MET searches for dark sectors at ATLAS

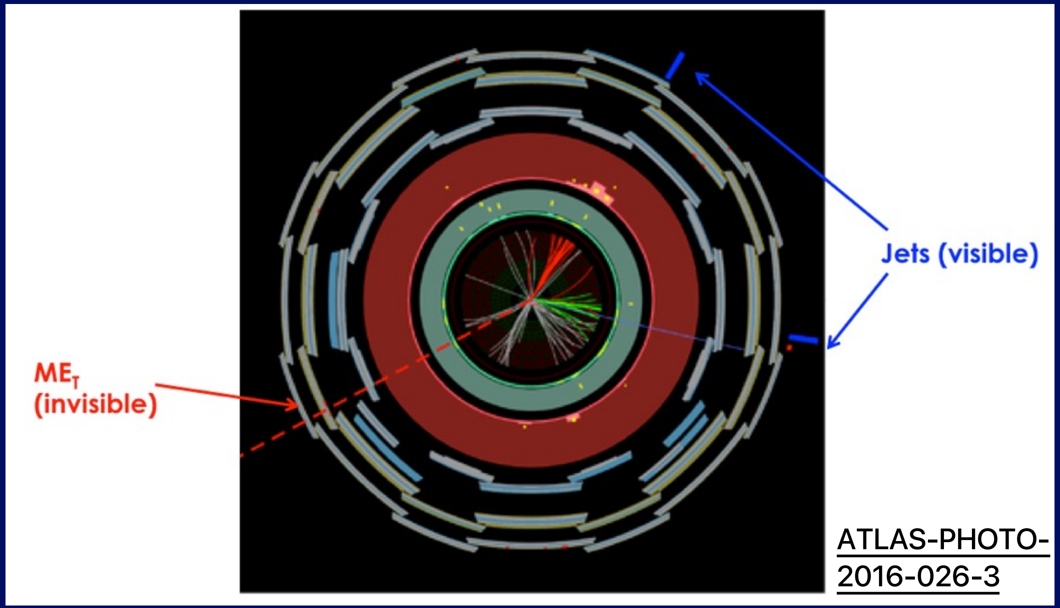
LHCP 2024 at Boston

June 3rd, 2024

Kaito Sugizaki on behalf of the ATLAS collaboration

The University of Tokyo

Why missing E_{T} (MET)?



Clear proxy to BSM physics in colliders

- ➢ Provides direct and model-independent signatures of BSM
- ➢ Helps in reducing SM backgrounds (e.g. multi-jet events)

“Dark sector” search programs at ATLAS (in a broad sense)

- ➢ Object-based invisible searches (e.g. $E_{\mathrm{T}}^{\mathrm{miss}} + X$)
- ➢ Supersymmetric DM (stau-bino coannhilation, wino, higgsino, and etc.)

Contents

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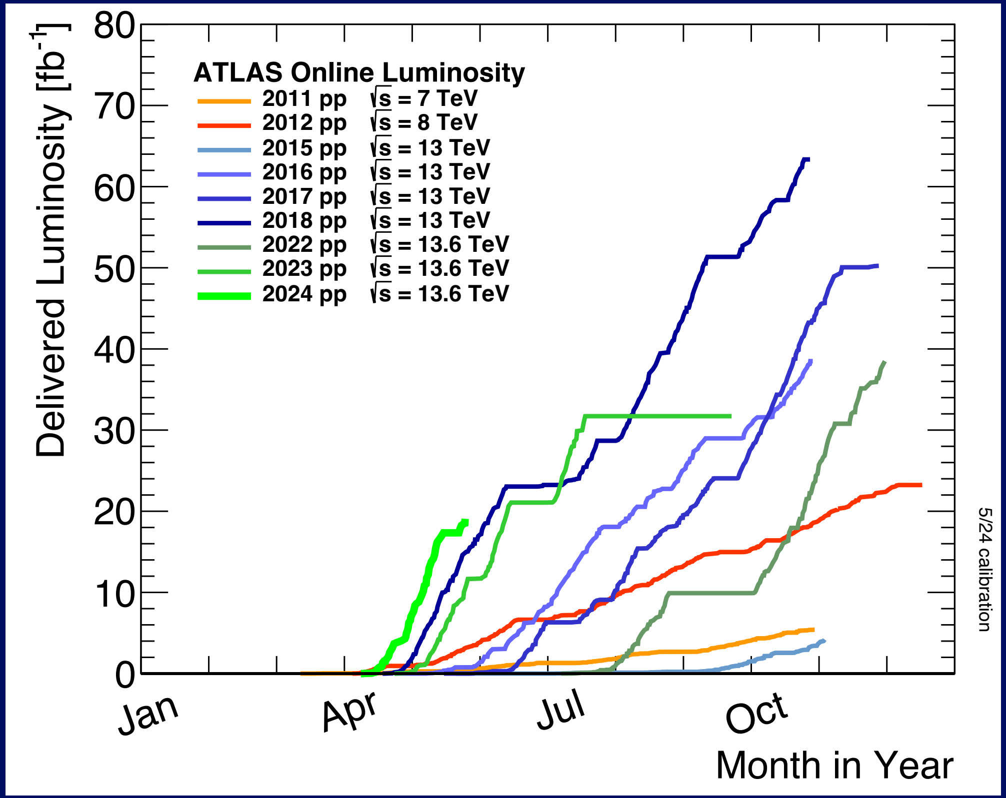
Four new BSM search results which use $E_{\mathrm{T}}^{\mathrm{miss}}$ with full Run 2 data

- DM s-channel mediator search summary
- Stau and electroweakino search with $E_{\mathrm{T}}^{\mathrm{miss}}$ + di-tau
- Higgsino search with $E_{\mathrm{T}}^{\mathrm{miss}}$ + displaced track
- SUSY EWK pMSSM summary



All results accessible from AtlasPublic page

DM with s-channel mediators

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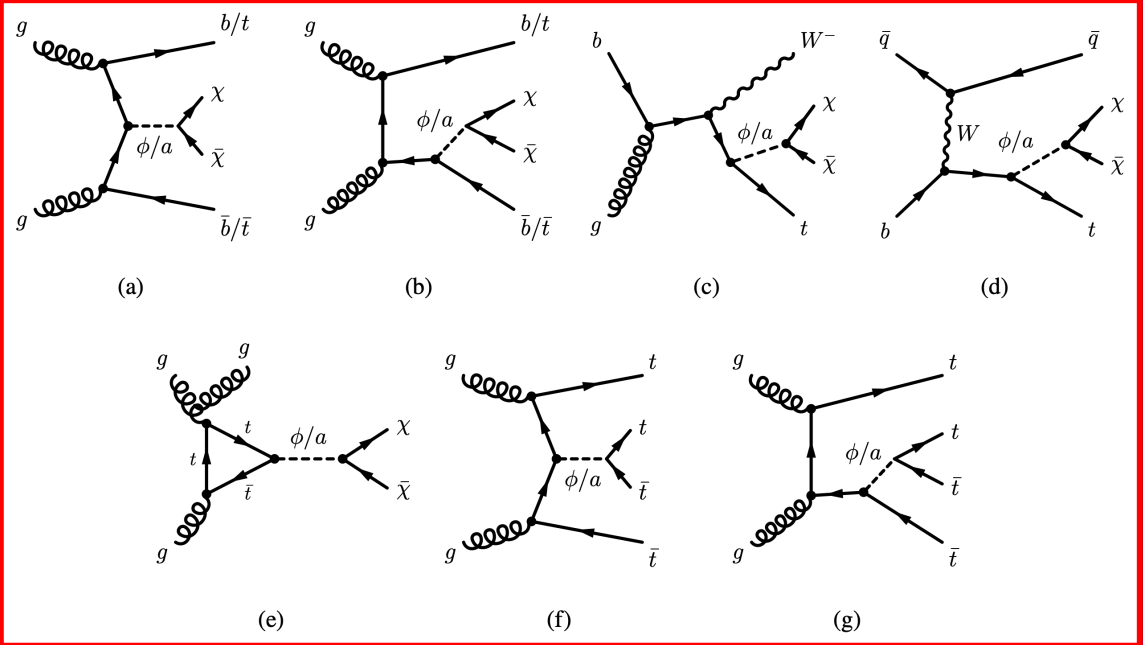
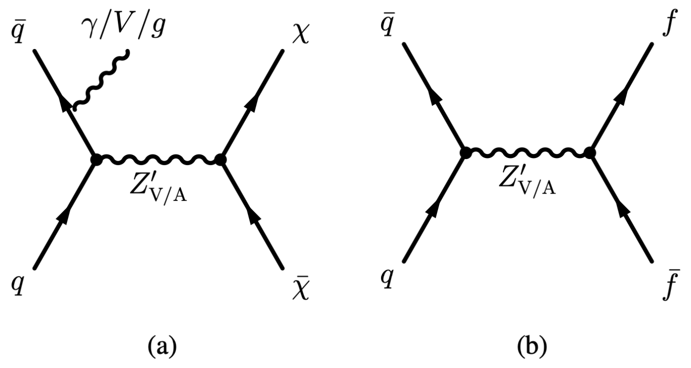
- ❖ Reinterpretation of ATLAS searches in the context of s-channel DM simplified models
  - ➢ Dirac fermion DM with spin-0 or spin-1 mediator

Benchmark models

Mediator	Acronym	Symbol	J^P	Couplings			Signatures
Spin-0				g_q		g_χ	
Scalar	S	ϕ	0^+	1.0		1.0	Jet + E_T^{miss}, $t\bar{t} + E_T^{miss}$, $b\bar{b} + E_T^{miss}$, $t(W/j) + E_T^{miss}$, $t\bar{t}t\bar{t}$
Pseudo-Scalar	PS	a	0^-	1.0		1.0	
Spin-1				g_q	g_l	g_χ	
Vector	V1	Z'_V	1^-	0.25	0.0	1.0	Jet/γ/W/Z +E_T^{miss}, Dilepton resonances, Dijet resonances
	V2			0.1	0.01	1.0	
	V3			0.07	0.0	1.0	
	V4			0.15	0.03	1.0	
Axial-Vector	A1	Z'_A	1^+	0.25	0.0	1.0	
	A2			0.1	0.1	1.0	
	A3			0.07	0.0	1.0	
	A4			0.2	0.05	1.0	





EXOT-2018-62

DM with s-channel mediators

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- Summary of considered analyses targeting spin-0 mediator models
  - Most have the typical $E_{\mathrm{T}}^{\mathrm{miss}}$ + X signatures

Analysis	Models targeted	Final state signature	Key Characteristics
$b\bar{b} + E_{\mathrm{T}}^{\mathrm{miss}}$ [53]	S/PS	2 b-jets, $E_{\mathrm{T}}^{\mathrm{miss}}$, 0 ℓ	Boosted decision tree and binned likelihood fit of $\cos\theta^*_{bb}$
$t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$ [54–57]	S/PS	0-1-2ℓ, $E_{\mathrm{T}}^{\mathrm{miss}}$, ≥ 1 b-jets	Statistical combination of $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$ final state analysis
tW + $E_{\mathrm{T}}^{\mathrm{miss}}$ 0-1ℓ [58]	S/PS	0-1ℓ, $E_{\mathrm{T}}^{\mathrm{miss}}$, ≥ 1 b-jets, W tagged jets	Binned likelihood fit of $E_{\mathrm{T}}^{\mathrm{miss}}$
tW + $E_{\mathrm{T}}^{\mathrm{miss}}$ 2ℓ [59]	S/PS	2ℓ, ≥ 1 b-jet, $E_{\mathrm{T}}^{\mathrm{miss}}$	Single bin likelihood fit
tj + $E_{\mathrm{T}}^{\mathrm{miss}}$ [59]	S/PS	1ℓ, 1-4 jet, 1-2 b-jet, $E_{\mathrm{T}}^{\mathrm{miss}}$	Binned likelihood fit of BDTs
Jet + $E_{\mathrm{T}}^{\mathrm{miss}}$ [60]	S/PS,V/AV	1 high-p_{T} jet, $E_{\mathrm{T}}^{\mathrm{miss}}$, 0 ℓ	Binned likelihood fit of $E_{\mathrm{T}}^{\mathrm{miss}}$
$t\bar{t}$ [71, 72]	V/AV, S/PS	ℓ+jets; 2 large-R jets	Binned likelihood fit of $m_{t\bar{t}}$
$t\bar{t}t\bar{t}$ [73]	S/PS	Same-sign $\ell^{\pm}\ell^{\pm}$ and $\ell^{\pm}\ell^{\pm}\ell^{\mp}$	Binned likelihood fit of BDT

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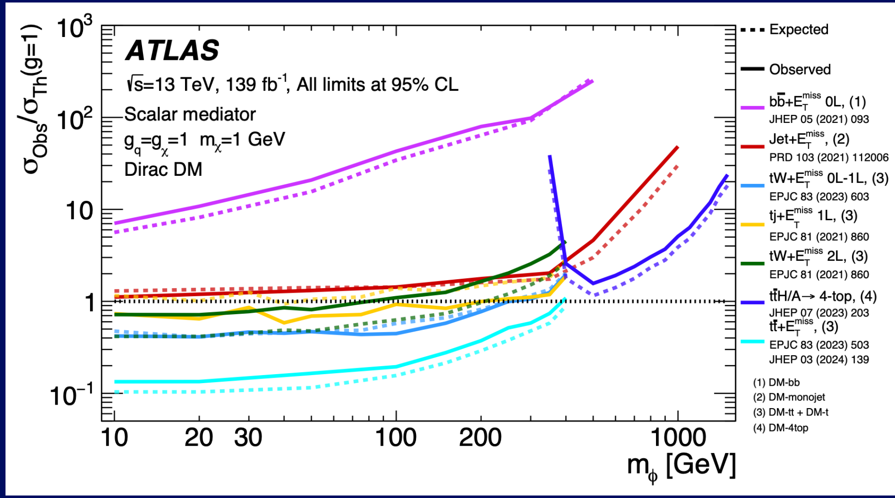
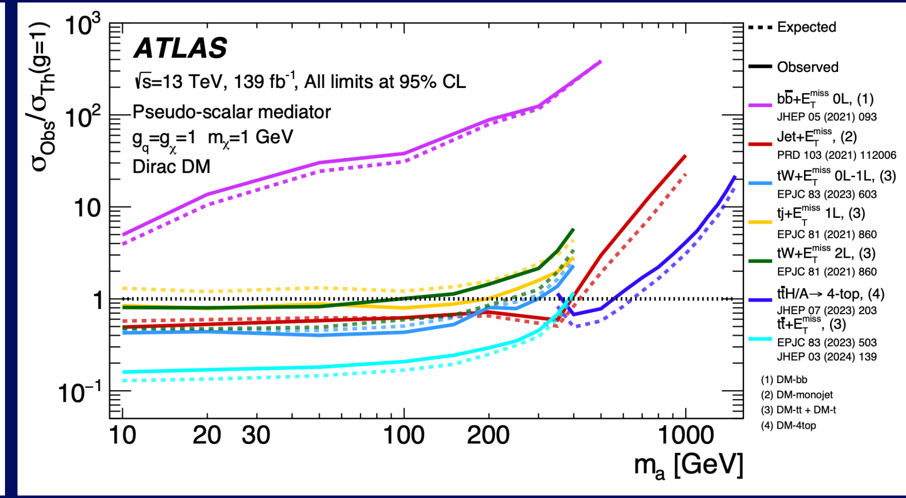
DM with s-channel mediators

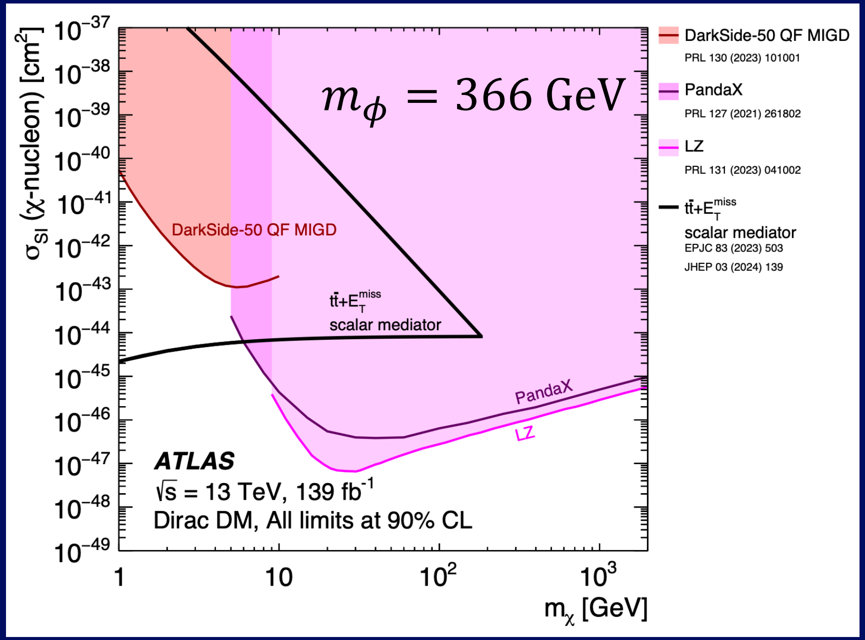
Limits on spin-0 mediators

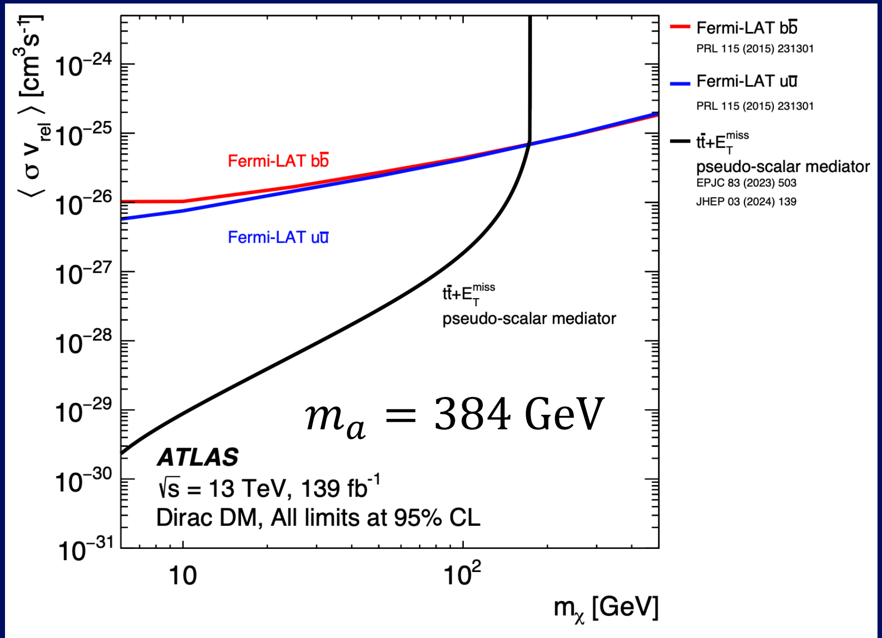
- $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$ combination has the most stringent limit for low mediator mass





- $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$ combination extend beyond direct detection experiments for low DM mass (for the considered benchmark model)





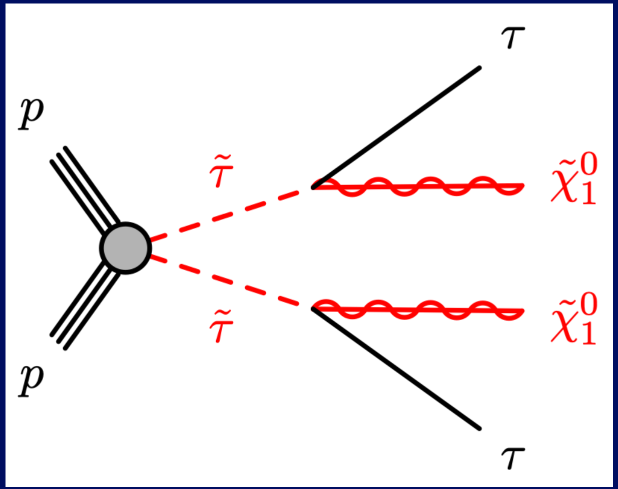
EXOT-2018-62

Stau and electroweakinos: $E_{\mathrm{T}}^{\mathrm{miss}}$ + di-τ

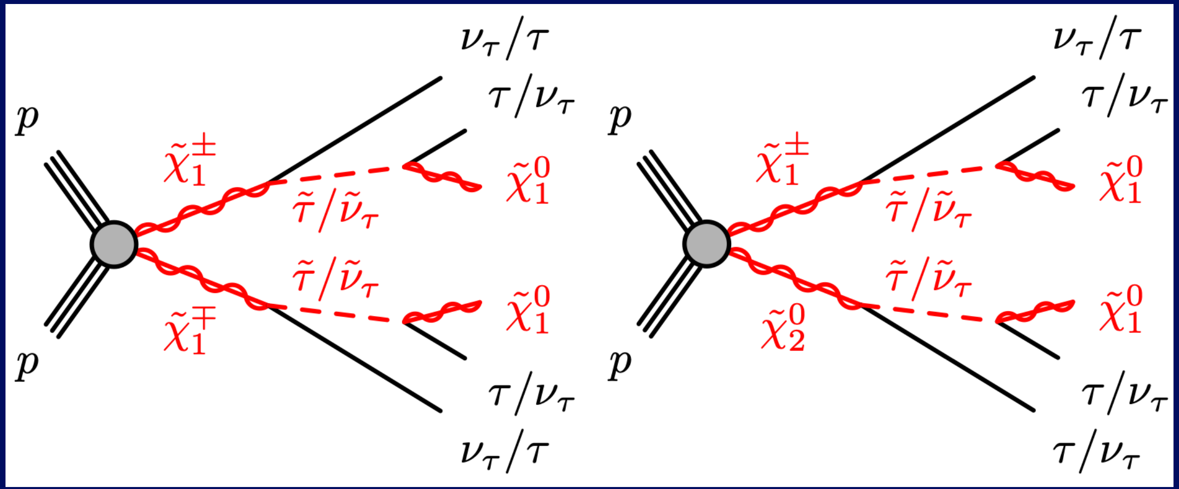
❖ Target physics

Motivated by stau-bino coannihilation scenarios

Direct stau production



Electroweakino pair production with intermediate staus



➢ Key features
- Di-τ trigger
- SR categorization by target mass $m(\tilde{\tau})$ and mass splitting $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$
- BDT trained for each SR using $E_{\mathrm{T}}^{\mathrm{miss}}$, p_{T} and m_{T} of taus, and their relative positions

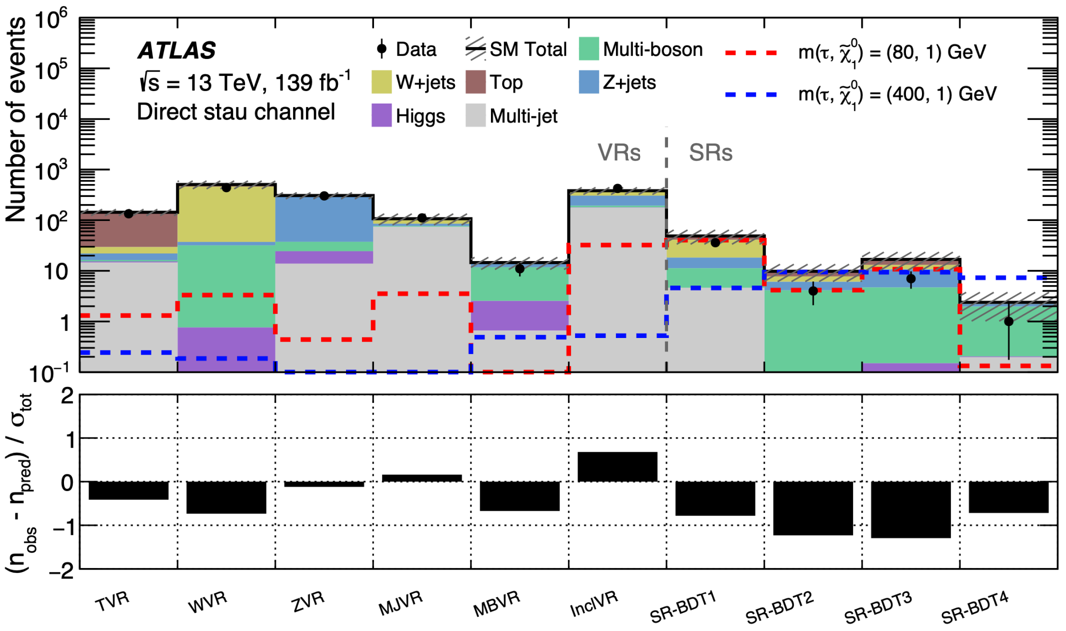
➢ Key features
- Di-τ and di-τ + $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers
- SR categorization by target electroweakino masses and tau charge combination

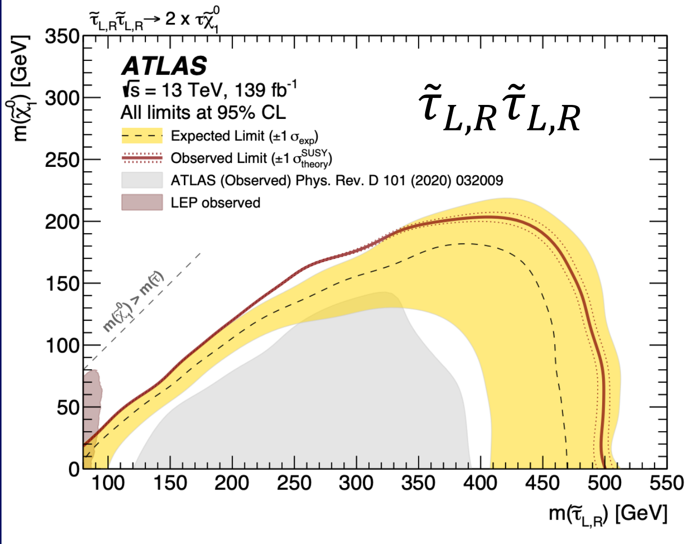
SUSY-2023-03

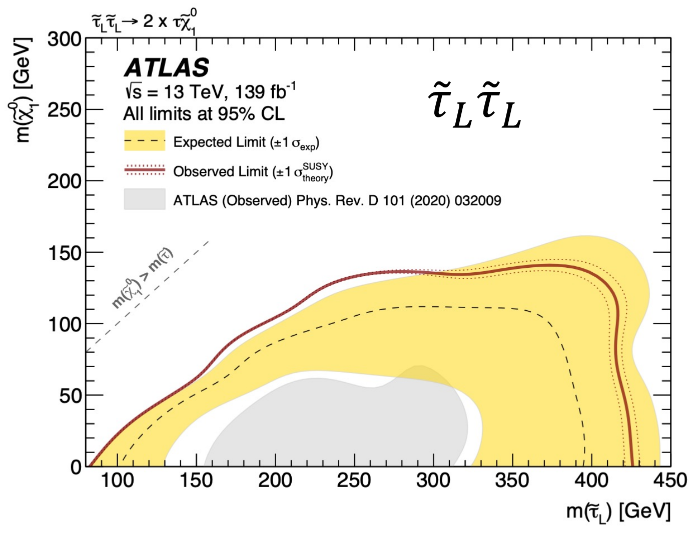
Stau and electroweakinos: $E_{\mathrm{T}}^{\mathrm{miss}}$ + di-τ

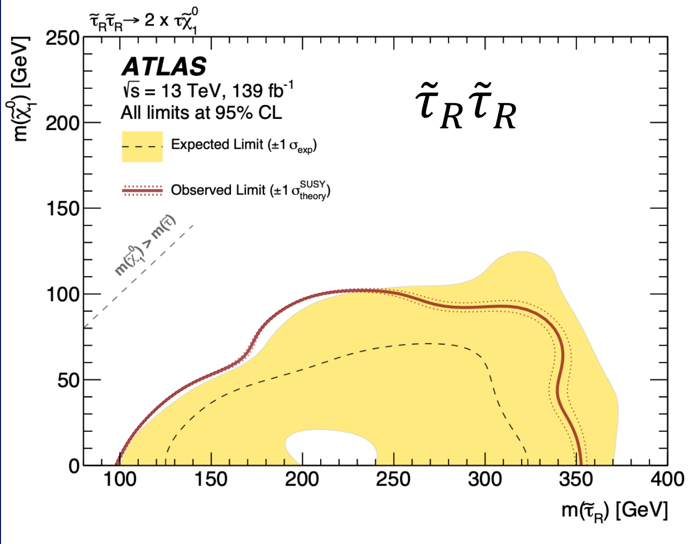
Direct stau production

- Background components and estimation
  - Multi-jet: data-driven ABCD method
  - W/Z + jets, multi-boson, and tops: normalized MC
- Exclusion limits set on mass-degenerate $\tilde{\tau}_{L,R}$ and separate $\tilde{\tau}_L$ and $\tilde{\tau}_R$ pair production
  - Significant improvement by the introduction of BDTs
    - Limits greatly extended for $\tilde{\tau}_{L,R}$ and $\tilde{\tau}_L$ productions
    - Sensitivity to $\tilde{\tau}_R$ production for the first time at ATLAS









SUSY-2023-03

Stau and electroweakinos: $E_{\mathrm{T}}^{\mathrm{miss}}$ + di-τ

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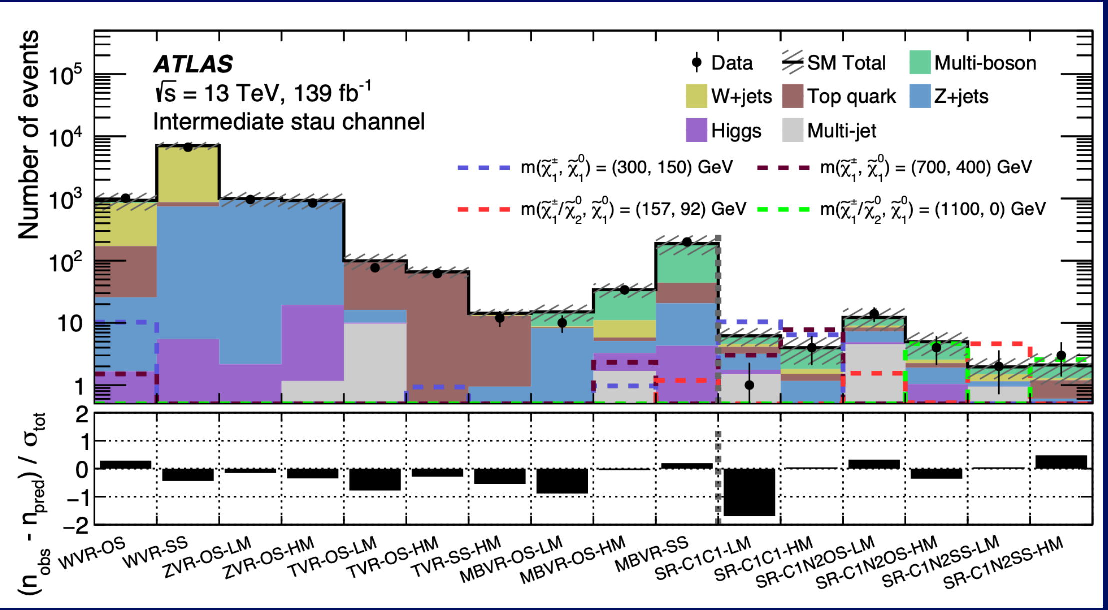
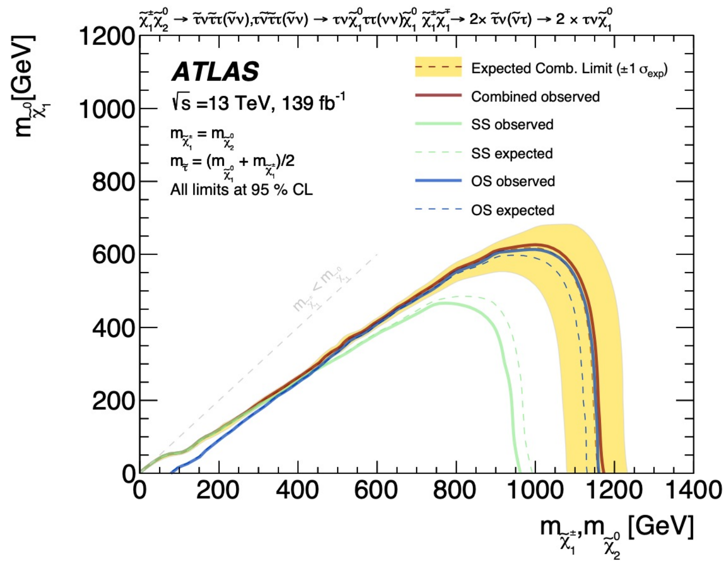
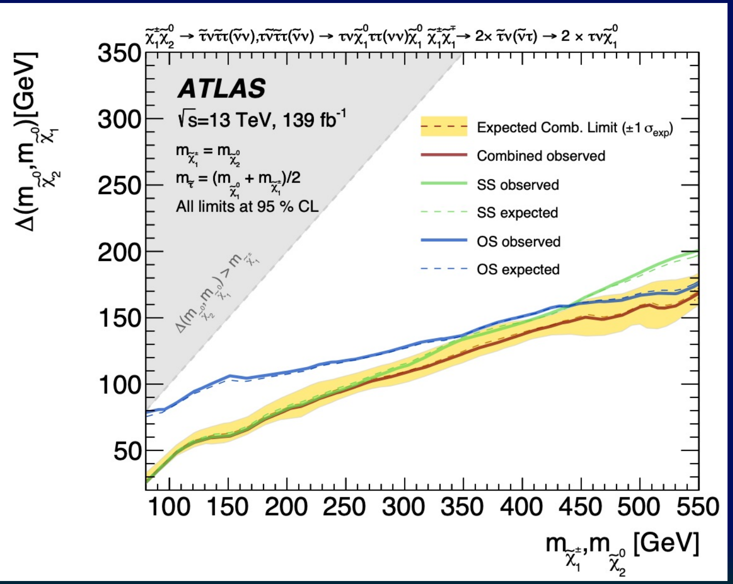
Electroweakino pair production with intermediate staus



- Background components and estimation
  - Multi-jet: data-driven ABCD method
  - W/Z + jets, multi-boson, and tops: normalized MC
- Exclusion limits set on wino-like electroweakinos decaying solely to staus and sneutrinos
  - Limit extended by about 400 GeV for higher masses
  - Sensitivity in compressed regions improved by addition of SS tau channel





SUSY-2023-03

Higgsinos: $E_{\mathrm{T}}^{\mathrm{miss}}$ + displaced track

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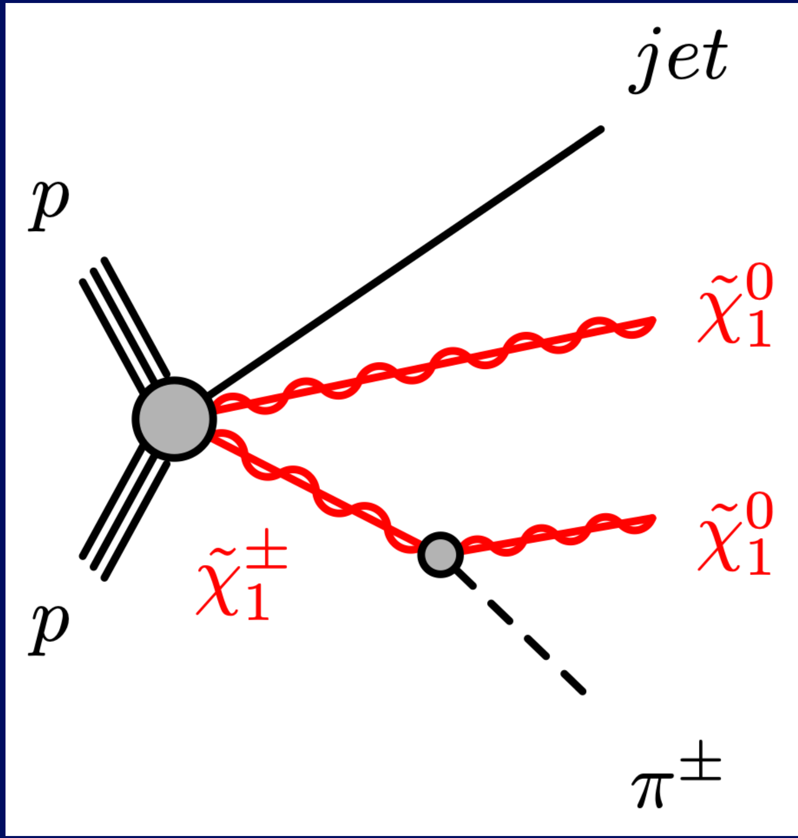
- Target physics: higgsino LSP with compressed mass spectra
  - $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ = 0.4-1 GeV, not yet searched at the LHC
  - Highly motivated by natural SUSY but very challenging

- Signature: jet + $E_{\mathrm{T}}^{\mathrm{miss}}$ + low-p_{T} displaced track
  - Main selections
    - $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
    - Leading jet p_{T} > 250 GeV & $E_{\mathrm{T}}^{\mathrm{miss}}$ > 600 GeV
    - Track with p_{T} = 2-5 GeV, d_0 significance > 8
    - Lepton and photon veto
  - Leading backgrounds
    - $W(\rightarrow \tau\nu)$ + jets with displaced tau track
    - W/Z + jets with displaced QCD track

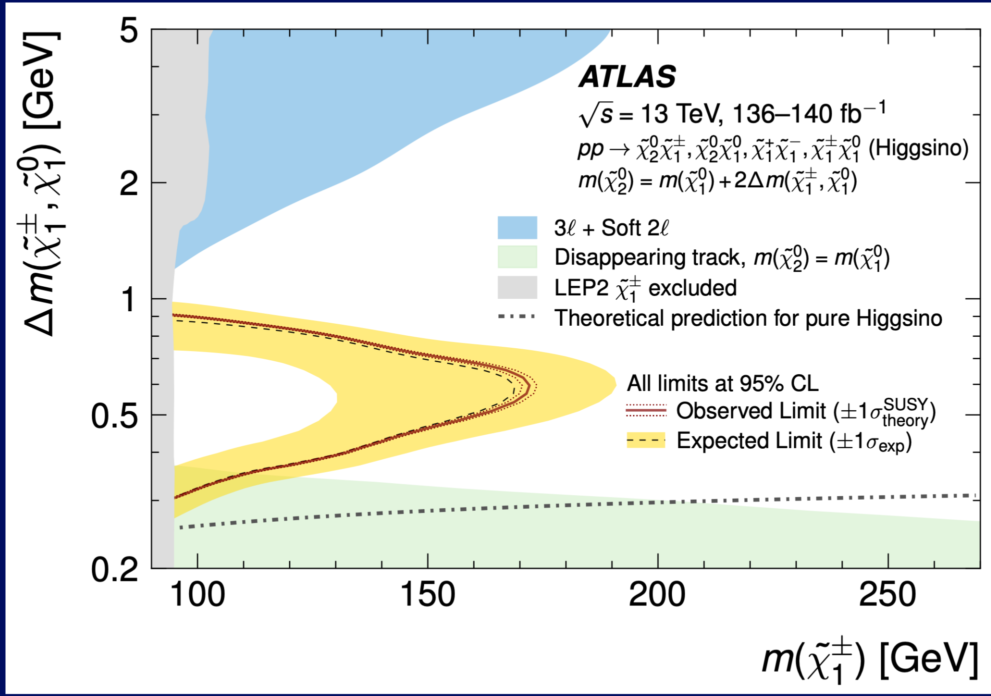


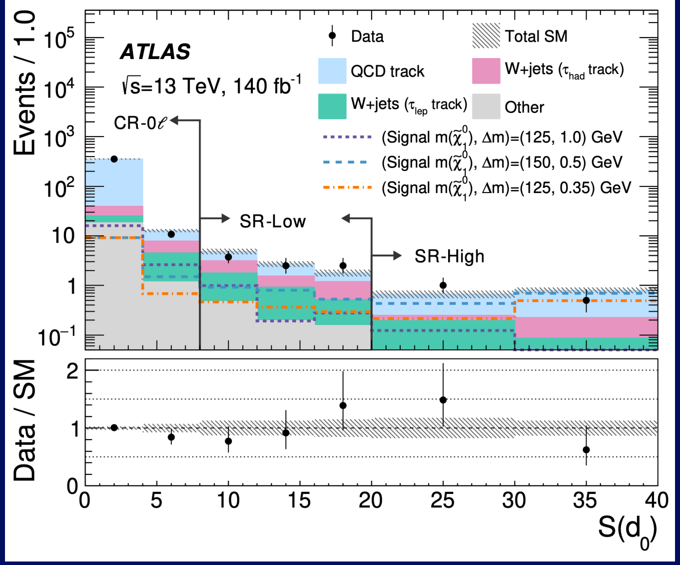
SUSY-2020-04

Higgsinos: $E_{\mathrm{T}}^{\mathrm{miss}}$ + displaced track

- Background estimation
  - Tau track: MC normalization using CR with higher track p_{T} (8-20 GeV)
  - QCD track: data-driven method using $W(\rightarrow \mu\nu)$ + jets dominated CR
- Excluded up to higgsino mass of 170 GeV
  - A step closer to closing the “higgsino gap” with LHC

	SR-Low	SR-High
Observed data	35	15
SM prediction	37 ± 4	14.8 ± 2.0
QCD track	14.0 ± 1.7	10.0 ± 1.6
$W(\rightarrow \tau_\ell \nu)$+jets	9.6 ± 1.6	2.0 ± 0.6
$W(\rightarrow \tau_h \nu)$+jets	10.6 ± 2.0	1.9 ± 0.8
Others	3.2 ± 0.7	0.8 ± 0.4
$\langle\epsilon\sigma\rangle_{\mathrm{obs}}^{95}$ [fb]	0.10	0.07
S_{obs}^{95}	13.5	9.9
S_{exp}^{95}	$15.1^{+6.3}_{-4.2}$	$9.6^{+4.4}_{-2.8}$





[SUSY-2020-04]

SUSY EWK pMSSM summary

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- Reinterpretation of eight ATLAS SUSY EWK searches in the context of 19-parameter phenomenological MSSM (pMSSM) model

pMSSM Parameter	Meaning
$\tan\beta$	Ratio of the Higgs vacuum expectation values for the two doublets
M_A	Pseudoscalar (CP-odd) Higgs boson mass parameter
μ	Higgsino mass parameter
M_1, M_2, M_3	Bino, wino and gluino mass parameters
A_t, A_b, A_τ	Third generation trilinear couplings
$M_{\tilde{q}}$, $M_{\tilde{u}_R}$, $M_{\tilde{d}_R}$, $M_{\tilde{l}}$, $M_{\tilde{e}_R}$	First/second generation sfermion mass parameters
$M_{\tilde{Q}}$, $M_{\tilde{t}_R}$, $M_{\tilde{b}_R}$, $M_{\tilde{L}}$, $M_{\tilde{\tau}_R}$	Third generation sfermion mass parameters

- Workflow (simplified)

Sample random pMSSM points obtained from scan

Calculate various observables & xsecs, filter models

Particle-level evaluation
- Event simulation
- SimpleAnalysis
- CL_s with PyHF

$0.001 \le \mathrm{CL}_s^{\mathrm{Exp.,best}} \le 0.1$

Yes

Detector-level evaluation
- ATLFastII
- RECAST

No

Use particle-level results

Exclude if $\mathrm{CL}_s^{\mathrm{Obs.}} < 0.05$ (with best exp. analysis)

SUSY-2020-15

SUSY EWK pMSSM summary

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- ❖ Two pMSSM scans performed for model sampling
  - ➢ General electroweakino scan (squarks and slepton decoupled)
  - ➢ Bino DM scan to compensate models in "funnel" regions, surviving the relic density constraint

Scan name	EWKino	BinoDM
$\lvert M_1 \rvert$ range	0 – 2 TeV	0 – 500 GeV
LSP type	Neutralino	Bino-like neutralino
Number of models generated:		
Sampled	20 000	437 500
Successful generation	16 667	370 017
Correct LSP type	15 321	286 267
Satisfy DM relic density constraint $\Omega h^2 \leq 0.12$	N/A	11 122
Satisfy LEP chargino mass constraint	13 969	10 174
120 GeV $<$ m(h) $<$ 130 GeV	12 280	8 897
Satisfy non-DM external constraints	7 956	5 752
Satisfy all external constraints	2 460	1 769

- ❖ Considered analyses

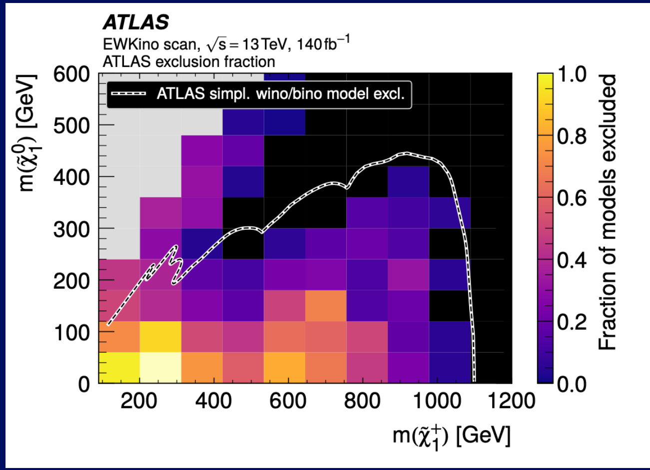
Analysis	Relevant simplified models targeted
FullHad [24]	Wino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via WZ, Wino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via Wh, Wino $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ via WW
1Lbb [15]	Wino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via Wh
2L0J [19]	Wino $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ via WW, slepton pairs
2L2J [25]	Wino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via WZ
3L [23]	Wino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via WZ, Wino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via Wh, higgsino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \tilde{\chi}_1^0$
4L [22]	Higgsino GGM
Compressed [20]	Wino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via WZ, higgsino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \tilde{\chi}_1^0$
Disappearing-track [27]	Wino $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$

SUSY-2020-15

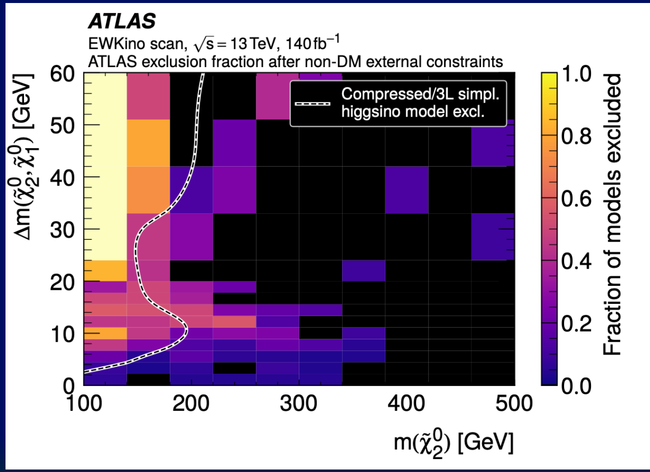
SUSY EWK pMSSM summary

- Result interpreted as the fraction of models excluded
  - Constraints on pMSSM are generally weaker than those on simplified models
  - Bino-LSP (including funnel regions) almost completely excluded, by also considering external constraints

Wino/bino for all considered models



Higgsino for after non-DM external constraints



Search	EWKino scan Bino-LSP	EWKino scan Higgsino-LSP	EWKino scan Wino-LSP	BinoDM scan
FullHad	5.3 %	2.6 %	3.0 %	0.2 %
1Lbb	1.2 %	0.0 %	0.0 %	0.1 %
Compressed	0.2 %	1.4 %	0.0 %	1.9 %
2L0J	2.2 %	0.0 %	0.0 %	0.8 %
2L2J	5.6 %	2.9 %	3.1 %	15.9 %
3L (off-shell)	1.4 %	0.6 %	0.0 %	11.7 %
3L (on-shell)	4.7 %	0.8 %	1.2 %	17.7 %
4L	0.3 %	0.1 %	0.0 %	2.4 %
Disappearing-track	0.1 %	0.1 %	45.7 %	1.9 %
Overall ATLAS Run 2 SUSY searches	**11.2 %**	**5.7 %**	**48.5 %**	**25.0 %**
$m(A) > 480$ GeV	0.4 %	1.6 %	0.4 %	4.8 %
$\mathcal{B}(h \to \text{inv.}) \leq 0.107$	0.4 %	0.0 %	0.0 %	8.1 %
Overall ATLAS Run 2	**11.6 %**	**7.2 %**	**48.7 %**	**28.3%**
Flavour constraints	33.8 %	22.8 %	32.5 %	28.8 %
Electroweak precision constraints	9.7 %	9.8 %	9.7 %	10.5 %
Relic density constraint	96.0 %	12.8 %	0.3 %	N/A
Direct detection constraints	83.8 %	67.7 %	24.4 %	64.7 %
All non-DM external constraints	39.3 %	29.3 %	37.8 %	35.4 %
All external constraints	98.8 %	75.8 %	54.0 %	80.1 %
Overall ATLAS Run 2 + non-DM external	**46.7 %**	**33.9 %**	**67.5 %**	**53.4 %**
Overall ATLAS Run 2 + external	**98.9 %**	**77.3 %**	**83.0 %**	**84.1 %**

SUSY-2020-15

Summary

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- Wide variety of search programs are conducted at ATLAS using $E_{\mathrm{T}}^{\mathrm{miss}}$ (MET)
  - DM mediator searches
  - Supersymmetry (staus and electroweakinos)
  - And many more, soon with Run 3 data

- Many nice results from Run 2 by deep understanding of collected data

- More results coming soon with Run 3 data
  - Addition of data for further sensitivity
  - A lot of effort put into exploring new phase spaces by detector upgrades, software updates, and sophisticated analyses

ATLAS EXPERIMENT

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Backup

Stau and electroweakinos: $E_{\mathrm{T}}^{\mathrm{miss}}$ + di-τ

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Direct stau production

Full list of BDT training inputs

$$E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}(\tau_{1,2}), m_{\mathrm{T}}(\tau_{1,2}), \Delta\phi(\tau_{1,2}, E_{\mathrm{T}}^{\mathrm{miss}}), \Delta\eta(\tau_1, \tau_2), \Delta\eta(\tau_{1,2}, E_{\mathrm{T}}^{\mathrm{miss}}), m(\tau_1, \tau_2), m_{\mathrm{eff}}, m_{\mathrm{Tsum}}$$

	BDT Training Preselection
N medium τ	≥ 2
Charge combination	OS
Trigger	asymm. di-τ
N e/μ	$= 0$
N b-jets	$= 0$
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 20
m_{T2} [GeV]	> 30
$m(\tau_1, \tau_2)$ [GeV]	> 120
$\Delta R(\tau_1, \tau_2)$	< 4

	SR-BDT1		SR-BDT2		SR-BDT3		SR-BDT4
	Bin 1	Bin 2	Bin 1	Bin 2	Bin 1	Bin 2	
Target scenario	Low $m(\tilde{\tau})$ Small $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$		Mid $m(\tilde{\tau})$ Large $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$		Mid $m(\tilde{\tau})$ Small $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$		High $m(\tilde{\tau})$
N medium τ	$= 2$						
BDT1 score	$\in (0.73, 0.78)$	> 0.78	–	–	–	–	–
BDT2 score	–	–	$\in (0.78, 0.82)$	> 0.82	–	–	–
BDT3 score	–	–	–	–	$\in (0.79, 0.86)$	> 0.86	–
BDT4 score	–	–	–	–	–	–	> 0.64

SUSY-2023-03

Stau and electroweakinos: E_T^{miss} + di-τ

Electroweakino pair production with intermediate staus

SR-	C1C1-LM	C1N2OS-LM	C1N2SS-LM	C1C1-HM	C1N2OS-HM	C1N2SS-HM
Trigger	asymm. di-τ			di-τ + E_T^{miss}		
E_T^{miss} [GeV]	< 150			> 150		
N medium τ	$= 2$	≥ 2	≥ 2	$= 2$	≥ 2	≥ 2
N tight τ	≥ 1	≥ 1	–	–	–	–
Charge combination	OS	OS	SS	OS	OS	SS
N b-jets	$= 0$	$= 0$	$= 0$	$= 0$	$= 0$	$= 0$
N jets	–	< 3	< 3	–	–	–
$\lvert\Delta\phi(\tau_1, \tau_2)\rvert$	> 1.6	–	> 1.5	–	–	–
$m(\tau_1, \tau_2)$ [GeV]	> 120	> 120	–	> 120	> 120	–
E_T^{miss} [GeV]	> 60	> 60	–	–	–	–
m_{Tsum} [GeV]	–	–	> 200	> 400	> 400	> 450
m_{T2} [GeV]	> 80	> 70	> 80	> 85	> 85	> 80

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Stau and electroweakinos: $E_{\mathrm{T}}^{\mathrm{miss}}$ + di-τ

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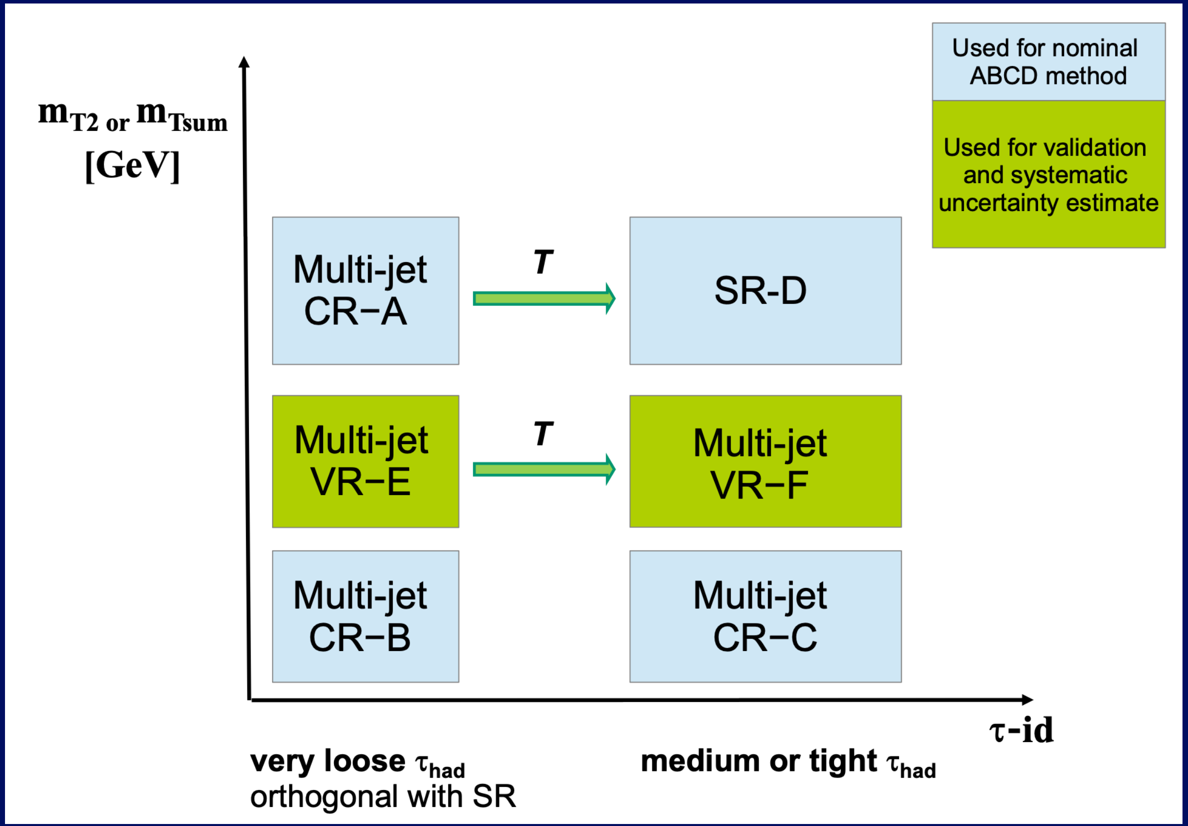
Background estimation for direct stau



Process	W+jets		Top	
Region	WCR	WVR	TCR	TVR
Charge combination	OS			
N medium τ	= 1		= 1	= 2
N tight τ	= 0		–	–
N e/μ	= 1 μ		= 1 μ	= 0
N b-jets	= 0		≥ 1	≥ 1
Trigger	single μ		single μ	asymm. di-τ
$p_{\mathrm{T}}(\tau_1)$ [GeV]	-		–	> 95
$p_{\mathrm{T}}(\tau_2)$ [GeV]	-		–	> 65
$\max[p_{\mathrm{T}}(\tau), p_{\mathrm{T}}(\mu)]$ [GeV]	> 95		> 95	–
$\min[p_{\mathrm{T}}(\tau), p_{\mathrm{T}}(\mu)]$ [GeV]	> 60		> 60	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 20		> 20	> 20
$m_{\mathrm{T},\mu}$ [GeV]	∈ (50, 150]		∈ (50, 150]	–
m_{T2} [GeV]	> 30		> 30	> 30
$m(\tau, \mu)$ [GeV]	> 120		> 120	—
$m(\tau_1, \tau_2)$ [GeV]	–		–	> 120
BDT score	All < 0.5	Any > 0.5	-	

Process	Z+jets		Multi-boson	Multi-jet	Inclusive
Region	ZCR	ZVR	MBVR	MJVR	InclVR
Charge combination	OS				
N medium τ	= 2		= 2	= 2	= 2
N e/μ	= 0		= 0	= 0	= 0
N b-jets	= 0		= 0	= 0	= 0
Trigger	asymm. di-τ		asymm. di-τ	asymm. di-τ	asymm. di-τ
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	-		> 20	< 50	> 20
m_{T2} [GeV]	> 30		> 30	> 30	> 30
$m(\tau_1, \tau_2)$ [GeV]	< 120		< 120	> 120	> 120
$\Delta R(\tau_1, \tau_2)$	< 4		< 4	> 3	< 4
BDT1 score	≤ 0.10	> 0.10	–	≤ 0.60	
BDT2 score	–	–	–	≤ 0.70	
BDT3 score	–	–	–	≤ 0.70	
BDT4 score	≤ 0.60	≤ 0.60	> 0.61	≤ 0.60	

SUSY-2023-03

Stau and electroweakinos: $E_{\mathrm{T}}^{\mathrm{miss}}$ + di-τ

Background estimation for electroweakino

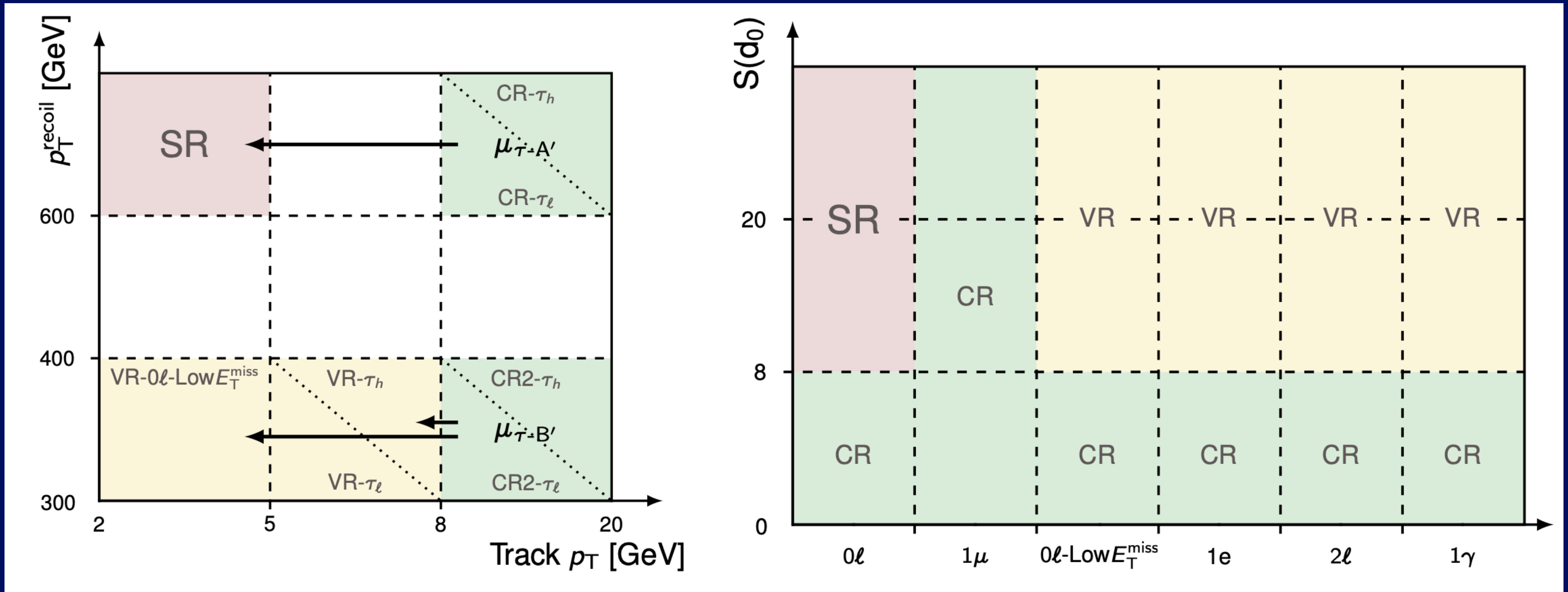
Channel	variable	CR-B / CR-C	VR-E / VR-F	CR-A / SR
C1C1-LM	m_{T2} [GeV] $E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$\in (15, 35]$ $\in (10, 150]$	$\in (35, 80]$ $\in (10, 150]$	> 80 $\in (60, 150]$
C1C1-HM	m_{T2} [GeV] m_{Tsum} [GeV] $E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$\in (35, 60]$ $\in (100, 300]$ > 50	$\in (60, 85]$ $\in (200, 400]$ > 50	> 85 > 400 > 150
C1N2OS-LM	m_{T2} [GeV] $E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$\in (15, 35]$ $\in (10, 150]$	$\in (35, 70]$ $\in (10, 150]$	> 70 $\in (60, 150]$
C1N2OS-HM	m_{T2} [GeV] m_{Tsum} [GeV] $E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$\in (35, 60]$ $\in (150, 300]$ > 50	$\in (60, 85]$ $\in (200, 400]$ > 50	> 85 > 400 > 150
C1N2SS-LM	m_{Tsum} [GeV] $\lvert\Delta\phi(\tau_1, \tau_2)\rvert$	< 100 < 1.5	$\in (100, 200]$ < 1.5	> 200 > 1.5
C1N2SS-HM	m_{Tsum} [GeV] $E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$\in (100, 200]$ > 50	$\in (200, 450]$ > 50	> 450 > 150

Process	W+jets				Top			
Region	WCR-OS	WVR-OS	WCR-SS	WVR-SS	TCR-SS-HM	TVR-SS-HM	TVR-OS-LM	TVR-OS-HM
Charge combination	OS		SS		SS		OS	
Trigger	single μ				di-τ + $E_{\mathrm{T}}^{\mathrm{miss}}$		asymm. di-τ	di-τ + $E_{\mathrm{T}}^{\mathrm{miss}}$
N medium τ	$= 1$				< 2		≥ 2	
N tight τ	-				-		≥ 1	
N loose τ	-				≥ 1		-	
N "very loose" τ	-				≥ 2		-	
N e/μ	$= 1$ μ				-		-	
N b-jets	$= 0$				≥ 1		≥ 1	$= 0$
$p_{\mathrm{T}}(\tau)$ [GeV]	> 50				-		-	
$p_{\mathrm{T}}(\mu)$ [GeV]	> 40				-		-	
Top tagged	veto		-		-		-	
$m_{\mathrm{T},\mu}$ [GeV]	< 140		$\in (50, 150]$		-		-	
$m_{\mathrm{T},\mu} + m_{\mathrm{T},\tau}$ [GeV]	-		> 80		-		-	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 60		> 50		> 150		$\in (20, 150]$	> 150
$m(\tau_1, \tau_2)$ [GeV]	–	–	–	–	–	-	> 120	> 120
m_{T2} [GeV]	$\in (40, 70]$	> 70	< 60	> 60	–	–	> 40	> 30
m_{Tsum} [GeV]	–	–	–	–	< 400	> 400	> 150	> 150
$\lvert\Delta\phi(\tau_1, \tau_2)\rvert$	–	–	–	–	–	–	> 1.0	> 1.0

Process	Z+jets		Multi-bosons		
Region	ZVR-OS-LM	ZVR-OS-HM	MBVR-OS-LM	MBVR-OS-HM	MBVR-SS
Charge combination	OS		OS		SS
Trigger	asymm. di-τ	di-τ + $E_{\mathrm{T}}^{\mathrm{miss}}$	asymm. di-τ	di-τ + $E_{\mathrm{T}}^{\mathrm{miss}}$	single μ
N medium τ	≥ 2				$= 1$
N tight τ	≥ 1				–
N μ	-				$= 2$
N b-jets	$= 0$				$= 0$
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$\in (40, 150]$	> 150	$\in (70, 150]$	> 150	> 100
$m(\tau_1, \tau_2)$ [GeV]	< 70	< 60	< 80	< 90	–
$\Delta R(\tau_1, \tau_2)$	< 1.0	< 1.0	< 1.2	< 1.2	–
$\lvert\Delta\phi(\tau_1, \tau_2)\rvert$	–	–	< 1.0	< 1.0	–
$\lvert\Delta\phi(\tau_1, E_{\mathrm{T}}^{\mathrm{miss}})\rvert$	–	–	–	–	≤ 1.75
m_{Tsum} [GeV]	–	–	> 180	> 180	–
m_{T2} [GeV]	< 60	< 60	> 60	> 60	–

SUSY-2023-03

Higgsinos: $E_{\mathrm{T}}^{\mathrm{miss}}$ + displaced track



Variable	SR	CR-τ_h	CR-τ_ℓ	VR(CR2)-τ_h	VR(CR2)-τ_ℓ
N_ℓ	= 0	= 0	= 1	= 0	= 1
m_{T} [GeV]	–	–	< 50	–	< 50
$p_{\mathrm{T}}^{\mathrm{recoil}}$ [GeV]	> 600	> 600		[300,400]	
Track p_{T}	[2,5]	[8,20]		[5,8] ([8,20])	
Track $S(d_0)$	> 8	> 3		> 3	

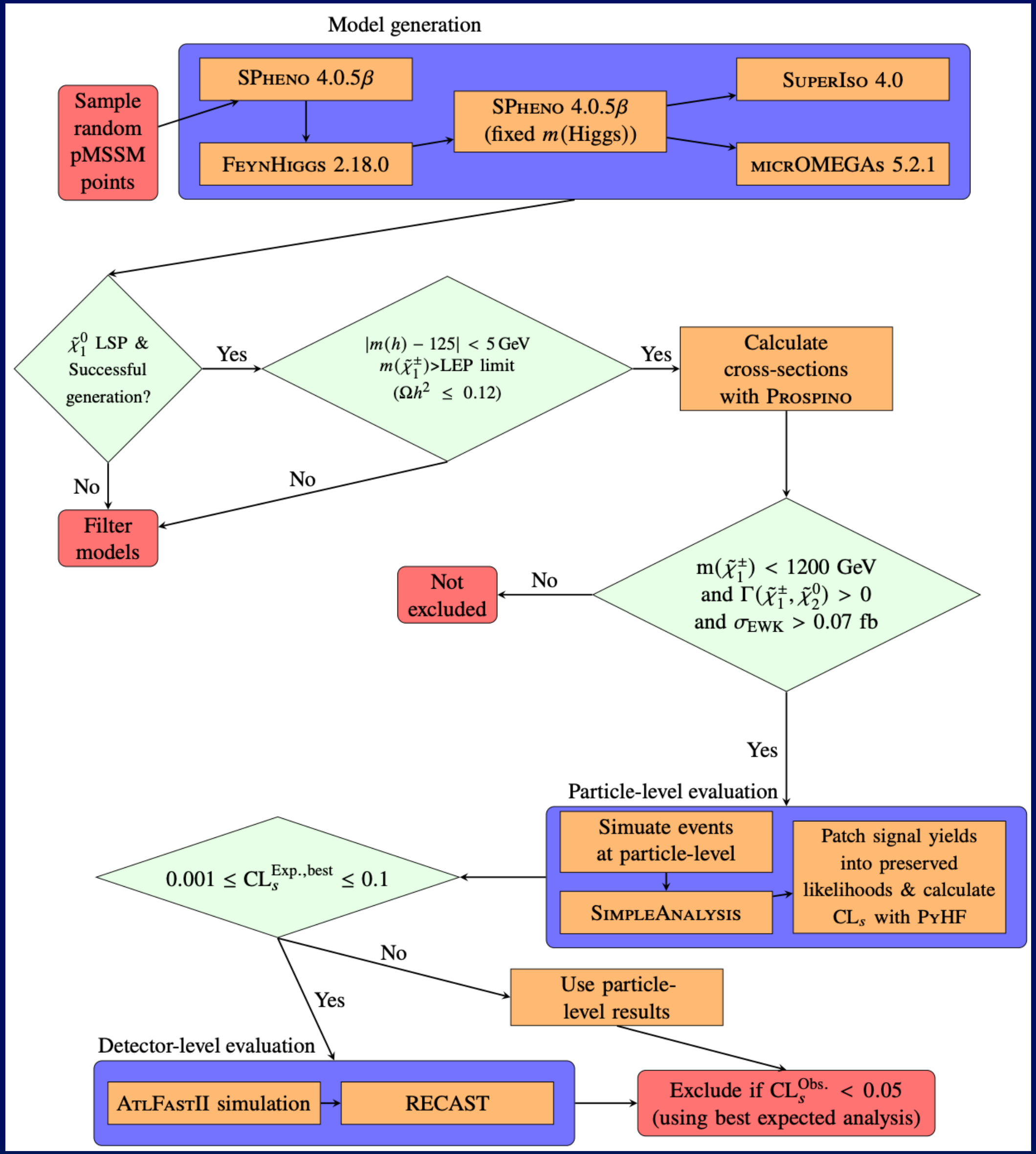
Variable	SR (CR-0ℓ)	CR-1μ	VR(CR)-0ℓ−low$E_{\mathrm{T}}^{\mathrm{miss}}$	VR(CR)-1e	VR(CR)-2ℓ	VR(CR)-1γ
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single-e	$E_{\mathrm{T}}^{\mathrm{miss}}$ or Single-e	Single Photon
$N(e)$	= 0	= 0	= 0	= 1	–	= 0
$N(\mu)$	= 0	= 1	= 0	= 0	–	= 0
$N(e$ or $\mu)$	= 0	= 1	= 0	= 1	= 2	= 0
N_γ	= 0	= 0	= 0	= 0	= 0	= 1
$p_{\mathrm{T}}(\ell_1)$ [GeV]	–	> 10	–	> 30	$p_{\mathrm{T}}(\mu) > 10$ ($p_{\mathrm{T}}(e) > 30$)	–
$p_{\mathrm{T}}(\ell_2)$ [GeV]	–	–	–	–	> 10	–
m_{ll} [GeV]	–	–	–	–	[66.2, 116.2]	–
m_{T} [GeV]	–	[56, 106]	–	[56, 106]	–	–
$p_{\mathrm{T}}^{\mathrm{recoil}}$ [GeV]	> 600	> 300	[300, 400]	> 300	> 300	> 600
Track $S(d_0)$	> 8 (< 8)	–	> 8 (< 8)			

SUSY-2020-04

SUSY EWK pMSSM

ICEPP The University of Tokyo

❖ Actual workflow



SUSY-2020-15

SUSY EWK pMSSM

ICEPP The University of Tokyo

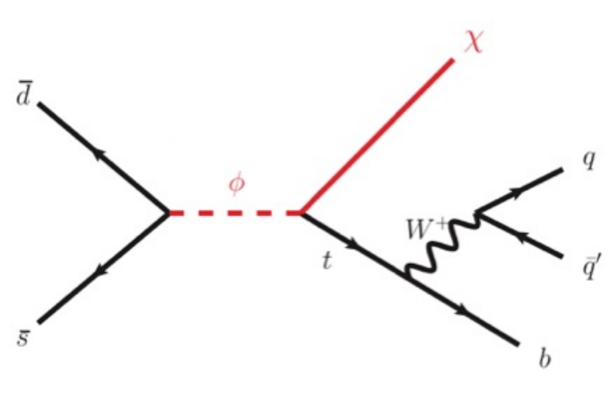
- ❖ Applied constraints
  - ➢ Chargino LEP constraint and Higgs mass constraint also applied

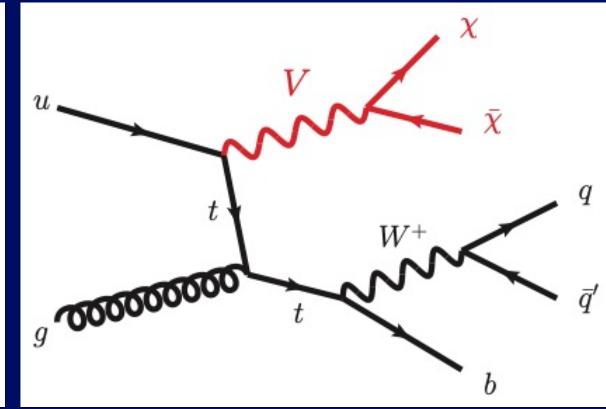
Category	Constraint	Lower bound	Upper bound	Notes
Flavour	$\mathcal{B}(b \to s\gamma)$	3.11×10^{-4}	3.87×10^{-4}	2022 PDG average (2σ window) [58]
	$\mathcal{B}(B_s \to \mu\mu)$	1.87×10^{-9}	4.31×10^{-9}	Most recent LHCb result (2σ window) [59]
	$\mathcal{B}(B^+ \to \tau\nu)$	6.10×10^{-5}	1.57×10^{-4}	2022 PDG average (2σ window) [58]
Precision electroweak	$\Delta\rho$	-0.0004	0.0018	Updated global electroweak fit by GFitter group [60] (not including CDF W mass measurement [61])
	$\Gamma_{\text{inv}}^{\text{BSM}}(Z)$	–	2 MeV	Beyond-the-Standard Model contributions to precision electroweak measurements on the Z-resonance from experiments at the SLC and LEP colliders [62].
	$m(W)$	80.347 GeV	80.407 GeV	2022 PDG result (excluding CDF W mass measurement [61]) [58] but with the 2σ window expanded by 6 MeV to allow for uncertainty due to the top-quark mass in the MSSM Higgs calculation [63]
DM	Relic density	–	0.12	Latest bound from Planck [64]
	Direct detection $\sigma_{\text{Spin-independent}}$			Exclusion contour on direct detection of DM from the LZ Collaboration [65]
	Direct detection $\sigma_{\text{Spin-dependent}}$			Exclusion contour on direct detection of DM from PICO-60 [66]

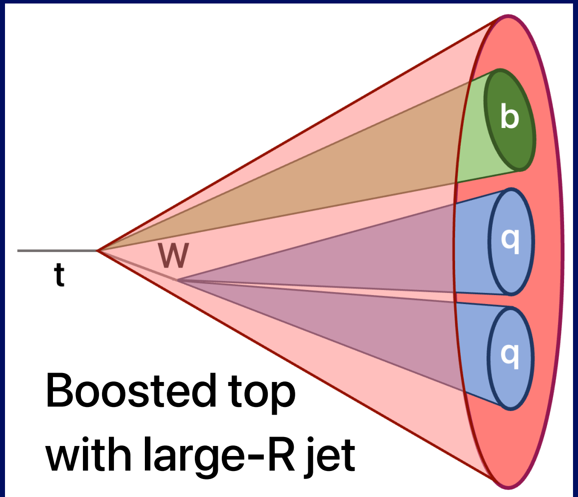
SUSY-2020-15

Top associated DM: $E_{\mathrm{T}}^{\mathrm{miss}}$ + mono-top

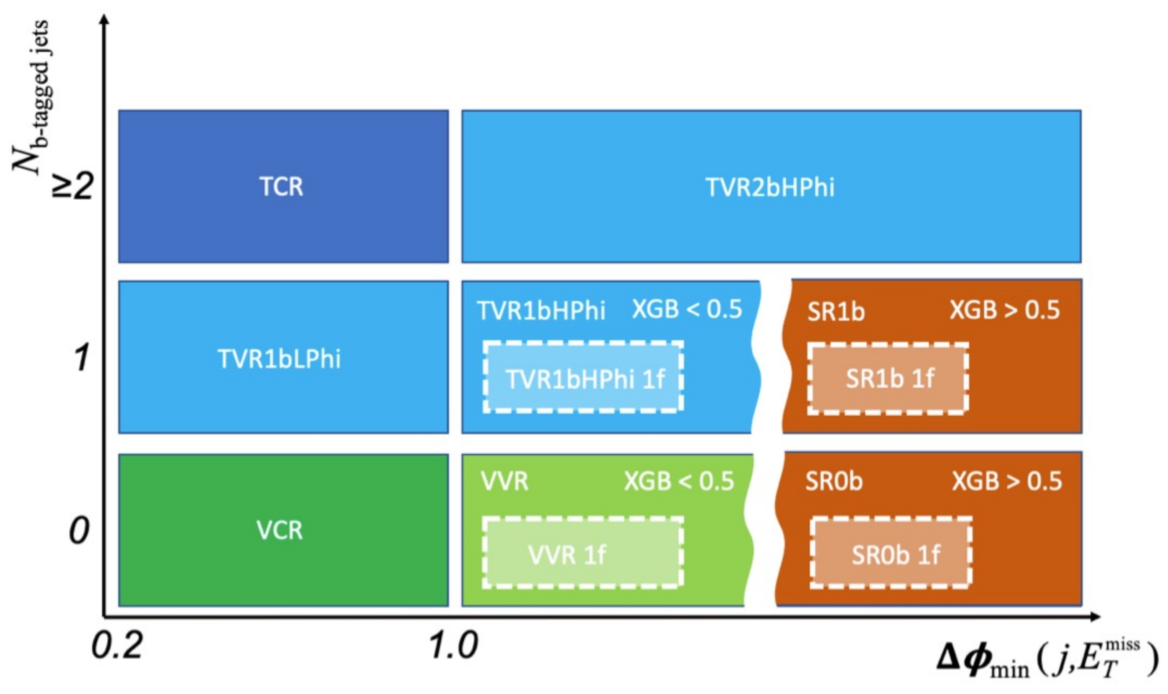
- Target physics
  - Scalar/vector DM mediator associated with top







- Signature
  - Main selections
    - $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
    - $E_{\mathrm{T}}^{\mathrm{miss}}$ > 250 GeV + top-tagged large-*R* jet (350 < p_{T} < 2500 GeV)
    - $\Delta\phi(j, E_{\mathrm{T}}^{\mathrm{miss}})$ > 1 to suppress $t\bar{t}$ background
    - BDT (XGBoost) trained for each target mainly with $E_{\mathrm{T}}^{\mathrm{miss}}$ and jet-related variables

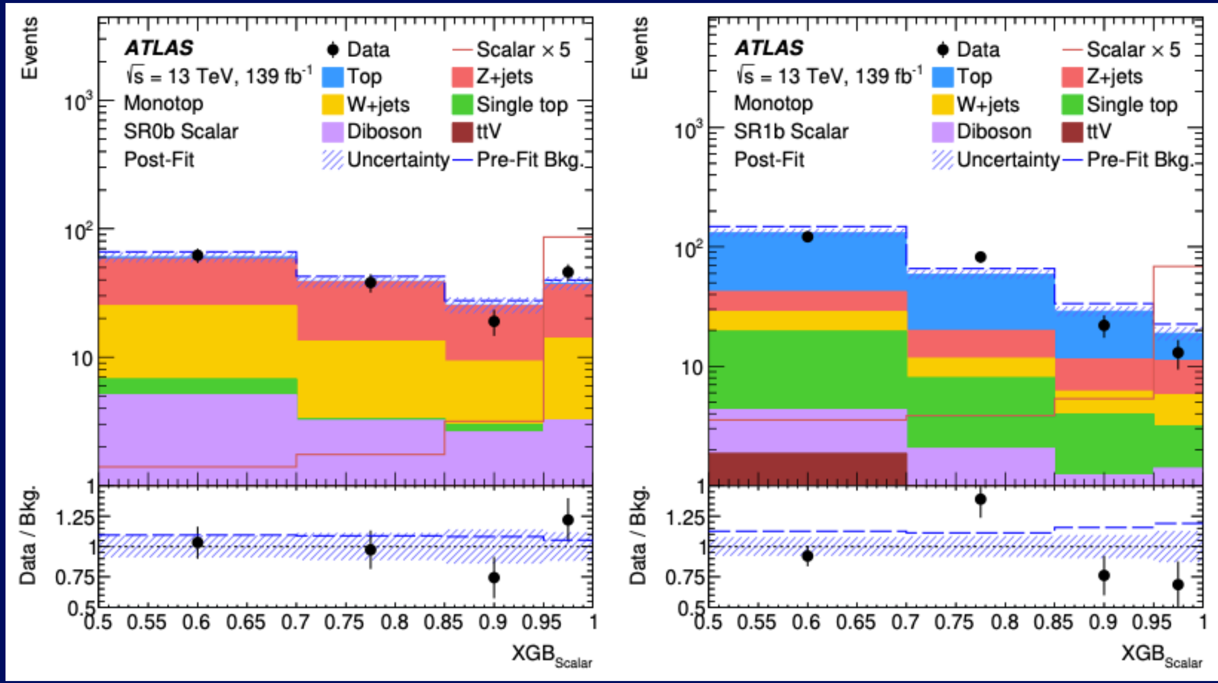


EXOT-2022-40

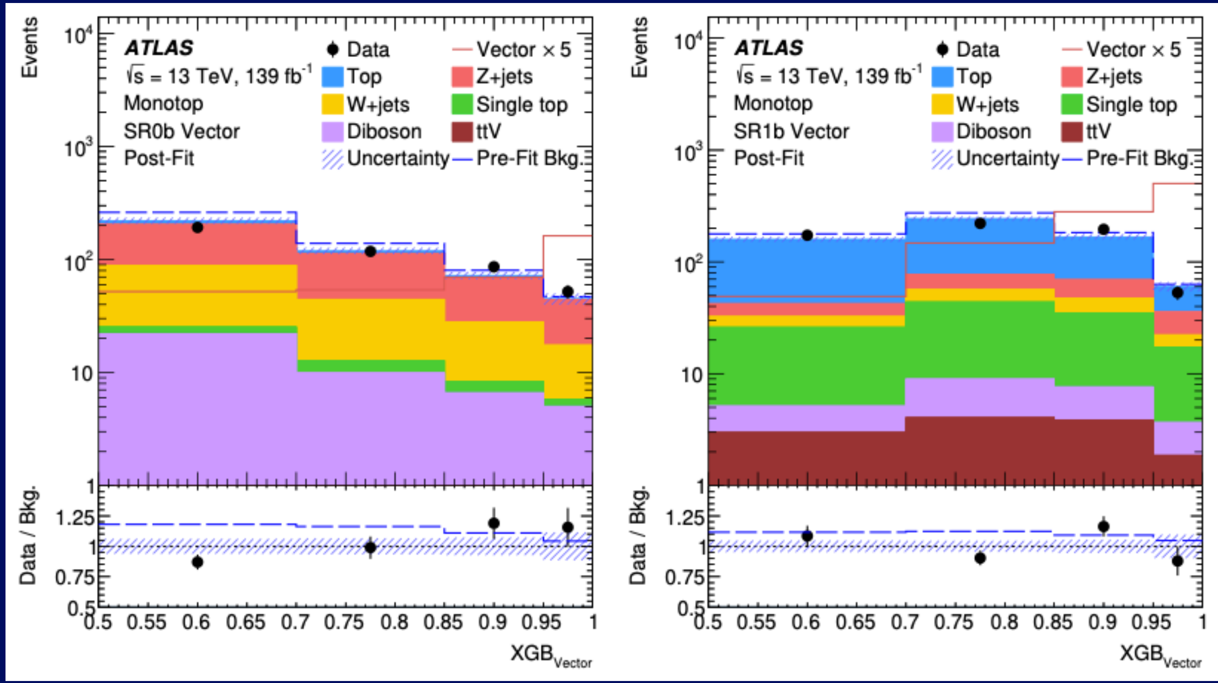
Top associated DM: $E_{\mathrm{T}}^{\mathrm{miss}}$ + mono-top

- Background components and estimation
  - $t\bar{t}$ in SR1b and V + jets in SR0b normalized using dedicated CRs
  - Background predictions validated in dedicated VRs

Scalar mediator SRs



Vector mediator SRs



EXOT-2022-40

Top associated DM: $E_{\mathrm{T}}^{\mathrm{miss}}$ + mono-top

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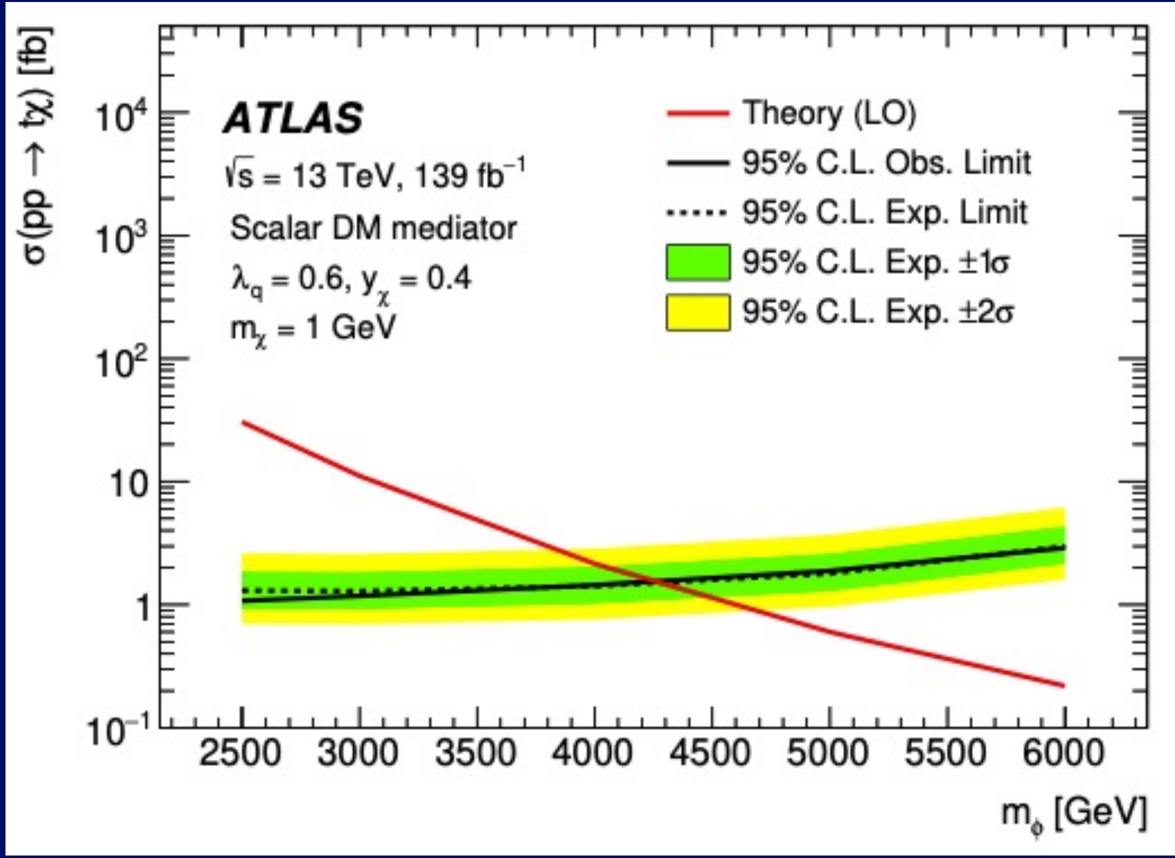
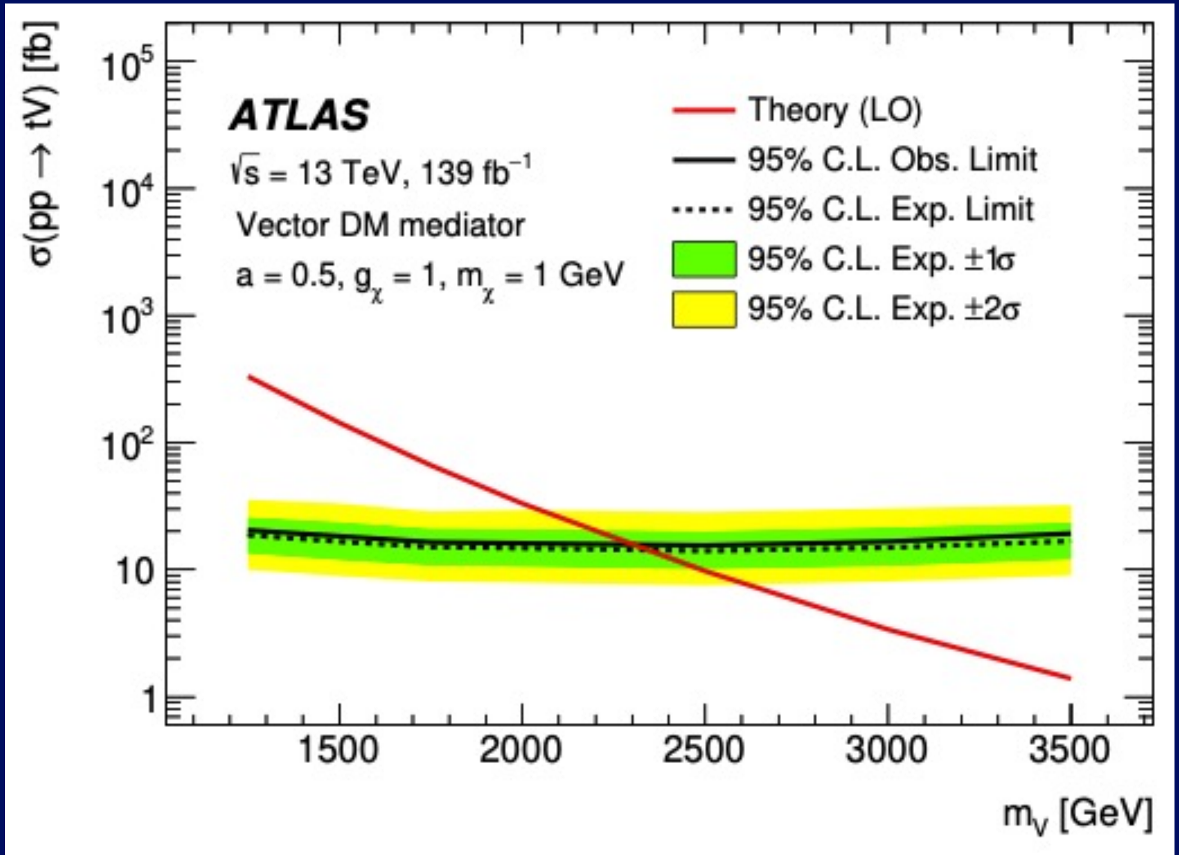
- Exclusion limits on signal cross sections
  - Limits extended with respect to early Run-2 by 800 (300) GeV for considered models of scalar (vector) mediator





EXOT-2022-40

Top associated DM: $E_{\mathrm{T}}^{\mathrm{miss}}$ + mono-top

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XGBoost inputs

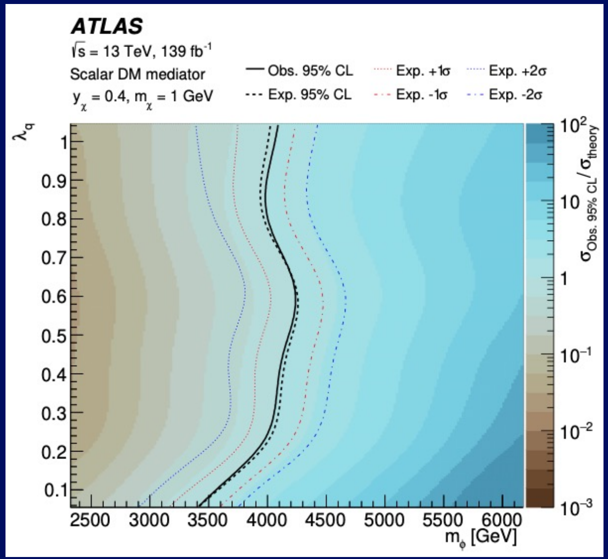
Variable	Description	Scalar DM mediator	Vector DM mediator	VLQ
$E_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum	✓	✓	✓
Ω	$E_{\mathrm{T}}^{\mathrm{miss}}$ and large-R jet p_{T} balance: $\frac{E_{\mathrm{T}}^{\mathrm{miss}}-p_{\mathrm{T}}(J)}{E_{\mathrm{T}}^{\mathrm{miss}}+p_{\mathrm{T}}(J)}$	✓	✓	✓
$\mathrm{N_{jets}}$	Small-R jet multiplicity	✓	✓	✓
ΔR_{max}	Maximum ΔR between two small-R jets	✓	✓	✓
$m_{\mathrm{T,min}}(E_{\mathrm{T}}^{\mathrm{miss}}, b\text{-tagged jet})$	Transverse mass of $E_{\mathrm{T}}^{\mathrm{miss}}$ and the closest b-tagged jet	✓	✓	✓
$m_{\text{top-tagged jet}}$	Mass of the large-R top-tagged jet	✓		✓
$\Delta p_{\mathrm{T}}\ (J, \mathrm{jets})$	Scalar difference of large-R jet p_{T} and the sum of p_{T} of all small-R jets.	✓	✓	
H_{T}	Sum of all small-R jet p_{T}		✓	✓
$H_{\mathrm{T}}/E_{\mathrm{T}}^{\mathrm{miss}}$	Ratio of H_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$		✓	✓
$\Delta E(E_{\mathrm{T}}^{\mathrm{miss}}, J)$	Energy difference between $E_{\mathrm{T}}^{\mathrm{miss}}$ and the large-R jet		✓	✓
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, J)$	Angular distance in the transverse plane between $E_{\mathrm{T}}^{\mathrm{miss}}$ and large-R jet		✓	✓
$p_{\mathrm{T}}(\mathrm{J})$	Large-R jet p_{T}			✓
$m_{\mathrm{T}}(E_{\mathrm{T}}^{\mathrm{miss}}, J)$	Transverse mass of the $E_{\mathrm{T}}^{\mathrm{miss}}$ and large-R jet			✓
$\Delta\phi(b\text{-tagged jet}, J)$	Angular distance in the transverse plane between the large-R jet and the leading b-tagged jet			✓

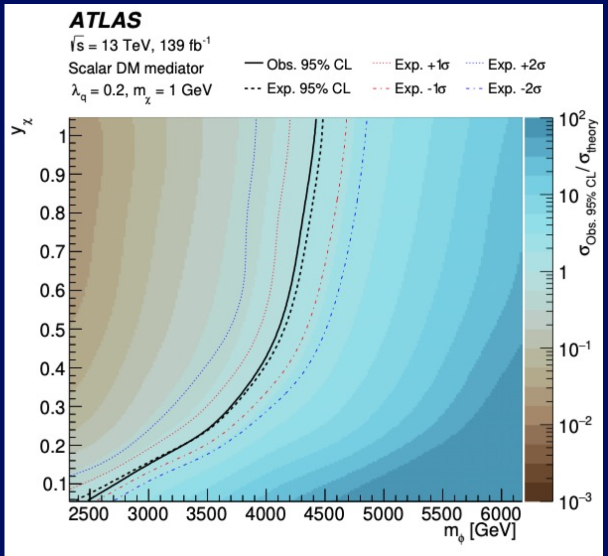
EXOT-2022-40

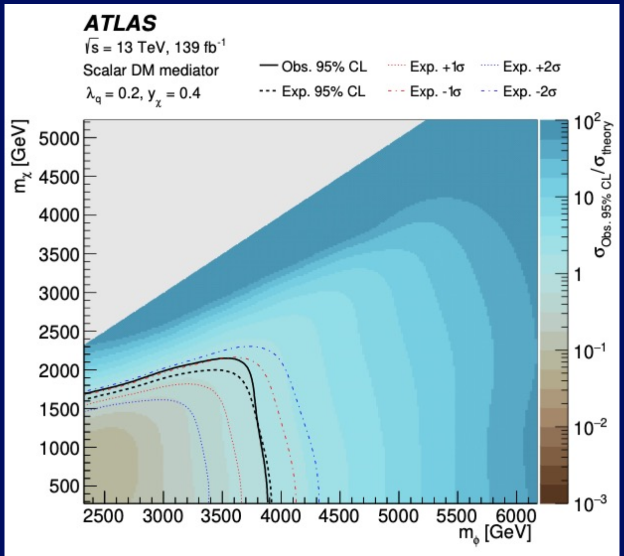
Top associated DM: $E_{\mathrm{T}}^{\mathrm{miss}}$ + mono-top

❖ Exclusion limits on various parameters

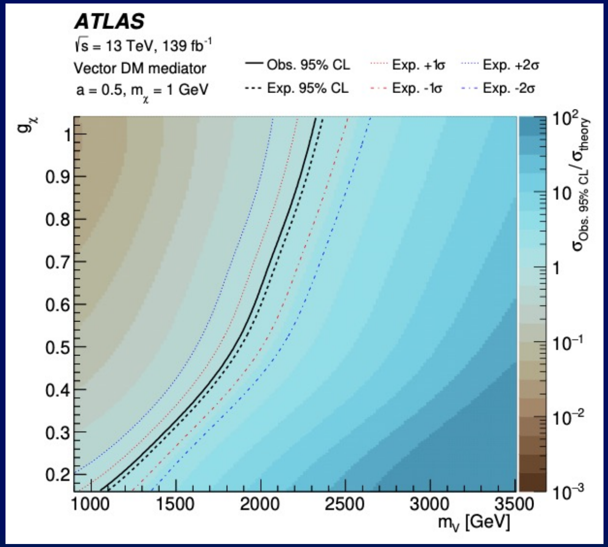
Scalar med.

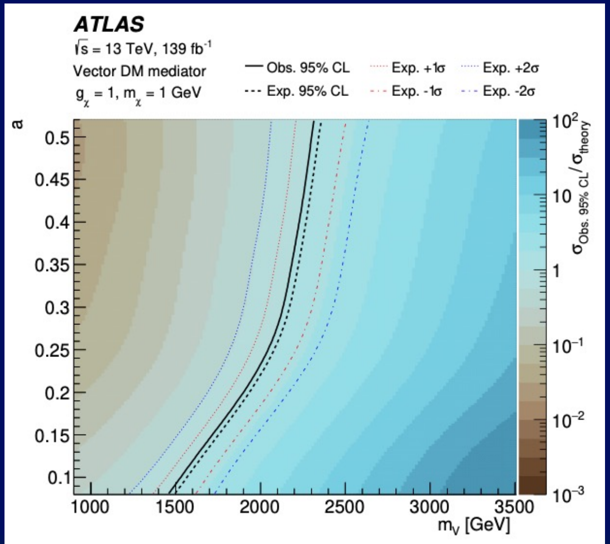


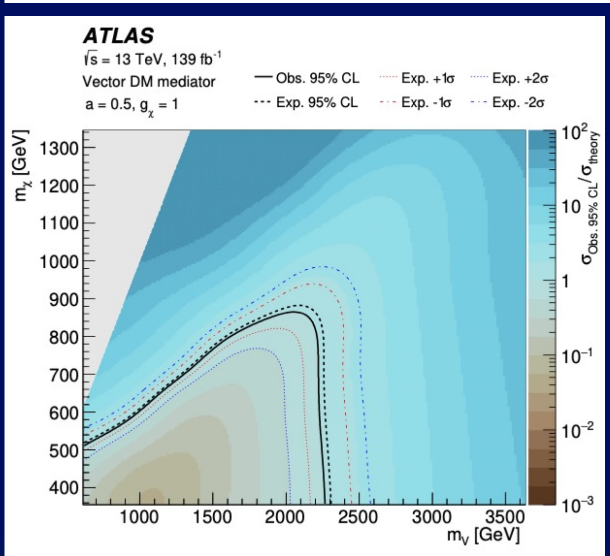




Vector med.



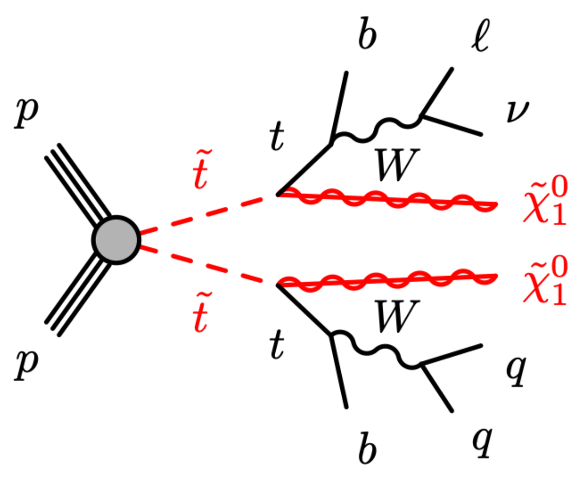


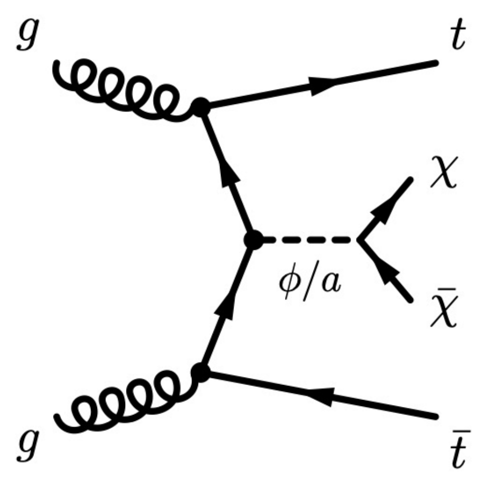


EXOT-2022-40

Stop and DM: $E_{\mathrm{T}}^{\mathrm{miss}}$ + top pairs (l+h)

- Target physics
  - Stop pair production
  - SM-singlet DM + (pseudo) scalar mediator





- Signature: $E_{\mathrm{T}}^{\mathrm{miss}}$ + one leptonic top + one hadronic top
  - Main selections
    - Single lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers
    - Resolved hadronic tops identified with dedicated "top-NN"
    - Event categorization based on large-*R* jet, b-jet, and top requirements

Stop/DM | Stop only

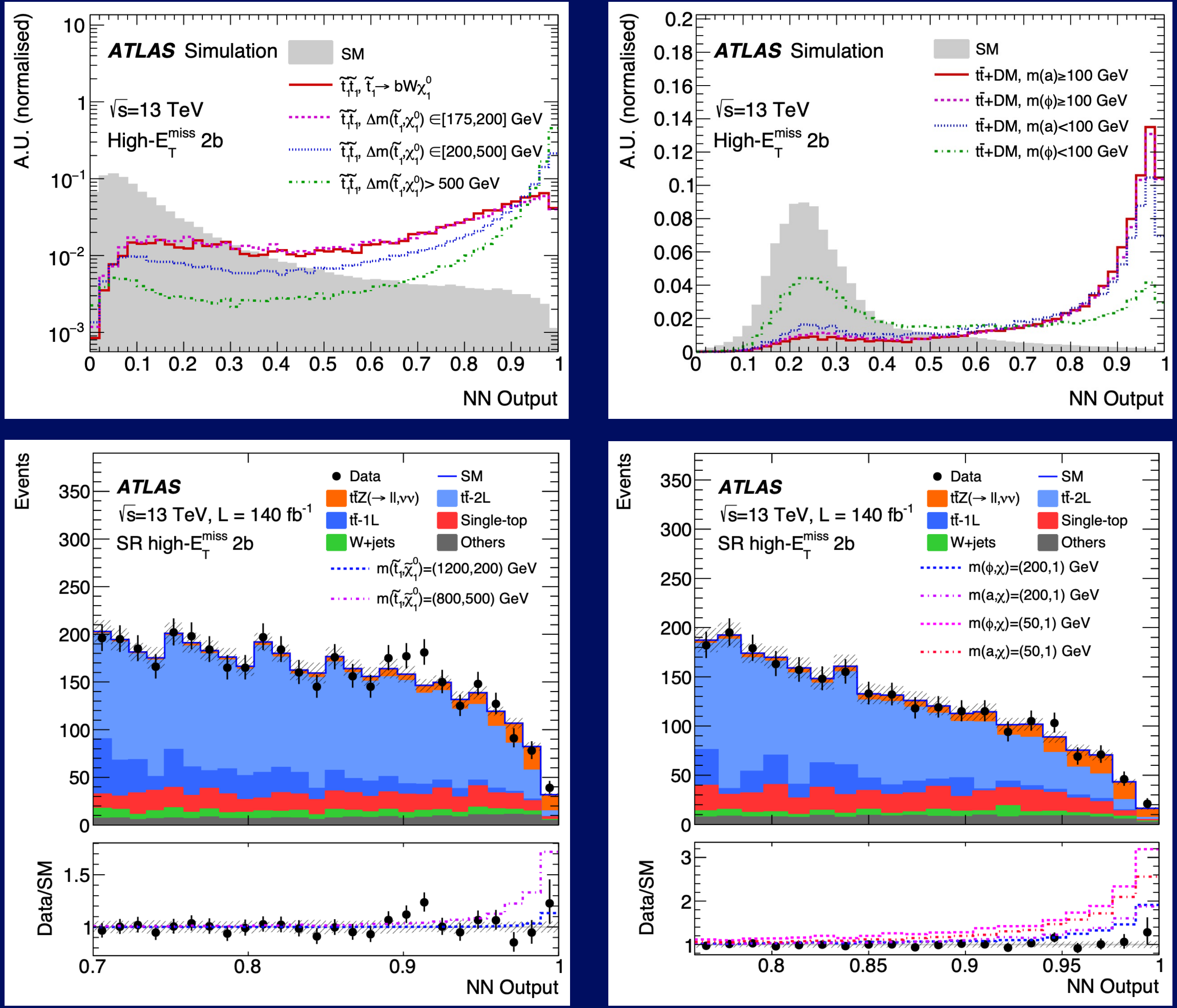
Analysis Category	High-$E_{\mathrm{T}}^{\mathrm{miss}}$ 1b	High-$E_{\mathrm{T}}^{\mathrm{miss}}$ 2b	Boosted 1b-lep-0t	Boosted 1b-had-0t	Boosted 2b-0t	Boosted 1b-lep-1t	Boosted 1b-had-1t	Boosted 2b-1t
N(*lR* jet, $p_{\mathrm{T}} > 600$ GeV)	0		≥ 1					
N(top-tagged *lR* jet)	-		0			≥ 1		
$N_{b-\mathrm{jet}}$ with $\Delta R(b, lR\text{ jet}) < 1.1$	-		0	≥ 1	≥ 1	0	≥ 1	≥ 1
$N_{b-\mathrm{jet}}$ with $\Delta R(b, lR\text{ jet}) > 1.1$	-		≥ 1	0	≥ 1	≥ 1	0	≥ 1
top-NN-tagged multiplet	✓		-					
$N_{b-\mathrm{jet}}$	1	≥ 2	-					
$N_{\mathrm{light-jet}}$	≥ 2	≥ 1	-					
top$_{\mathrm{had}}$ candidate	top-NN multiplet		*lR* jet					
top$_{\mathrm{lep}}$ candidate	ℓ + j	$\ell + b$	$\ell + b$	ℓ(+j)	$\ell + b$	$\ell + b$	ℓ(+j)	$\ell + b$
Event NN selection	See Table 3							

SUSY-2023-22

Stop and DM: E_T^{miss} + top pairs (l+h)

- ❖ Event NN trained in each category
  - ➢ "Stop-NN" and "DM-NN" using momentum components of each object
- ❖ Background components and estimation
  - ➢ $t\bar{t}$, single-top, W+ jets, and $t\bar{t}Z(\rightarrow \nu\bar{\nu})$
  - ➢ All backgrounds estimated from MC with fits to low-NN-score CRs

Stop-NN DM-NN

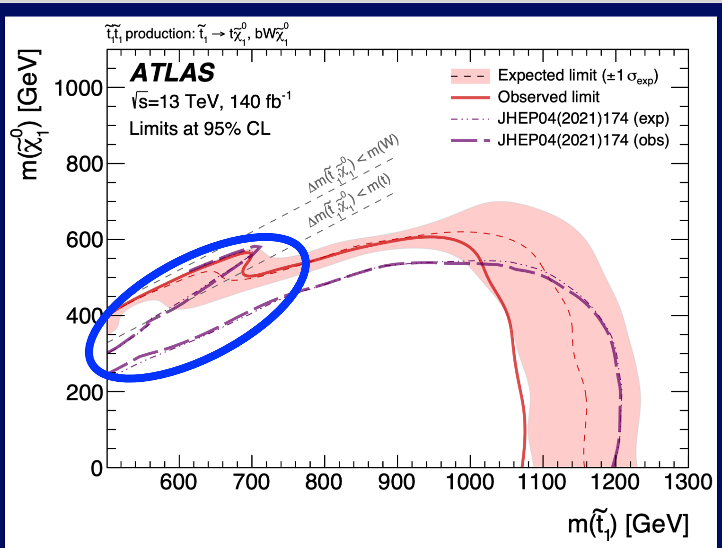


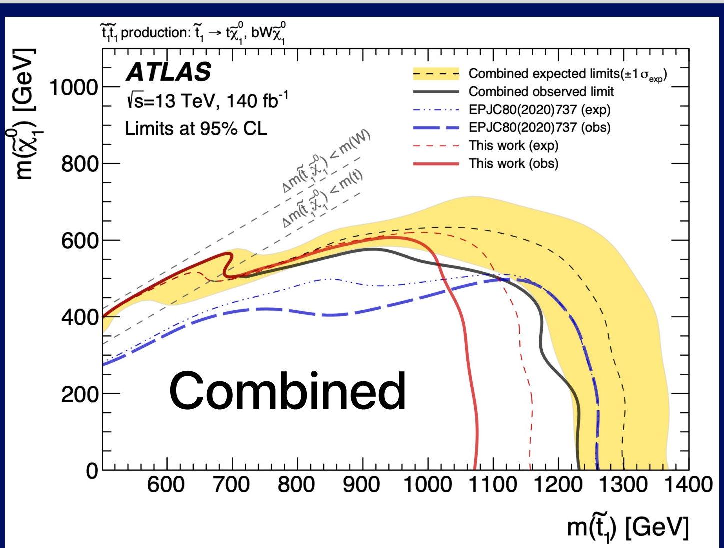
[SUSY-2023-22]

Stop and DM: $E_{\mathrm{T}}^{\mathrm{miss}}$ + top pairs (l+h)

❖ Exclusion on stop pair production

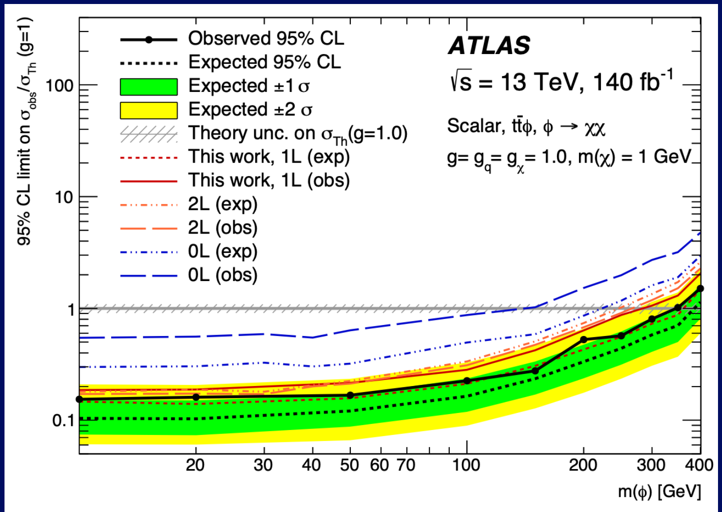
- ➢ Significant improvement in mass regions with $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \sim m(t)$
- ➢ Statistical combination with all-hadronic $t\bar{t}$ + $E_{\mathrm{T}}^{\mathrm{miss}}$

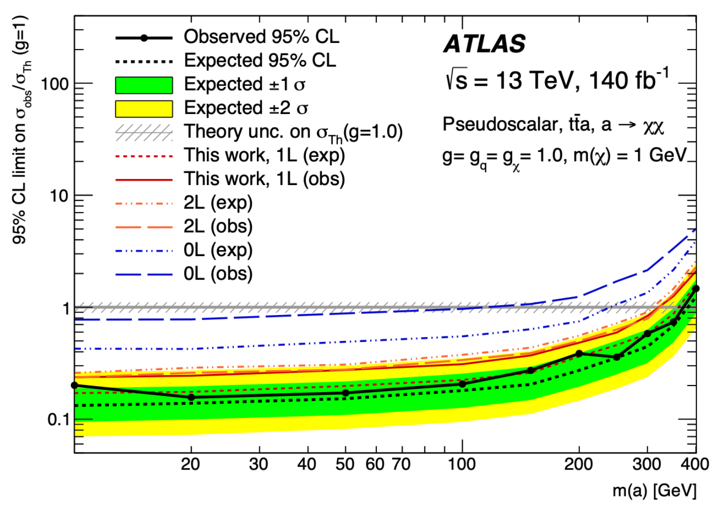




❖ Exclusion on $t\bar{t}$ + SM-singlet DM

- ➢ Combined limits with 0L and 2L channels drawn as a function of (pseudo) scalar mediator mass
- ➢ Mediator mass excluded up to 350 GeV for this assumption

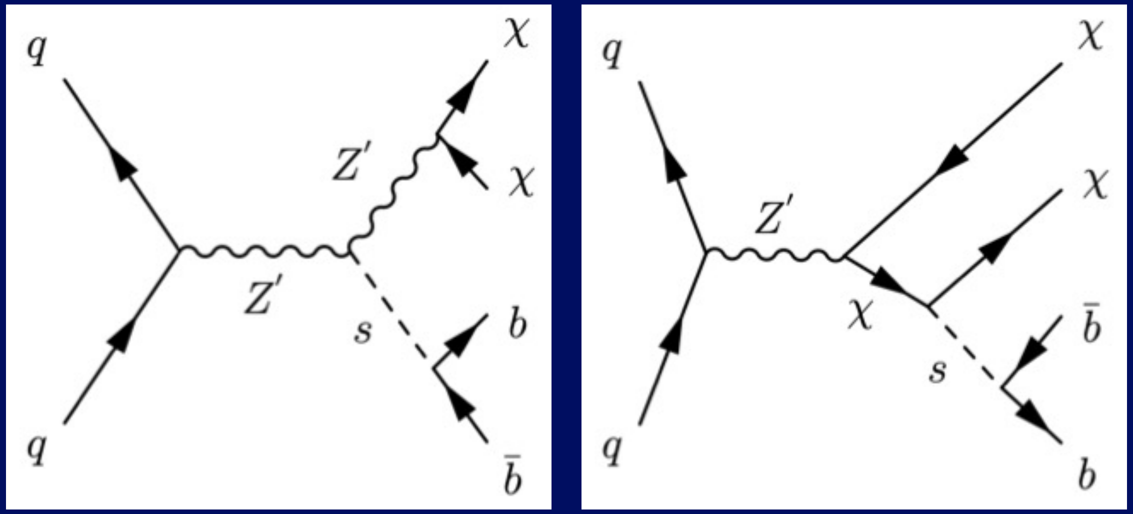




SUSY-2023-22

Dark Higgs: $E_{\mathrm{T}}^{\mathrm{miss}} + b\bar{b}$

- Target physics
  - Two-mediator DM model with Z' and dark Higgs s
  - Three interpretation scenarios
    - m_χ = 200 GeV
    - m_χ = 900 GeV
    - m_s = 70 GeV

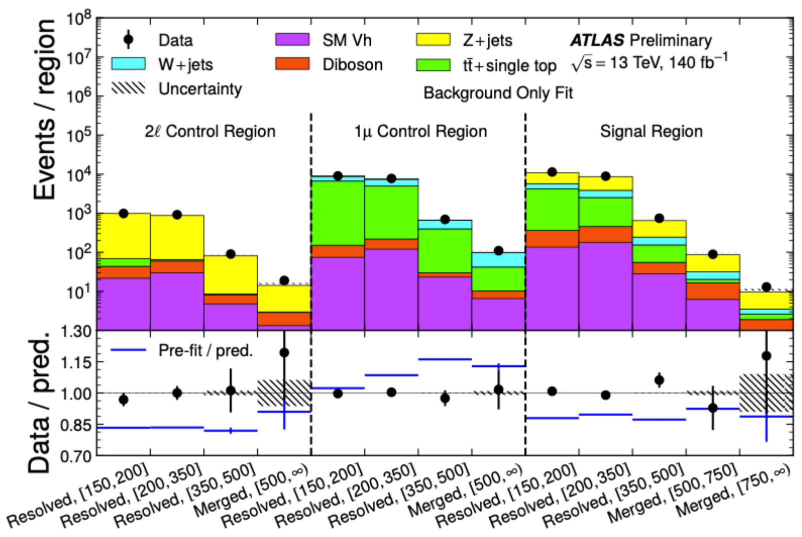


- Signature: $E_{\mathrm{T}}^{\mathrm{miss}} + b\bar{b}$
  - Main selections
    - $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
    - $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
    - Two *b*-tagged small-*R* jets (resolved) or one large-*R* jet with two *b*-quarks (merged)
  - Leading backgrounds
    - $Z(\rightarrow \nu\bar{\nu})$ + jets for both topologies
    - Resolved: $t\bar{t}$, $W(\rightarrow \ell\nu)$ + jets
    - Merged: Diboson, $W(\rightarrow \ell\nu)$ + jets

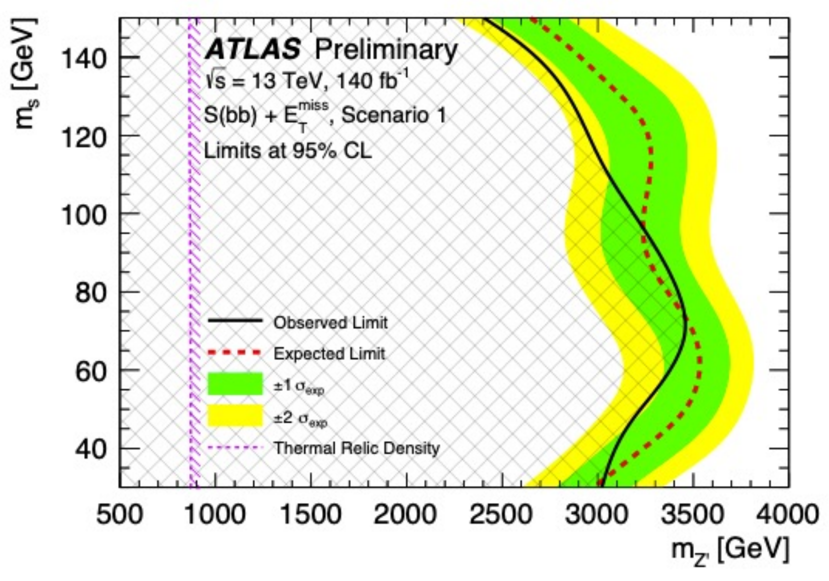
CONF-2024-004

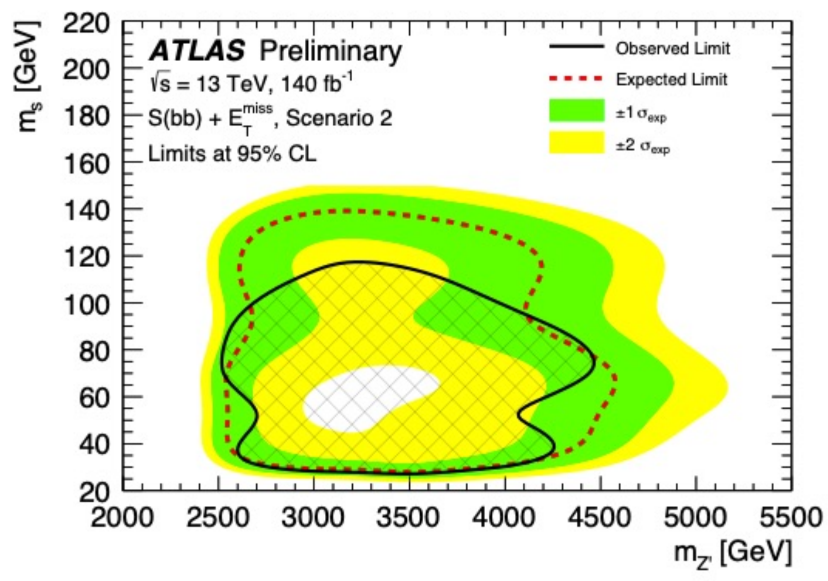
Dark Higgs: $E_{\mathrm{T}}^{\mathrm{miss}} + b\bar{b}$

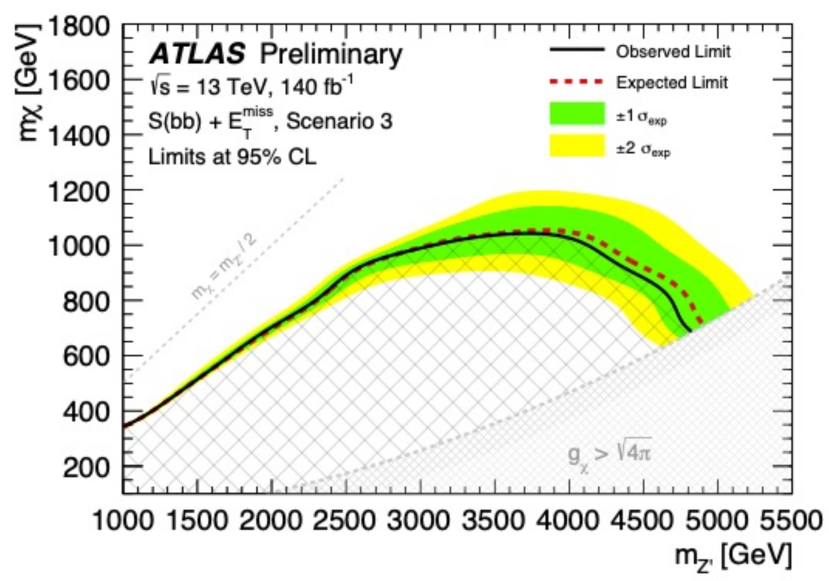
- Background estimation
  - Z + jets, W + jets, and $t\bar{t}$ MC are normalized in dedicated CRs



- Exclusion limits for three scenarios
  - Scenario 1: up to $m_{Z'}$ = 3.4 TeV excluded for m_s = 70 GeV
  - Scenario 2: up to $m_{Z'}$ = 4.1 TeV excluded for m_s = 75 GeV
  - Scenario 3: up to $m_{Z'}$ = 4.8 TeV excluded for m_χ = 700 GeV







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