"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".

ATLAS-CONF-2022-007

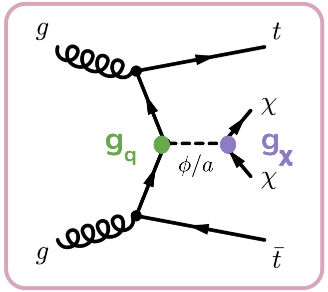
Moriond EW 2022 — YSF talks
15th March 2022

Marianna Liberatore, on behalf of the ATLAS collaboration
DESY Zeuthen

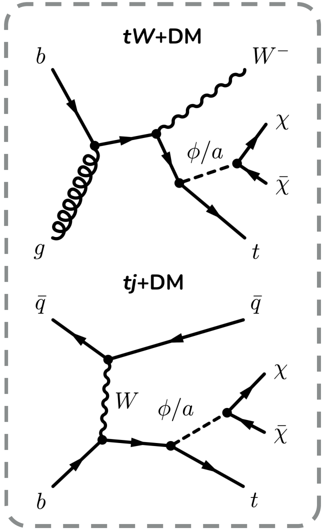
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Motivation of this analysis — (ATLAS-CONF-2022-007).

- **Improve current constraints** to mediator-based simplified Dark Matter models
  - WIMPs, dirac fermion DM candidate (χ)
  - Scalar (ϕ) / pseudoscalar (**a**) mediator
  - Free parameters m_χ, m_ϕ, benchmark $g_\chi = g_q = 1$
  - Yukawa-type couplings $\propto m_q$ → preference for **top quark**
- **Statistical combination of three** $t\bar{t}$+DM **searches**
  - **2 top quarks** decaying to **0**, **1**, **2 leptons** → **tt0L, tt1L, tt2L**
  - At least 1 ***b***-jet
  - Missing transverse momentum (**MET**)
- Improve sensitivity with $t/\bar{t}$+DM channel

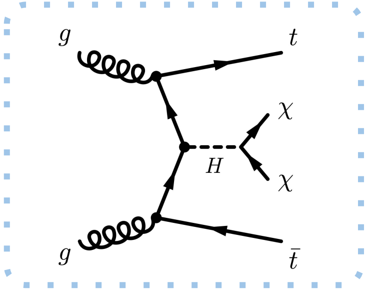


Dominant production mode



Contribution at high mediator masses

- In addition, **upper limits on the B(H→inv)** in $t\bar{t}H$→inv process
  - Special case → SM 125 GeV Higgs is the mediator
  - If Higgs field generates WIMP mass → $B(H\to inv)_{DM} >> B(H\to inv)_{SM}$



Previous searches.

ATL-PHYS-PUB-2021-045

In all analyses, same signal regions (SRs)+control regions strategy

tt2L - JHEP 04 (2021) 165

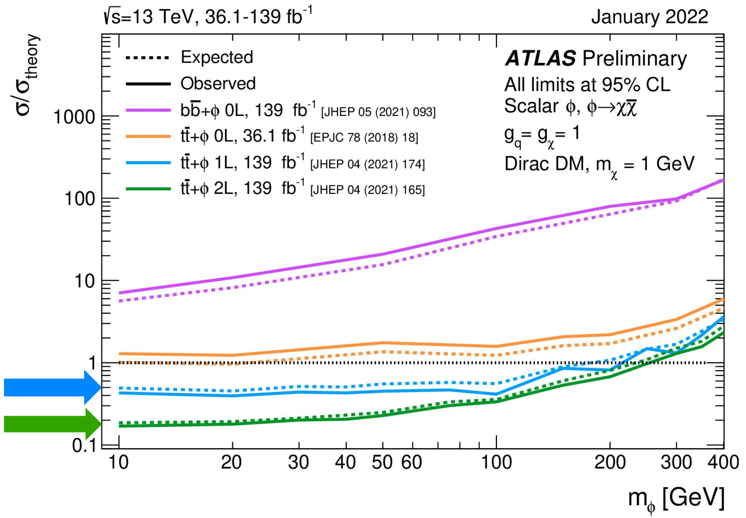
- Exclusion up to $m_{\phi/a}$=**250(300) GeV** for scalar(pseudoscalar) mediator

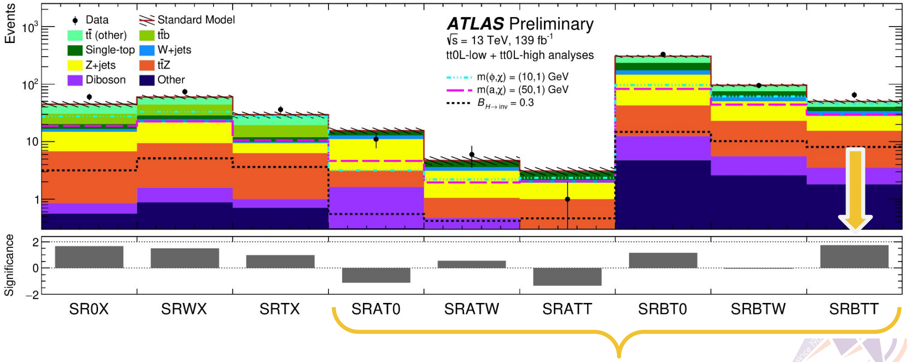
tt1L - JHEP 04 (2021) 174

- Exclusion up to **200 GeV**

tt0L - EPJC 80 (2020) 737

- Originally for stop searches
- 2σ excess found





Combination searches.

In all analyses, same signal regions (SRs)+control regions strategy

tt2L - JHEP 04 (2021) 165

- Exclusion up to $\boldsymbol{m_{\phi/a}}$**=250(300) GeV** for scalar(pseudoscalar) mediator

tt1L - JHEP 04 (2021) 174

- Exclusion up to **200 GeV**

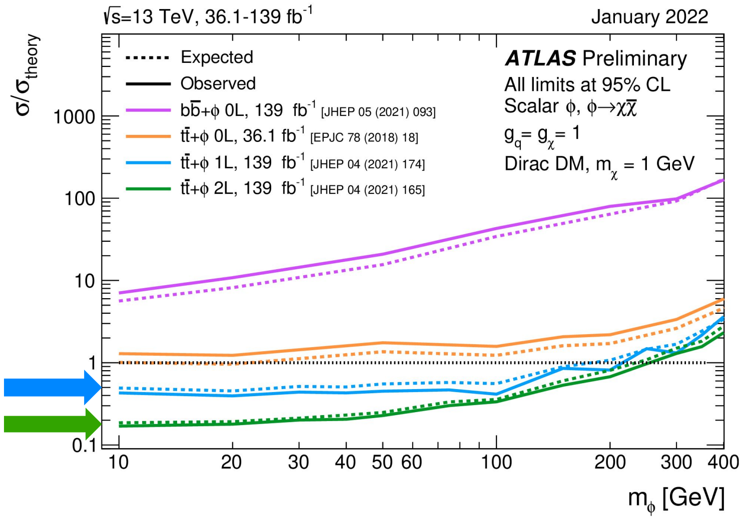
tt0L-high MET - EPJC 80 (2020) 737

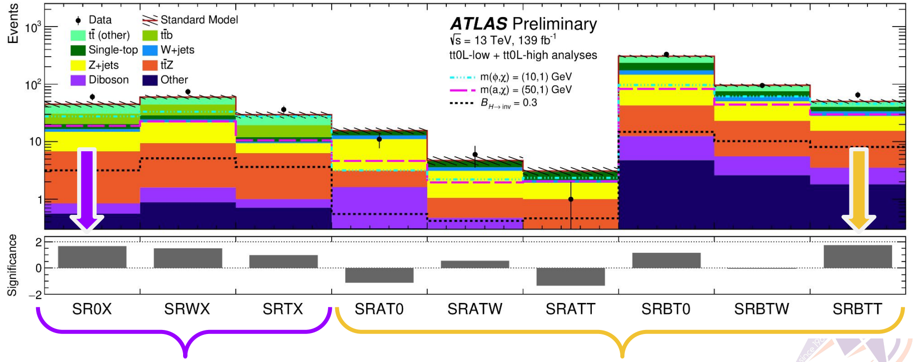
- Originally for stop searches
- 2σ excess found

tt0L-low MET - this analysis

- tt0L extended and improved
- Explore **softer** hadronic $t\bar{t}$ pairs
  - Include data recorded by *b*-tagged jet triggers
  - Increases sensitivity to **light** mediator masses
- 2σ excess found

ATL-PHYS-PUB-2021-045





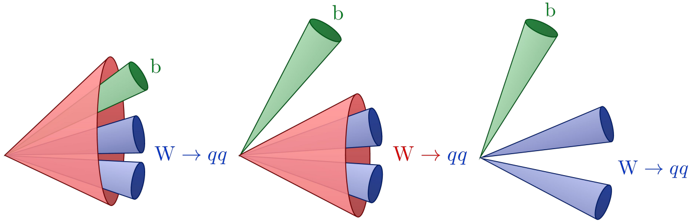
tt0L combination.

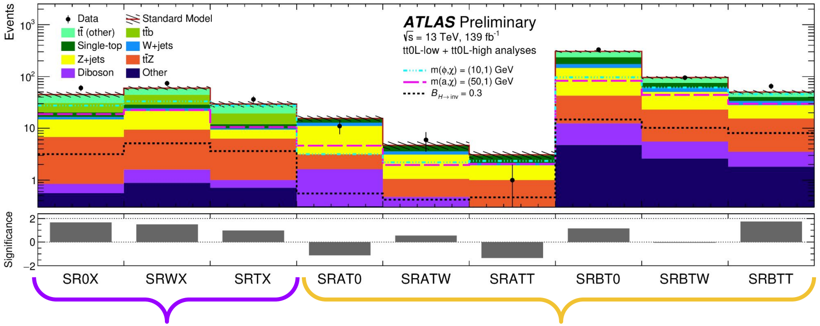
tt0L-high MET - EPJC 80 (2020) 737

MET trigger

MET>250 GeV, MET significance $\mathcal{S}$>14, large-radius jet (R=1.2) → highly energetic top quark

SRs based on mass of subleading large-radius jet (R=1.2) → presence of m_t, m_W or *neither*





tt0L-low MET - this analysis

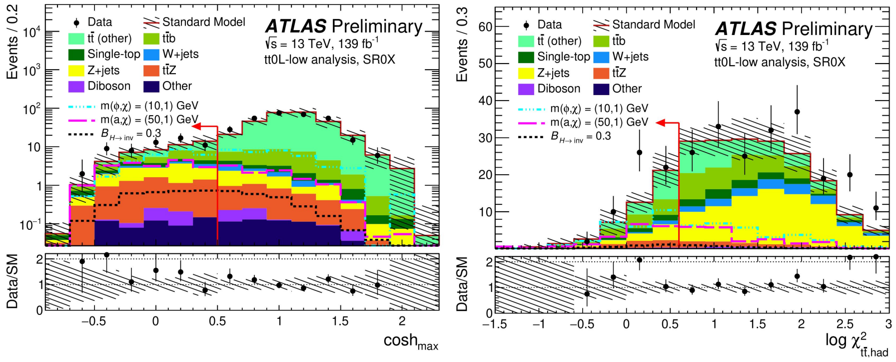
MET trigger	*b*-jet trigger
MET>250 GeV but $\mathcal{S}$<14 OR no large-radius (R=1.2) jets → highly energetic top quark	MET∈[160,250] GeV

Discriminating variables

$\cosh_{max}$ to reduce bkg with top quark + missing lepton

$\chi^2_{t\bar{t},had}$ to identify events with fully hadronic top quark pairs

SRs based on mass of the highest large-radius (R=1) jet → presence of m_t, m_W or *none*



Results — Exclusion limits on mediator masses.

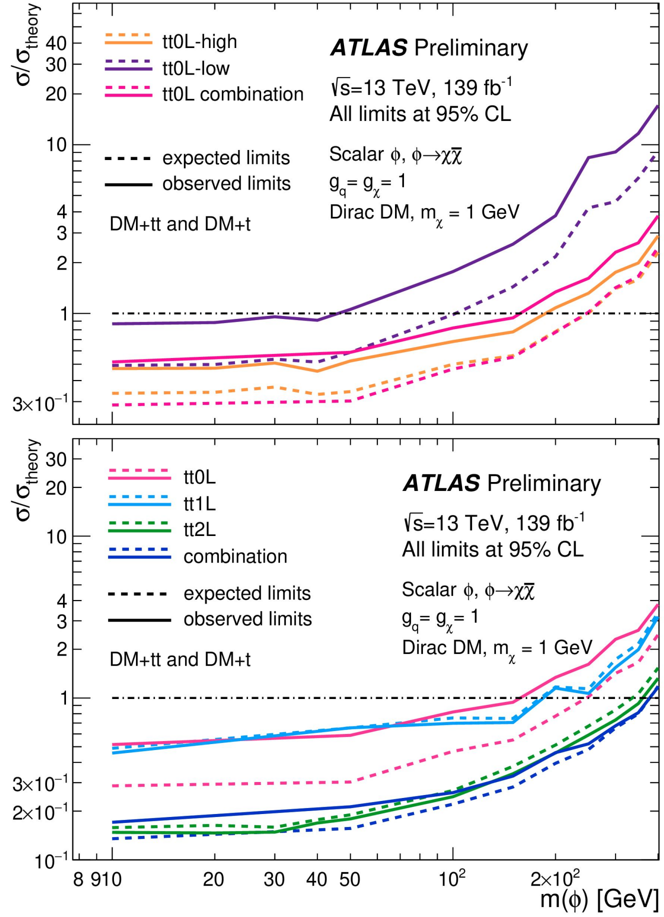
- Exclusion limits at 95% CL are presented for DM models with a spin-0 scalar or pseudoscalar mediator particle

tt0L combination

- **tt0L-low MET** extends the **tt0L-high MET** sensitivity for low mediator models
- Improvement **up to ~15%(5%)** for scalar(pseudoscalar) mediator masses

Total combination

- For **scalar(pseudoscalar)** dark matter models, excluded mass range extended by **100(30) GeV** wrt the best of the individual channels (= **tt2L**)
  - excluding mediator masses **up to 370 GeV** for unitary couplings assumptions



Results — Upper limits on B(H→inv).

[1] ATLAS [Phys. Rev. Lett. 122 (2019) 231801]
[2] CMS [Phys. Lett. B 793 (2019) 520]
[3] ATLAS [arXiv:2202.07953]

tt0L combination

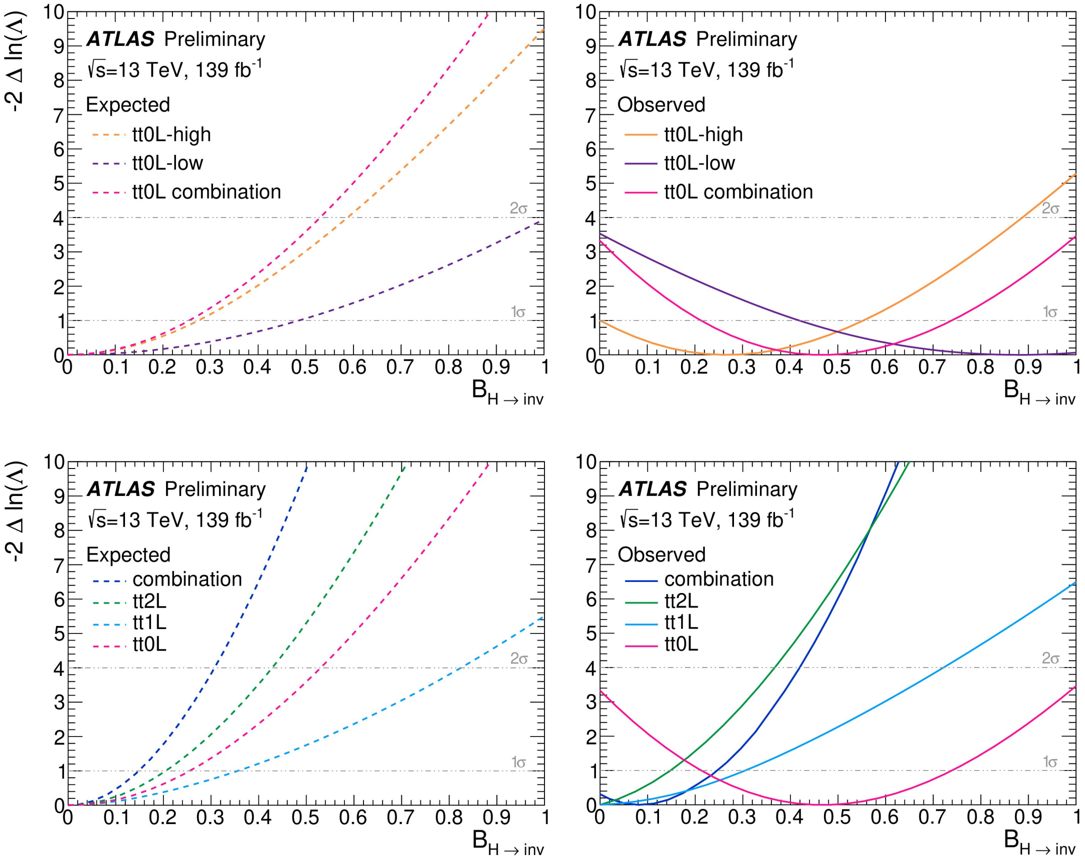
- Low improvement at the Higgs mass

Total combination

- Combined best fit value **consistent with the SM prediction** (=0.12%)
- Observed(expected) UL → **0.40(0.30)**

VBF/VH comb.	**0.26(0.17)**	[1]
VBF/VH/ggH comb.	**0.19(0.15)**	[2]
VBF (latest results)	**0.145(0.130)**	[3]

Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit
tt0L-low	0.88 ± 0.48	1.80	$1.09^{+0.50}_{-0.26}$
tt0L-high	0.27 ± 0.27	0.80	$0.59^{+0.29}_{-0.18}$
tt0L comb.	0.48 ± 0.26	0.95	$0.52^{+0.23}_{-0.16}$
tt1L	-0.04 ± 0.32	0.74	$0.80^{+0.40}_{-0.26}$
tt2L	-0.09 ± 0.21	0.39	$0.42^{+0.18}_{-0.12}$
$t\bar{t}H$ comb.	0.08 ± 0.15	0.40	$0.30^{+0.13}_{-0.09}$



Summary.

- Searching for DM @ the LHC → focus on WIMPs in simplified models with **top quarks**
- **Combination of three $t\bar{t}$+DM searches** to improve the sensitivity to DM simplified models
  - Focus on 0L, 1L, 2L final state
- New mass constraints extended for **scalar(pseudoscalar)** mediator by **100(30) GeV** wrt the best of the individual channels → up to **370 GeV**
- Upper limit on the Higgs boson invisible branching ratio of **0.40 (0.30)** is **observed (expected)**

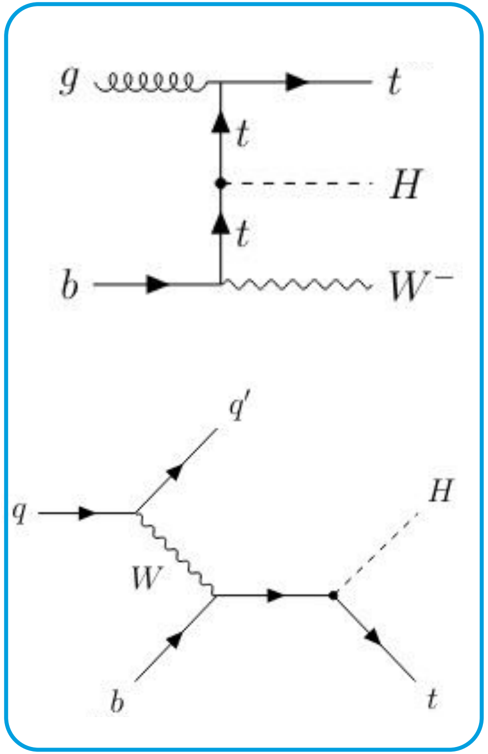
Thank you!

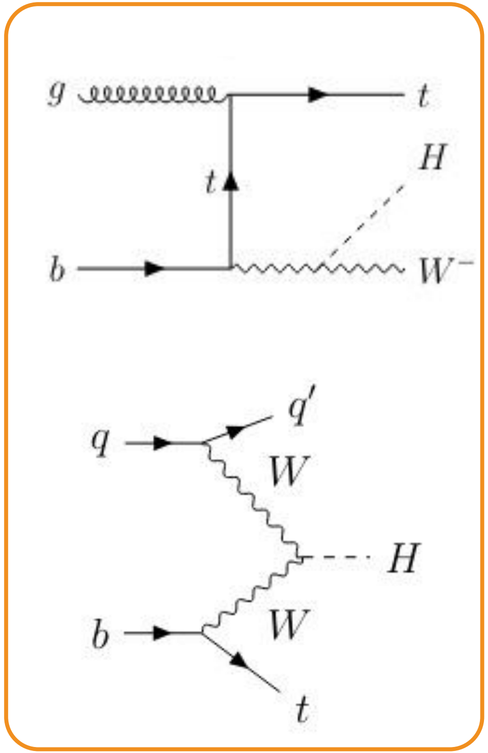
Backup.

More details on Invisible Higgs decay

For H→inv study ***tWH*** and ***tjH*** production not included

→ destructive interference between **top-**/**W-radiated** Higgs





More details on single analyses

tt0L-high MET

- No leptons (e,μ,tau), MET trigger, ≥ 2 b-jets, large MET significance $\mathcal{S}$, high top mass

$$\mathcal{S} = \frac{E_{\mathrm{T}}^{\mathrm{miss}}}{\sqrt{\sigma_{\mathrm{L}}^2(1-\rho_{\mathrm{LT}}^2)}}$$

- stop search
- SRA and SRB optimized for 2-body decays
  - TT, TW, T0 depending on reconstructed top candidate mass
- yields change due to updated JES and JER (~6-15%)
- Dominating backgrounds: *Z*+jets, $t\bar{t}$, *W*+jets, singletop (*tW*) and $t\bar{t}Z$

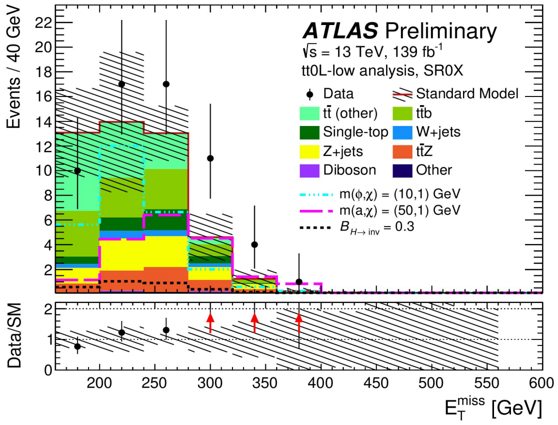
Variable/SR	SRA-TT	SRA-TW	SRA-T0	SRB-TT	SRB-TW	SRB-T0
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$					
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 250 GeV					
N_ℓ	Exactly 0					
N_{j}	≥ 4					
$p_{\mathrm{T},2}$	> 80 GeV					
$p_{\mathrm{T},4}$	> 40 GeV					
$\lvert\Delta\phi_{\min}(\mathbf{p}_{\mathrm{T},1-4}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})\rvert$	> 0.4					
N_b	≥ 2					
$m_{\mathrm{T}}^{b,\min}$	> 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		
$m_{\mathrm{T}}^{b,\max}$	–			> 200 GeV		
$\mathcal{S}$	> 25			> 14		
m_{T2,χ^2}	> 450 GeV			< 450 GeV		

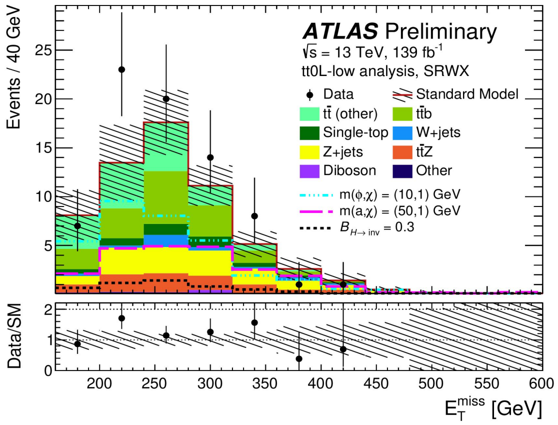
More details on single analyses

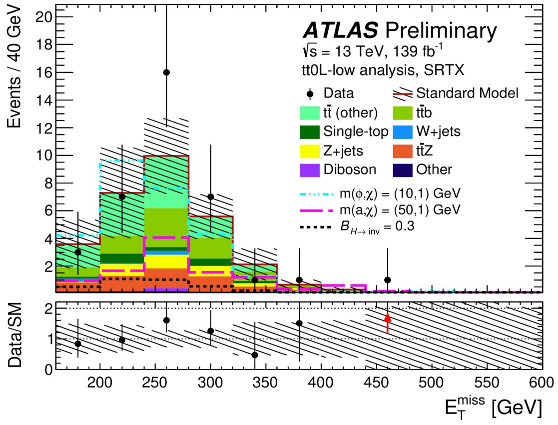
tt0L-low MET

- Low MET, lower $\mathcal{S}$ and/or lower momentum large-R jet
- SR0X, SRWX, SRTX depending on large-R jet mass

Variables	SR0X	SRWX	SRTX
N_{lepton}	$= 0$		
Orthogonalisation	$E_{\mathrm{T}}^{\text{miss}} < 250$ GeV or $\mathcal{S} < 14$ or $m^{R=1.2}_{\text{large-radius jet}} < 120$ GeV		
$E_{\mathrm{T}}^{\text{miss}}$ [GeV]	> 160 < 250, when passing b-jet triggers		
$\mathcal{S}$	> 10		
$\Delta\phi_{\text{min}}(\boldsymbol{p}_{\mathrm{T},1\text{-}4}, \boldsymbol{p}_{\mathrm{T}}^{\text{miss}})$	> 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
$p_{\mathrm{T}}^{t\bar{t}}/E_{\mathrm{T}}^{\text{miss}}$	$(0.7, 1.2)$	$(0.5, 1.2)$	







More details on single analyses

tt0L discriminating variable definition

cosh$_{\text{max}}$ → designed to discriminate signal events against single-top events in the *tW* channel and $t\bar{t}$ events with a lepton missed by the reconstruction algorithms (top with lost lepton), which are among the main backgrounds in the analysis.
Such events may enter the signal regions due to high MET originating from the $t \to bW \to bl\nu$ decay, and the lost lepton

$$\cosh_{\max} = \max\{\cosh(\eta_W - \eta_{b_1}), \cosh(\eta_W - \eta_{b_2})\}$$

with b_1 and b_2 the leading two *b*-tagged jets in the event and

$$\cosh(\eta_W - \eta_b) \sim \frac{m_t^2 - m_W^2}{2p_T^W p_T^b} + \cos(\phi_W - \phi_b)$$
$$\sim \frac{m_t^2 - m_W^2}{2E_T^{\text{miss}} p_T^b} + \cos(\phi_{E_T^{\text{miss}}} - \phi_b)$$

□$^2_{t\bar{t},\text{had}}$ → attempts to quantify how likely an event is to include two hadronically decaying top quarks. It is therefore used primarily to reject backgrounds containing no hadronic top quarks, such as *Z*+jets events.

$$\chi^2_{t\bar{t},\,\text{had}} = \left(\frac{m_{W_1} - m_{W_{\text{ref}}}}{\sigma_{m_W}}\right)^2 + \left(\frac{(m_{t_1} - m_{W_1}) - (m_{t_{\text{ref}}} - m_{W_{\text{ref}}})}{\sigma_{m_t - m_W}}\right)^2 + \left(\frac{(m_{t_2} - m_{W_2}) - (m_{t_{\text{ref}}} - m_{W_{\text{ref}}})}{\sigma_{m_t - m_W}}\right)^2$$

More details on single analyses

tt0L-low MET background estimation

Main backgrounds normalised in dedicated CRs

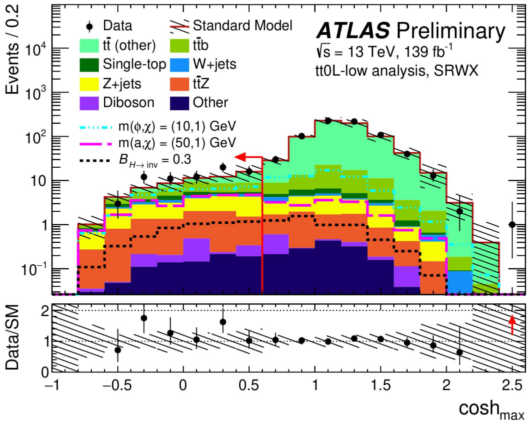
- $t\bar{t}$, $t\bar{t}$+b, single-top
- Z+jets
- $t\bar{t}Z$ will be constrained in CR $t\bar{t}Z$ from tt2L analysis

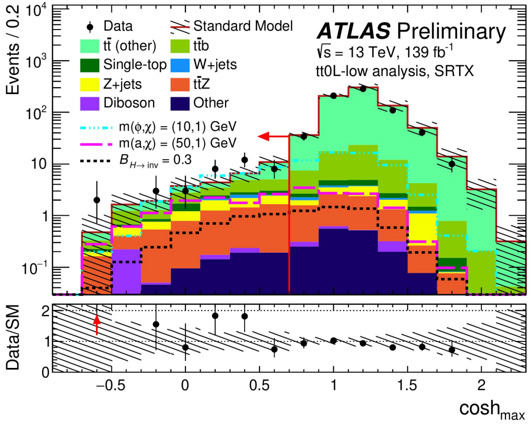
	Variables	CR0X	CRWX	CRTX
shared selections	$\mathrm{N}_{\text{lepton}}$	$= 1$		
	$E_{\mathrm{T,\,no\ lepton}}^{\mathrm{miss}}$ [GeV]	> 160		
	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	< 250, when passing b-jet triggers		
	$\mathcal{S}_{\text{no lepton}}$	> 10		
	$\Delta\phi_{\min}(\boldsymbol{p}_{\mathrm{T},1\text{-}4}, \boldsymbol{p}_{\mathrm{T,no\ lepton}}^{\mathrm{miss}})$	> 1.0	> 0.5	
	$\Delta R\,(b_1, b_2)$	> 1.2		
	$\mathrm{N}_{\text{large-radius jet}}$	$= 0$	> 0	
	$m_{\text{large-radius jet}}$ [GeV]	—	(40, 130)	≥ 130
	$\Delta R_{\min}$(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
	$p_{\mathrm{T}}^{t\bar{t}}/E_{\mathrm{T,\,no\ lepton}}^{\mathrm{miss}}$	(0.7, 1.2)	(0.5, 1.2)	
$t\bar{t}$ enriched selections	**Variables**	**CR0X$_{t\bar{t}}$**	**CRWX$_{t\bar{t}}$**	**CRTX$_{t\bar{t}}$**
	$\chi^2_{t\bar{t},\,\text{lep}}$	< 6		
$t\bar{t}+b$ enriched selections	**Variables**	**CR0X$_{t\bar{t}+b}$**	**CRWX$_{t\bar{t}+b}$**	**CRTX$_{t\bar{t}+b}$**
	$\chi^2_{t\bar{t},\,\text{lep}}$	≥ 6		
	$\mathrm{N}_{\text{extra }b\text{-tagged jet}}$	≥ 1		
single-top enriched selections	**Variables**	**CR0X$_{\text{single-top}}$**	**CRWX$_{\text{single-top}}$**	**CRTX$_{\text{single-top}}$**
	$\chi^2_{t\bar{t},\,\text{lep}}$	≥ 30		
	$\mathrm{N}_{\text{extra }b\text{-tagged jet}}$	$= 0$		
	$\cosh_{\text{max, no lepton}}$	< 0.5	< 0.6	< 0.7

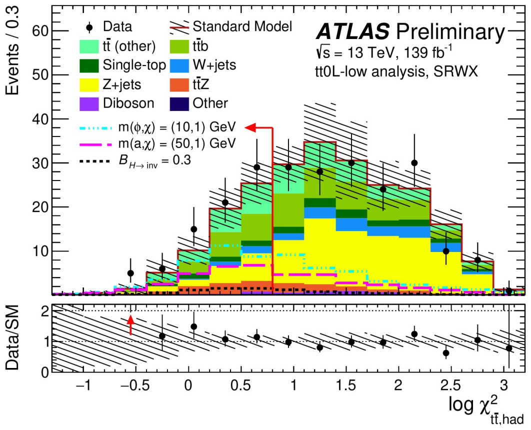
Variables	CR0X$_{Z\text{+jets}}$	CRWX$_{Z\text{+jets}}$	CRTX$_{Z\text{+jets}}$
$\mathrm{N}_{\text{lepton}}$	$= 2$		
Orthogonalisation	$\mathrm{N}_{\text{large-radius jet}}^{R=1.2} < 2$ or $m_{\text{subleading large-radius jet}}^{R=1.2} < 60$ GeV		
$E_{\mathrm{T,\,no\ lepton}}^{\mathrm{miss}}$ [GeV]	>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

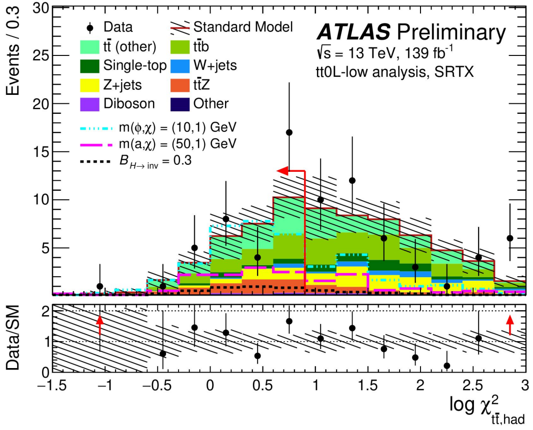
More details on single analyses

tt0L-low additional SR plots









More details on single analyses

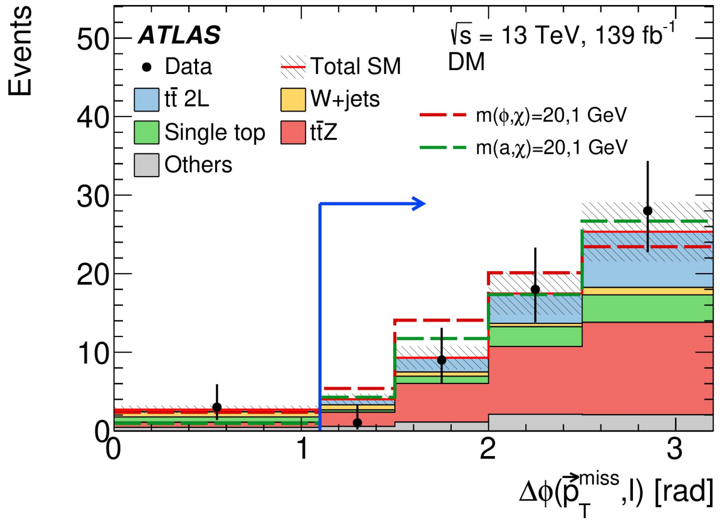
tt0L-low MET yields

Process	SR0X	SRWX	SRTX
Observed data	60	74	36
Expected SM events	45 ± 8	59 ± 6	28 ± 5
$t\bar{t}$	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

More details on single analyses

tt1L detailed selection and plots

Dominating backgrounds:
$t\bar{t}$, W+jets, single top (tW), $t\bar{t}Z$



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]	$> (80, 25)$	
$E_{\text{T}}^{\text{miss}}$	[GeV]	> 230	
$H_{\text{T,sig}}^{\text{miss}}$		> 15	
m_{T}	[GeV]	> 180	
Topness		> 8	
$m_{\text{top}}^{\text{reclustered}}$	[GeV]	> 150	
$\Delta\phi(\text{jet}_i, \vec{p}_{\text{T}}^{\text{miss}}), i \in [1,4]$	[rad]	> 0.9	
$\Delta\phi(\vec{p}_{\text{T}}^{\text{miss}}, \ell)$	[rad]	> 1.1	> 1.5
Exclusion technique		Based on shape-fit in $\Delta\phi(\vec{p}_{\text{T}}^{\text{miss}}, \ell)$	
Bin boundaries in $\Delta\phi(\vec{p}_{\text{T}}^{\text{miss}}, \ell)$		$\{1.1, 1.5, 2.0, 2.5, \pi\}$	

More details on single analyses

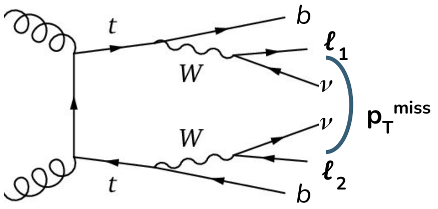
tt2L detailed selection and plots

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

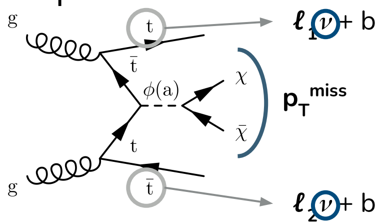
	SR^{2-body}	
Leptons flavour	DF	SF
$p_T(\ell_1)$ [GeV]	> 25	
$p_T(\ell_2)$ [GeV]	> 20	
$m_{\ell\ell}$ [GeV]	> 20	
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	–	> 20
n_{b-jets}	≥ 1	
$\Delta\phi_{boost}$ [rad]	< 1.5	
E_T^{miss} significance	> 12	
$m_{T2}^{\ell\ell}$ [GeV]	> 110	

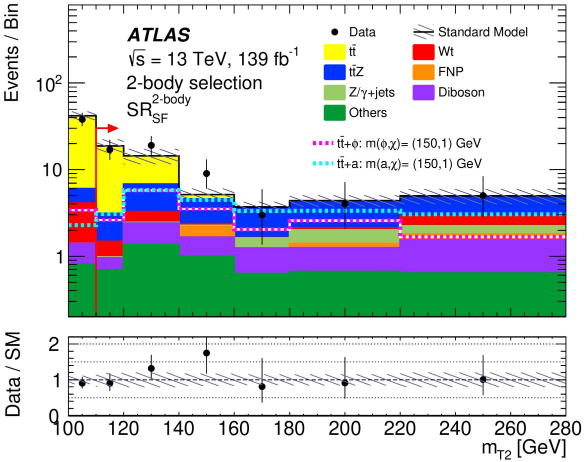
$$m_{T2}(\mathbf{p}_T^{l_1}, \mathbf{p}_T^{l_2}, \mathbf{p}_T^{miss}) = \min_{\mathbf{p}_{T,1}^{miss}+\mathbf{p}_{T,2}^{miss}=\mathbf{p}_T^{miss}} \left[\max\left(m_T(\mathbf{p}_T^{l_1}, \mathbf{p}_{T,1}^{miss}), m_T(\mathbf{p}_T^{l_2}, \mathbf{p}_{T,2}^{miss})\right)\right]$$

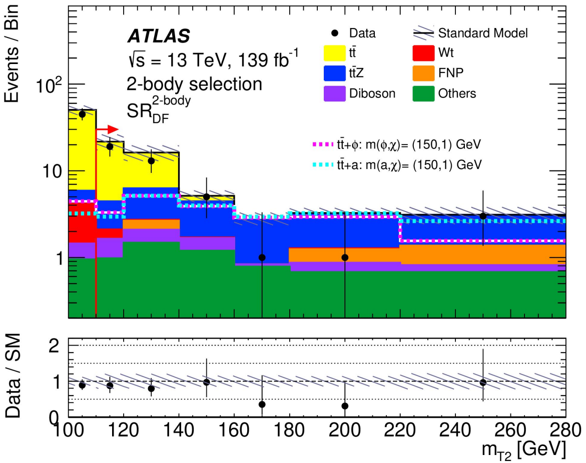
$t\bar{t}$ background



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







Experimental signatures and previous searches.

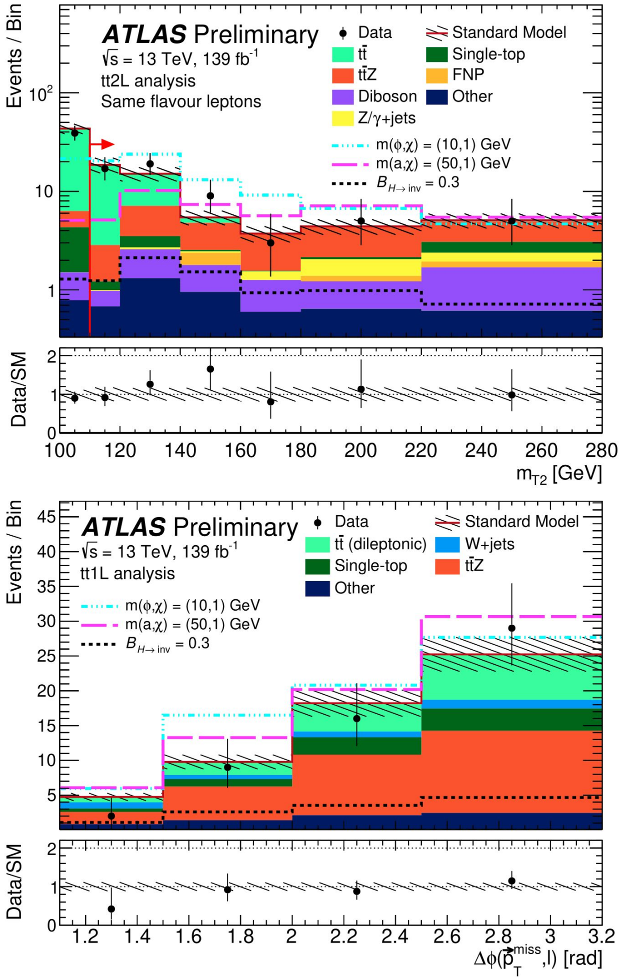
In all analyses, defining signal enriched regions using specific discriminating variables

tt2L - JHEP 04 (2021) 165

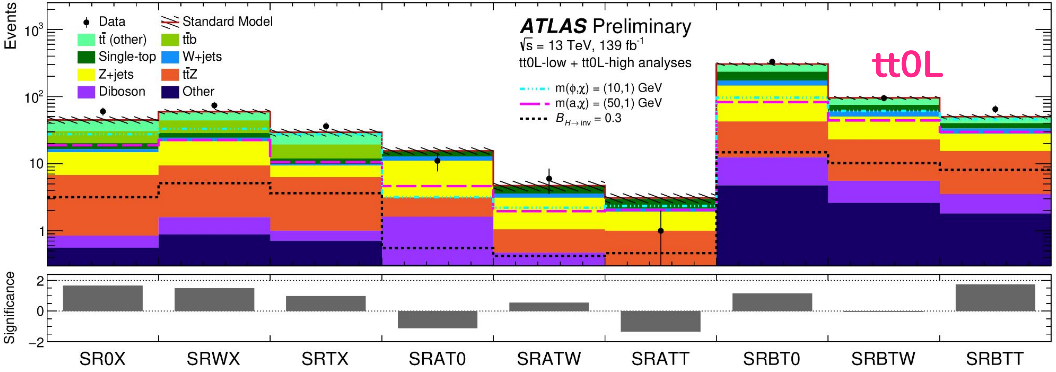
- 2 leptons opposite sign + at least 1 *b*-jet
- Dilepton trigger
- Shape fit on m_{T2} also wrt lepton flavour
  - m_{T2} → identifies pair-produced particles decaying to visible + invisible particles (e.g. $t\bar{t}$)
- Exclusion up to $m_{\phi/a}$=**250(300) GeV** for scalar(pseudoscalar) mediator

tt1L - JHEP 04 (2021) 174

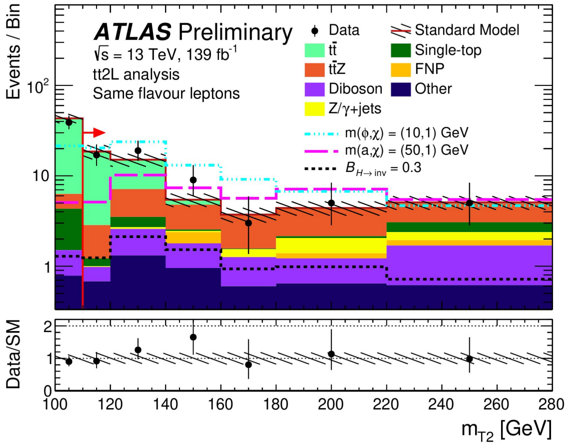
- Exactly 1 lepton + 2 *b*-jets
- MET trigger
- SR binned in **Δϕ(MET, lepton)**
- Exclusion up to **200 GeV**



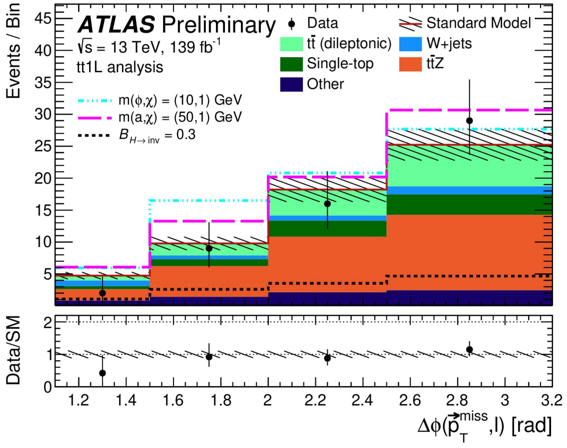
Combination strategy.



tt2L (same flavour)



tt1L



- Harmonization of the objects selections and datasets
- Statistical combination → Signal and Control Regions statistical **independent**
  - Combining tt0L 3+6, tt1L 4, tt2L 2x6 = 25 bins + CRs
  - “Orthogonalization” requirements on kinematic variables
- Uncertainties
  - **Correlated** → experimental uncertainties and signal modelling
  - **Uncorrelated** → background modelling
- Maximising a **profile likelihood ratio** from product of individual analyses likelihoods

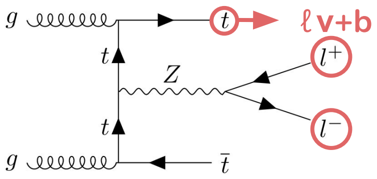
Orthogonalization strategy

Signal regions

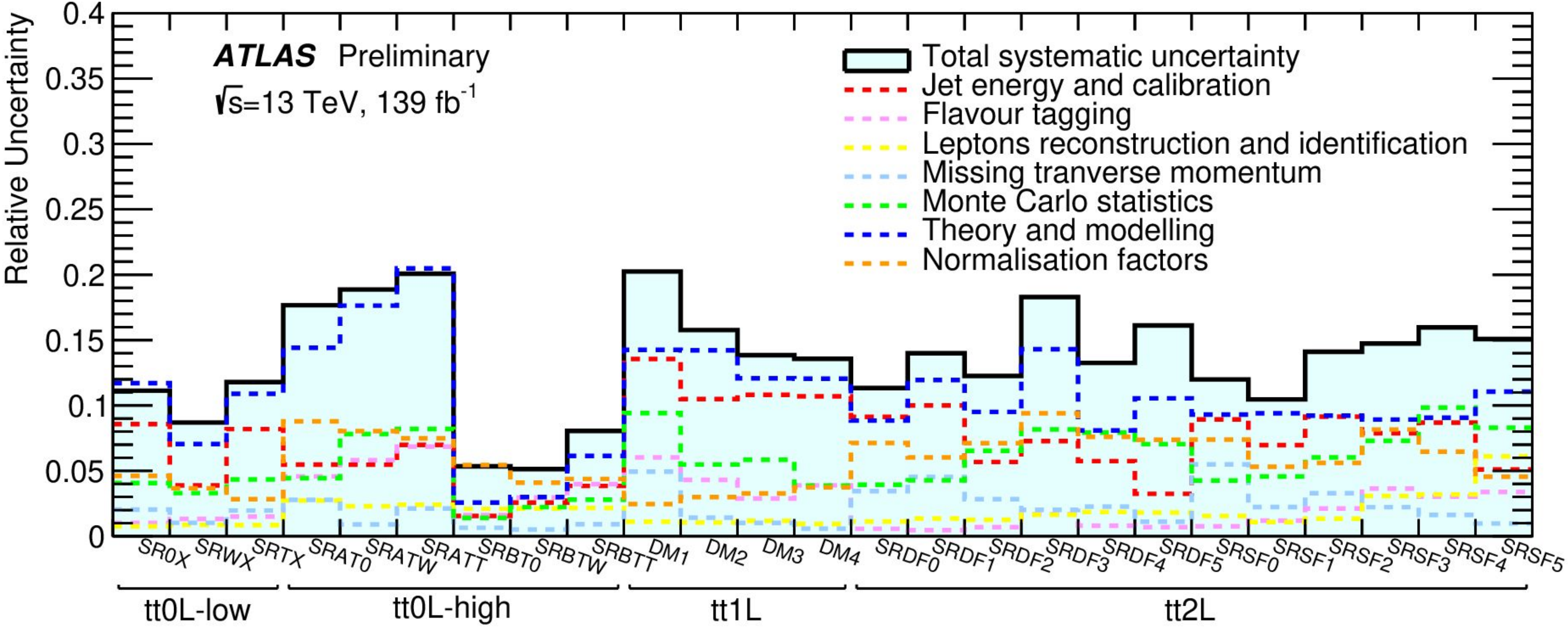
- Already orthogonal by lepton multiplicity requirement
- tt0L → orthogonalization requirements on large-radius jet, MET and $\mathcal{S}$ in tt0L-low SRs

Control regions

- In tt0L
  - CRZAB-T0 removed from tt0L-high
  - orthogonalization requirements on large-radius jets in tt0L-low Z+jets enriched CRs
- Rest of CRs orthogonal
- Exception $t\bar{t}Z$ CRs → large overlap in all analyses
  - all analyses adopted a similar strategy and constrained the $t\bar{t}Z$ (Z→νν) process using 3-lepton $t\bar{t}Z$ (Z→ℓℓ) enriched CRs
  - $t\bar{t}Z$→4ℓ very low stat. to define CR
    - "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
  - common CR → using tt2L $t\bar{t}Z$ CR as the most inclusive



Impact of background systematics



Results exclusion limits for pseudoscalar mediator