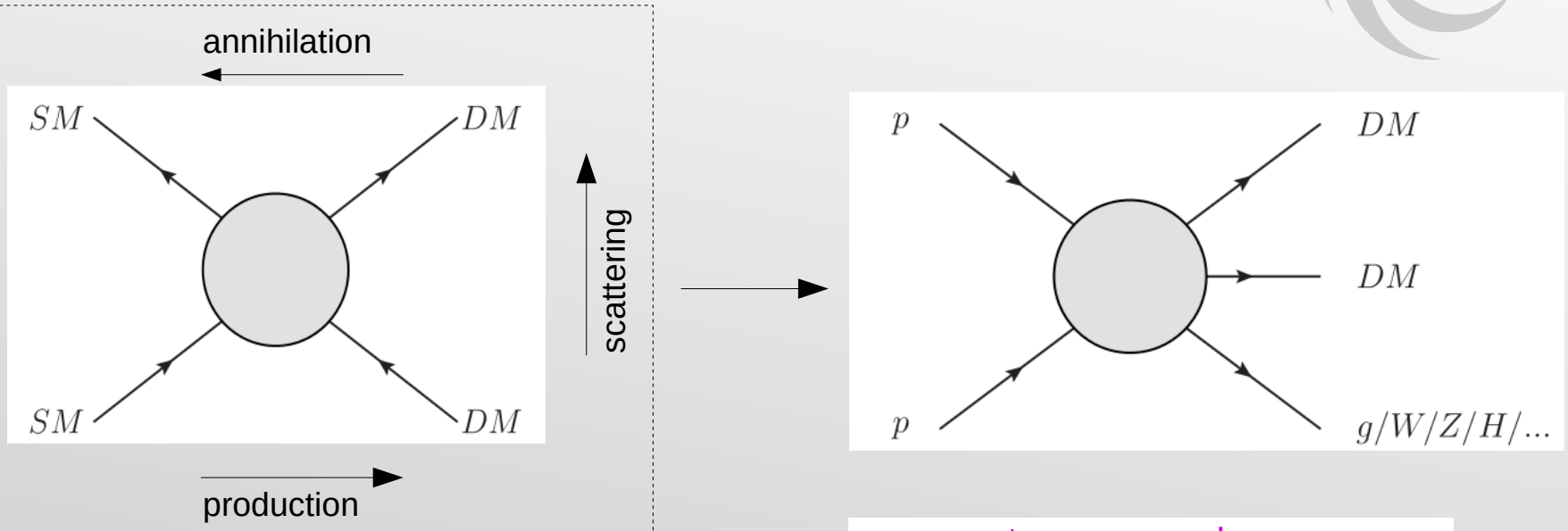


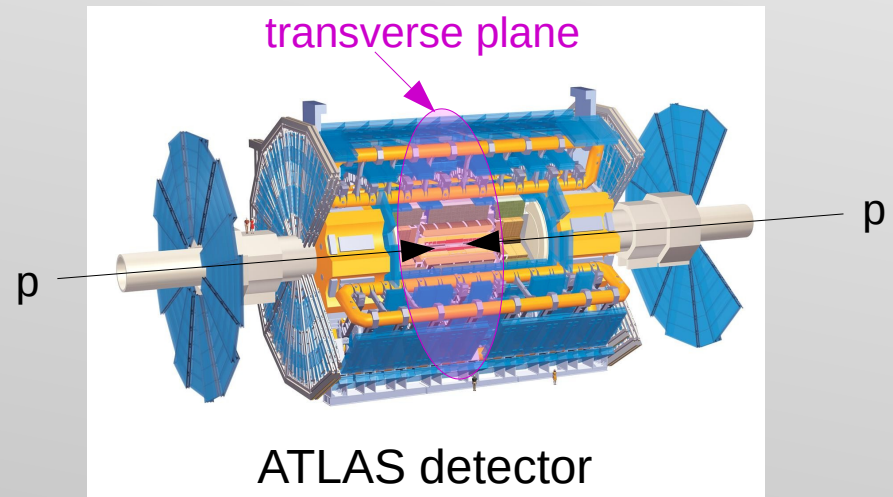
Searches for dark matter with the ATLAS detector

SUSY 2022 – Ioannina
Philipp Mogg
on behalf of the ATLAS collaboration
27.06.2022

Dark matter at the LHC



- Dark matter is invisible to the detector (no interaction) (for DM candidates covered in this talk)
- creates momentum imbalance in the transverse plane
 - “missing transverse momentum” (magnitude: $E_{T,miss}$)
 - same as neutrinos



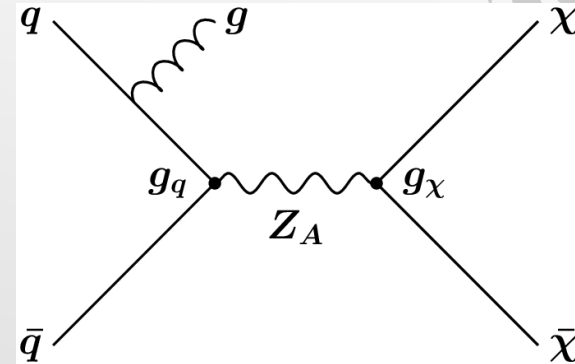
Simplified 1-mediator models (s-channel)

- cover a large set of models
- easy reinterpretation

Complete models with
extended Higgs or gauge
sector

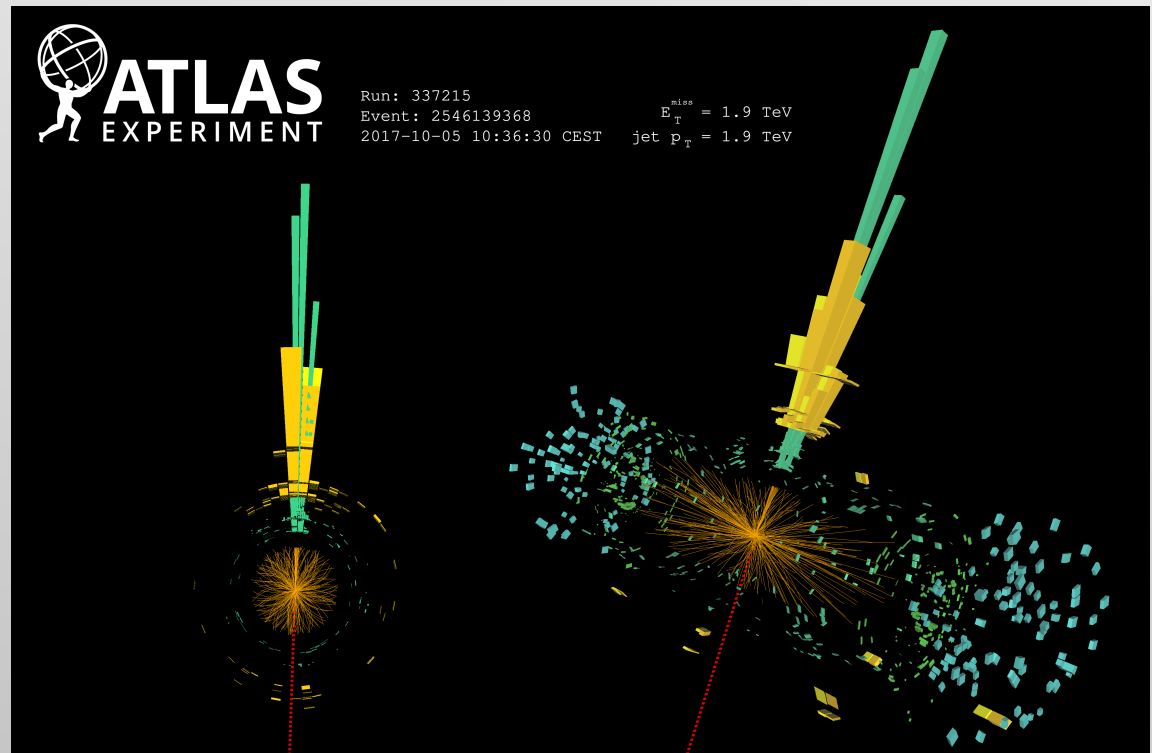
Monojet search

- ISR of a gluon can always happen in p–p collisions
→ Jet + $E_{T,\text{miss}}$ covers a variety of dark matter models



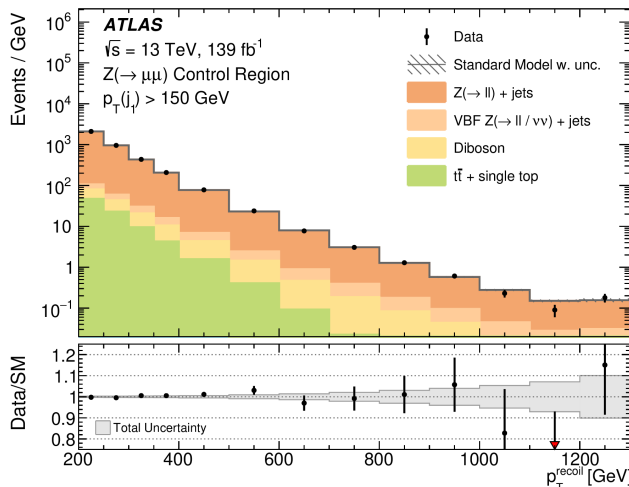
Considered models:

- s-channel exchange of a spin-1 (axial-vector) or spin-0 (pseudoscalar) mediator
- SUSY: Squarks in compressed mass scenarios
- Dark energy (Horndeski model)
- Extra dimensions (KK graviton escaping into extra dimensions)
- Axion-like particles (ALPs)
- Invisible Higgs decays

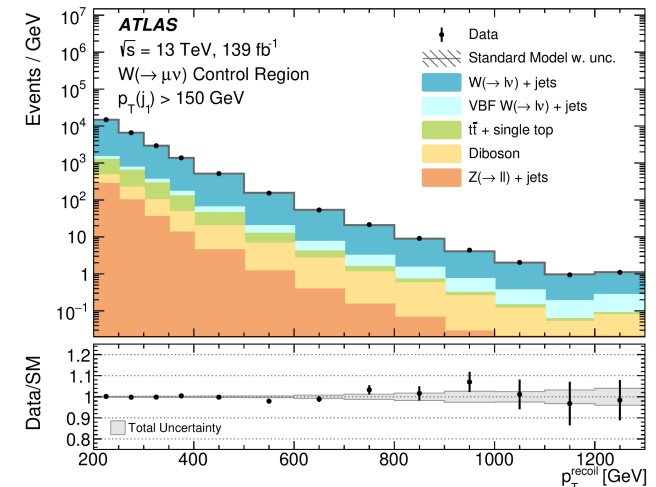


Monojet strategy

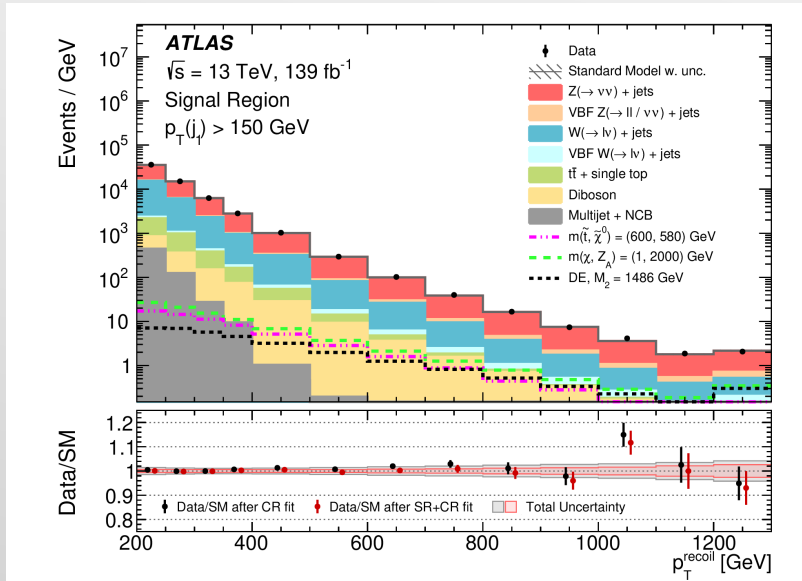
- Require $E_{T,\text{miss}} > 200$ GeV and at least one jet with $p_T > 150$ GeV
- Up to 3 additional jets
- Shape fit: 13 bins in $E_{T,\text{miss}}$
- Irreducible $Z(\nu\nu)$ +jet background (dominant)
- Furthermore: W +jets, Diboson, $t\bar{t}$, and smaller backgrounds
 - Large backgrounds need to be well constrained in order to be sensitive to smaller signals.
 - 1 & 2 lepton control regions both constrain Z +jets and W +jets



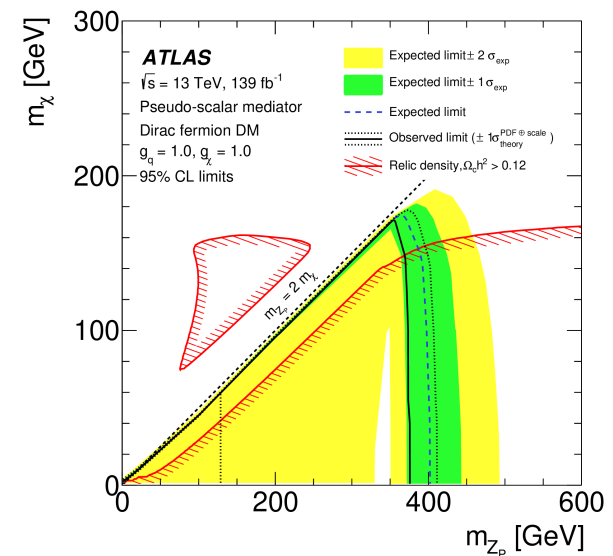
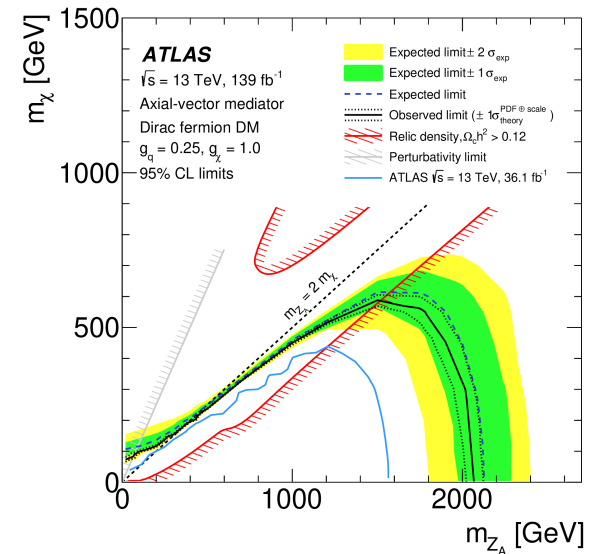
Z+jets vs W+jets
 difference
 calculated at
 NNLO(α_S)
 +NNLL(α_S),
 NLO(α_{EW})



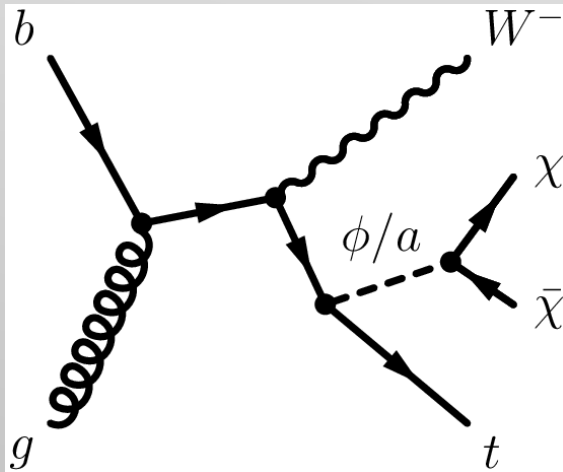
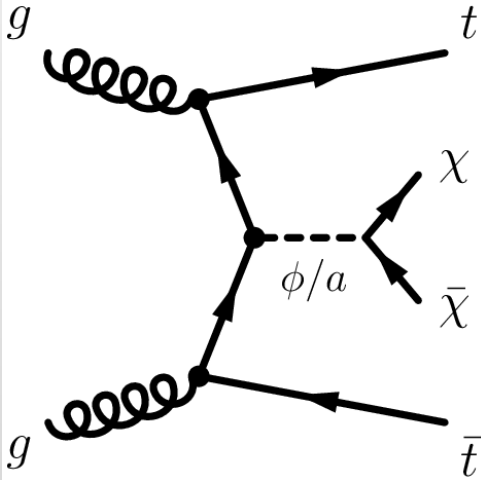
Monojet results



- Background modelling describes data in signal region well, no significant excess.
- Various interpretations, e.g. dark matter via axial-vector or pseudoscalar mediator.
- See also dark-sector reinterpretation: [ATL-PHYS-PUB-2021-020](#)



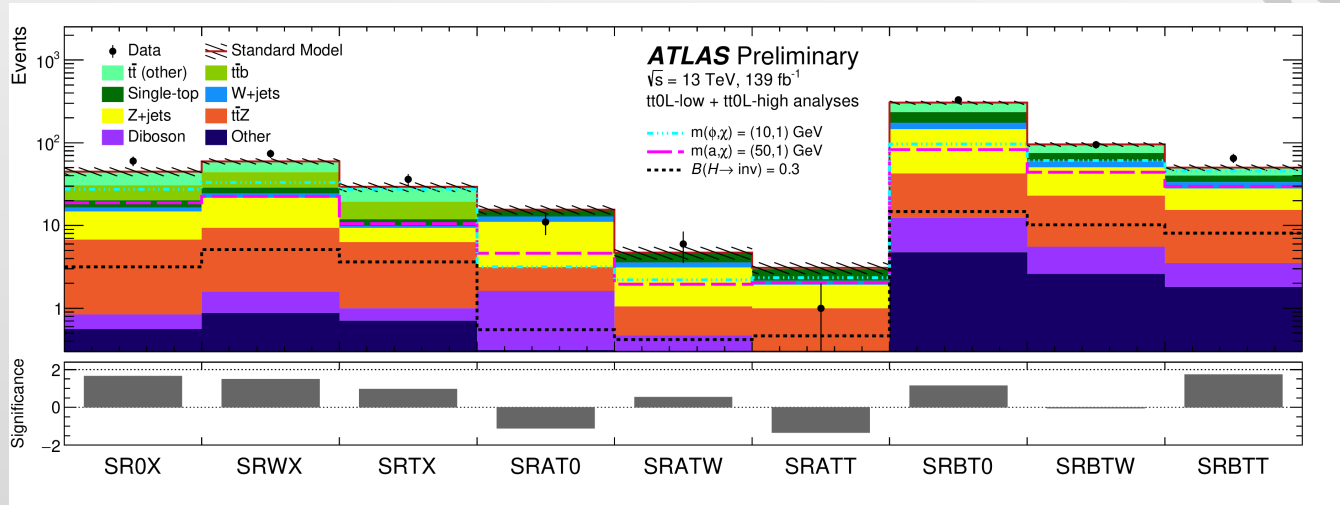
$tt + E_{T,\text{miss}}$ combination



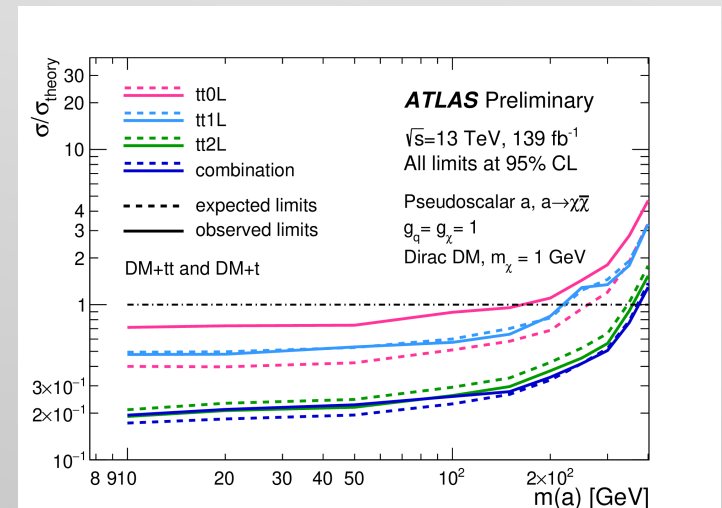
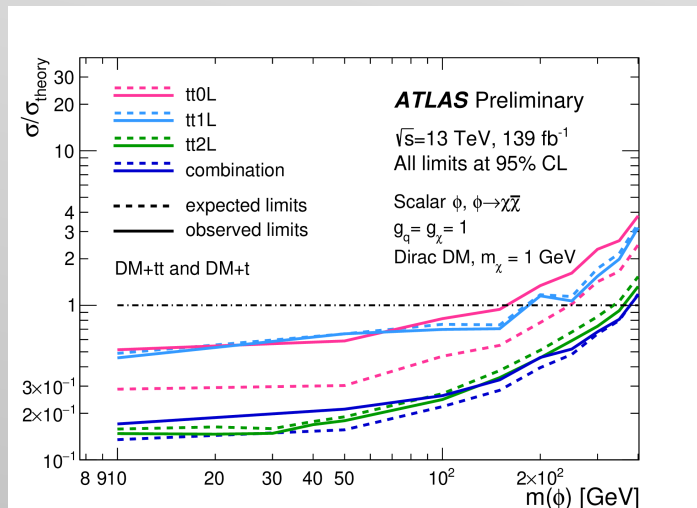
- For spin 0 mediators DM is assumed to be produced preferably in association with top quarks due to Yukawa-type couplings (for Minimal Flavour Violation).
- New combination of $tt + E_{T,\text{miss}}$ analyses with 2, 1 and 0 leptons.
 - new 0l low- $E_{T,\text{miss}}$ channel, making use of b-jet triggers
- Targetting scalar and pseudoscalar mediators (including SM Higgs).
- Same signature as stop pair production.
- Contribution also from tW +DM production.

$t\bar{t} + E_{T,miss}$ combination - results

All 0l signal region bins.
No excesses in 1l and 2l categories.



2l channel dominates sensitivity



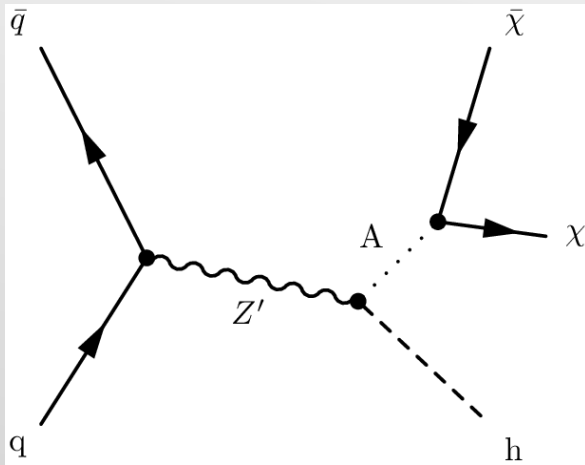
Simplified 1-mediator models (s-channel)

- cover a large set of models
- easy reinterpretation

Complete models with extended Higgs or gauge sector

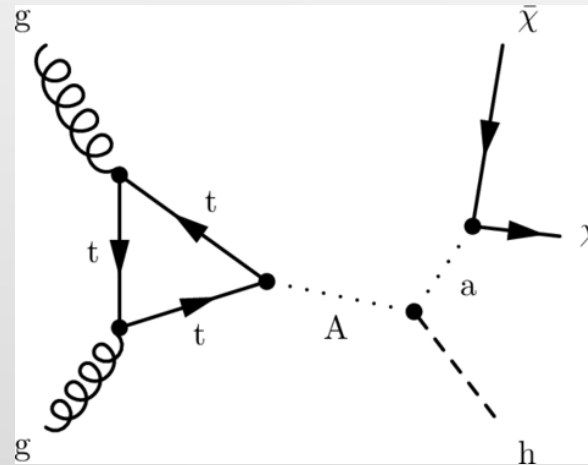
- cover only specific models
 - usually better sensitivity in these models
 - a discovery would tell us more about the underlying theory
- more free parameters

Mono-Higgs searches



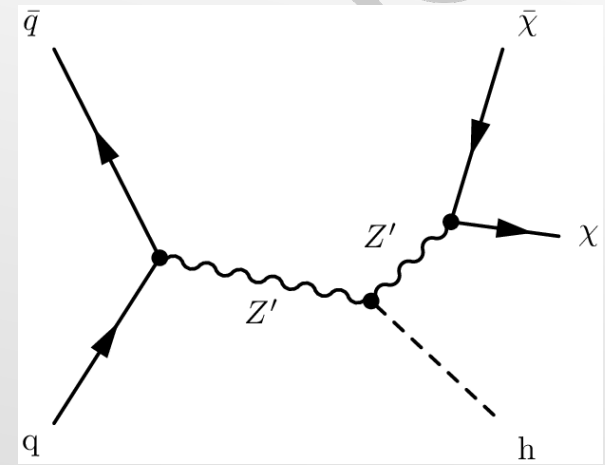
2HDM+Z'

- 5 new Higgs bosons
- 1 new vector boson



2HDM+a

- additional pseudoscalar which couples to SM fermions and DM
- allows gluon–gluon fusion



Z_B

- new $U(1)_B$ baryon number symmetry with new Z' and baryonic Higgs

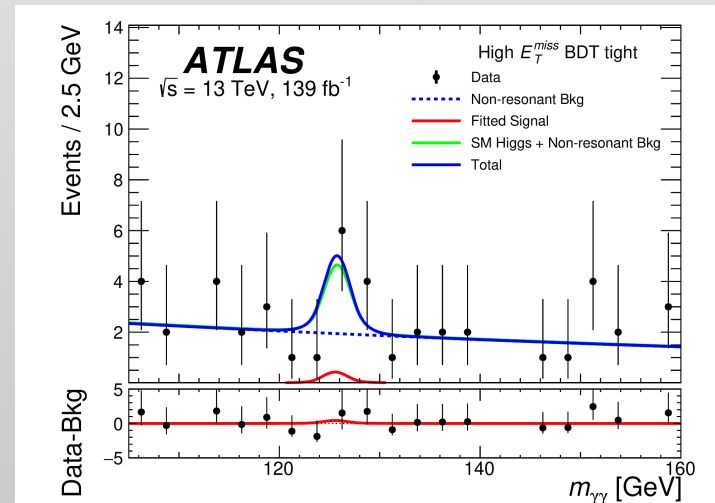
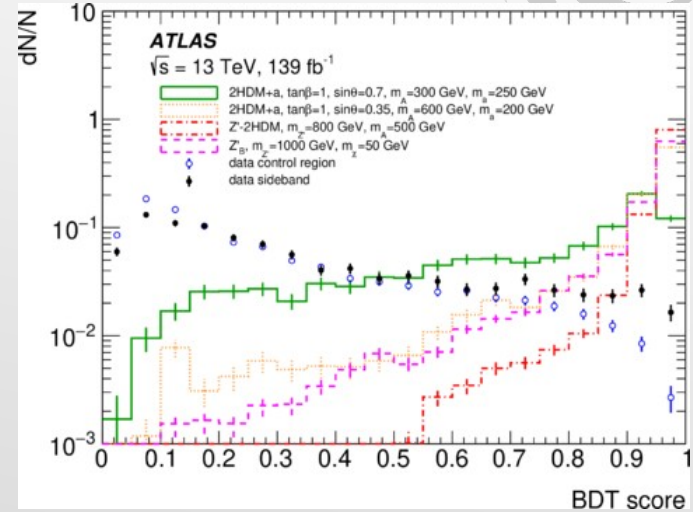
Mono-Higgs into photons

- Require $E_{T,\text{miss}} > 90$ GeV and two photons with $105 > m_{\gamma\gamma}/\text{GeV} > 160$.

- BDT using the two most discriminating variables $p_T^{\gamma\gamma}$ and $E_{T,\text{miss}}$ significance.

$$S_{E_T^{\text{miss}}} = E_T^{\text{miss}} / \sqrt{\sum E_T}$$

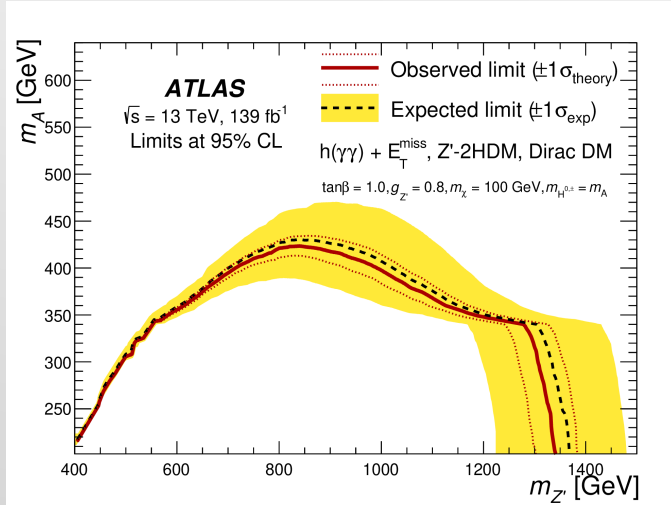
- signal: 2HDM+a model
- background: data from control region where one photon fails the identification/isolation criteria and with $120 > m_{\gamma\gamma}/\text{GeV} > 130$ vetoed
- 4 categories with high/low BDT score and high/low $E_{T,\text{miss}}$.
- Signal diphoton invariant mass distribution modelled with double-sided Crystal Ball function.
- Normalization of non-resonant background (exp. function) through fit to data, resonant background normalized to theory expectation.



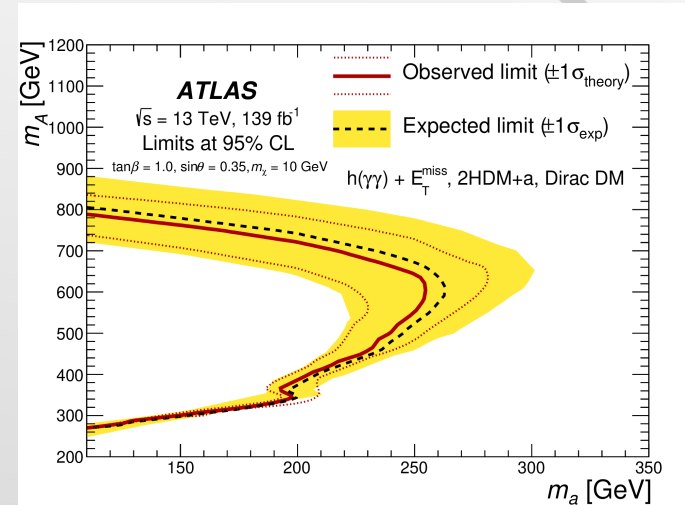
no significant excesses

Mono-Higgs into photons - results

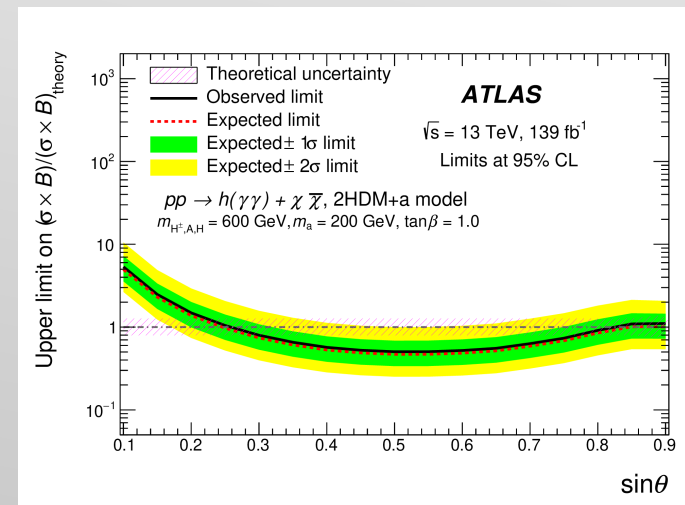
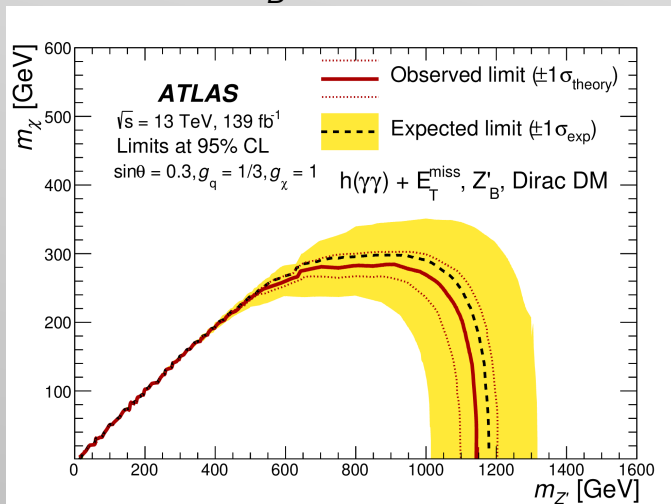
2HDM+Z'



2HDM+a



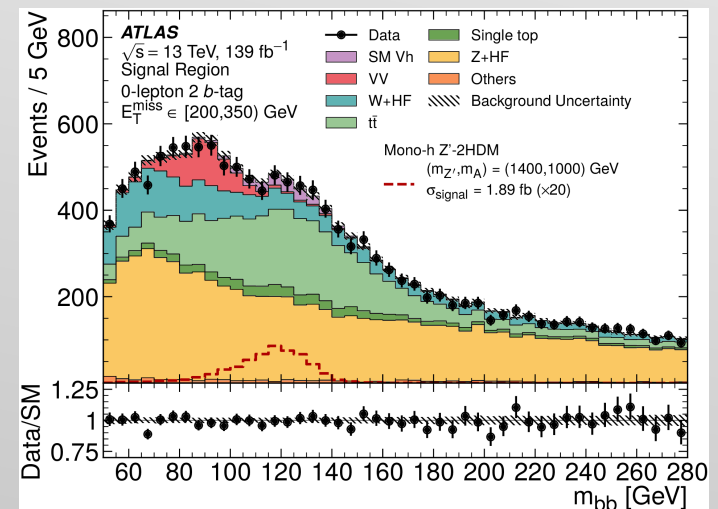
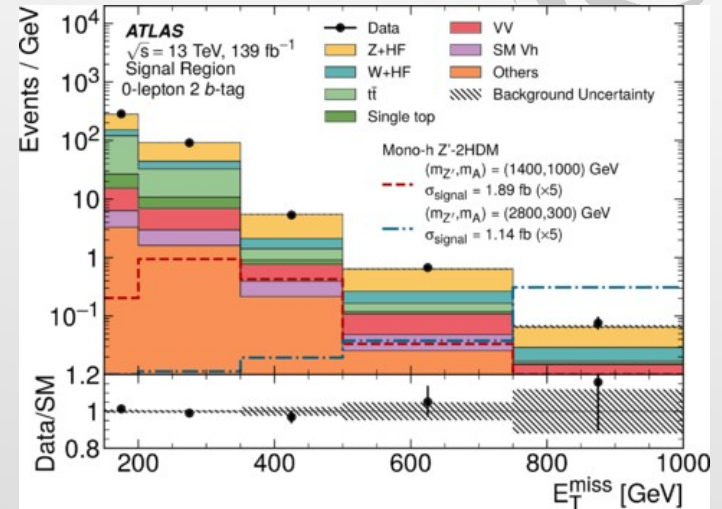
Z'_B



When the mixing angle θ between pseudoscalars a and A is 0 or $\pi/2$, signal vanishes.

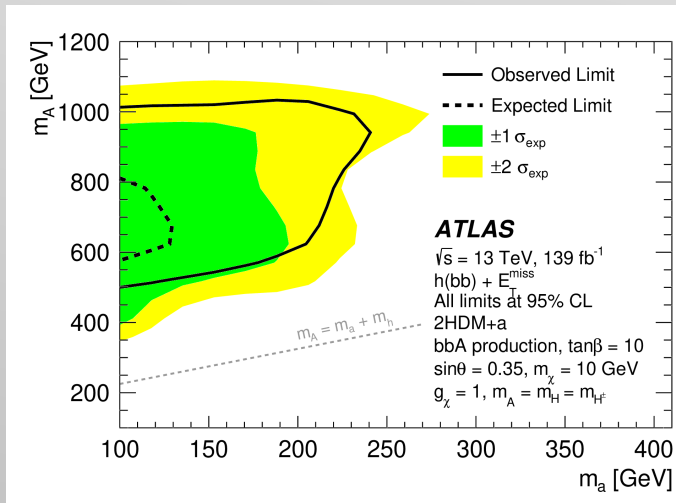
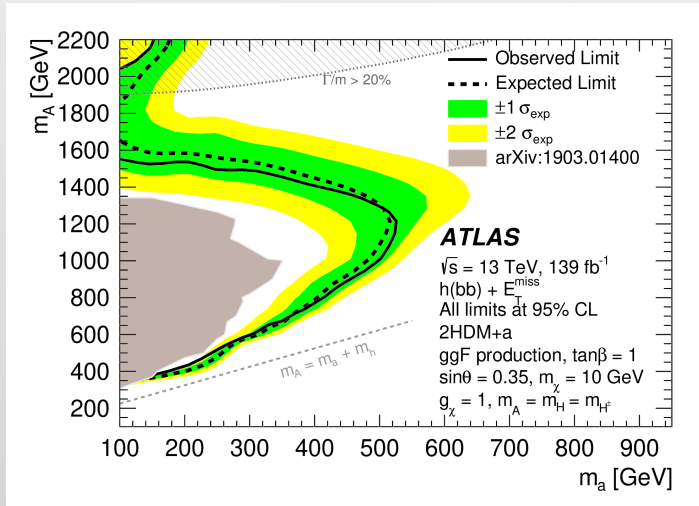
Mono-Higgs into b-quarks

- Require $E_{T,\text{miss}} > 150$ GeV and a $h \rightarrow bb$ candidate with two methods:
 - Resolved regime ($E_{T,\text{miss}} < 500$ GeV): 2 b-tagged small- R jets ($R=0.4$)
 - Boosted regime ($E_{T,\text{miss}} > 500$ GeV): one single large- R jet ($R=1$) with two associated b-tagged variable- R track jets
- Split into $E_{T,\text{miss}}$ and 2 b-tag/ ≥ 3 b-tag categories.
- Dedicated control regions to normalize non-resonant backgrounds:
 - 2-lepton CR for Z
 - 1-muon, split by charge, for W and tt
- Resonant background normalized to theory prediction.
- Simultaneous fit in m_{bb} spectrum.

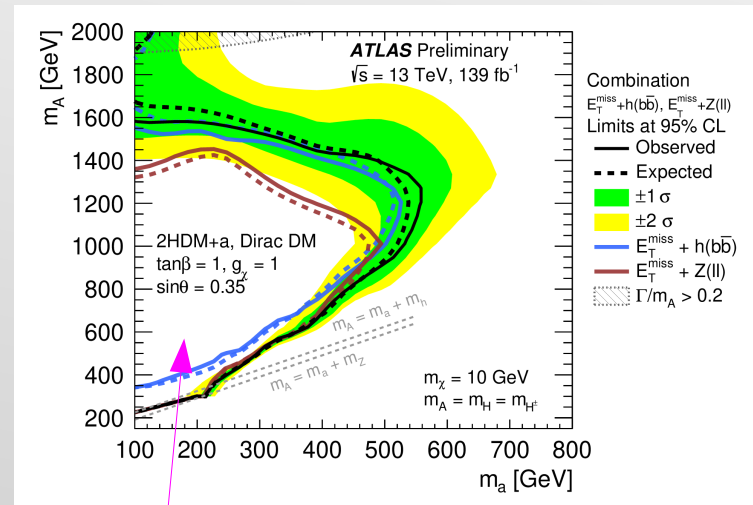


Mono-Higgs into b-quarks - results

2HDM+a



- Similarly sensitive as Z(II) channel
 → statistical combination



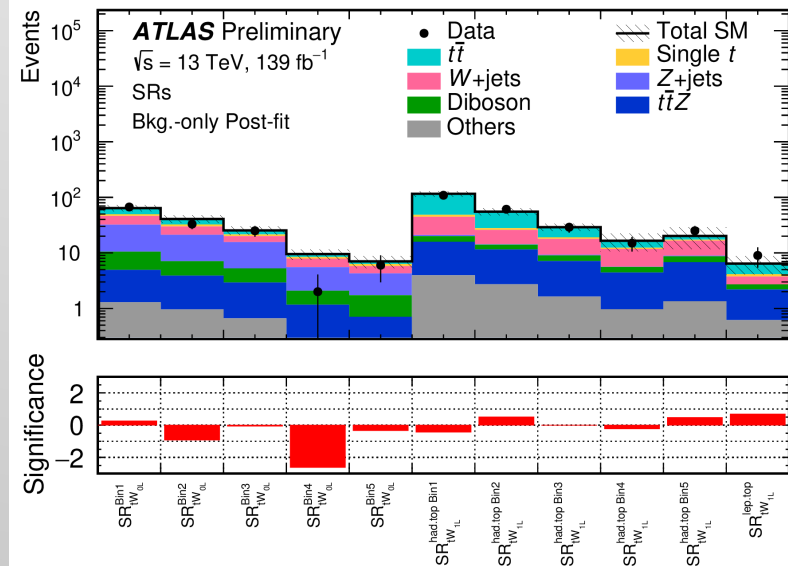
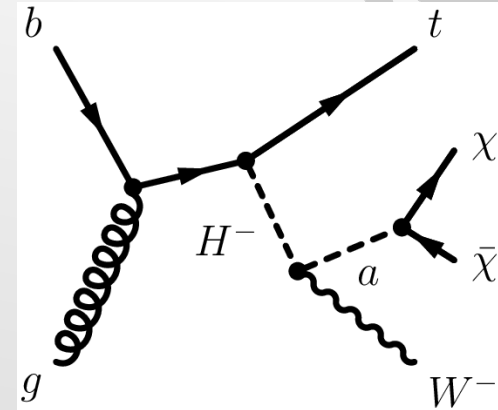
ATLAS-CONF-2021-036, [web](#)

$h(\gamma\gamma)$ mostly sensitive at
 $300 < m_A/\text{GeV} < 800$

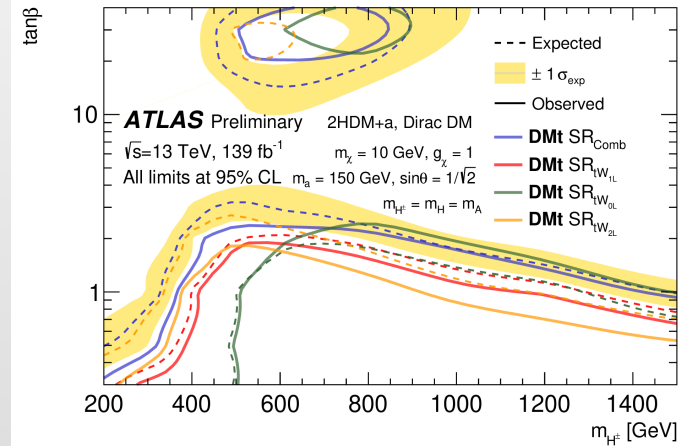
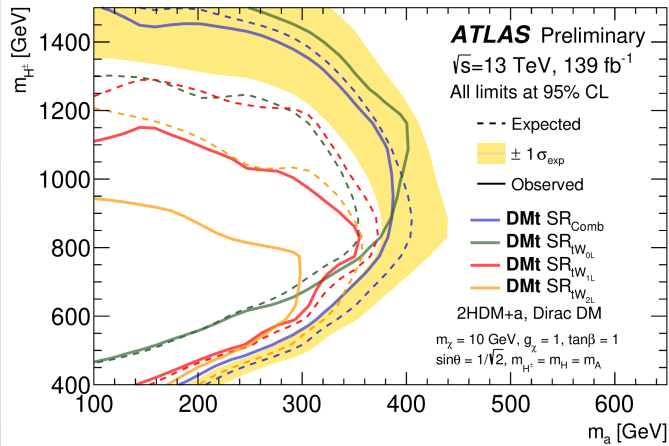
bbA production, targetted by ≥ 3 b-tag region

tW + dark matter

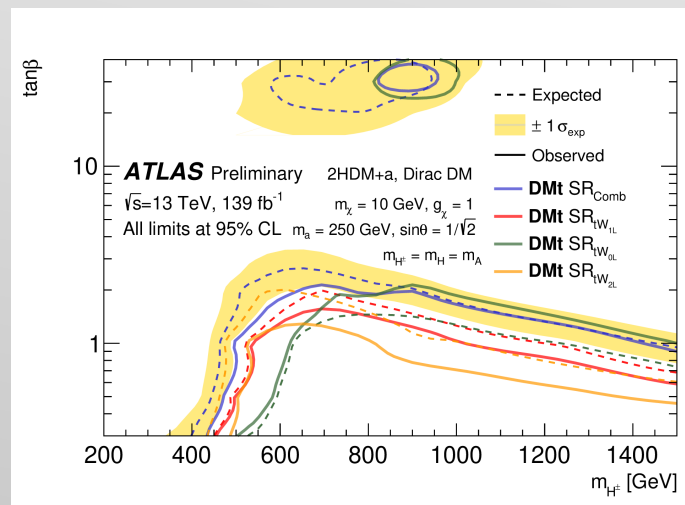
- Targetting scenario with a singletop quark and a high p_T W boson, motivated by 2HDM+a model.
- Require $E_{T,miss} > 250$ GeV and ≥ 1 b-jet.
- Channels with 0l and 1l (hadronic and leptonic top).
- Large- R jets ($R=1$) with W-tagging or two small- R jets for hadronic W candidate.
- Binning in $E_{T,miss}$.
- Dedicated CRs for main backgrounds ($t\bar{t}$, Z/W , $t\bar{t}Z$).
- Combination with previous 2l analysis.



tW + dark matter - results

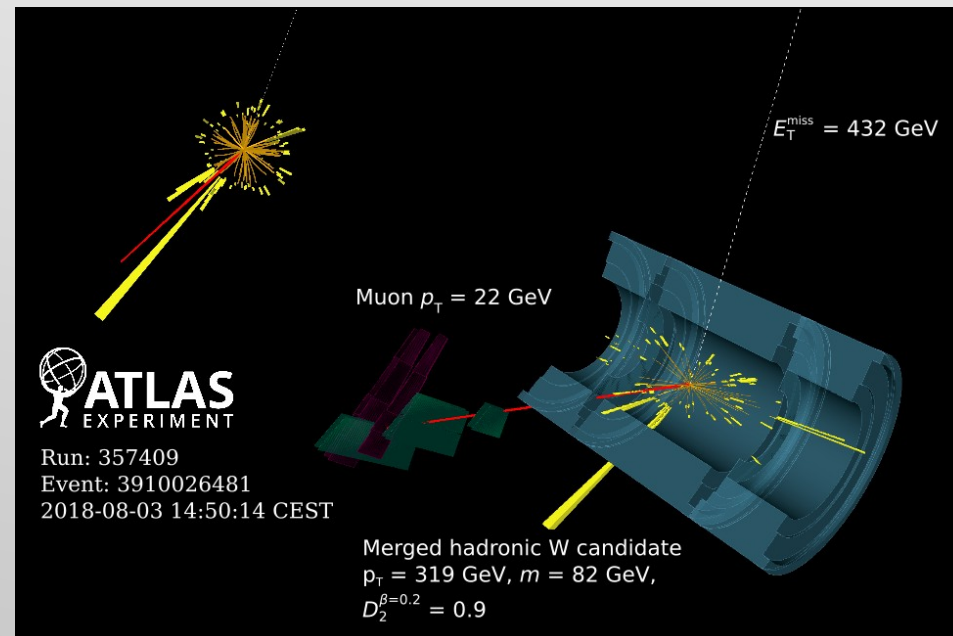
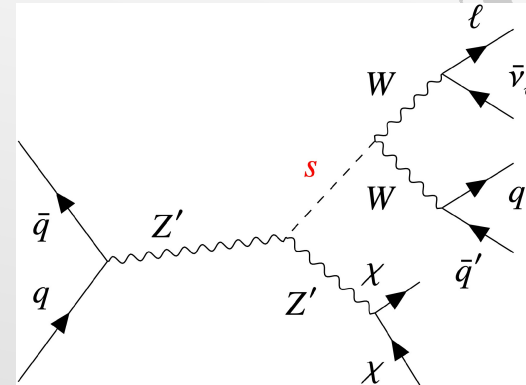


no significant excess
 → exclusion in (m_a, m_{H^\pm}) or $(m_{H^\pm}, \tan\beta)$ plane

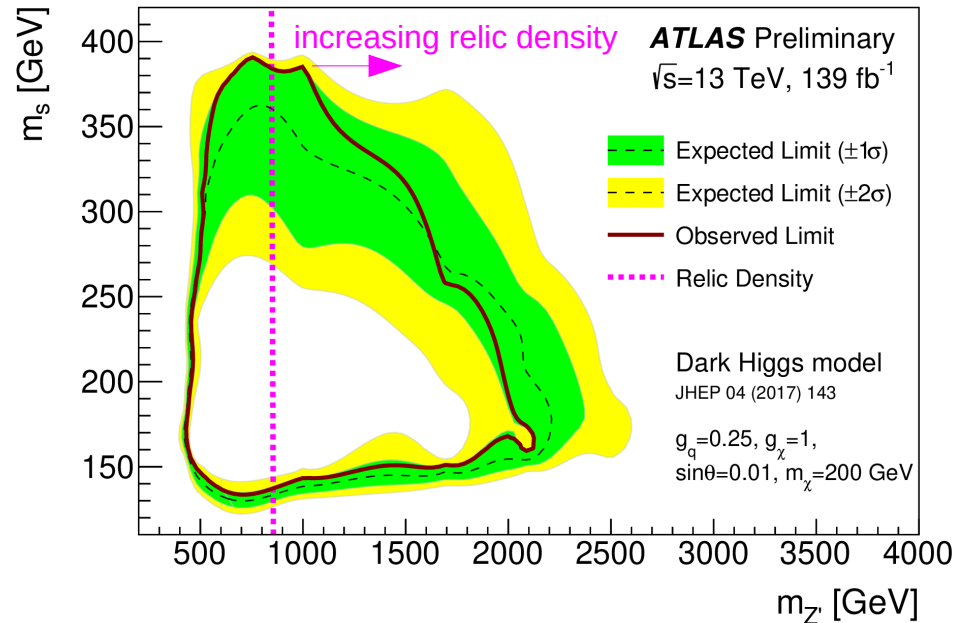
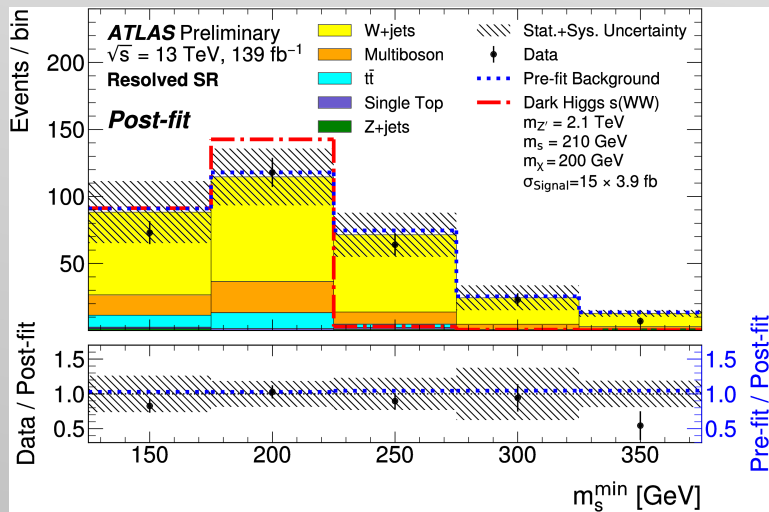
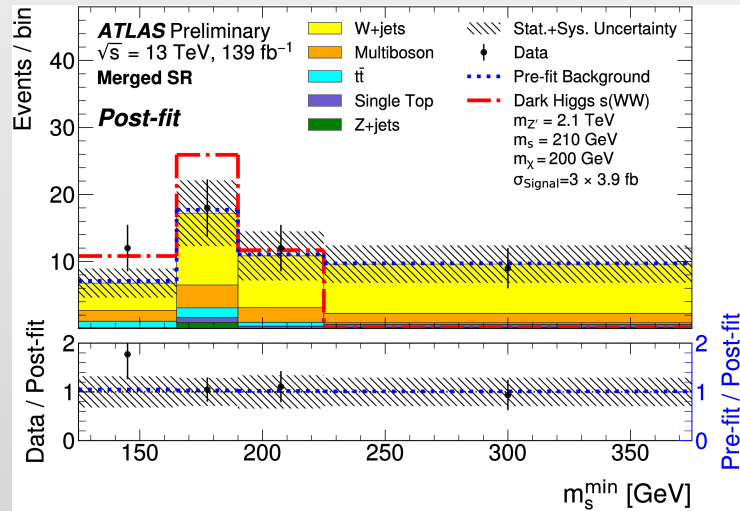


Mono-s(WW)

- Dark Higgs model provides Majorana fermion DM candidate, vector boson Z' , and dark Higgs boson s .
- Require high $E_{T,miss} > 200$ GeV and $=1$ lepton.
- Hadronic W candidate:
 - Merged category: large- R jet ($R=1$) using [track-assisted reclustering \(TAR\)](#) to deal with dense environment with hadronic activity + close-by lepton
 - Resolved category: two small- R jets
- Dedicated control regions for dominant W (large $\Delta R(W_{cand}, l)$) and $t\bar{t}$ (≥ 2 b-jets) backgrounds.
- Fit $m_{s,min}$ (\equiv approximate dark Higgs reconstruction considering invisible neutrino) distribution to data.

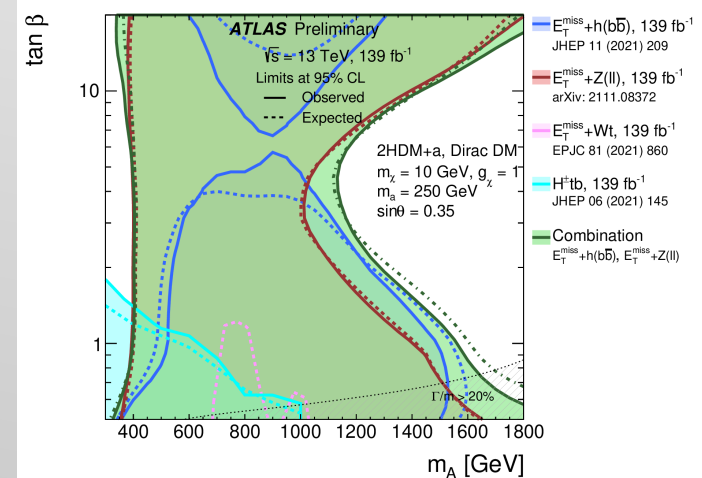
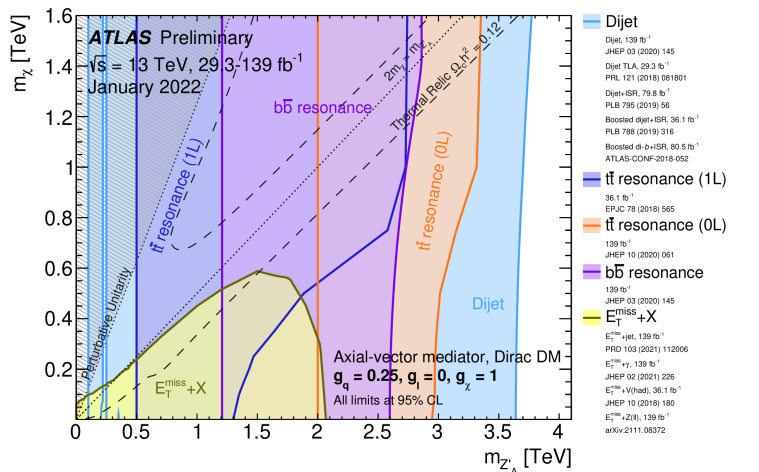
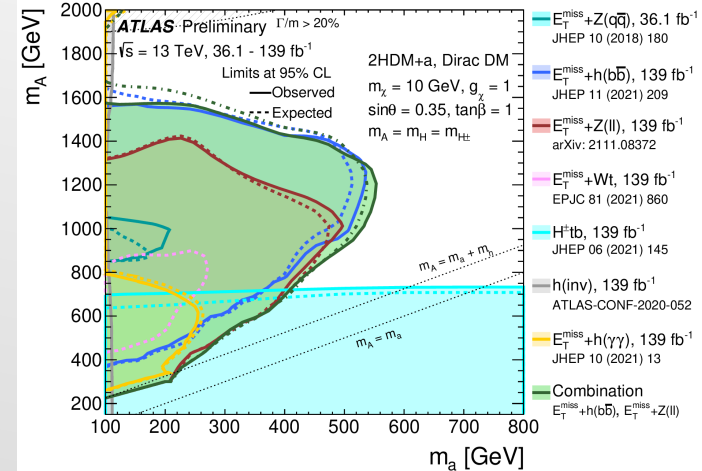
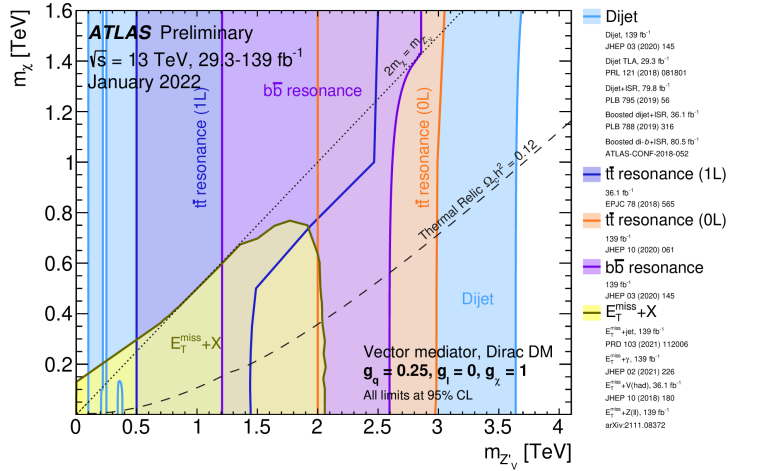


Mono-S(WW) - results



- No significant excess.
→ exclusion in $(m_{Z'}, m_s)$ plane
- Complementary to searches for $s \rightarrow b\bar{b}$ and $s \rightarrow VV \rightarrow \text{hadronic}$.

Summary plots



Summary plots available for s-channel and 2HDM+a: [ATL-PHYS-PUB-2021-045](#).
All ATLAS results available [here](#).

Conclusion

- Presented a selection of the latest results of ATLAS searches for dark matter.
 - more public results [here](#)
- Multiple new exclusion limits available:
 - One-mediator s-channel models
 - Complete models with several mediators (e.g. 2HDM+ a)
- Summary plots available showing the excluded regions from all results for specific models.
- Wide search program for DM, stay tuned for new results!
- Run-3 data soon!

Thank you!



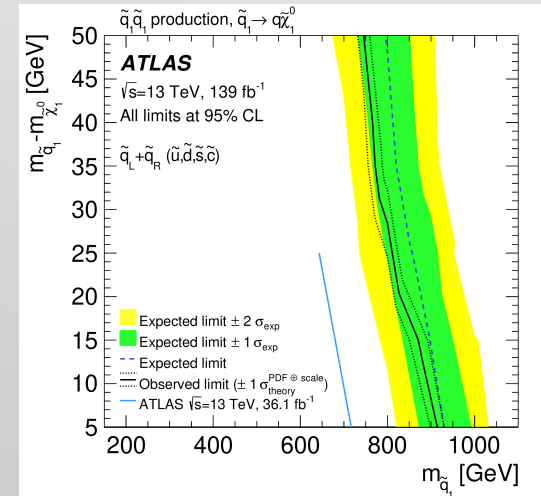
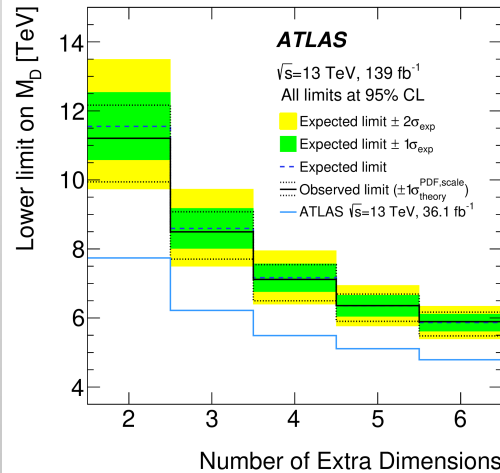
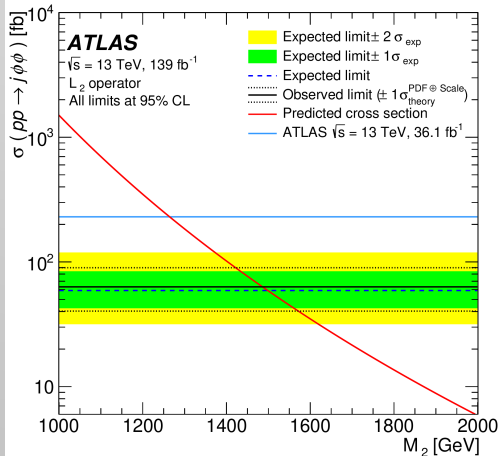
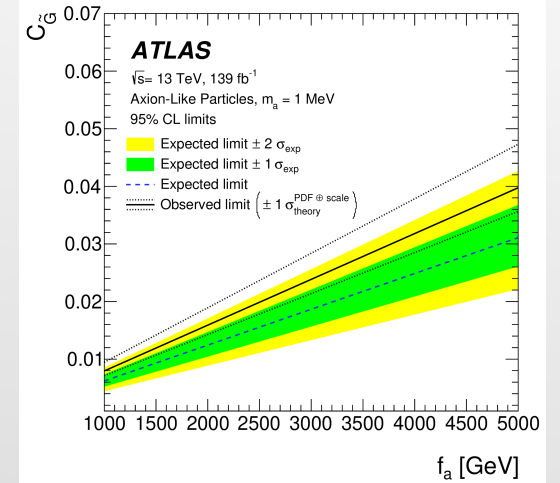
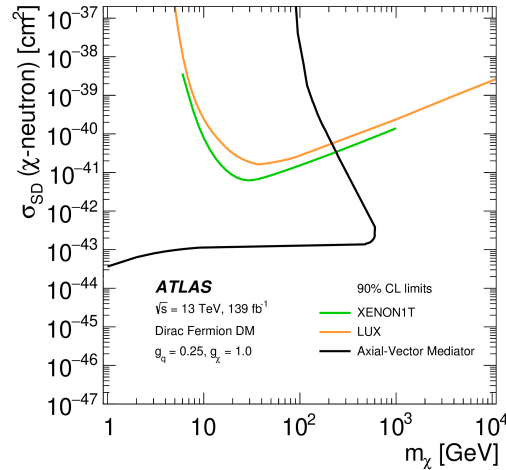
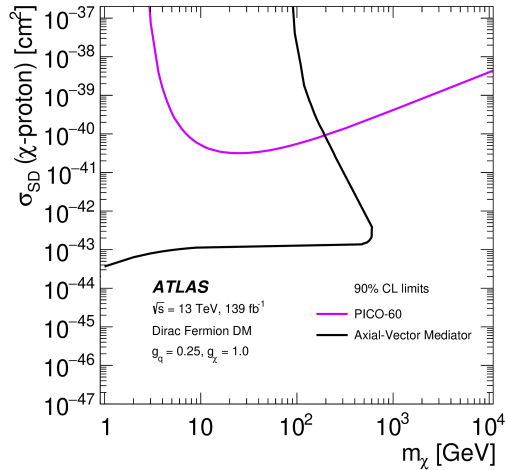
Backup



Monojet – selection

Requirement	SR	$W \rightarrow \mu\nu$	$Z \rightarrow \mu\mu$	$W \rightarrow e\nu$	$Z \rightarrow ee$	Top
Primary vertex	at least one with ≥ 2 associated tracks with $p_T > 500$ MeV					
Trigger	E_T^{miss}			single-electron		E_T^{miss} , single-electron
p_T^{recoil} cut	$E_T^{\text{miss}} > 200$ GeV	$ \mathbf{p}_T^{\text{miss}} + \mathbf{p}_T(\mu) > 200$ GeV	$ \mathbf{p}_T^{\text{miss}} + \mathbf{p}_T(\mu\mu) > 200$ GeV	$ \mathbf{p}_T^{\text{miss}} + \mathbf{p}_T(e) > 200$ GeV	$ \mathbf{p}_T^{\text{miss}} + \mathbf{p}_T(ee) > 200$ GeV	$ \mathbf{p}_T^{\text{miss}} + \mathbf{p}_T(\mu) > 200$ GeV or $ \mathbf{p}_T^{\text{miss}} + \mathbf{p}_T(e) > 200$ GeV
Jets	up to 4 with $p_T > 30$ GeV, $ \eta < 2.8$					
$ \Delta\phi(\text{jets}, \mathbf{p}_T^{\text{recoil}}) $	> 0.4 (> 0.6 if $200 \text{ GeV} < E_T^{\text{miss}} \leq 250 \text{ GeV}$)					
Leading jet	$p_T > 150$ GeV, $ \eta < 2.4$, $f_{\text{ch}}/f_{\text{max}} > 0.1$					
b -jets	any	none	any	none	any	at least one
Electrons or muons	none	exactly one muon, with $p_T > 10$ GeV, $30 < m_T < 100$ GeV; no electron	exactly two muons, with $p_T > 10$ GeV, $66 < m_{\mu\mu} < 116$ GeV; no electron	exactly one electron, tight, with $p_T > 30$ GeV, $ \eta \notin (1.37, 1.52)$, tight isolation, $30 < m_T < 100$ GeV; no muon	exactly two electrons, with $p_T > 30$ GeV, $66 < m_{ee} < 116$ GeV; no muon	same as for $W \rightarrow \mu\nu$ or same as for $W \rightarrow e\nu$
τ -leptons	none					
Photons	none					

Monojet – interpretation (1)

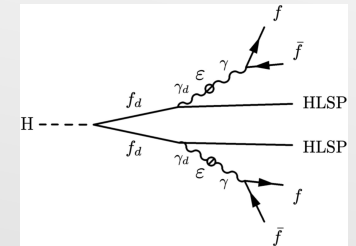
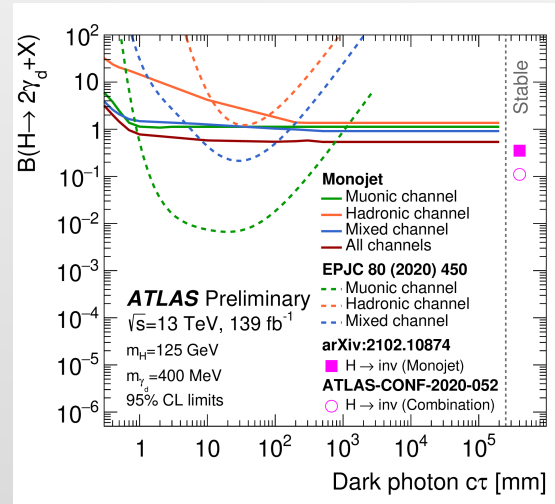


Monojet – interpretations (2)

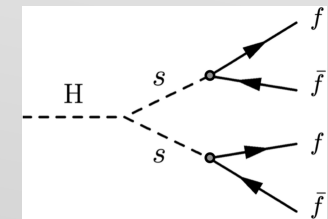
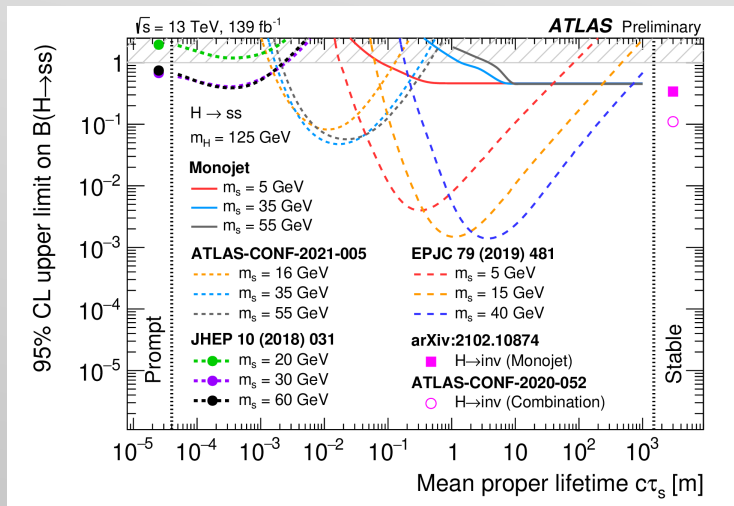
Higgs to invisible

- Signal: gluon-gluon fusion (73%), VBF (18%), VH (8%), ttH (1%)
- Result: $BF(H \rightarrow \text{inv}) \leq 34\%$ (39% exp.)

Dark sector



FRVZ model



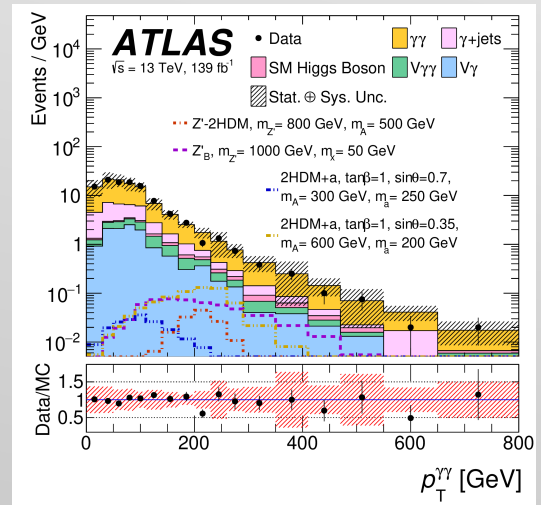
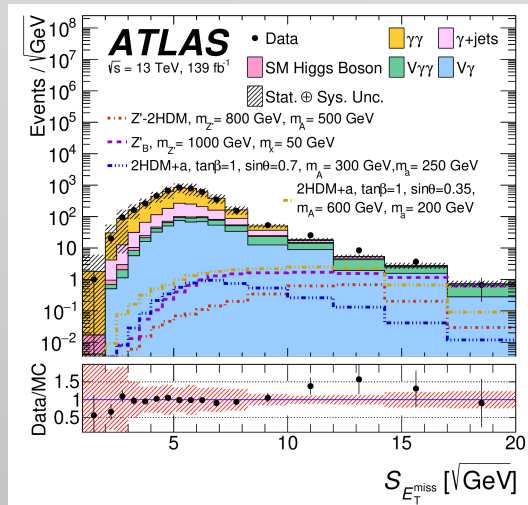
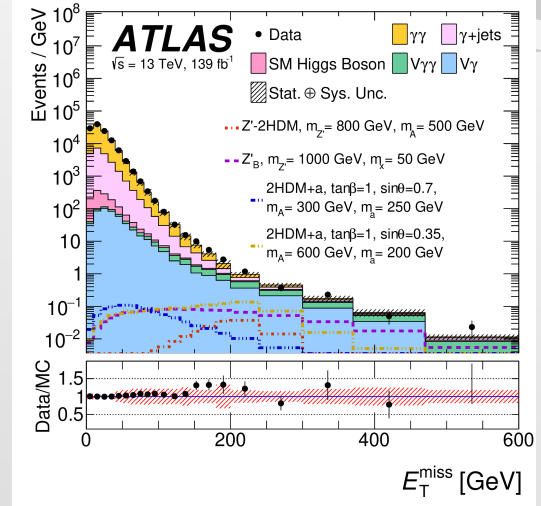
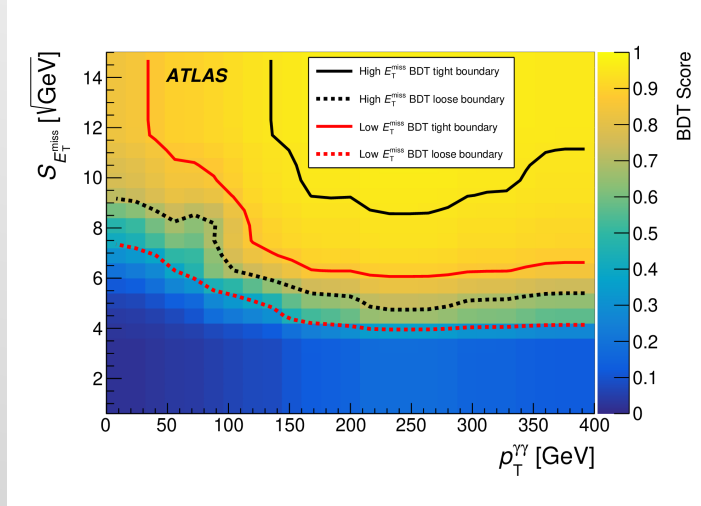
Long-lived scalar particles

Monojet – systematics



Source of uncertainty and effect on the total SR background estimate [%]			
Flavor tagging	0.1 – 0.9	τ -lepton identification efficiency	0.1 – 0.07
Jet energy scale	0.17 – 1.0	Luminosity	0.01 – 0.05
Jet energy resolution	0.15 – 1.3	Noncollision background	0.2 – 0.0
Jet JVT efficiency	0.01 – 0.03	Multijet background	1.0 – 0.0
Pileup reweighting	0.4 – 0.24	Diboson theory	0.01 – 0.22
E_T^{miss} resolution	0.34 – 0.04	Single-top theory	0.13 – 0.28
E_T^{miss} scale	0.5 – 0.25	$t\bar{t}$ theory	0.06 – 0.7
Electron and photon energy resolution	0.01 – 0.08	V+jets τ -lepton definition	0.04 – 0.16
Electron and photon energy scale	0.3 – 0.7	V+jets pure QCD corrections	0.24 – 1.1
Electron identification efficiency	0.5 – 1.0	V+jets pure EW corrections	0.17 – 2.2
Electron reconstruction efficiency	0.15 – 0.2	V+jets mixed QCD–EW corrections	0.02 – 0.7
Electron isolation efficiency	0.04 – 0.19	V+jets PDF	0.01 – 0.7
Muon identification efficiency	0.03 – 0.9	VBF EW V+jets backgrounds	0.02 – 1.1
Muon reconstruction efficiency	0.4 – 1.5	Limited MC statistics	0.05 – 1.9
Muon momentum scale	0.1 – 0.7		
Total background uncertainty in the Signal Region: 1.5%–4.2%			

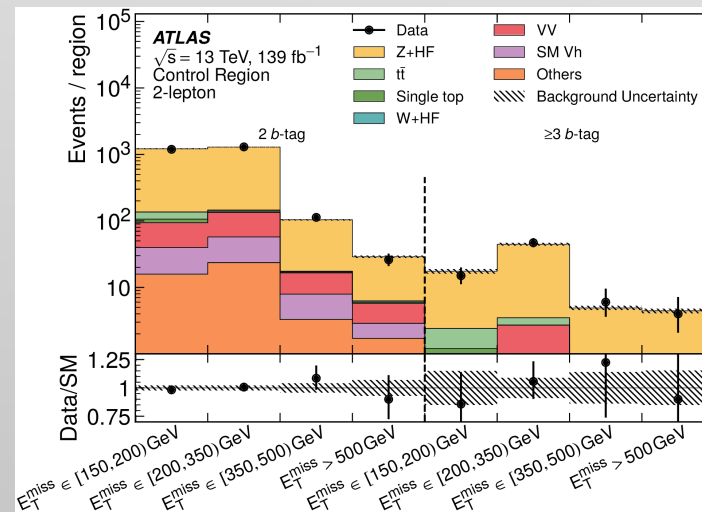
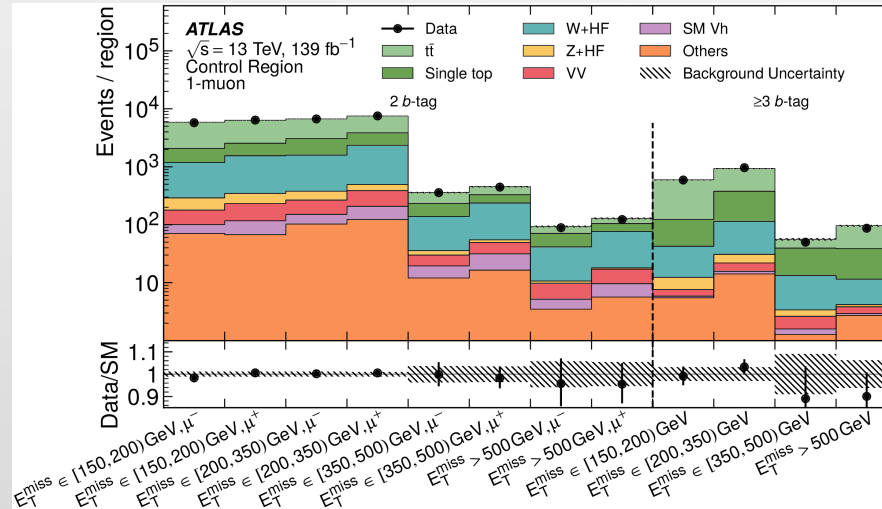
Mono-Higgs to photons - distributions



Higgs to photons - systematics

Source	Signals [%]	Backgrounds [%]	
		SM Higgs boson	Non-resonant background
Experimental			
Luminosity	1.7	1.7	—
Trigger efficiency	1.0	1.0	—
Vertex selection (inclusive cat.)	0.01	0.01	—
Photon energy scale	1.0	1.2	—
Photon energy resolution	0.3	0.4	—
Photon identification efficiency	1.3	1.3	—
Photon isolation efficiency	1.3	1.4	—
ATLFASTII simulation	2.0	—	—
$E_{\text{T}}^{\text{miss}}$ reconstruction and jet uncertainty	2.8	1.7	—
Pile-up reweighting	2.3	2.0	—
Signal efficiency interpolation	< 13	—	—
Non-resonant background modelling	—	—	6.8
Theoretical			
Factorization and renormalization scale in migration	1.3	3.5	—
PDF+ α_{s} in migration	1.2	1.0	—
Factorization and renormalization scale in cross section	—	2.8	—
PDF+ α_{s} in cross section	—	2.8	—
Multi-parton interactions, ISR/FSR, hadronization	3.0	3.0	—
$B(H \rightarrow \gamma\gamma)$	1.7	1.7	—

Mono-Higgs to b-quarks - control regions



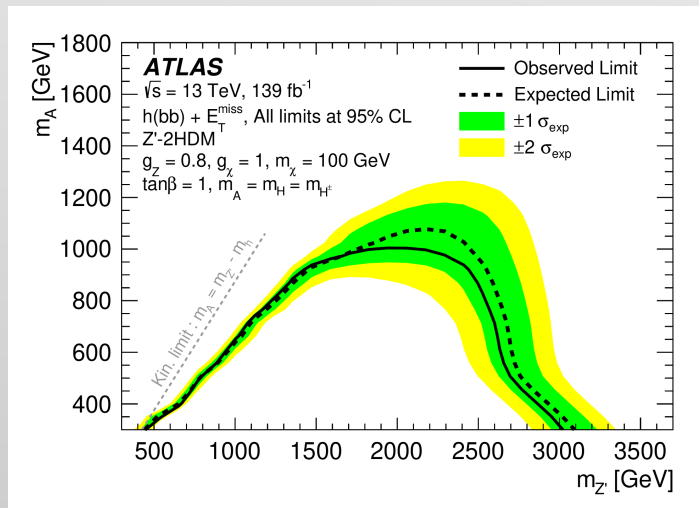
Mono-Higgs to b-quarks - selections

Resolved	Merged
Primary E_T^{miss} trigger	
Data quality selections	
$E_T^{\text{miss}} > 150 \text{ GeV}$	
Lepton veto & extended τ -lepton veto	
$\Delta\phi(\text{jet}_{1,2,3}, E_T^{\text{miss}}) > 20^\circ$	
$E_T^{\text{miss}} < 500 \text{ GeV}$	$E_T^{\text{miss}} > 500 \text{ GeV}$
At least 2 small- R jets	At least 1 large- R jet
At least 2 b -tagged small- R jets	At least 2 b -tagged associated variable- R track-jets
$p_{T_h} > 100 \text{ GeV}$ if $E_T^{\text{miss}} < 350 \text{ GeV}$	—
$p_{T_h} > 300 \text{ GeV}$ if $E_T^{\text{miss}} > 350 \text{ GeV}$	
$m_T^{b,\text{min}} > 170 \text{ GeV}$	—
$m_T^{b,\text{max}} > 200 \text{ GeV}$	—
$S > 12$	—
$N_{\text{small-}R \text{ jets}} \leq 4$ if 2 b -tag	—
$N_{\text{small-}R \text{ jets}} \leq 5$ if ≥ 3 b -tag	
$50 \text{ GeV} < m_h < 280 \text{ GeV}$	$50 \text{ GeV} < m_h < 270 \text{ GeV}$

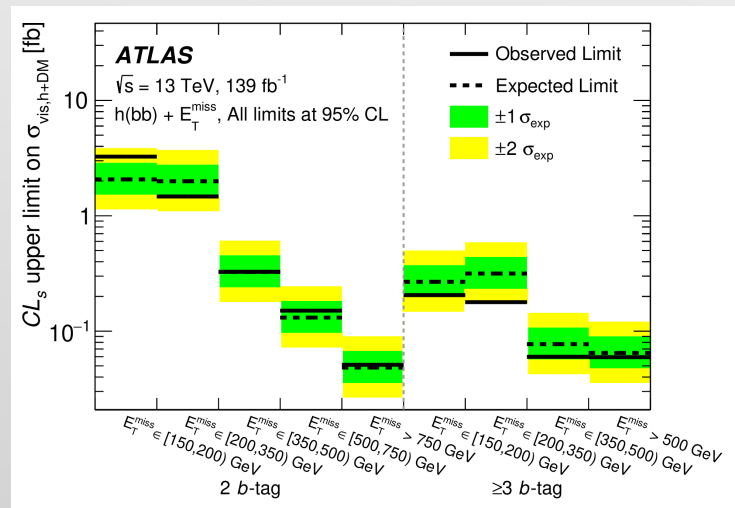
	0 lepton	1 muon	2 leptons
Aim	Signal regions	$t\bar{t}$ and W +HF control region	Z +HF control regions
Fitted observable	m_h distribution	Muon charge (2 b -tag) Yields (≥ 3 b -tag)	Yields
b -tag multiplicities	resolved (small- R jets): 2, ≥ 3 merged (variable- R track-jets): 2 (inside h candidate), ≥ 3 (2 inside h candidate)		
E_T^{miss} proxy	E_T^{miss}	$E_{T, \text{lep. invis.}}^{\text{miss}}$	$E_{T, \text{lep. invis.}}^{\text{miss}}$
Bins in E_T^{miss} proxy	resolved: [150, 200), [200, 350) and [350, 500) GeV		
	2 b -tag merged signal regions (0 lepton): [500, 750) and [750, ∞) GeV Other merged regions: [500, ∞) GeV		

Mono-Higgs to b-quarks – more interpretations

2HDM+Z'



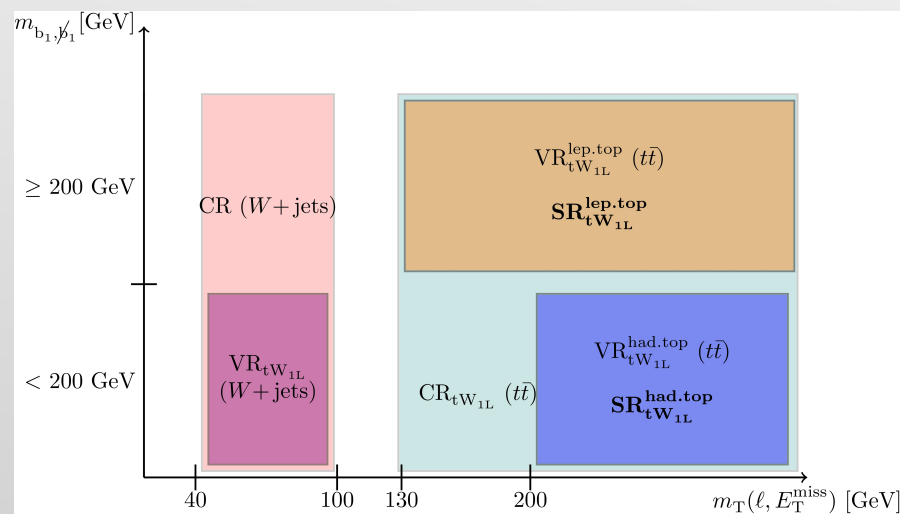
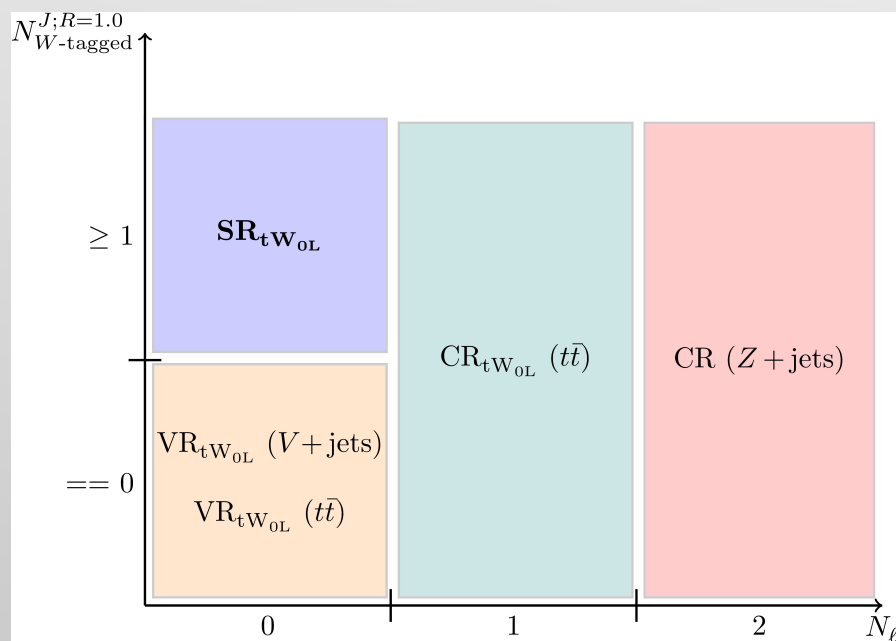
model-independent limits



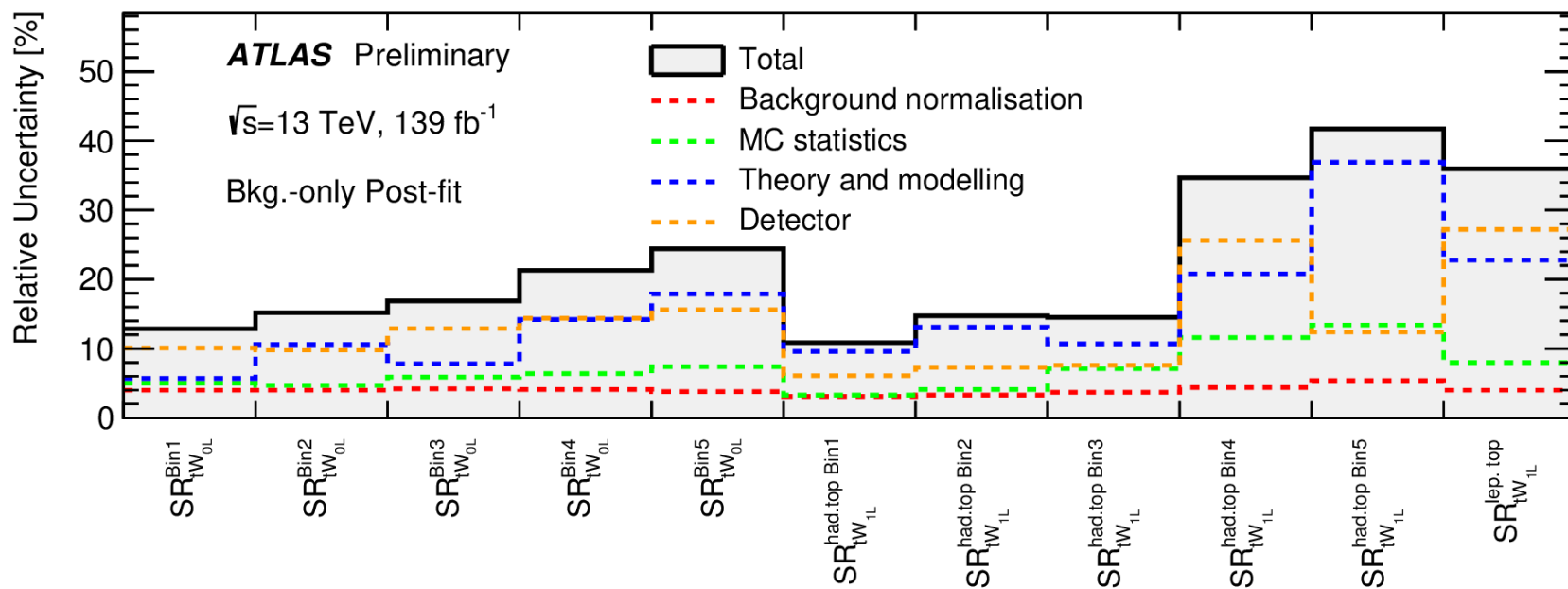
Mono-Higgs to b-quarks - systematics

Source of uncertainty	Fractional squared uncertainty in μ		
	Z' -2HDM signals, (m'_Z, m_A) [GeV]		
	(800, 500)	(1400, 1000)	(2800, 300)
Z +HF normalisation	0.11	0.03	<0.01
W +HF normalisation	0.02	0.01	<0.01
$t\bar{t}$ normalisation	0.16	0.04	<0.01
Z modelling uncertainties	0.02	0.07	<0.01
W modelling uncertainties	<0.01	0.01	<0.01
$t\bar{t}$ modelling uncertainties	0.13	0.05	<0.01
Single- t modelling uncertainties	0.18	0.02	<0.01
Other modelling uncertainties	0.05	0.01	<0.01
Jets	0.20	0.06	0.01
b -tagging	0.01	0.01	0.04
E_T^{miss} soft term and pile-up	<0.01	<0.01	<0.01
Other experimental systematic uncertainties	0.01	<0.01	<0.01
Signal systematic uncertainties	<0.01	<0.01	<0.01
MC sample size	0.08	0.07	0.11
Statistical uncertainty	0.27	0.61	0.79
Total systematic uncertainties	0.73	0.39	0.21

tW + DM - regions



tW + DM - systematics



Mono-s(WW) – selections

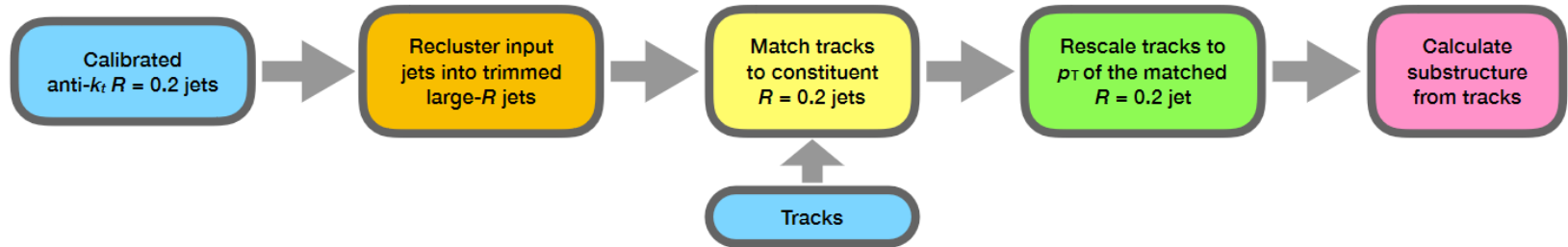


Requirement	SR	CRW	CRTT
Trigger N_ℓ m_T [GeV] E_T^{miss} [GeV]	E_T^{miss} or single muon = 1 > 220 > 200		
$N_{b\text{-Jets}}$ $N_{\text{TAR Jets}}$ $m_{W_{\text{cand}}}$ [GeV] \mathcal{S} $\Delta R(W_{\text{cand}}, \ell)$ $D_2^{\beta=1}$	0 > 16 < 1.2	0 ≥ 1 [68, 89] > 12 > 1.8 < 1.1	≥ 2 > 12 < 1.2
m_s^{min} binning [GeV]	[125, 165, 190, 225, 375]	incl.	incl.

Requirement	SR	CRW	CRTT
Orthogonality	Fails merged category selections		
Trigger N_ℓ m_T [GeV] E_T^{miss} [GeV]	E_T^{miss} or single muon = 1 > 200 > 250		
$N_{b\text{-Jets}}$ N_{Jets} $m_{W_{\text{cand}}}$ [GeV] \mathcal{S} $\Delta R(W_{\text{cand}}, \ell)$ $p_{T, W_{\text{cand}}}$ [GeV]	0 < 1.4	0 ≥ 2 [65, 95] > 16 > 1.4 > 150	≥ 2 < 1.4
m_s^{min} binning [GeV]	[125, 175, 225, 275, 325, 375]	incl.	incl.

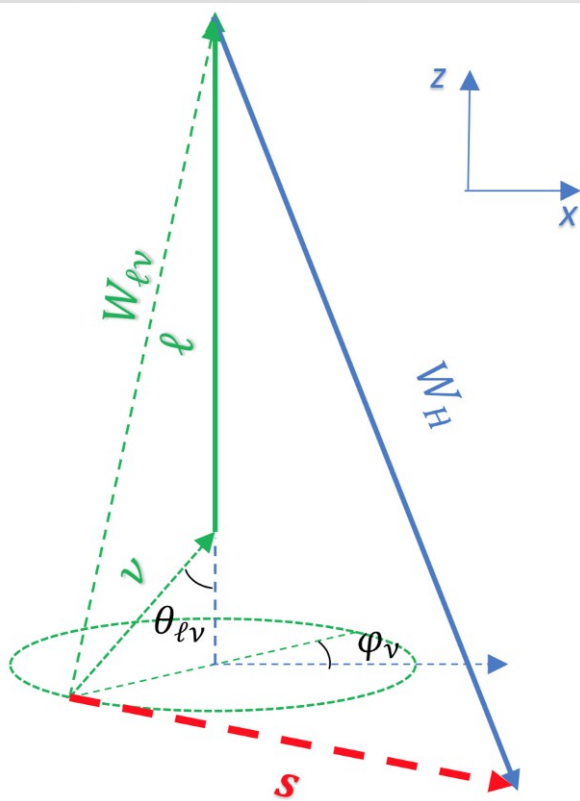
Mono-s(WW) – methods

TAR



Analytical solution of $s \rightarrow WW \rightarrow qq\ell\nu$ system

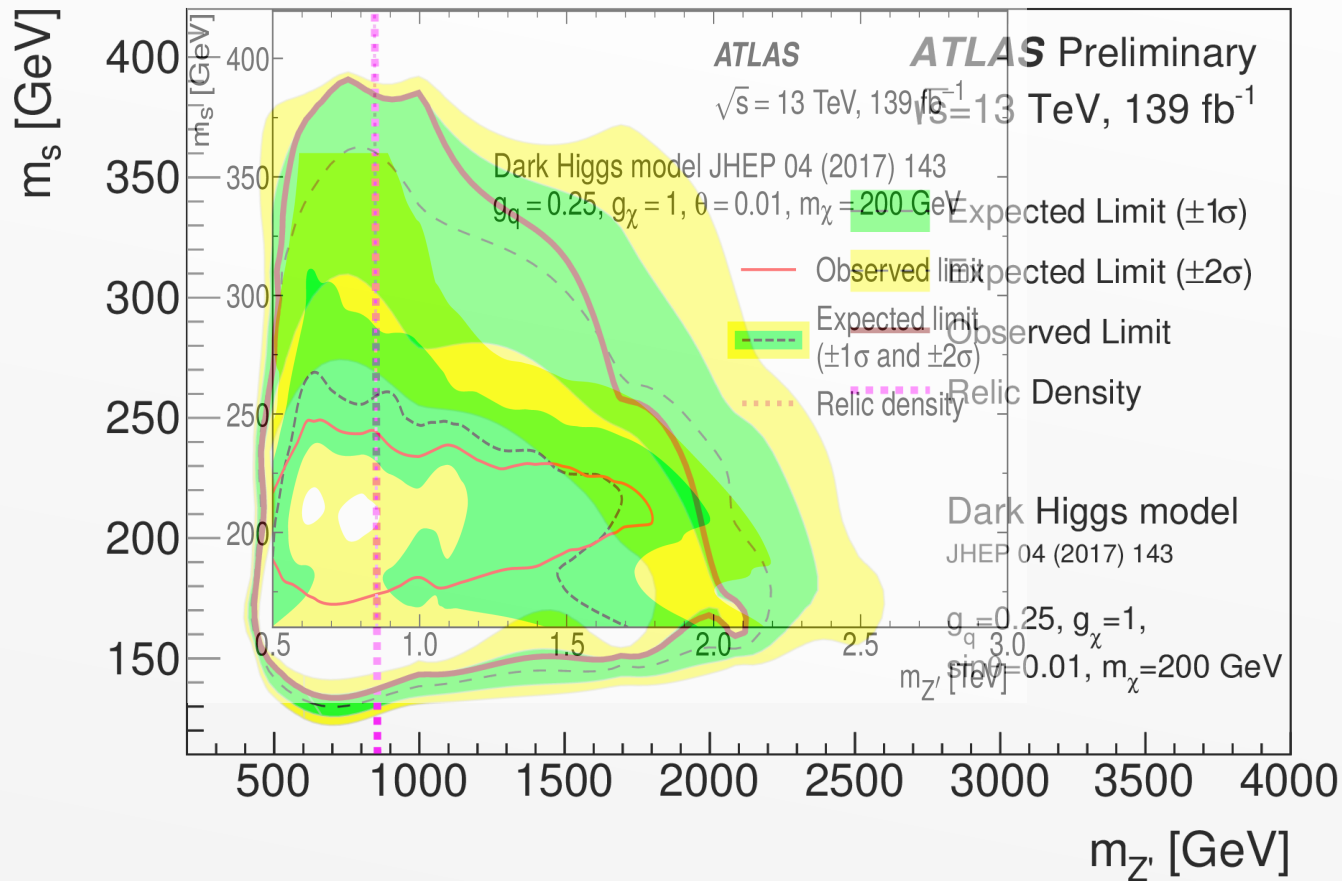
- Find minimum m_s consistent with observed W_{had} and lepton momenta and $m_W = 80.4$ GeV constraint.
- Use a rotated frame of reference with lepton along z-axis and hadronic W in x-z plane.
- m_s^{min} occurs at $\phi_v = 0$.
- Solve numerically for θ_{lv} subject to m_W constraint



Mono-s(WW) – systematics

Source of uncertainty	Uncertainty [%]		
	(2100, 210)	(1000, 140)	(1000, 360)
W +jets modelling	4	5	2
Diboson modelling	5	4	1
$t\bar{t}$ modelling	7	4	1
Single top modelling	9	5	11
Signal modelling	1	3	0
MC statistics	26	15	29
$R = 0.4$ jet energy scale	11	12	14
$R = 0.4$ jet energy resolution	9	4	7
$R = 0.2$ jet energy scale	9	9	14
$R = 0.2$ jet energy resolution	13	10	16
E_T^{miss}	7	1	7
Track reconstruction	5	2	2
Lepton reconstruction	2	3	1
Systematic uncertainty	38	28	40
Statistical uncertainty	38	32	37
Total uncertainty	53	43	55

Mono-s comparison



New result overlaid with previous result (mono-s ($\rightarrow VV \rightarrow qqqq$))
 Phys. Rev. Lett. 126 (2021) 121802, [web](#)

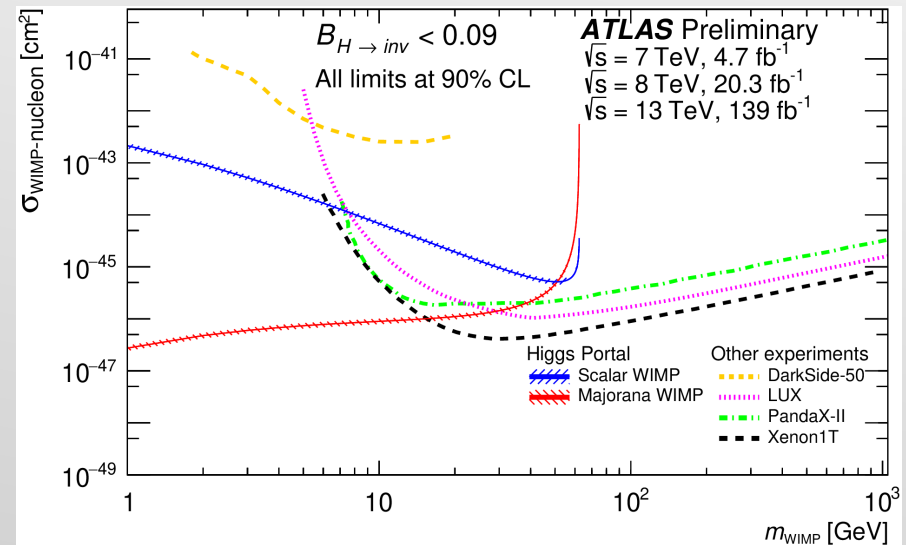
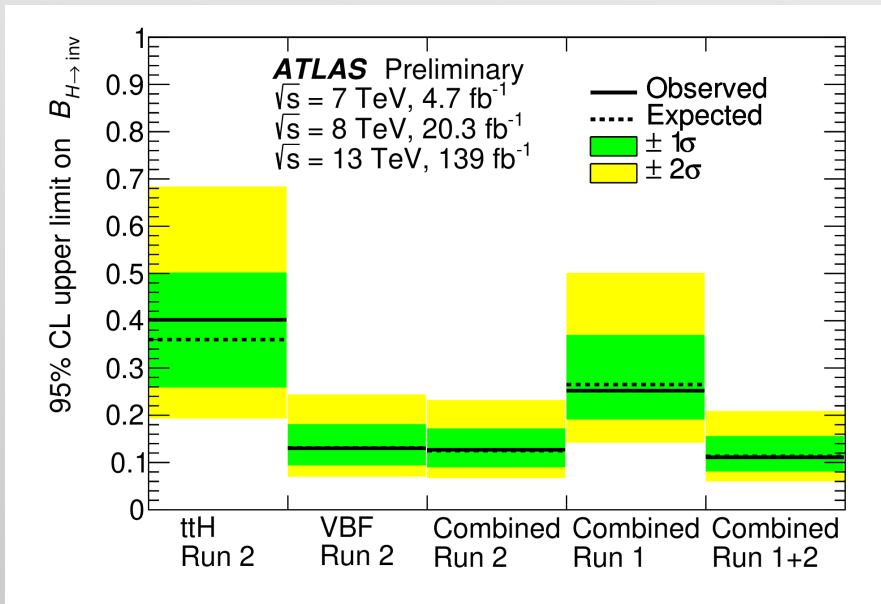
Higgs to invisible

Run 1&2 combination

Most stringent direct limit so far

$\text{BF}(H \rightarrow \text{inv.}) \leq 11\%$ (11% exp)

ATLAS-CONF-2020-052



New VBF+E_{T,miss} result (most sensitive channel):

$\text{BF}(H \rightarrow \text{inv.}) \leq 14.5\%$ (10.3% exp) (submitted to JHEP, [web](#))