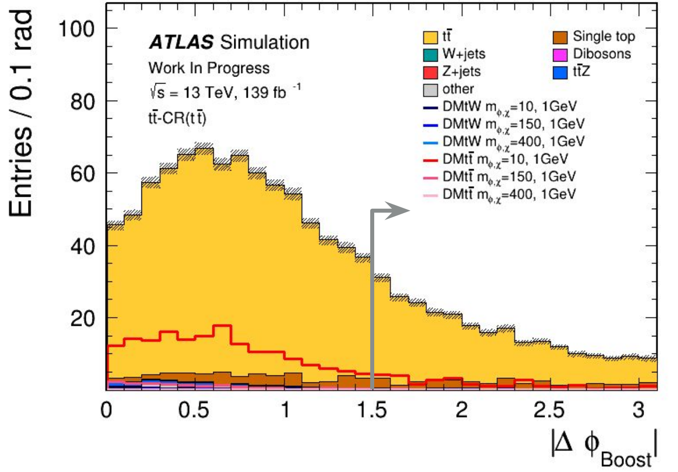
CRs($t\bar{t}$)

	tW-CR($t\bar{t}$)
n_ℓ	=2 (OS)
$m_{\ell\ell}$ [GeV]	$\notin$ [71,111]
n_{jet}	≥1
$n_{b\text{-jet}}$	≥1
$m_{b\ell}^{\text{min}}$ [GeV]	<170
$m_{b\ell}^{\text{t}}$ [GeV]	<150
m_{T2} [GeV]	[40,80]
$\Delta\phi_{min}$ [rad]	>1.1

	$t\bar{t}$-CR($t\bar{t}$)
n_ℓ	2
Leptons flavour	Different
$m_{\ell\ell}$ [GeV]	>20
$n_{b\text{-jets}}$	≥1
$\Delta\phi_{boost}$ [rad]	≥1.5
$E_{\text{T}}^{\text{miss}}$ significance	>8
m_{T2} [GeV]	[100,120]

- Orthogonal to their respective SRs
- In tW-CR($t\bar{t}$)
  - Inverted SR cut on m^{t}_{bl}
- In $t\bar{t}$-CR($t\bar{t}$)
  - Inverted SR cut on $\Delta\phi_{\text{boost}}$
- Both have looser cuts on $\boldsymbol{m_{T2}}$
- CRs($t\bar{t}$) in 2 different $\boldsymbol{m_{T2}}$ phase spaces → **orthogonal**





Control region definition

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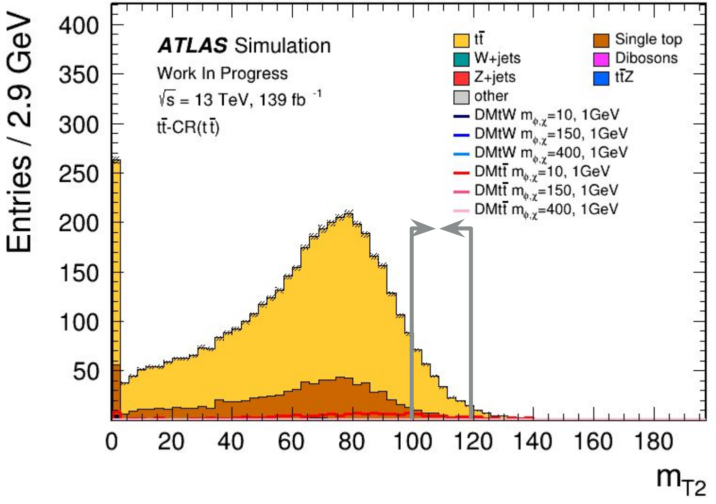
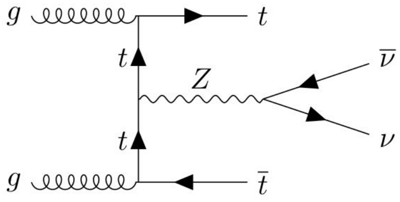
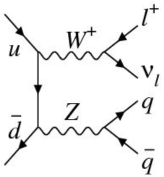
- In tW-CR($t\bar{t}$)
    - Inverted SR cut on m^{t}_{bl}
- In $t\bar{t}$-CR($t\bar{t}$)
    - Inverted SR cut on $\Delta\phi_{boost}$
- Both have looser cuts on $\boldsymbol{m_{T2}}$
- CRs($t\bar{t}$) in 2 different $\boldsymbol{m_{T2}}$ phase spaces → orthogonal
- After Background Only fit, turns out $\mu_{tt}^{tW2L} \sim \mu_{tt}^{tt2L}$ → **common CR**
- Choice set on ***$t\bar{t}$*-CR($t\bar{t}$)** → lower yields but higher SRs multiplicity compensate



Control region definition

CR(ttZ) & CR(WZ)

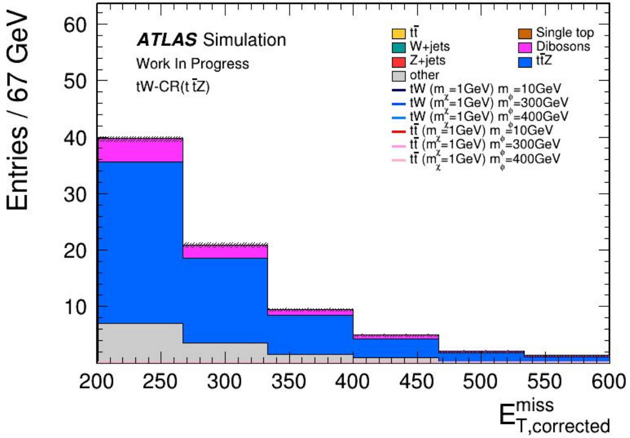


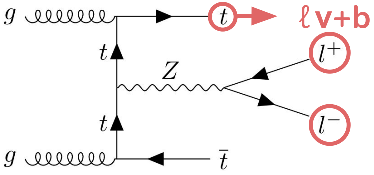


Only in DM+*tW* to estimate WZ processes in CR(ttZ)

	tW-CR(ttZ)	tW-CR(WZ)
n_ℓ	3 (≥1 SFOS)	3 (≥1 SFOS)
$m_{\ell\ell}$ [GeV]	∈[71,111]	∈[71,111]
n_{jet}	≥3	[1,3]
$n_{b\text{-jet}}$	≥1 (≥2 if n_{jet}=3)	1
$m_{b\ell}^{\text{min}}$ corr. [GeV]	<170	>170
m_{T2} corr. [GeV]	>90	>90

	$t\bar{t}$-CR(ttZ)
n_ℓ	3
Leptons flavour	≥1 SFOS
$m_{\ell\ell}$ [GeV]	—
$\|m_{\ell\ell}-m_Z\|$ [GeV]	<20 (≥1 SFOS)
$n_{b\text{-jets}}$	≥2 with n_{jets}≥3
$E_{\text{T}}^{\text{miss}}$ corr. [GeV]	>140

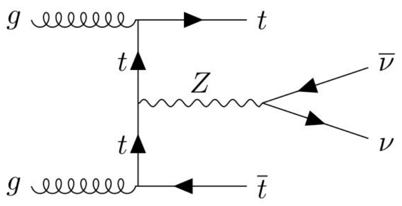


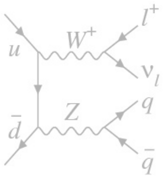


- ttZ→4ℓ much lower stat. + tt̄ contamination
  - "trick" defining a CR for ttZ→3ℓ (with Z→ℓℓ)
  - Define "corrected" variables using p_T of leptons from the Z in the E_T^{miss} derivation

Control region definition

CR(ttZ) & CR(WZ)

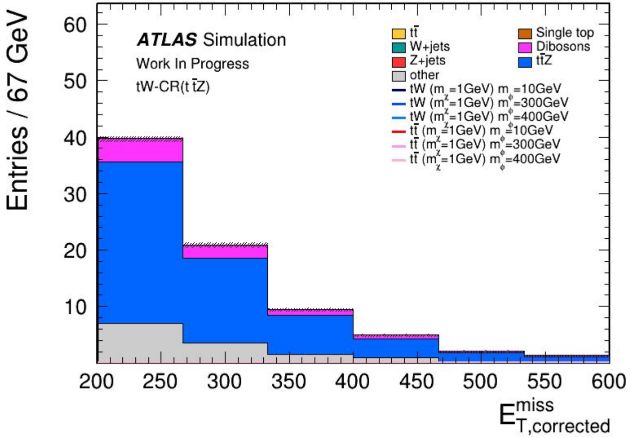


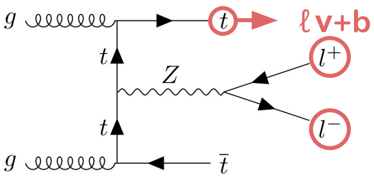


Only in DM+tW to estimate WZ processes in CR(ttZ)

	tW-CR(ttZ)	tW-CR(WZ)
n_ℓ	3 (≥1 SFOS)	3 (≥1 SFOS)
$m_{\ell\ell}$ [GeV]	∈[71,111]	∈[71,111]
n_{jet}	≥3	[illegible]
$n_{b\text{-jet}}$	≥1 (≥2 if n_{jet}=3)	1
$m_{b\ell}^{\text{min}}$ corr. [GeV]	<170	>170
m_{T2} corr. [GeV]	>90	>90

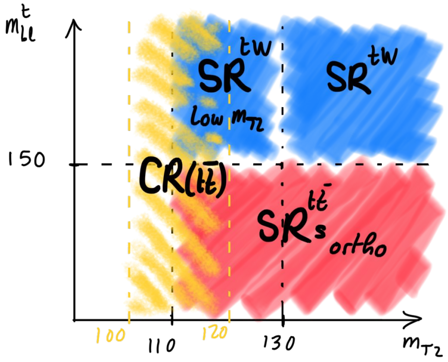
	$t\bar{t}$-CR(ttZ)
n_ℓ	3
Leptons flavour	≥1 SFOS
$m_{\ell\ell}$ [GeV]	—
$\lvert m_{\ell\ell}-m_Z \rvert$ [GeV]	<20 (≥1 SFOS)
$n_{b\text{-jets}}$	≥2 with n_{jets}≥3
$E_{\text{T}}^{\text{miss}}$ corr. [GeV]	>140

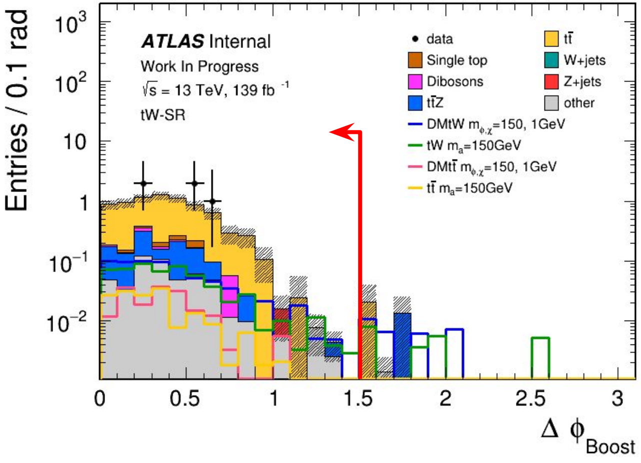




- ttZ→4ℓ much lower stat. + $t\bar{t}$ contamination
  - "trick" defining a CR for ttZ→3ℓ (with Z→ℓℓ)
  - Define "corrected" variables using p_T of leptons from the Z in the E_T^{miss} derivation
- CRs($t\bar{t}Z$) very similar → **common region**
- CR(WZ) not considered anymore as yields way too low to be relevant in SRs

CR(ttbar) and $SR^{tW}_{low\ mT2}$ overlap check





- Overlap between $SR^{tW}_{low\ mT2}$ and CR(ttbar) as cut on $\Delta\phi_{boost}$ not applied in this region
- Check potential contamination
  - SR yields with and without $\Delta\phi_{boost}$ cut
  - Yields variation extremely low → no need for extra cut

table.results.yields channel	SRxtraBin	SRxtraBin_dphiB
Observed events	5	5
Fitted bkg events	7.22 ± 0.64	7.18 ± 0.64
Fitted ttbar events	5.48 ± 0.55	5.46 ± 0.55
Fitted Wt events	0.17 ± 0.01	0.17 ± 0.01
Fitted Zjets events	0.01 ± 0.00	0.01 ± 0.00
Fitted VV events	0.27 ± 0.02	0.27 ± 0.02
Fitted ttZ events	0.89 ± 0.13	0.88 ± 0.13
Fitted other events	0.41 ± 0.12	0.40 ± 0.12
Fitted DDFakes events	0.00 ± 0.00	0.00 ± 0.00
MC exp. SM events	7.87 ± 0.52	7.83 ± 0.52
MC exp. ttbar events	6.18 ± 0.40	6.16 ± 0.40
MC exp. Wt events	0.17 ± 0.01	0.17 ± 0.01
MC exp. Zjets events	0.01 ± 0.00	0.01 ± 0.00
MC exp. VV events	0.27 ± 0.02	0.27 ± 0.02
MC exp. ttZ events	0.85 ± 0.05	0.84 ± 0.05
MC exp. other events	0.41 ± 0.13	0.40 ± 0.12
MC exp. DDFakes events	0.00 ± 0.00	0.00 ± 0.00

ttbar SF choice.

SF

- $\mu_{ttbar}{}^{tW} \approx \mu_{ttbar}{}^{tt}$ → One CRttbar could be sufficient then
- **Problem:** would need to recompute theoretical uncertainties as implemented manually in HistFitter
- However Top yields are very low in DMtW SR
  - if theoretical systematics impact is low on SR yields could avoid absorbing uncertainty in TF → full theoretical uncertainty on SR
- To check whether approach is doable → use ttCRttbar in tW workspace and look at theoretical syst impact on all background + top sample only
- Compare with INT note

Syst tables

before switching CRttbar (all backgrounds)

Uncertainty of channel	SR2L	tW2L_CRttbar
Total background expectation	6.01	1633.36
Total statistical ($\sqrt{N_{\text{exp}}}$)	±2.45	±40.41
Total background systematic	±1.27 [21.10%]	±7.86 [0.48%]
alpha_singletopSyst	±1.18 [19.6%]	±0.00 [0.00%]
gamma_stat_SR2L_cuts_bin_0	±0.38 [6.3%]	±0.00 [0.00%]
alpha_MatrixElement-Top2L	±0.19 [3.1%]	±0.00 [0.00%]
alpha_Sherpa-ttV	±0.11 [1.9%]	±0.17 [0.01%]
alpha_ISR-Top2L	±0.08 [1.4%]	±0.00 [0.00%]
alpha_qsf-Zjets	±0.08 [1.4%]	±0.00 [0.00%]
alpha_muR_muF-Zjets	±0.08 [1.4%]	±0.00 [0.00%]
alpha_ckkw-Zjets	±0.08 [1.4%]	±0.00 [0.00%]
alpha_muR_muF-ttV	±0.04 [0.69%]	±0.02 [0.00%]
alpha_muR_muF-Diboson	±0.03 [0.47%]	±0.06 [0.00%]
Lumi	±0.03 [0.46%]	±2.30 [0.14%]
alpha_PartonShower-Top2L	±0.03 [0.43%]	±0.00 [0.00%]
alpha_FSR-Top2L	±0.01 [0.12%]	±0.00 [0.00%]
mu_ttZ	±0.00 [0.00%]	±0.00 [0.00%]
mu_tt_2L	±0.00 [0.00%]	±0.15 [0.01%]
mu_vv	±0.00 [0.00%]	±0.00 [0.00%]
gamma_stat_tW2L_CRttbar_cuts_bin_0	±0.00 [0.00%]	±7.51 [0.46%]
gamma_stat_tW2L_CRWZ_cuts_bin_0	±0.00 [0.00%]	±0.00 [0.00%]
gamma_stat_tW2L_CRttZ_cuts_bin_0	±0.00 [0.00%]	±0.00 [0.00%]

Pre-fit

Uncertainty of channel	SR2L	tW2L_CRttbar
Total background expectation	5.86	1448.94
Total statistical ($\sqrt{N_{\text{exp}}}$)	±2.42	±38.06
Total background systematic	±1.33 [22.68%]	±38.06 [2.63%]
alpha_singletopSyst	±1.18 [20.1%]	±0.00 [0.00%]
mu_ttZ	±0.45 [7.7%]	±0.87 [0.06%]
gamma_stat_SR2L_cuts_bin_0	±0.37 [6.3%]	±0.00 [0.00%]
alpha_MatrixElement-Top2L	±0.16 [2.8%]	±0.00 [0.00%]
alpha_Sherpa-ttV	±0.11 [1.9%]	±0.16 [0.01%]
mu_vv	±0.10 [1.8%]	±0.82 [0.06%]
alpha_qsf-Zjets	±0.08 [1.5%]	±0.00 [0.00%]
alpha_ckkw-Zjets	±0.08 [1.5%]	±0.00 [0.00%]
alpha_muR_muF-Zjets	±0.08 [1.5%]	±0.00 [0.00%]
alpha_ISR-Top2L	±0.07 [1.3%]	±0.00 [0.00%]
alpha_muR_muF-ttV	±0.04 [0.69%]	±0.02 [0.00%]
alpha_muR_muF-Diboson	±0.03 [0.52%]	±0.06 [0.00%]
Lumi	±0.03 [0.47%]	±2.29 [0.16%]
mu_tt_2L	±0.03 [0.47%]	±38.72 [2.7%]
alpha_PartonShower-Top2L	±0.02 [0.38%]	±0.00 [0.00%]
alpha_FSR-Top2L	±0.01 [0.10%]	±0.00 [0.00%]
gamma_stat_tW2L_CRttbar_cuts_bin_0	±0.00 [0.00%]	±6.63 [0.46%]
gamma_stat_tW2L_CRWZ_cuts_bin_0	±0.00 [0.00%]	±0.00 [0.00%]
gamma_stat_tW2L_CRttZ_cuts_bin_0	±0.00 [0.00%]	±0.00 [0.00%]

Post-fit

Syst tables

before switching CRttbar (Top background)

Uncertainty of channel	SR2L_Top2L	tW2L_CRttbar_Top2L
Total background expectation	1.06	1488.18
Total statistical ($\sqrt{N_{\text{exp}}}$)	±1.03	±38.58
Total background systematic	±0.22 [20.64%]	±6.85 [0.46%]
alpha_MatrixElement-Top2L	±0.19 [17.8%]	±0.00 [0.00%]
alpha_ISR-Top2L	±0.08 [8.0%]	±0.00 [0.00%]
gamma_stat_SR2L_cuts_bin_0	±0.07 [6.3%]	±0.00 [0.00%]
alpha_PartonShower-Top2L	±0.03 [2.4%]	±0.00 [0.00%]
alpha_FSR-Top2L	±0.01 [0.65%]	±0.00 [0.00%]
mu_tt_2L	±0.00 [0.01%]	±0.15 [0.01%]
mu_vv	±0.00 [0.00%]	±0.00 [0.00%]
alpha_qsf-Zjets	±0.00 [0.00%]	±0.00 [0.00%]
alpha_muR_muF-ttV	±0.00 [0.00%]	±0.00 [0.00%]
mu_ttZ	±0.00 [0.00%]	±0.00 [0.00%]
gamma_stat_tW2L_CRttbar_cuts_bin_0	±0.00 [0.00%]	±6.85 [0.46%]
alpha_muR_muF-Zjets	±0.00 [0.00%]	±0.00 [0.00%]
gamma_stat_tW2L_CRWZ_cuts_bin_0	±0.00 [0.00%]	±0.00 [0.00%]
alpha_Sherpa-ttV	±0.00 [0.00%]	±0.00 [0.00%]
Lumi	±0.00 [0.00%]	±0.00 [0.00%]
gamma_stat_tW2L_CRttZ_cuts_bin_0	±0.00 [0.00%]	±0.00 [0.00%]
alpha_ckkw-Zjets	±0.00 [0.00%]	±0.00 [0.00%]
alpha_singletopSyst	±0.00 [0.00%]	±0.00 [0.00%]
alpha_muR_muF-Diboson	±0.00 [0.00%]	±0.00 [0.00%]

Pre-fit

Uncertainty of channel	SR2L_Top2L	tW2L_CRttbar_Top2L
Total background expectation	0.93	1303.52
Total statistical ($\sqrt{N_{\text{exp}}}$)	±0.96	±36.10
Total background systematic	±0.19 [20.73%]	±38.15 [2.93%]
alpha_MatrixElement-Top2L	±0.16 [17.7%]	±0.00 [0.00%]
alpha_ISR-Top2L	±0.07 [8.0%]	±0.00 [0.00%]
gamma_stat_SR2L_cuts_bin_0	±0.06 [6.3%]	±0.00 [0.00%]
mu_tt_2L	±0.03 [3.0%]	±38.72 [3.0%]
alpha_PartonShower-Top2L	±0.02 [2.4%]	±0.00 [0.00%]
alpha_FSR-Top2L	±0.01 [0.65%]	±0.00 [0.00%]
mu_vv	±0.00 [0.00%]	±0.00 [0.00%]
alpha_qsf-Zjets	±0.00 [0.00%]	±0.00 [0.00%]
alpha_muR_muF-ttV	±0.00 [0.00%]	±0.00 [0.00%]
mu_ttZ	±0.00 [0.00%]	±0.00 [0.00%]
gamma_stat_tW2L_CRttbar_cuts_bin_0	±0.00 [0.00%]	±5.96 [0.46%]
gamma_stat_tW2L_CRWZ_cuts_bin_0	±0.00 [0.00%]	±0.00 [0.00%]
alpha_Sherpa-ttV	±0.00 [0.00%]	±0.00 [0.00%]
Lumi	±0.00 [0.00%]	±0.00 [0.00%]
gamma_stat_tW2L_CRttZ_cuts_bin_0	±0.00 [0.00%]	±0.00 [0.00%]
alpha_ckkw-Zjets	±0.00 [0.00%]	±0.00 [0.00%]
alpha_singletopSyst	±0.00 [0.00%]	±0.00 [0.00%]
alpha_muR_muF-Zjets	±0.00 [0.00%]	±0.00 [0.00%]
alpha_muR_muF-Diboson	±0.00 [0.00%]	±0.00 [0.00%]

Post-fit

Syst tables

after switching CRttbar (all backgrounds)

Uncertainty of channel	SR2L
Total background expectation	6.01
Total statistical ($\sqrt{N_{exp}}$)	±2.45
Total background systematic	±1.27 [21.11%]
alpha_singletopSyst	±1.18 [19.6%]
gamma_stat_SR2L_cuts_bin_0	±0.38 [6.3%]
alpha_MatrixElement-Top2L	±0.19 [3.1%]
alpha_Sherpa-ttV	±0.12 [2.0%]
alpha_ISR-Top2L	±0.08 [1.4%]
alpha_qsf-Zjets	±0.08 [1.4%]
alpha_muR_muF-Zjets	±0.08 [1.4%]
alpha_ckkw-Zjets	±0.08 [1.4%]
alpha_muR_muF-ttV	±0.04 [0.71%]
alpha_muR_muF-Diboson	±0.03 [0.48%]
Lumi	±0.03 [0.46%]
alpha_PartonShower-Top2L	±0.03 [0.43%]
alpha_FSR-Top2L	±0.01 [0.12%]
mu_ttZ	±0.00 [0.00%]
mu_tt_2L	±0.00 [0.00%]
mu_vv	±0.00 [0.00%]
gamma_stat_tW2L_CRttbar_cuts_bin_0	±0.00 [0.00%]
gamma_stat_tW2L_CRWZ_cuts_bin_0	±0.00 [0.00%]
gamma_stat_tW2L_CRttZ_cuts_bin_0	±0.00 [0.00%]

Pre-fit

Uncertainty of channel	SR2L
Total background expectation	5.86
Total statistical ($\sqrt{N_{exp}}$)	±2.42
Total background systematic	±1.33 [22.69%]
alpha_singletopSyst	±1.18 [20.1%]
mu_ttZ	±0.45 [7.7%]
gamma_stat_SR2L_cuts_bin_0	±0.37 [6.3%]
alpha_MatrixElement-Top2L	±0.16 [2.8%]
alpha_Sherpa-ttV	±0.12 [2.0%]
mu_vv	±0.11 [1.8%]
alpha_qsf-Zjets	±0.08 [1.4%]
alpha_ckkw-Zjets	±0.08 [1.4%]
alpha_muR_muF-Zjets	±0.08 [1.4%]
alpha_ISR-Top2L	±0.07 [1.3%]
mu_tt_2L	±0.07 [1.2%]
alpha_muR_muF-ttV	±0.04 [0.70%]
alpha_muR_muF-Diboson	±0.03 [0.53%]
Lumi	±0.03 [0.47%]
alpha_PartonShower-Top2L	±0.02 [0.38%]
alpha_FSR-Top2L	±0.01 [0.10%]
gamma_stat_tW2L_CRttbar_cuts_bin_0	±0.00 [0.00%]
gamma_stat_tW2L_CRWZ_cuts_bin_0	±0.00 [0.00%]
gamma_stat_tW2L_CRttZ_cuts_bin_0	±0.00 [0.00%]

Post-fit

Syst tables

after switching CRttbar (Top background)

Uncertainty of channel	SR2L_Top2L
Total background expectation	1.06
Total statistical ($\sqrt{N_{\text{exp}}}$)	±1.03
Total background systematic	±0.22 [20.64%]
alpha_MatrixElement-Top2L	±0.19 [17.8%]
alpha_ISR-Top2L	±0.08 [8.0%]
gamma_stat_SR2L_cuts_bin_0	±0.07 [6.3%]
alpha_PartonShower-Top2L	±0.03 [2.4%]
alpha_FSR-Top2L	±0.01 [0.65%]
mu_tt_2L	±0.00 [0.01%]
mu_vv	±0.00 [0.00%]
alpha_qsf-Zjets	±0.00 [0.00%]
alpha_muR_muF-ttV	±0.00 [0.00%]
mu_ttZ	±0.00 [0.00%]
gamma_stat_tW2L_CRttbar_cuts_bin_0	±0.00 [0.00%]
alpha_muR_muF-Zjets	±0.00 [0.00%]
gamma_stat_tW2L_CRWZ_cuts_bin_0	±0.00 [0.00%]
alpha_Sherpa-ttV	±0.00 [0.00%]
Lumi	±0.00 [0.00%]
gamma_stat_tW2L_CRttZ_cuts_bin_0	±0.00 [0.00%]
alpha_ckkw-Zjets	±0.00 [0.00%]
alpha_singletopSyst	±0.00 [0.00%]
alpha_muR_muF-Diboson	±0.00 [0.00%]

Pre-fit

Uncertainty of channel	SR2L_Top2L
Total background expectation	0.93
Total statistical ($\sqrt{N_{\text{exp}}}$)	±0.97
Total background systematic	±0.20 [21.86%]
alpha_MatrixElement-Top2L	±0.16 [17.7%]
alpha_ISR-Top2L	±0.07 [8.0%]
mu_tt_2L	±0.07 [7.5%]
gamma_stat_SR2L_cuts_bin_0	±0.06 [6.3%]
alpha_PartonShower-Top2L	±0.02 [2.4%]
alpha_FSR-Top2L	±0.01 [0.65%]
mu_vv	±0.00 [0.00%]
alpha_qsf-Zjets	±0.00 [0.00%]
alpha_muR_muF-ttV	±0.00 [0.00%]
mu_ttZ	±0.00 [0.00%]
gamma_stat_tW2L_CRttbar_cuts_bin_0	±0.00 [0.00%]
gamma_stat_tW2L_CRWZ_cuts_bin_0	±0.00 [0.00%]
alpha_Sherpa-ttV	±0.00 [0.00%]
Lumi	±0.00 [0.00%]
gamma_stat_tW2L_CRttZ_cuts_bin_0	±0.00 [0.00%]
alpha_ckkw-Zjets	±0.00 [0.00%]
alpha_singletopSyst	±0.00 [0.00%]
alpha_muR_muF-Zjets	±0.00 [0.00%]
alpha_muR_muF-Diboson	±0.00 [0.00%]

Post-fit

In tW INT notes

tW INT note (respective syst are all 0 in CRttbar)

Uncertainty of channel	SR2L
Total background expectation	6.72
Total statistical ($\sqrt{N_{exp}}$)	±2.59
Total background systematic	±1.12 [16.61%]
alpha_JES_Group2	±0.37 [5.5%]
alpha_JES_Group1	±0.38 [5.7%]
alpha_JET_Flavor_Response	±0.27 [4.0%]
alpha_ISR-Top2L	±0.09 [1.4%]
alpha_MatrixElement-Top2L	±0.21 [3.1%]
gamma_stat_tW2L_VRtt_cuts_bin_0	±0.00 [0.00%]
alpha_pileup	±0.03 [0.39%]
alpha_JES_Group3	±0.02 [0.36%]
alpha_MET_SoftTrk_ResoPara	±0.01 [0.13%]
alpha_JER_EffectiveNP_1	±0.38 [5.7%]
alpha_JVT	±0.01 [0.19%]
alpha_EG_RESOLUTION_ALL	±0.03 [0.50%]
alpha_FSR-Top2L	±0.01 [0.11%]
alpha_MUON_MS	±0.00 [0.03%]
Lumi	±0.02 [0.29%]
alpha_EG_SCALE_ALL	±0.00 [0.03%]
alpha_PartonShower-Top2L	±0.03 [0.42%]
alpha_EG_Eff	±0.03 [0.39%]
alpha_MUON_Trig_sys	±0.09 [1.4%]
alpha_JER_EffectiveNP_2	±0.37 [5.5%]

Pre-fit

Uncertainty of channel	SR2L
Total background expectation	5.85
Total statistical ($\sqrt{N_{exp}}$)	±2.42
Total background systematic	±1.21 [20.69%]
alpha_JES_Group2	±0.34 [5.8%]
alpha_JES_Group1	±0.35 [6.0%]
mu_tt_2L	±0.04 [0.64%]
alpha_JET_Flavor_Response	±0.25 [4.3%]
alpha_ISR-Top2L	±0.09 [1.6%]
alpha_MatrixElement-Top2L	±0.21 [3.5%]
gamma_stat_tW2L_VRtt_cuts_bin_0	±0.00 [0.00%]
alpha_pileup	±0.03 [0.57%]
alpha_JES_Group3	±0.02 [0.32%]
alpha_MET_SoftTrk_ResoPara	±0.00 [0.03%]
alpha_JER_EffectiveNP_1	±0.38 [6.4%]
alpha_JVT	±0.01 [0.20%]
alpha_EG_RESOLUTION_ALL	±0.03 [0.51%]
alpha_MUON_MS	±0.01 [0.09%]
alpha_FSR-Top2L	±0.01 [0.13%]
Lumi	±0.02 [0.34%]
mu_dib	±0.18 [3.0%]
alpha_EG_SCALE_ALL	±0.00 [0.03%]
alpha_PartonShower-Top2L	±0.03 [0.48%]
alpha_EG_Eff	±0.02 [0.32%]

Post-fit

Summary tables

all bkg	SR with tW CRttbar		SR with tt CRttbar		SR INT note	
	prefit	postfit	prefit	postfit	prefit	postfit
total bkg expect	6.01	5.86	6.01	5.86	6.72	5.85
total stat	±2.45	±2.42	±2.45	±2.42	±2.59	±2.42
total bkg syst	±1.27 [21.10%]	±1.33 [22.68%]	±1.27 [21.11%]	±1.33 [22.69%]	±1.12 [16.61%]	±1.21 [20.69%]
Matrix Element	±0.19 [3.1%]	±0.16 [2.8%]	±0.19 [3.1%]	±0.16 [2.8%]	±0.21 [3.1%]	±0.21 [3.5%]
Parton Shower	±0.03 [0.43%]	±0.02 [0.38%]	±0.03 [0.43%]	±0.02 [0.38%]	±0.03 [0.42%]	±0.03 [0.48%]
ISR	±0.08 [1.4%]	±0.07 [1.3%]	±0.08 [1.4%]	±0.07 [1.3%]	±0.09 [1.4%]	±0.09 [1.6%]
FSR	±0.01 [0.12%]	±0.01 [0.10%]	±0.01 [0.12%]	±0.01 [0.10%]	±0.01 [0.11%]	±0.01 [0.13%]

Top sample	SR with tW CRttbar		SR with tt CRttbar	
	prefit	postfit	prefit	postfit
total bkg expect	1.06	0.96	1.06	0.93
total stat	±1.03	±0.96	±1.03	±0.97
total bkg syst	±0.22 [20.64%]	±0.19 [20.73%]	±0.22 [20.64%]	±0.20 [21.86%]
Matrix Element	±0.19 [17.8%]	±0.16 [17.7%]	±0.19 [17.8%]	±0.16 [17.7%]
Parton Shower	±0.03 [2.4%]	±0.02 [2.4%]	±0.03 [2.4%]	±0.02 [2.4%]
ISR	±0.08 [8.0%]	±0.07 [8.0%]	±0.08 [8.0%]	±0.07 [8.0%]
FSR	±0.01 [0.65%]	±0.01 [0.65%]	±0.01 [0.65%]	±0.01 [0.65%]

Overall the impact of top theo syst remains mildly unchanged

Top theoretical systematics

name	region	total up	total down
MatrixElement-Top2L	SR2L	25.97%	-25.97%
	tW2L_CRttbar	17.89%	-17.89%
PartonShower-Top2L	SR2L	6.60%	2.28%
	tW2L_CRttbar	18.93%	-21.77%
FSR-Top2L	SR2L	8.32%	-8.32%
	tW2L_CRttbar	15.54%	-15.54%
ISR-Top2L	SR2L	0.63%	-2.24%
	tW2L_CRttbar	12.67%	-12.63%

Yields breakdown.

BkgOnly fit

CRs

table.results.yields channel	CRTOP	CRttZ
Observed events	234	254
Fitted bkg events	234.00 ± 15.29	254.00 ± 15.92
Fitted ttbar events	200.20 ± 16.39	0.00 ± 0.00
Fitted Wt events	31.11 ± 5.48	0.00 ± 0.00
Fitted Zjets events	0.00 ± 0.00	0.00 ± 0.00
Fitted VV events	1.14 ± 0.63	18.33 ± 4.64
Fitted ttZ events	0.49 ± 0.39	173.10 ± 23.74
Fitted other events	1.06 ± 0.35	44.35 ± 13.54
Fitted DDFakes events	$0.01^{+0.12}_{-0.01}$	18.22 ± 9.50
MC exp. SM events	259.35 ± 8.77	245.61 ± 17.72
MC exp. ttbar events	225.57 ± 6.24	0.00 ± 0.00
MC exp. Wt events	31.11 ± 5.52	0.00 ± 0.00
MC exp. Zjets events	0.00 ± 0.00	0.00 ± 0.00
MC exp. VV events	1.14 ± 0.64	18.33 ± 4.67
MC exp. ttZ events	0.47 ± 0.36	164.71 ± 0.98
MC exp. other events	1.06 ± 0.35	44.34 ± 13.64
MC exp. DDFakes events	$0.01^{+0.12}_{-0.01}$	18.22 ± 9.57

μ_{tt}	0.89
μ_{ttZ}	1.06

BkgOnly fit

tW-SR

table.results.yields channel	SR2L
Observed events	11
Fitted bkg events	6.12 ± 1.12
Fitted ttbar events	0.86 ± 0.64
Fitted Wt events	$0.25^{+0.54}_{-0.25}$
Fitted Zjets events	0.01 ± 0.00
Fitted VV events	0.61 ± 0.16
Fitted ttZ events	2.84 ± 0.72
Fitted other events	1.37 ± 0.43
Fitted DDFakes events	0.18 ± 0.01
MC exp. SM events	6.09 ± 1.17
MC exp. ttbar events	0.97 ± 0.72
MC exp. Wt events	$0.25^{+0.54}_{-0.25}$
MC exp. Zjets events	0.01 ± 0.00
MC exp. VV events	0.61 ± 0.16
MC exp. ttZ events	2.70 ± 0.55
MC exp. other events	1.37 ± 0.43
MC exp. DDFakes events	0.18 ± 0.01

BkgOnly fit

SRDF

before ortho

table.results.yields channel	SRDF0	SRDF1	SRDF2	SRDF3	SRDF4	SRDF5
Observed events	19	12	5	2	1	3
Fitted bkg events	21.98 ± 3.70	16.48 ± 3.02	5.11 ± 0.73	2.88 ± 0.58	3.26 ± 0.43	3.10 ± 0.49
Fitted ttbar events	17.61 ± 3.69	10.20 ± 2.96	0.69 ± 0.46	$0.02^{+0.08}_{-0.02}$	0.15 ± 0.12	0.05 ± 0.04
Fitted Wt events	0.59 ± 0.54	$0.06^{+0.18}_{-0.06}$	$0.02^{+0.03}_{-0.02}$	$0.01^{+0.02}_{-0.01}$	0.03 ± 0.01	$0.02^{+0.02}_{-0.02}$
Fitted Zjets events	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Fitted VV events	0.54 ± 0.26	0.57 ± 0.22	0.50 ± 0.16	0.06 ± 0.06	0.23 ± 0.11	0.14 ± 0.08
Fitted ttZ events	2.30 ± 0.56	3.58 ± 0.79	2.76 ± 0.59	2.00 ± 0.57	1.83 ± 0.36	1.72 ± 0.38
Fitted other events	0.94 ± 0.29	1.44 ± 0.44	1.14 ± 0.36	0.78 ± 0.26	0.66 ± 0.22	0.63 ± 0.20
Fitted DDFakes events	0.00 ± 0.00	0.63 ± 0.59	0.00 ± 0.00	0.00 ± 0.00	0.36 ± 0.23	0.54 ± 0.41
MC exp. SM events	24.10 ± 3.93	17.60 ± 3.36	5.07 ± 0.78	2.78 ± 0.55	3.19 ± 0.47	3.02 ± 0.55
MC exp. ttbar events	19.85 ± 3.87	11.49 ± 3.22	0.78 ± 0.53	$0.03^{+0.09}_{-0.03}$	0.16 ± 0.13	0.05 ± 0.05
MC exp. Wt events	0.59 ± 0.54	$0.06^{+0.18}_{-0.06}$	$0.02^{+0.03}_{-0.02}$	$0.01^{+0.02}_{-0.01}$	0.03 ± 0.01	$0.02^{+0.02}_{-0.02}$
MC exp. Zjets events	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
MC exp. VV events	0.54 ± 0.26	0.57 ± 0.22	0.50 ± 0.16	0.06 ± 0.06	0.23 ± 0.11	0.14 ± 0.08
MC exp. ttZ events	2.18 ± 0.43	3.41 ± 0.56	2.62 ± 0.40	1.90 ± 0.46	1.74 ± 0.24	1.64 ± 0.27
MC exp. other events	0.94 ± 0.29	1.44 ± 0.45	1.14 ± 0.36	0.78 ± 0.26	0.66 ± 0.22	0.63 ± 0.20
MC exp. DDFakes events	0.00 ± 0.00	0.63 ± 0.60	0.00 ± 0.00	0.00 ± 0.00	0.36 ± 0.23	0.54 ± 0.41

after ortho

table.results.yields channel	SRDF0	SRDF1	SRDF2	SRDF3	SRDF4	SRDF5
Observed events	9	3	4	0	0	2
Fitted bkg events	11.89 ± 2.27	9.94 ± 1.90	3.24 ± 0.57	2.10 ± 0.51	1.59 ± 0.42	1.94 ± 0.52
Fitted ttbar events	9.25 ± 2.20	5.29 ± 1.81	0.44 ± 0.33	$0.01^{+0.03}_{-0.01}$	0.04 ± 0.03	0.00 ± 0.00
Fitted Wt events	$0.10^{+0.36}_{-0.10}$	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Fitted Zjets events	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Fitted VV events	$0.15^{+0.15}_{-0.15}$	0.15 ± 0.07	$0.02^{+0.03}_{-0.02}$	0.03 ± 0.01	0.04 ± 0.03	$0.01^{+0.02}_{-0.01}$
Fitted ttZ events	1.84 ± 0.48	2.71 ± 0.62	2.16 ± 0.56	1.59 ± 0.48	1.20 ± 0.40	1.14 ± 0.38
Fitted other events	0.52 ± 0.17	0.86 ± 0.28	0.62 ± 0.21	0.47 ± 0.17	0.32 ± 0.12	0.19 ± 0.07
Fitted DDFakes events	$0.02^{+0.06}_{-0.02}$	0.92 ± 0.72	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.60 ± 0.43
MC exp. SM events	12.97 ± 2.42	10.48 ± 2.13	3.19 ± 0.55	2.02 ± 0.47	1.54 ± 0.39	1.88 ± 0.55
MC exp. ttbar events	10.42 ± 2.31	5.96 ± 1.97	0.50 ± 0.38	$0.01^{+0.04}_{-0.01}$	0.04 ± 0.03	0.00 ± 0.00
MC exp. Wt events	$0.10^{+0.37}_{-0.10}$	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
MC exp. Zjets events	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
MC exp. VV events	$0.15^{+0.15}_{-0.15}$	0.15 ± 0.07	$0.02^{+0.03}_{-0.02}$	0.03 ± 0.01	0.04 ± 0.03	$0.01^{+0.02}_{-0.01}$
MC exp. ttZ events	1.75 ± 0.37	2.58 ± 0.45	2.05 ± 0.44	1.51 ± 0.41	1.14 ± 0.35	1.09 ± 0.32
MC exp. other events	0.52 ± 0.17	0.86 ± 0.28	0.62 ± 0.21	0.47 ± 0.18	0.32 ± 0.12	0.19 ± 0.07
MC exp. DDFakes events	$0.02^{+0.06}_{-0.02}$	0.92 ± 0.73	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.60 ± 0.43

BkgOnly fit

SRSF

before ortho

table.results.yields channel	SRSF0	SRSF1	SRSF2	SRSF3	SRSF4	SRSF5
Observed events	17	19	9	3	5	5
Fitted bkg events	18.60 ± 3.23	15.09 ± 2.40	5.47 ± 0.90	3.72 ± 0.68	4.42 ± 0.77	5.07 ± 0.85
Fitted ttbar events	15.75 ± 3.17	7.98 ± 2.21	0.69 ± 0.42	$0.01^{+0.02}_{-0.01}$	0.08 ± 0.07	0.15 ± 0.15
Fitted Wt events	$0.22^{+0.25}_{-0.22}$	0.81 ± 0.39	0.09 ± 0.04	$0.03^{+0.03}_{-0.03}$	0.10 ± 0.04	0.68 ± 0.28
Fitted Zjets events	$0.02^{+0.05}_{-0.02}$	0.11 ± 0.05	$0.08^{+0.22}_{-0.08}$	0.28 ± 0.16	0.66 ± 0.41	0.44 ± 0.32
Fitted VV events	0.30 ± 0.17	1.27 ± 0.58	0.83 ± 0.31	0.66 ± 0.38	0.58 ± 0.30	1.08 ± 0.48
Fitted ttZ events	1.63 ± 0.37	3.61 ± 0.67	2.24 ± 0.59	2.15 ± 0.46	2.18 ± 0.52	1.87 ± 0.43
Fitted other events	0.68 ± 0.21	1.31 ± 0.41	0.95 ± 0.31	0.60 ± 0.19	0.65 ± 0.21	0.62 ± 0.20
Fitted DDFakes events	0.00 ± 0.00	0.00 ± 0.00	0.59 ± 0.07	0.00 ± 0.00	0.17 ± 0.14	0.25 ± 0.19
MC exp. SM events	20.52 ± 3.43	15.93 ± 2.61	5.45 ± 0.93	3.62 ± 0.66	4.32 ± 0.77	5.00 ± 0.89
MC exp. ttbar events	17.75 ± 3.35	8.99 ± 2.38	0.78 ± 0.49	$0.01^{+0.02}_{-0.01}$	0.10 ± 0.08	$0.17^{+0.17}_{-0.17}$
MC exp. Wt events	$0.22^{+0.25}_{-0.22}$	0.81 ± 0.40	0.09 ± 0.04	$0.03^{+0.03}_{-0.03}$	0.10 ± 0.04	0.68 ± 0.28
MC exp. Zjets events	$0.02^{+0.05}_{-0.02}$	0.11 ± 0.05	$0.08^{+0.22}_{-0.08}$	0.28 ± 0.16	0.66 ± 0.41	0.44 ± 0.33
MC exp. VV events	0.30 ± 0.17	1.27 ± 0.58	0.83 ± 0.31	0.66 ± 0.39	0.58 ± 0.30	1.08 ± 0.48
MC exp. ttZ events	1.55 ± 0.28	3.44 ± 0.40	2.13 ± 0.46	2.05 ± 0.32	2.07 ± 0.39	1.78 ± 0.32
MC exp. other events	0.68 ± 0.21	1.31 ± 0.41	0.95 ± 0.31	0.60 ± 0.19	0.65 ± 0.21	0.62 ± 0.20
MC exp. DDFakes events	0.00 ± 0.00	0.00 ± 0.00	0.59 ± 0.07	0.00 ± 0.00	0.17 ± 0.14	0.25 ± 0.19

after ortho

table.results.yields channel	SRSF0	SRSF1	SRSF2	SRSF3	SRSF4	SRSF5
Observed events	8	10	3	2	1	0
Fitted bkg events	10.42 ± 2.04	7.99 ± 1.33	2.84 ± 0.60	1.99 ± 0.44	2.21 ± 0.46	1.33 ± 0.37
Fitted ttbar events	8.53 ± 1.97	4.01 ± 1.29	0.40 ± 0.29	0.00 ± 0.00	0.04 ± 0.03	0.00 ± 0.00
Fitted Wt events	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Fitted Zjets events	0.00 ± 0.00	0.04 ± 0.00	0.00 ± 0.00	0.15 ± 0.11	0.28 ± 0.09	0.05 ± 0.02
Fitted VV events	0.24 ± 0.15	0.44 ± 0.18	0.19 ± 0.10	0.15 ± 0.13	$0.11^{+0.14}_{-0.11}$	0.13 ± 0.06
Fitted ttZ events	1.22 ± 0.35	2.76 ± 0.56	1.72 ± 0.53	1.49 ± 0.41	1.44 ± 0.38	0.97 ± 0.36
Fitted other events	0.43 ± 0.14	0.74 ± 0.23	0.53 ± 0.17	0.21 ± 0.08	0.34 ± 0.12	0.18 ± 0.06
Fitted DDFakes events	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
MC exp. SM events	11.44 ± 2.15	8.36 ± 1.45	2.81 ± 0.59	1.92 ± 0.40	2.15 ± 0.44	1.29 ± 0.35
MC exp. ttbar events	9.61 ± 2.06	4.52 ± 1.41	0.45 ± 0.33	0.00 ± 0.00	0.05 ± 0.04	0.00 ± 0.00
MC exp. Wt events	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
MC exp. Zjets events	0.00 ± 0.00	0.04 ± 0.00	0.00 ± 0.00	0.15 ± 0.11	0.28 ± 0.09	0.05 ± 0.02
MC exp. VV events	0.24 ± 0.15	0.44 ± 0.18	0.19 ± 0.10	0.15 ± 0.13	$0.11^{+0.14}_{-0.11}$	0.13 ± 0.06
MC exp. ttZ events	1.16 ± 0.29	2.63 ± 0.37	1.64 ± 0.44	1.41 ± 0.34	1.37 ± 0.30	0.92 ± 0.32
MC exp. other events	0.43 ± 0.14	0.74 ± 0.23	0.53 ± 0.17	0.21 ± 0.08	0.34 ± 0.12	0.18 ± 0.06
MC exp. DDFakes events	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00

Systematics breakdown.

Systematics breakdown (BkgOnly fit)

CRs

Signal region	CR($t\bar{t}$)	CR($t\bar{t}Z$)	CR($t\bar{t}$)	CR($t\bar{t}Z$)
Total background uncertainties	3.3%	7.2%	6.9%	7.2%
$t\bar{t}$ theoretical uncertainties	2.1%	–	2.0%	–
$t\bar{t}Z$ theoretical uncertainties	–	–	–	–
VV theoretical uncertainties	–	1.6%	–	1.5%
$t\bar{t}$-Wt interference	–	–	–	–
Other theoretical uncertainties	–	5.4%	–	5.2%
MC statistical uncertainties	1.4%	0.51%	1.4%	0.51%
$t\bar{t}$ normalization	–	–	7.9%	–
$t\bar{t}Z$ normalization	–	–	–	11%
Jet energy scale	1.5%	1.2%	1.9%	2.0%
Jet energy resolution	1.1%	–	1.2%	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ mismodelling	0.88%	–	0.97%	–
Lepton modelling	0.62%	0.94%	0.68%	0.9%
Flavour tagging	–	1.4%	–	1.3%
Pile-up reweighting and JVT	–	–	–	–
Fake and non-prompt leptons	–	3.9%	–	3.7%

Pre-fit **Post-fit**

Systematics breakdown (BkgOnly fit)

tW-SR

Signal region	$SR^{tW}_{low\ m_{T2}}$	SR^{tW}	$SR^{tW}_{low\ m_{T2}}$	SR^{tW}
Total background uncertainties	28%	19%	29%	18%
$t\bar{t}$ theoretical uncertainties	–	6.0%	–	5.2%
$t\bar{t}Z$ theoretical uncertainties	2.4%	6.2%	2.7%	6.5%
VV theoretical uncertainties	–	–	–	–
$t\bar{t}$-Wt interference	–	–	–	–
Other theoretical uncertainties	1.6%	6.7%	1.7%	6.7%
MC statistical uncertainties	6.4%	6.2%	6.4%	6.2%
$t\bar{t}$ normalization	–	–	7.0%	1.3%
$t\bar{t}Z$ normalization	–	–	1.9%	7.3%
Jet energy scale	18%	3.7%	18%	4.6%
Jet energy resolution	20%	13%	19%	12%
E_T^{miss} mismodelling	4.8%	3.3%	4.4%	3.1%
Lepton modelling	2.2%	2.3%	2.1%	2.2%
Flavour tagging	1.4%	0.84%	1.4%	0.82%
Pile-up reweighting and JVT	0.63%	–	0.61%	–
Fake and non-prompt leptons	–	–	–	–

Pre-fit **Post-fit**

Systematic breakdown (BkgOnly fit)

SFSF

Pre-fit

Signal region	SR-SF$^{t\bar{t}}_{[110,120)}$	SR-SF$^{t\bar{t}}_{[120,140)}$	SR-SF$^{t\bar{t}}_{[140,160)}$	SR-SF$^{t\bar{t}}_{[160,180)}$	SR-SF$^{t\bar{t}}_{[180,220)}$	SR-SF$^{t\bar{t}}_{[220,\infty)}$
Total background uncertainties	18%	17%	21%	21%	20%	27%
$t\bar{t}$ theoretical uncertainties	9.9%	10%	7.9%	–	1.4%	–
$t\bar{t}Z$ theoretical uncertainties	1.6%	2.2%	12%	14%	8.0%	23%
VV theoretical uncertainties	0.62%	1.8%	1.9%	2.4%	1.7%	4.1%
$t\bar{t}$-Wt interference	–	–	–	–	–	–
Other theoretical uncertainties	1.1%	2.6%	5.7%	3.3%	4.7%	4.1%
MC statistical uncertainties	5.5%	5.7%	8.7%	11%	16%	12%
$t\bar{t}$ normalization	–	–	–	–	–	–
$t\bar{t}Z$ normalization	–	–	–	–	–	–
Jet energy scale	11%	8.8%	3.4%	3.5%	1.9%	4.3%
Jet energy resolution	7.3%	5.1%	7.1%	7.6%	6.8%	5.7%
$E_{\mathrm{T}}^{\mathrm{miss}}$ mismodelling	1.7%	1.6%	5.6%	3.9%	1.7%	1.9%
Lepton modelling	1.6%	1.4%	2.6%	4.9%	1.6%	2.2%
Flavour tagging	0.95%	0.82%	0.94%	1.5%	2.9%	1.2%
Pile-up reweighting and JVT	–	–	–	–	–	–
Fake and non-prompt leptons	–	–	–	–	–	–

Post-fit

Signal region	SR-SF$^{t\bar{t}}_{[110,120)}$	SR-SF$^{t\bar{t}}_{[120,140)}$	SR-SF$^{t\bar{t}}_{[140,160)}$	SR-SF$^{t\bar{t}}_{[160,180)}$	SR-SF$^{t\bar{t}}_{[180,220)}$	SR-SF$^{t\bar{t}}_{[220,\infty)}$
Total background uncertainties	19%	16%	21%	23%	21%	28%
$t\bar{t}$ theoretical uncertainties	9.9%	10%	7.9%	–	1.4%	–
$t\bar{t}Z$ theoretical uncertainties	1.9%	2.4%	13%	14%	8.2%	22.7%
VV theoretical uncertainties	–	1.9%	1.8%	2.3%	1.6%	3.9%
$t\bar{t}$-Wt interference	–	–	–	–	–	–
Other theoretical uncertainties	1.2%	2.8%	5.6%	3.1%	4.6%	3.9%
MC statistical uncertainties	5.5%	5.7%	8.7%	11%	16%	11.7%
$t\bar{t}$ normalization	7.6%	4.7%	1.3%	–	–	–
$t\bar{t}Z$ normalization	1.8%	5.4%	9.5%	12%	10%	11%
Jet energy scale	11%	8.1%	3.9%	3.7%	2.9%	4.7%
Jet energy resolution	7.2%	4.7%	6.9%	7.5%	6.6%	5.6%
$E_{\mathrm{T}}^{\mathrm{miss}}$ mismodelling	1.6%	1.3%	5.0%	3.7%	1.8%	1.9%
Lepton modelling	1.6%	1.4%	2.5%	4.7%	1.7%	2.2%
Flavour tagging	0.93%	0.75%	0.93%	1.5%	2.8%	1.2%
Pile-up reweighting and JVT	–	–	–	–	–	–
Fake and non-prompt leptons	–	–	–	–	–	–

Systematic breakdown (BkgOnly fit)

SFDF

Pre-fit

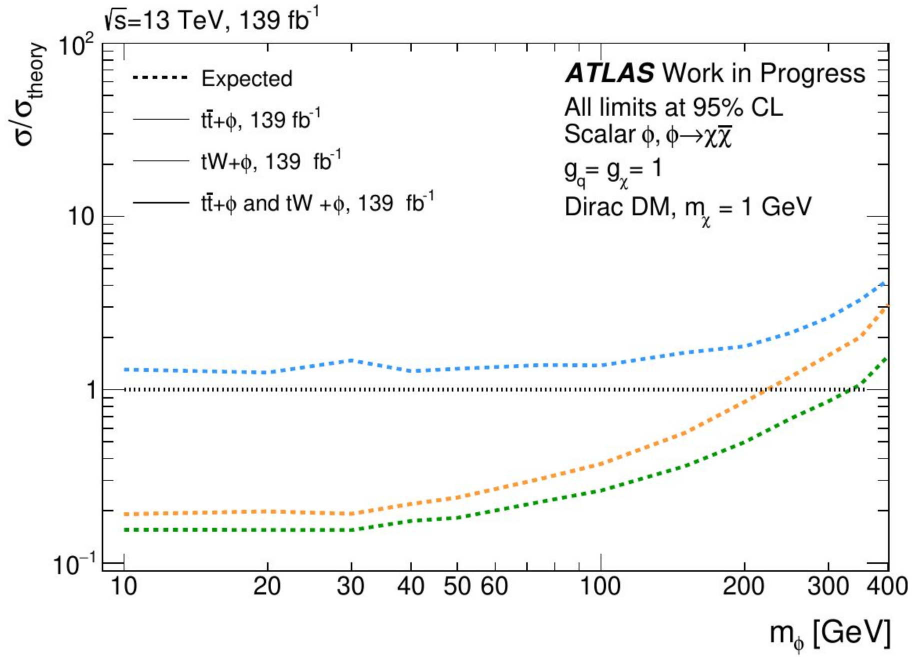
Signal region	$\text{SR-DF}^{t\bar{t}}_{[110,120)}$	$\text{SR-DF}^{t\bar{t}}_{[120,140)}$	$\text{SR-DF}^{t\bar{t}}_{[140,160)}$	$\text{SR-DF}^{t\bar{t}}_{[160,180)}$	$\text{SR-DF}^{t\bar{t}}_{[180,220)}$	$\text{SR-DF}^{t\bar{t}}_{[220,\infty)}$
Total background uncertainties	18%	20%	17%	23%	25%	29%
$t\bar{t}$ theoretical uncertainties	9.8%	11.5%	8.7%	0.36%	2.1%	–
$t\bar{t}Z$ theoretical uncertainties	2.1%	3.4%	3.5%	15.6%	18.6%	14.3%
VV theoretical uncertainties	–	0.51%	–	–	0.81%	–
$t\bar{t}$-Wt interference	–	–	–	–	–	–
Other theoretical uncertainties	1.2%	2.5%	5.9%	7.0%	6.2%	3.0%
MC statistical uncertainties	5.2%	5.2%	8.0%	9.2%	12.6%	8.4%
$t\bar{t}$ normalization	–	–	–	–	–	–
$t\bar{t}Z$ normalization	–	–	–	–	–	–
Jet energy scale	10%	11%	2.4%	4.0%	3.2%	3.1%
Jet energy resolution	7.4%	3.6%	9.3%	12%	7.2%	3.1%
$E_{\mathrm{T}}^{\mathrm{miss}}$ mismodelling	4.7%	4.0%	3.8%	1.2%	3.4%	2.3%
Lepton modelling	1.5%	1.6%	1.6%	1.8%	3.3%	1.9%
Flavour tagging	0.62%	–	1.1%	1.4%	1.2%	0.97%
Pile-up reweighting and JVT	–	–	–	–	–	–
Fake and non-prompt leptons	0.50%	6.9%	–	–	–	23.1%

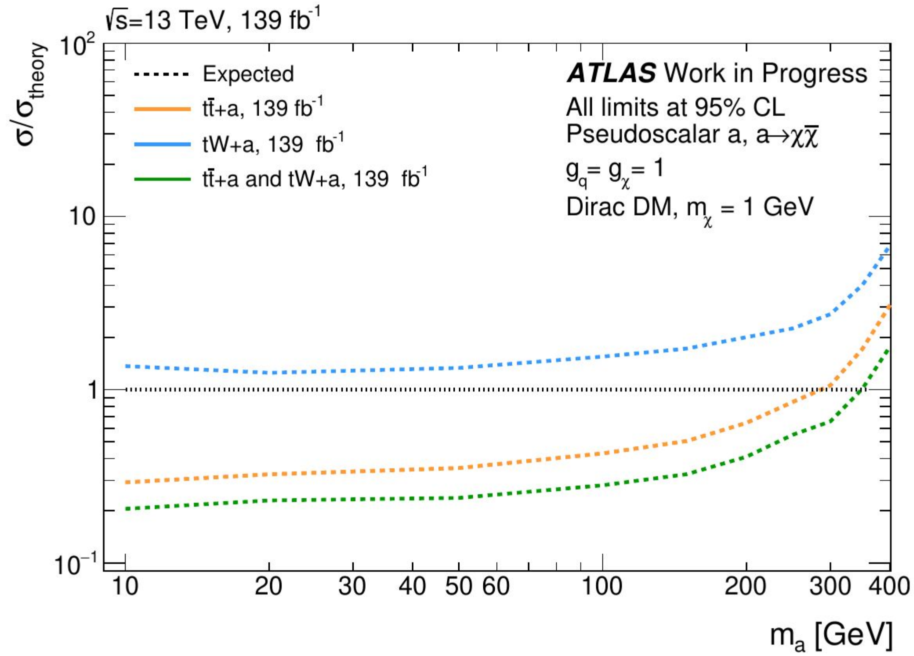
Post-fit

Signal region	$\text{SR-DF}^{t\bar{t}}_{[110,120)}$	$\text{SR-DF}^{t\bar{t}}_{[120,140)}$	$\text{SR-DF}^{t\bar{t}}_{[140,160)}$	$\text{SR-DF}^{t\bar{t}}_{[160,180)}$	$\text{SR-DF}^{t\bar{t}}_{[180,220)}$	$\text{SR-DF}^{t\bar{t}}_{[220,\infty)}$
Total background uncertainties	18%	19%	18%	25%	26%	27%
$t\bar{t}$ theoretical uncertainties	9.4%	11%	7.6%	0.3%	1.7%	–
$t\bar{t}Z$ theoretical uncertainties	2.4%	3.7%	3.7%	16%	19%	15%
VV theoretical uncertainties	0.38%	0.53%	0.21%	0.39%	0.78%	0.17%
$t\bar{t}$-Wt interference	–	–	–	–	–	–
Other theoretical uncertainties	1.3%	2.6%	5.7%	6.7%	5.9%	2.9%
MC statistical uncertainties	5.2%	5.1%	8.0%	9.2%	13%	8.6%
$t\bar{t}$ normalization	7.2%	4.9%	1.3%	–	–	–
$t\bar{t}Z$ normalization	2.4%	4.3%	10%	12%	12%	9.2%
Jet energy scale	9.5%	11%	2.8%	4.3%	3.6%	3.2%
Jet energy resolution	7.4%	3.2%	9.6%	12%	7.2%	3.1%
$E_{\mathrm{T}}^{\mathrm{miss}}$ mismodelling	4.6%	3.8%	3.8%	1.2%	3.4%	2.3%
Lepton modelling	1.5%	1.6%	1.7%	1.8%	3.3%	1.9%
Flavour tagging	0.60%	0.39%	1.1%	1.5%	1.2%	1.0%
Pile-up reweighting and JVT	–	–	–	–	–	–
Fake and non-prompt leptons	0.54%	7.3%	–	–	–	22%

Additional exclusion plots.

Exclusion plots in combined and separated analyses



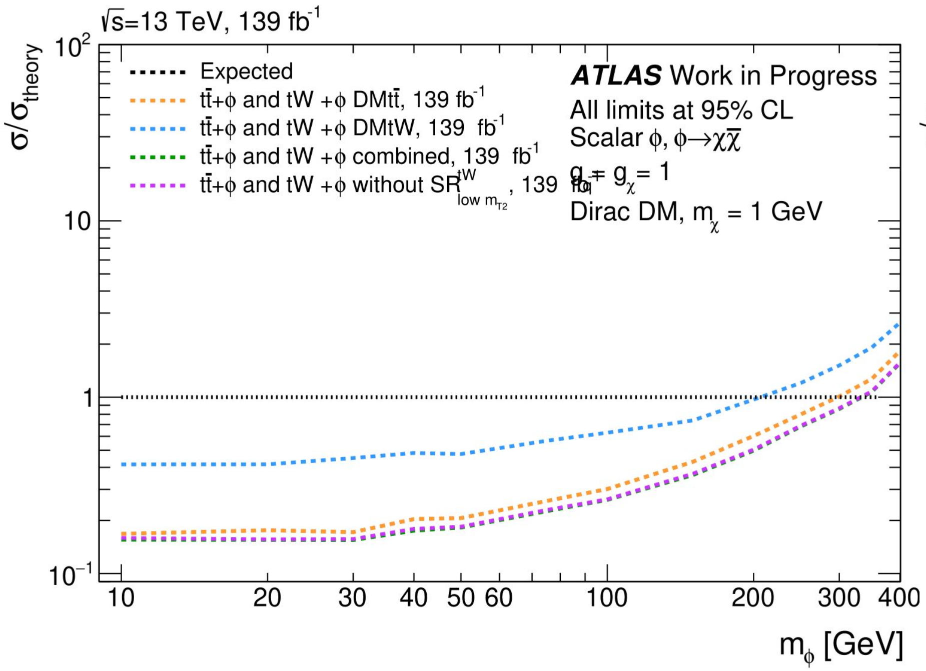


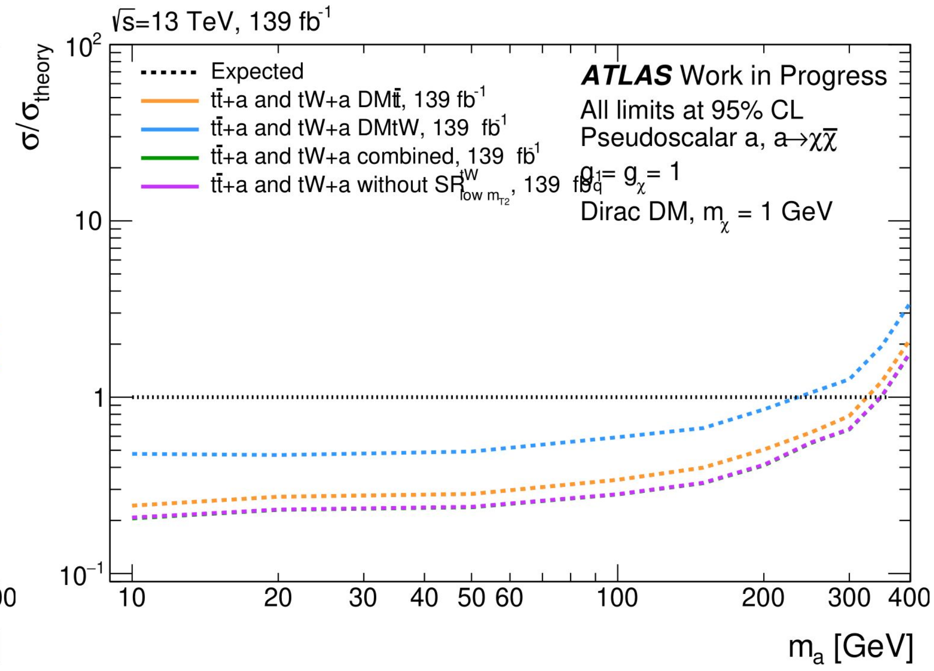
tW+DM signal in DM*tW* analysis

$t\bar{t}$+DM signal in DM$t\bar{t}$ analysis

combined signal and analyses

Exclusion plots in combined and separated analyses





$t\bar{t}$+DM and tW+DM signals in DMtW analysis

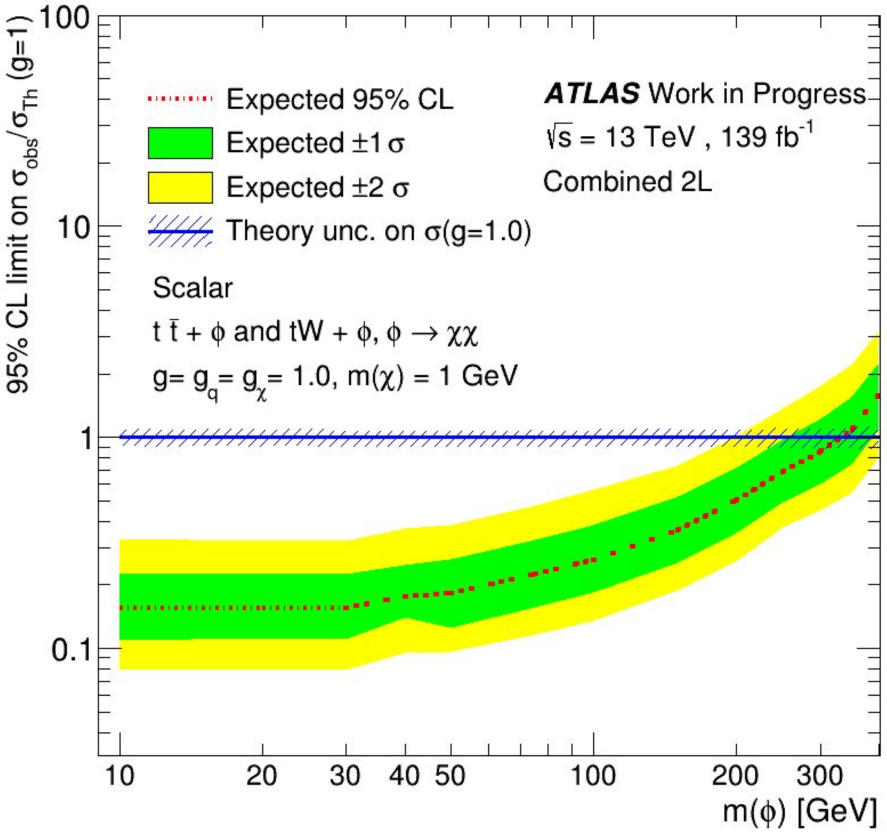
$t\bar{t}$+DM and tW+DM signals in DM$t\bar{t}$ analysis

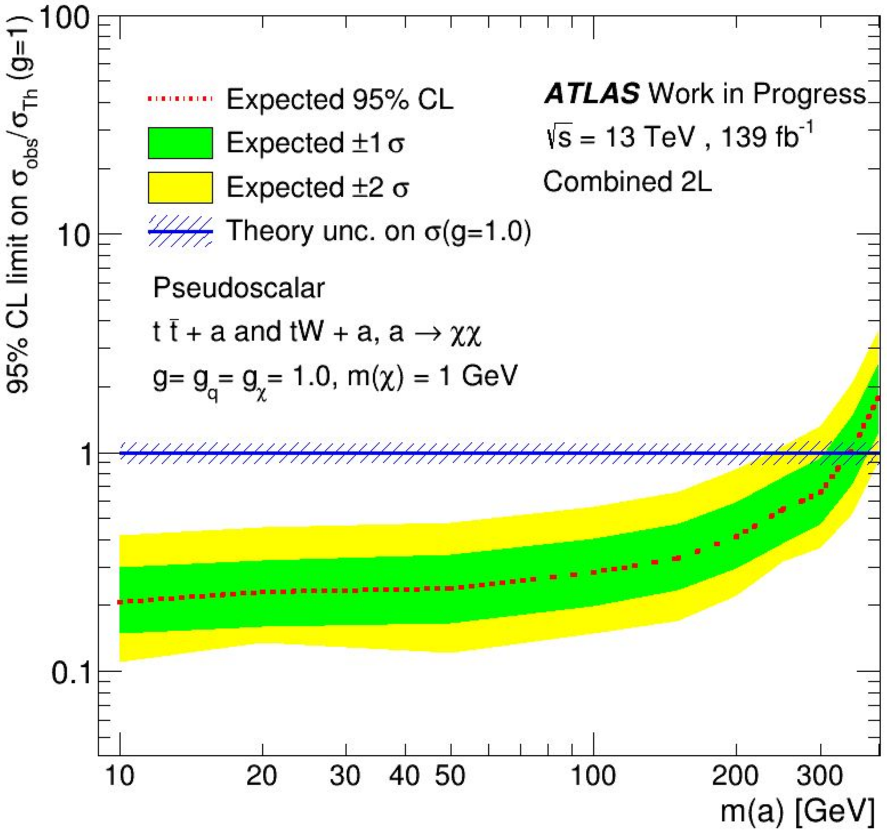
$t\bar{t}$+DM and tW+DM signals in combined analyses

$t\bar{t}$+DM and tW+DM signals in combined analyses without extra tW-SR

Scalar.

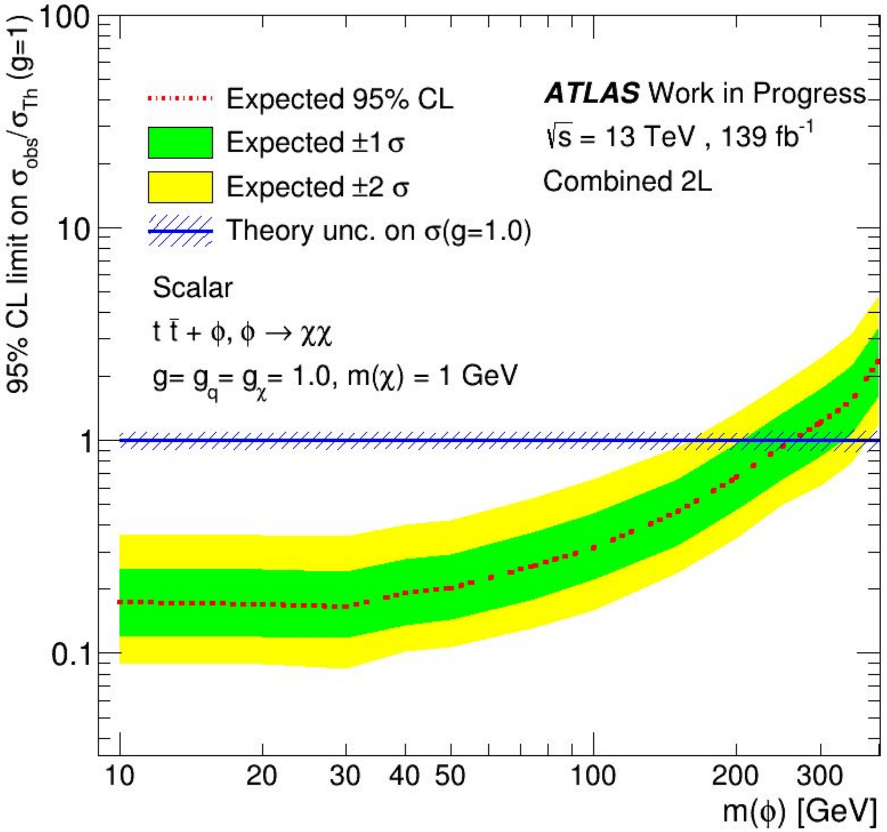
Exclusion plots in combined WSs

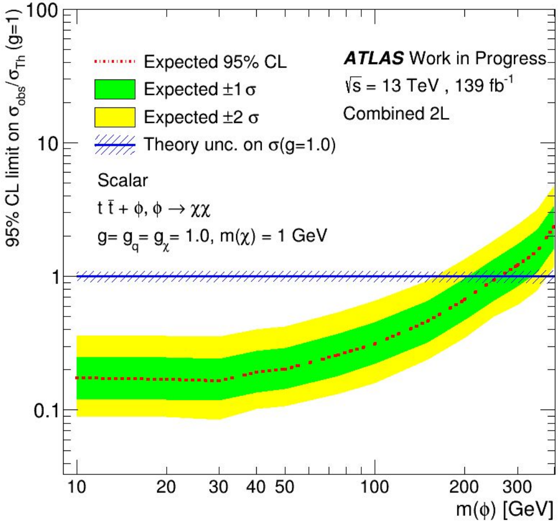


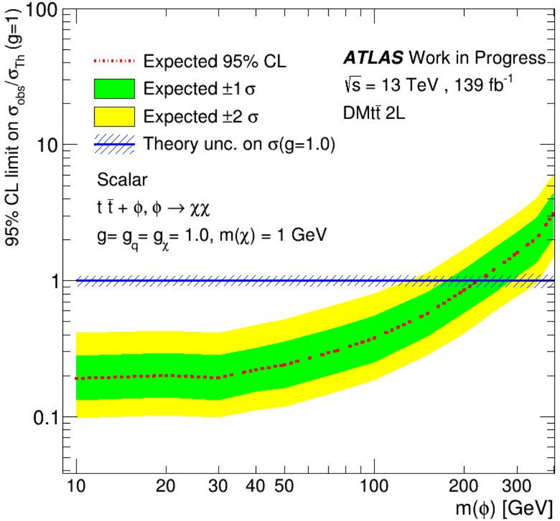


Exclusion plots in combined and separated WSs

$t\bar{t}$+DM — scalar mediator ϕ

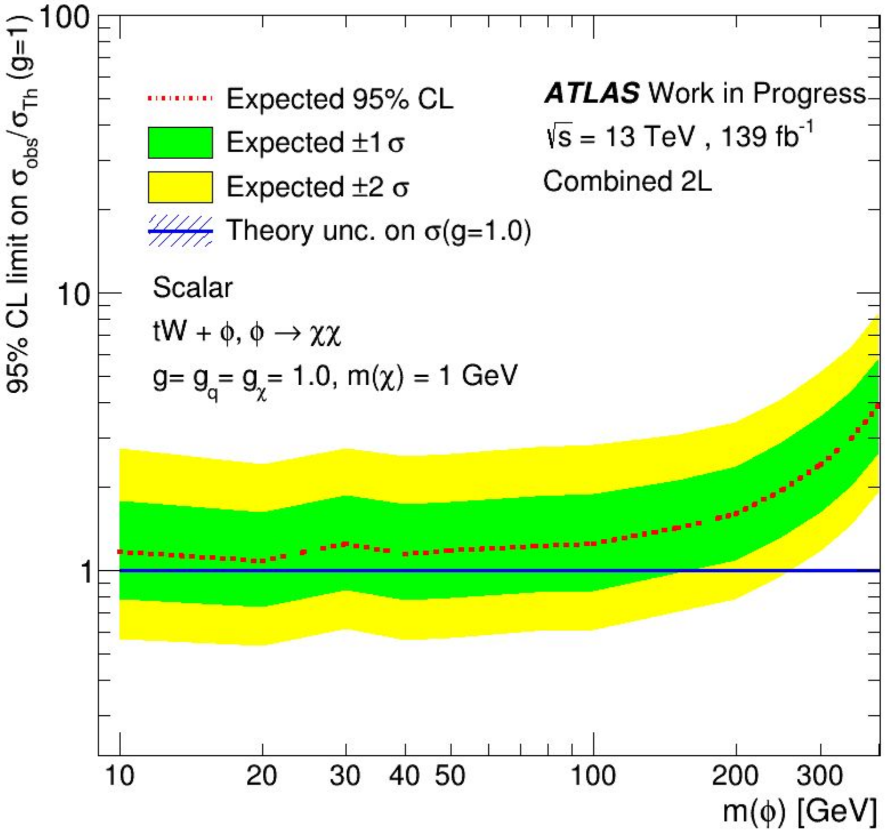


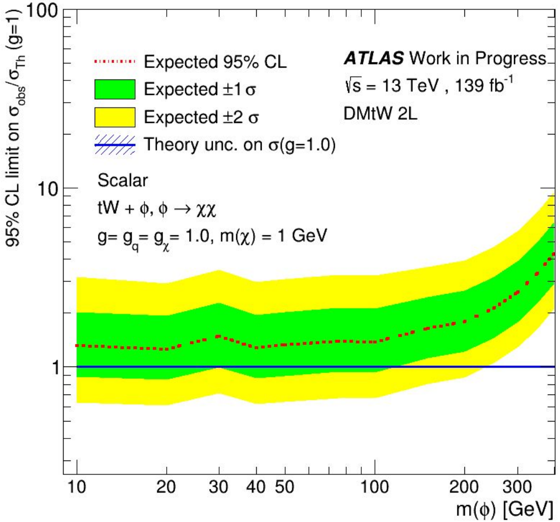


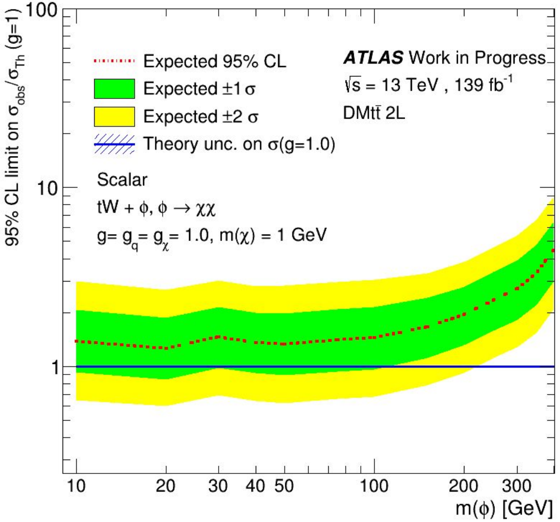


Exclusion plots in combined and separated WSs

tW+DM — scalar mediator ϕ

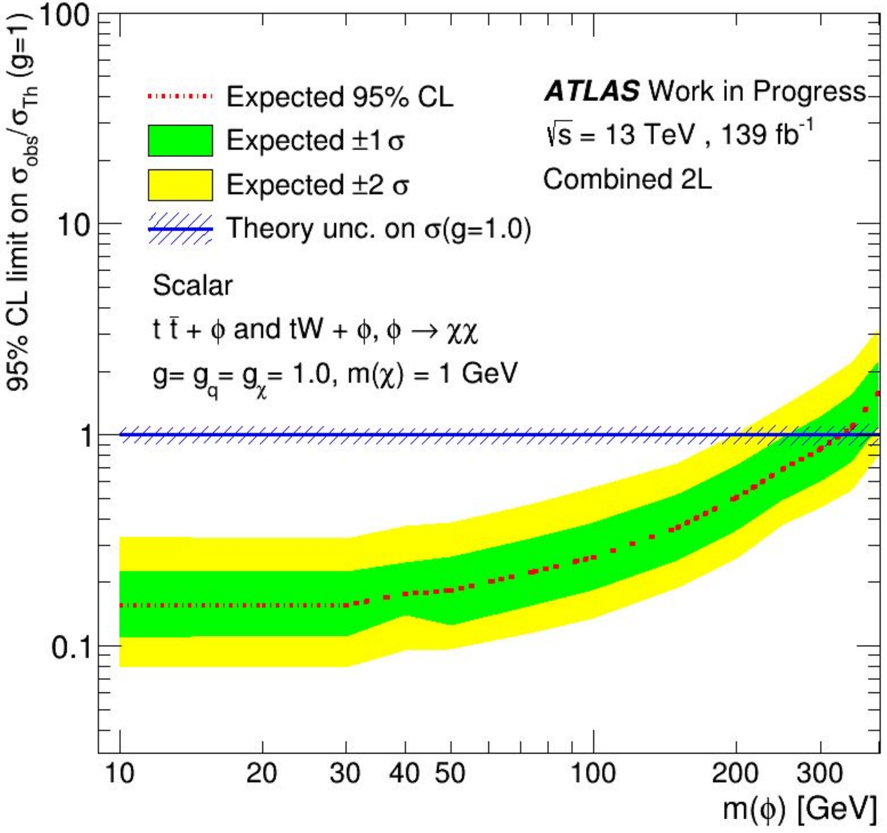


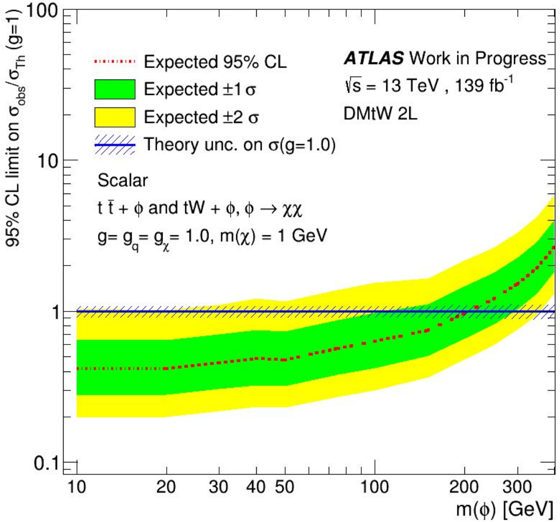


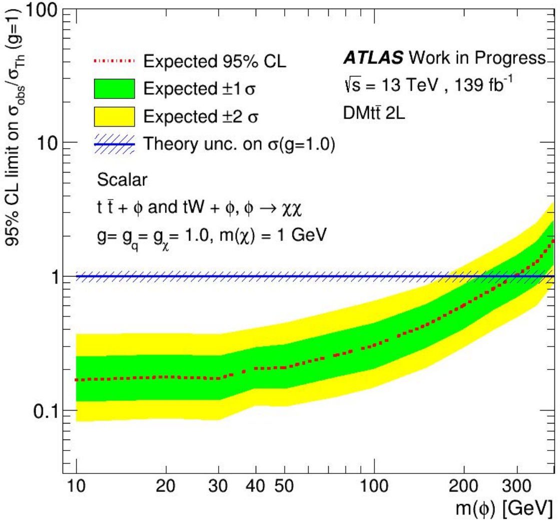


Exclusion plots in combined and separated WSs

$t\bar{t}$+DM and tW+DM — scalar mediator ϕ



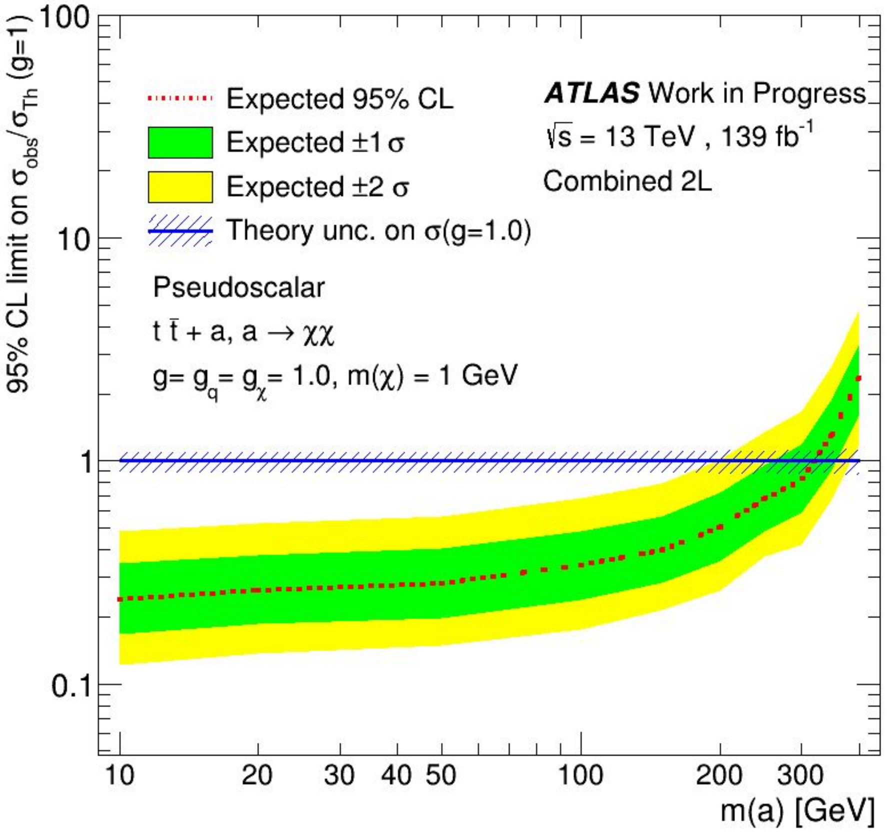


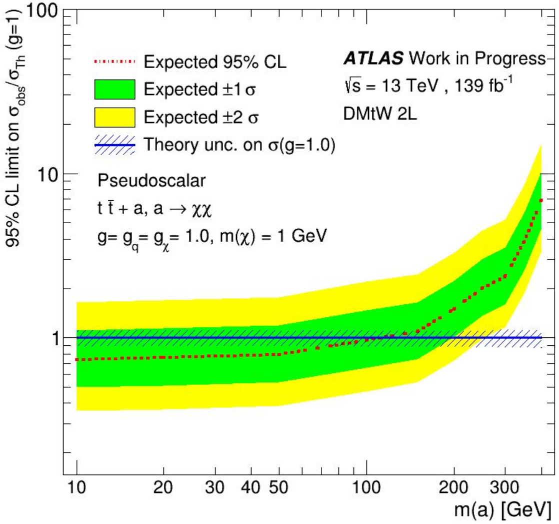


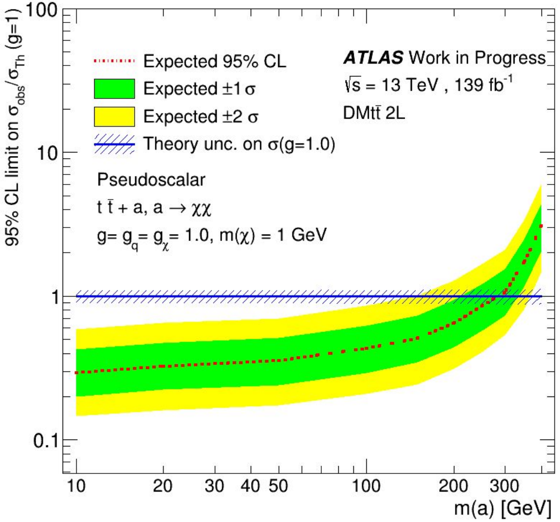
Pseudoscalar.

Exclusion plots in combined and separated WSs

$t\bar{t}$+DM — pseudoscalar mediator a

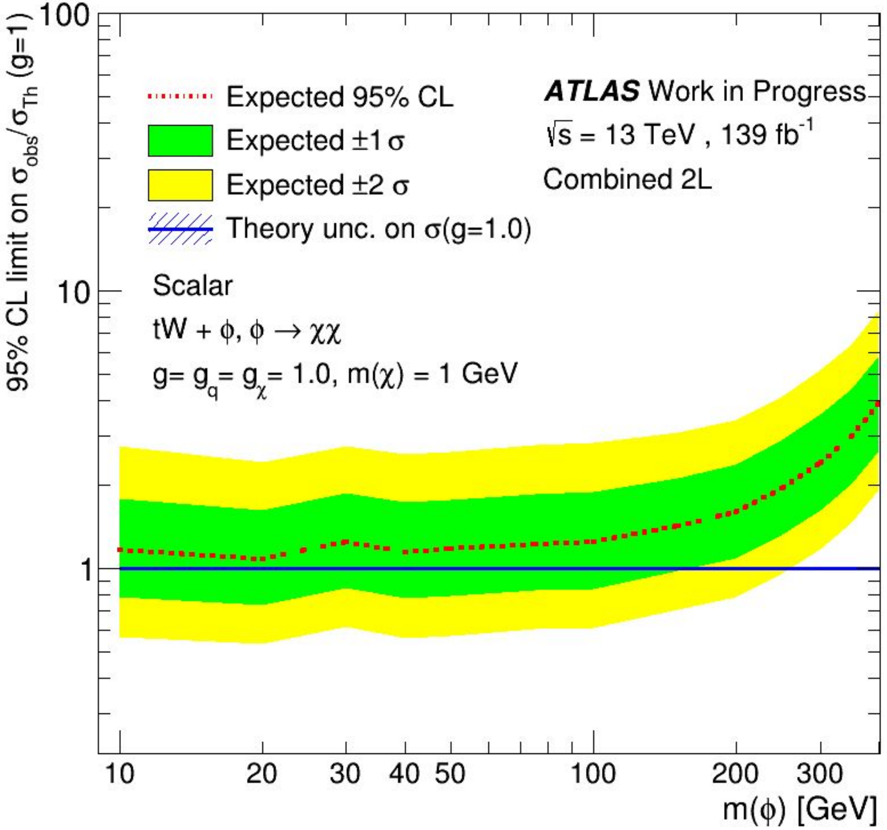


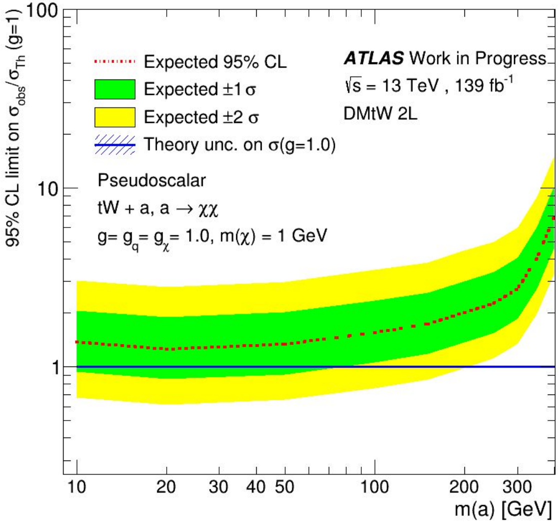


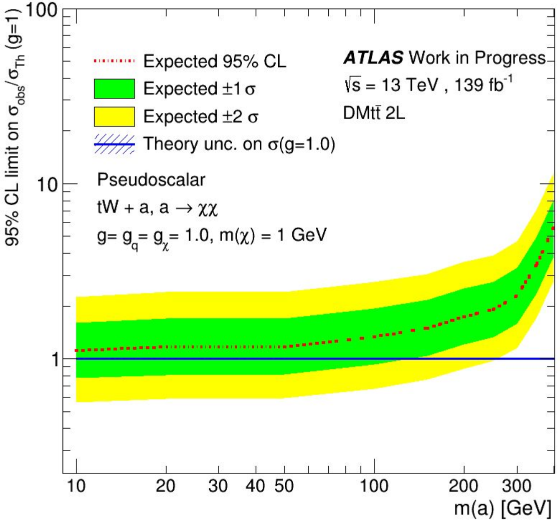


Exclusion plots in combined and separated WSs

tW+DM — pseudoscalar mediator a







Exclusion plots in combined and separated WSs

$t\bar{t}$+DM and tW+DM — pseudoscalar mediator a