

Searches for Dark Matter with the ATLAS Experiment at the LHC

Joe Haley
Oklahoma State U.

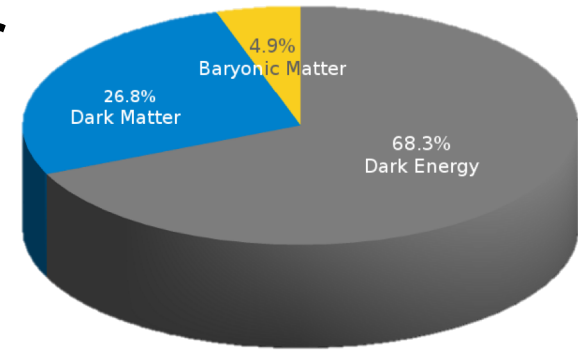
HEP2023

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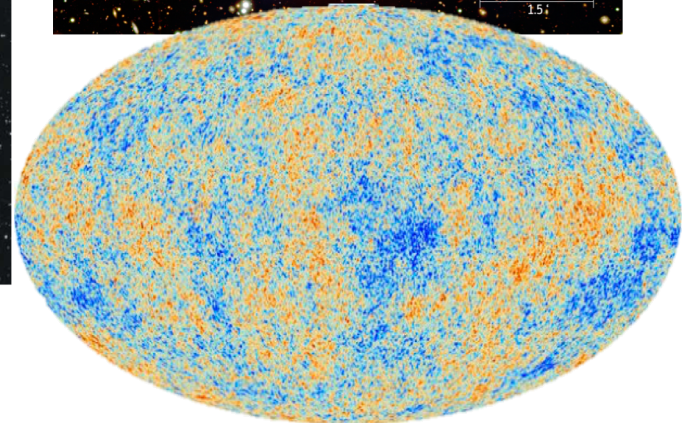
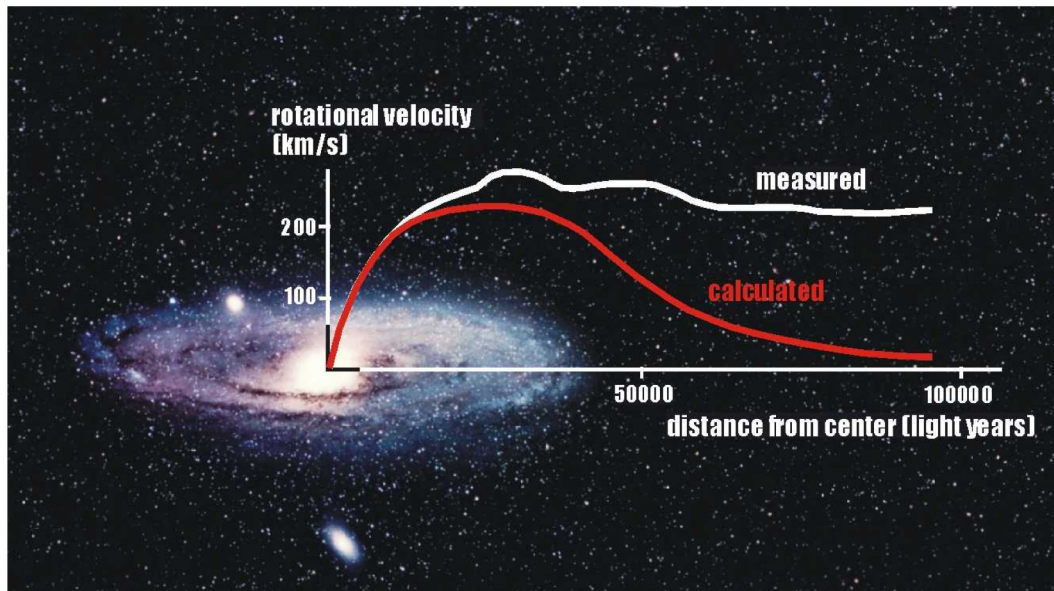


Dark Matter

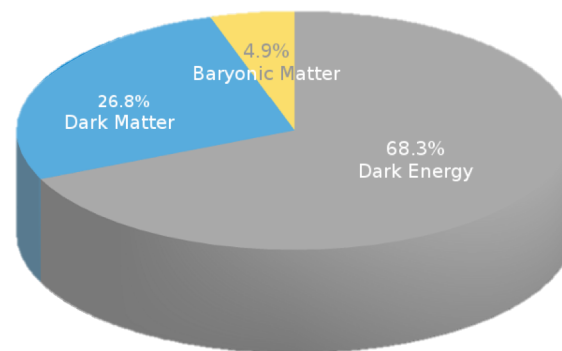


Favorite collider candidate: WIMP

- Heavy, stable, & couples to SM
- Naturally accounts for observed relic density (WIMP Miracle)
- *Should* be produced at the LHC



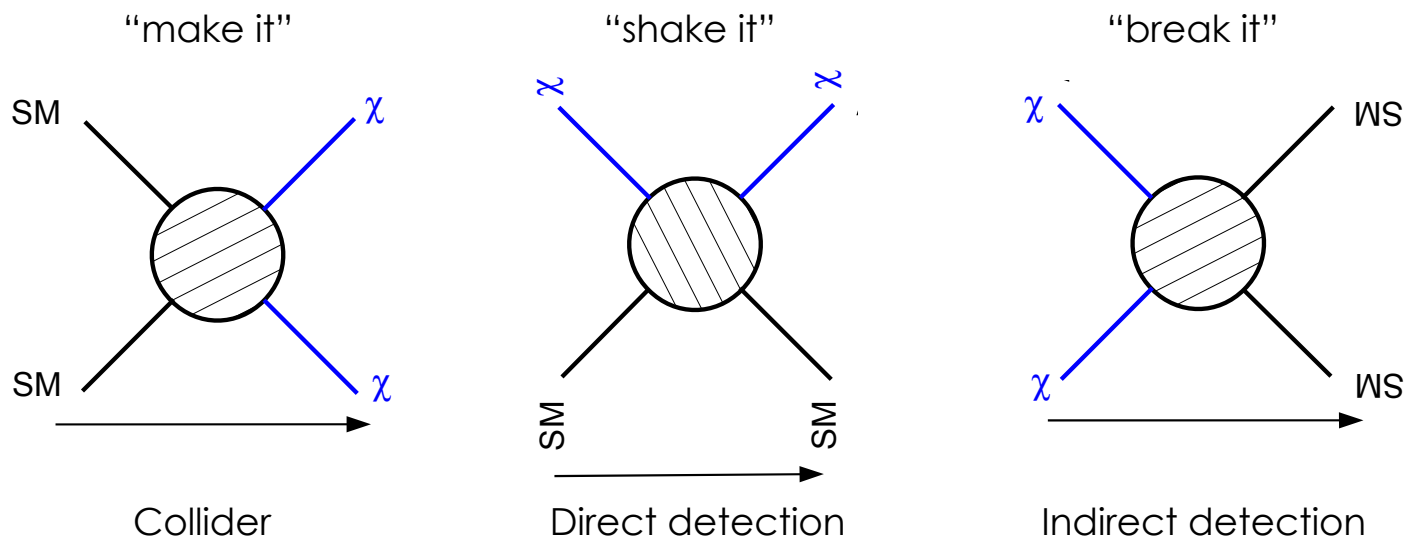
Dark Matter



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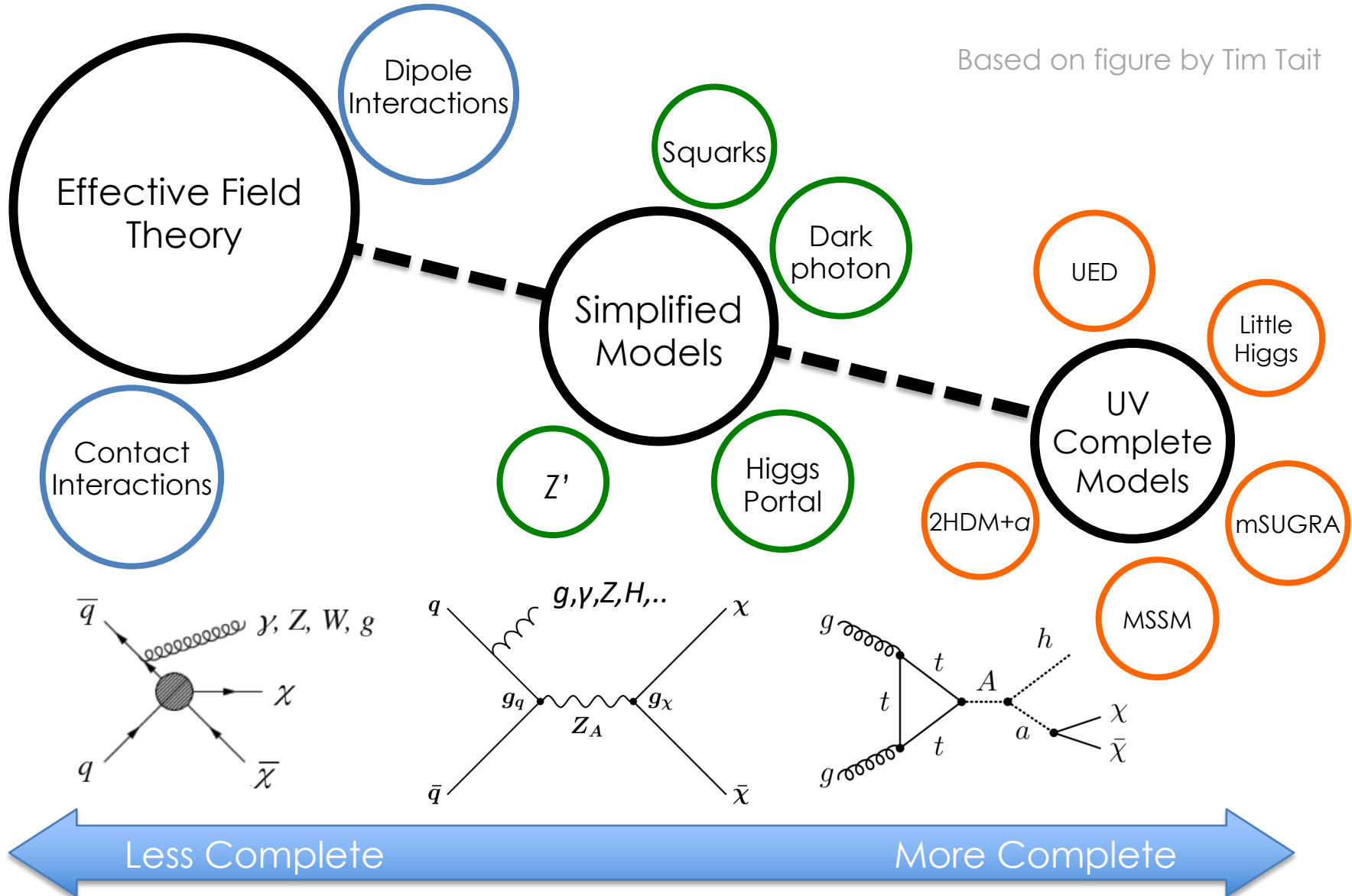
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Complementary to dedicated DM experiments



Interpreting DM Production

Based on figure by Tim Tait

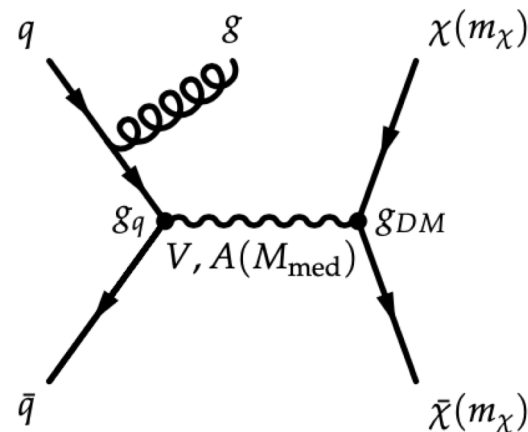
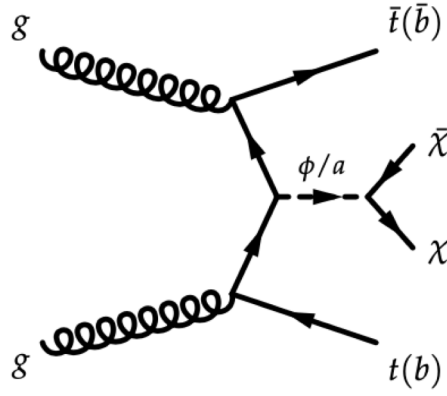
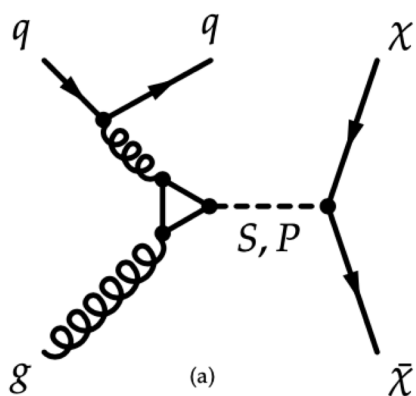


Simplified DM Models

Benchmark models defined in
CMS/ATLAS Dark Matter Forum

[Physics of the Dark Universe 27 \(2020\) 100371](#)

- Dark matter assumed to be a Dirac fermion WIMP: χ
- Boson mediator between SM and DM
 - Spin-0: Scalar (S) or pseudo-scalar (P/a)
 - Spin-1: Vector (V/Z') or axial-vector (A)
- Minimal set of parameters: $M_\chi, M_{\text{med}}, g_\chi, g_q, g_\ell$



This Talk



- $E_T^{\text{miss}} + X$
 - $Z + E_T^{\text{miss}}$
 - $tt + E_T^{\text{miss}}$
 - Summary Plots



- $H \rightarrow \text{invisible}$
 - $VBF + E_T^{\text{miss}}$
 - Combination



- **Novel search for semi-visible jets**



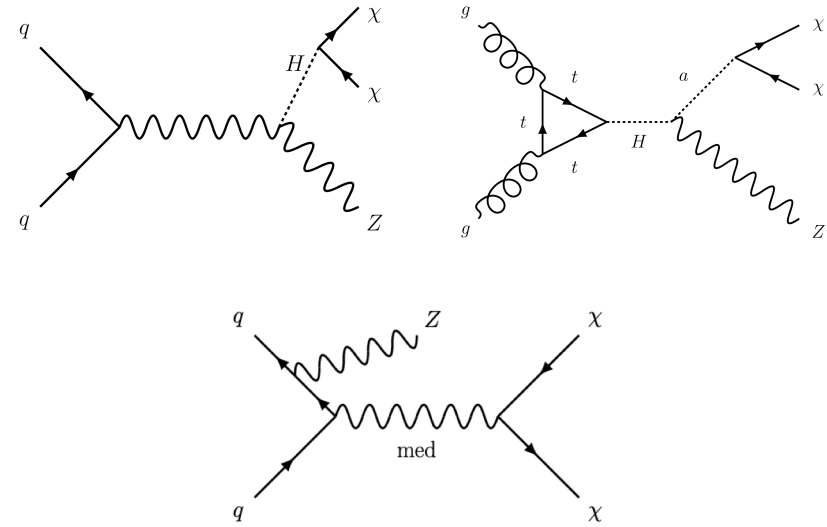
- **Briefly advertise**
 - SUSY Electroweakinos
 - Dark Higgs
 - $2\text{HDM}+a H \rightarrow \tau\tau$

$Z(\ell\ell) + E_T^{\text{miss}}$

Interpreted in simplified DM models, 2HDM+ a , and $H \rightarrow$ invisible

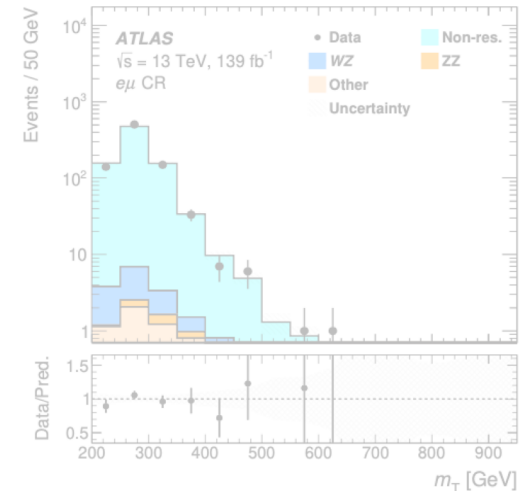
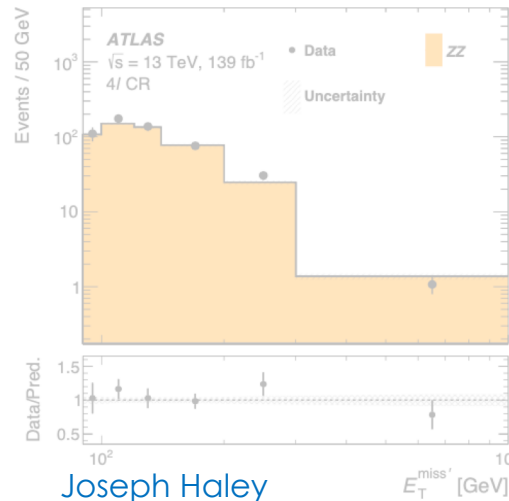
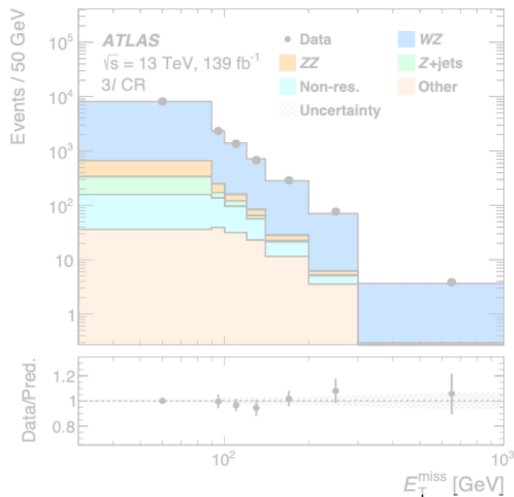
Select Signal Region (SR) with:

- Two opposite-charge leptons (e^+e^- , $\mu^+\mu^-$)
- $m_{\ell\ell} \in [76, 106]$ GeV, $\Delta R_{\ell\ell} < 1.8$
- $E_T^{\text{miss}} > 90$ GeV, E_T^{miss} signif. > 9



Dominant backgrounds from ZZ and WZ

- Constrained using three Control Regions (CRs):

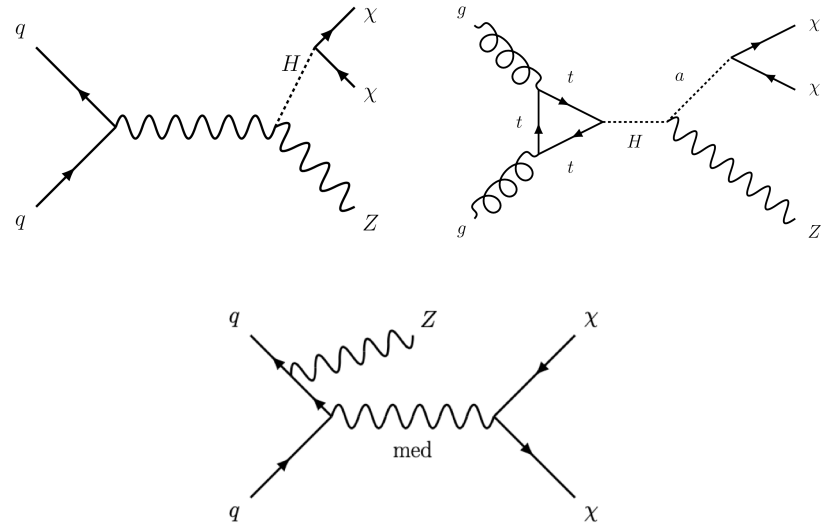


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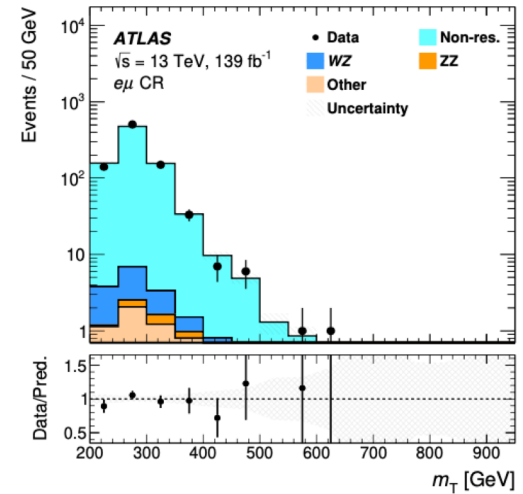
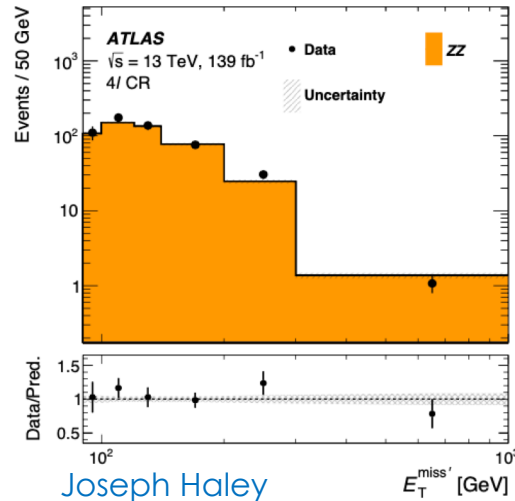
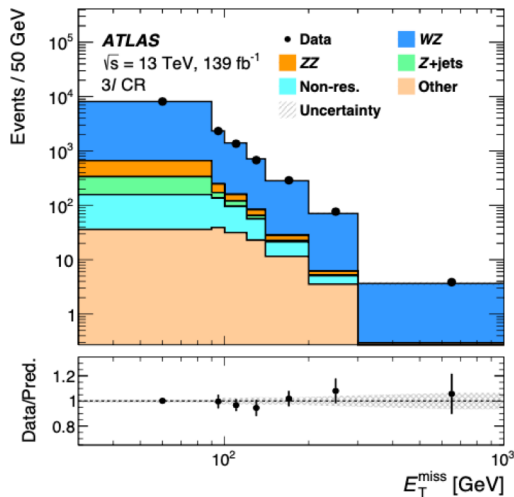
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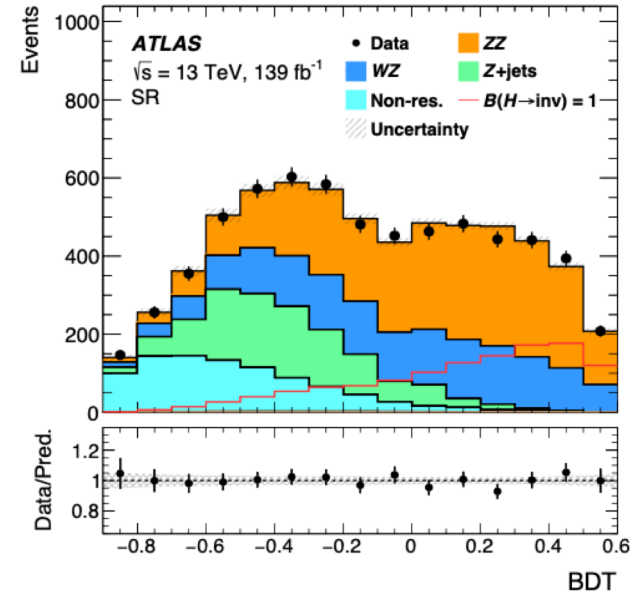
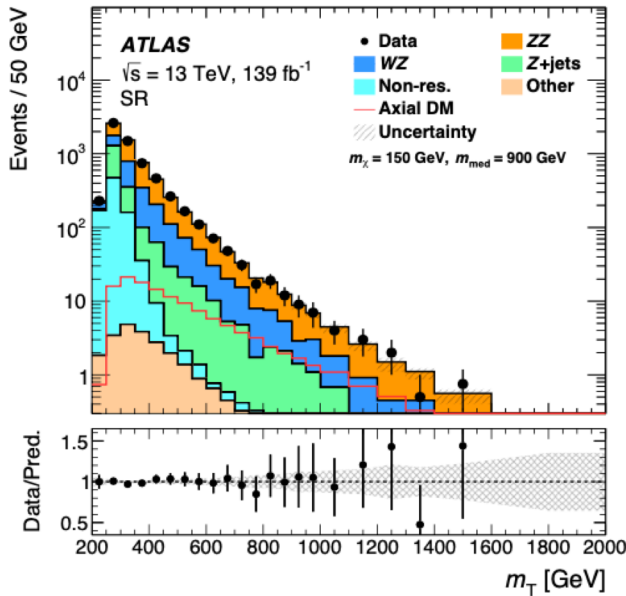
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Simultaneous profile likelihood fit in SR and three CRs

- Simplified DM and 2HDM+ a model use m_T distribution
- $H \rightarrow \text{inv.}$ uses Boosted Decision Tree discriminant

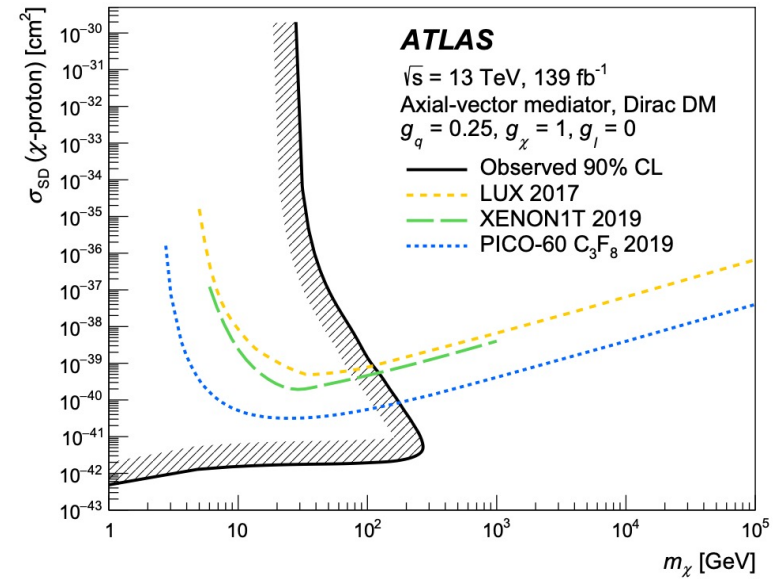
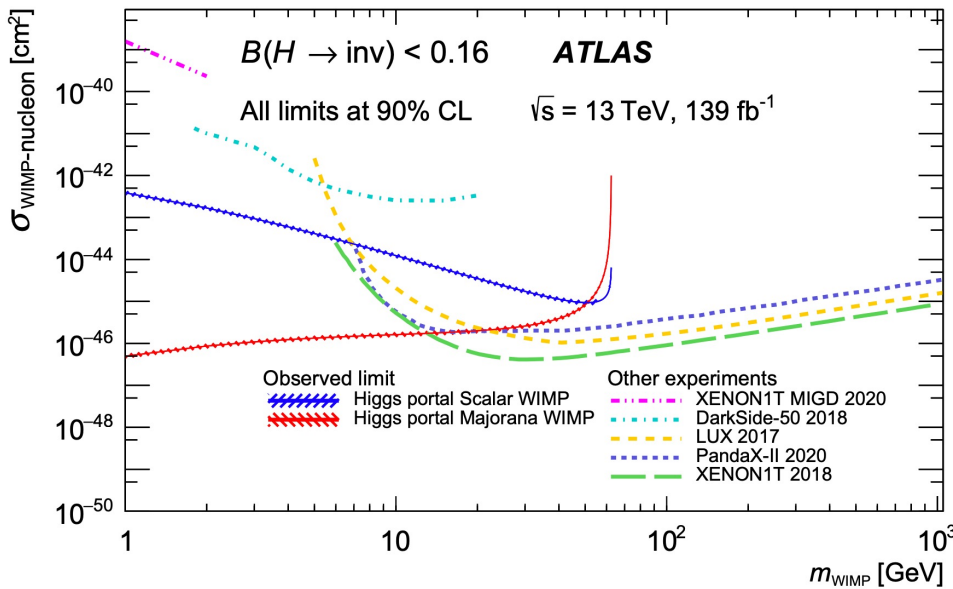


$$m_T = \sqrt{\left[\sqrt{m_Z^2 + (p_T^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_T^{\text{miss}})^2} \right]^2 - \left[\vec{p}_T^{\ell\ell} + \vec{E}_T^{\text{miss}} \right]^2}$$

Good agreement with SM prediction :-)
 ⇒ Set limits on model parameters

$Z(\ell\ell) + E_T^{\text{miss}}$

Limits on WIMP-nucleon cross-section complementary to direct detection



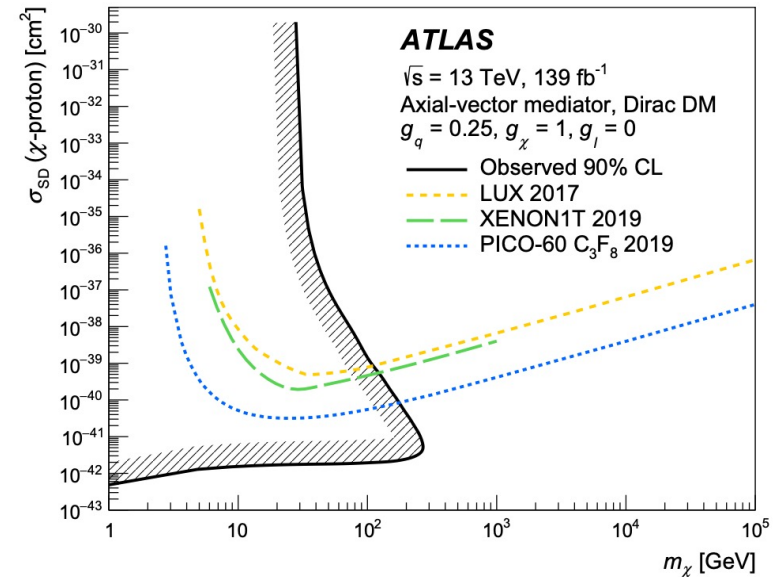
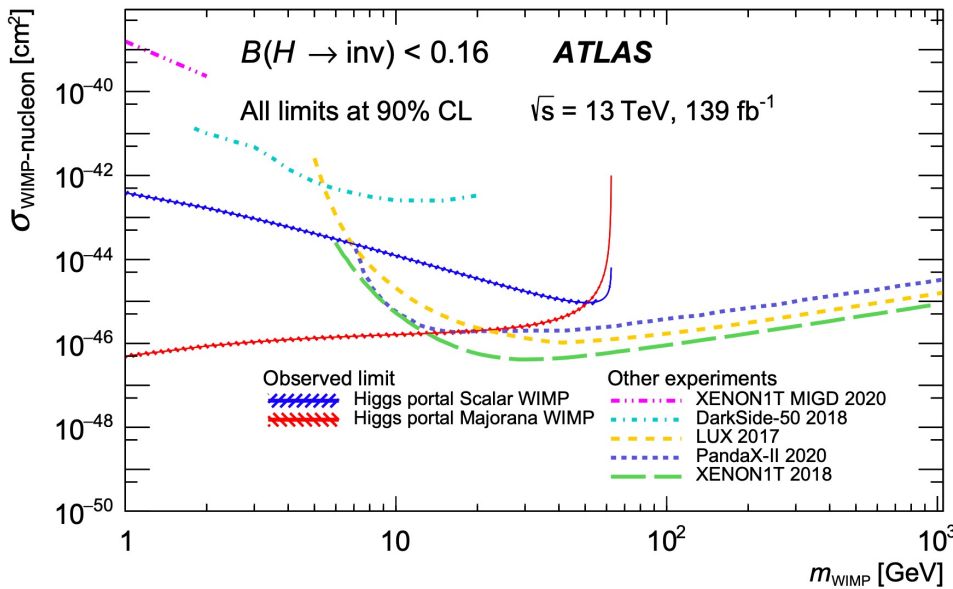
Interpreting as SM Higgs \rightarrow invisible: $BR(H \rightarrow \text{inv.}) = 0.003 \pm 0.09$

- 45% better sensitivity beyond increase in luminosity!
- Competitive with VBF $H \rightarrow$ invisible

(Also interpreted in 2HDM+a and simplified DM parameters)

$$Z(\ell\ell) + E_T^{\text{miss}}$$

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$tt (tW, tq) + E_T^{\text{miss}}$

Focus on DM with spin-0 mediator

- Important in models with Min. Flavor Violation
- Yukawa-like coupling to mediator $\propto m_f$

Combination of 0, 1, & 2 lepton searches

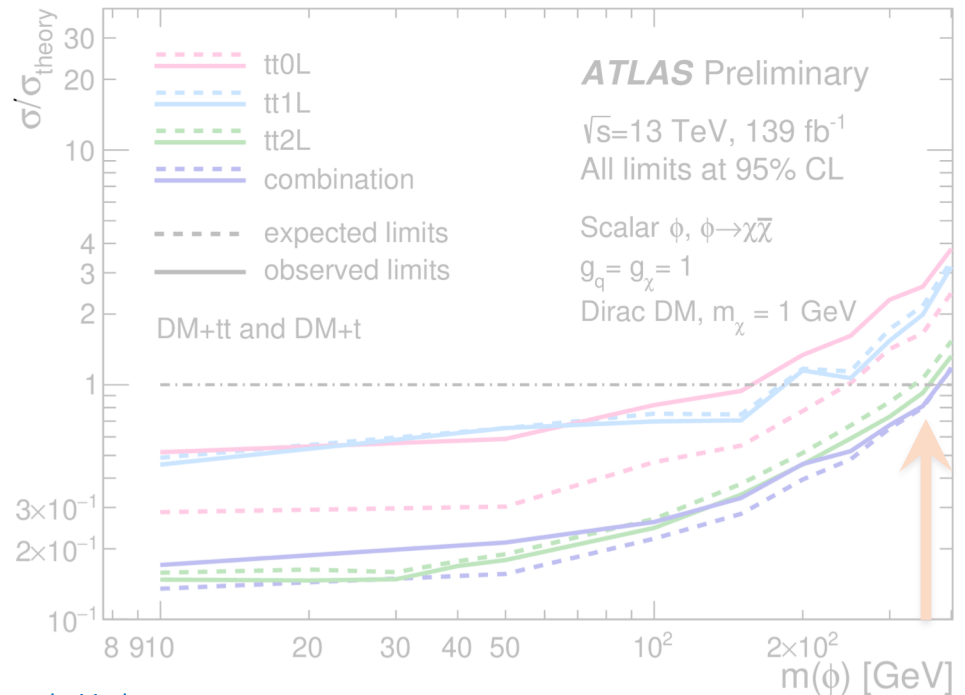
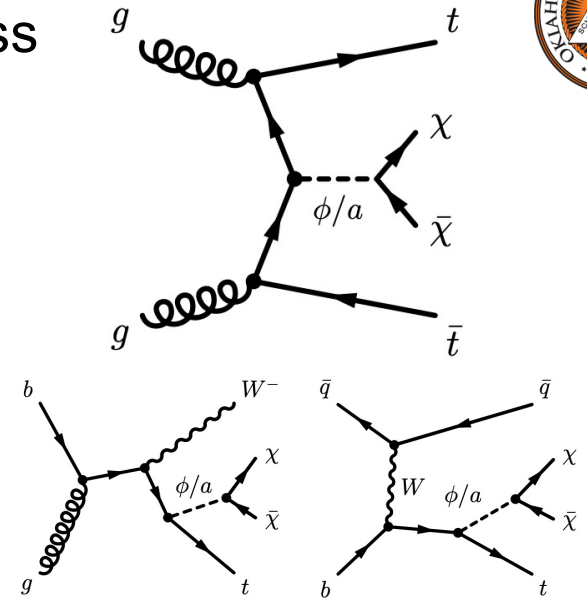
Eur. Phys. J. C 80 (2020) 737, JHEP 04 (2020) 174, JHEP 04 (2021) 165

- Set limits on $\sigma/\sigma_{\text{theory}}$ vs. $m_{\phi(a)}$

\Rightarrow Exclude m_ϕ up to 370 GeV

- Interpreting as $H \rightarrow$ invisible

Analysis	Best fit $\mathcal{B}_{H \rightarrow \text{inv}}$	Observed upper limit	Expected upper limit
tt0L	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$
tt1L	$-0.04^{+0.35}_{-0.29}$	0.74	$0.80^{+0.40}_{-0.26}$
tt2L	$-0.09^{+0.22}_{-0.20}$	0.39	$0.42^{+0.18}_{-0.12}$
$t\bar{t}H$ comb.	$0.08^{+0.16}_{-0.15}$	0.40	$0.30^{+0.13}_{-0.09}$



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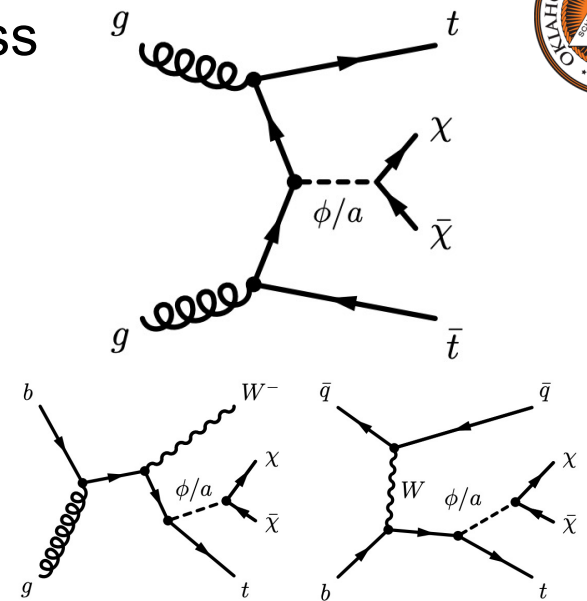
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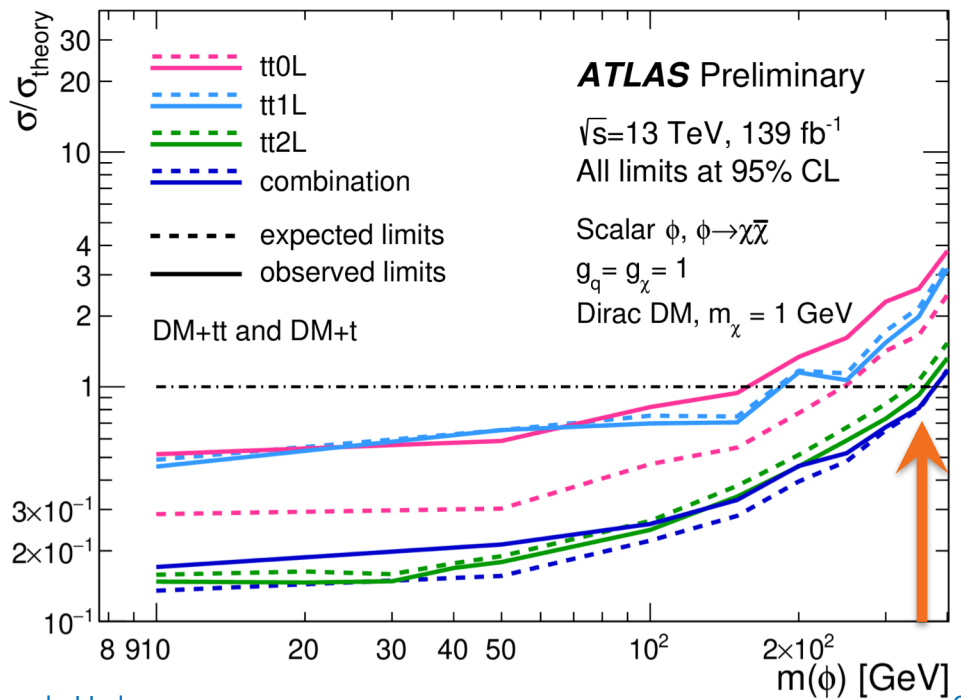
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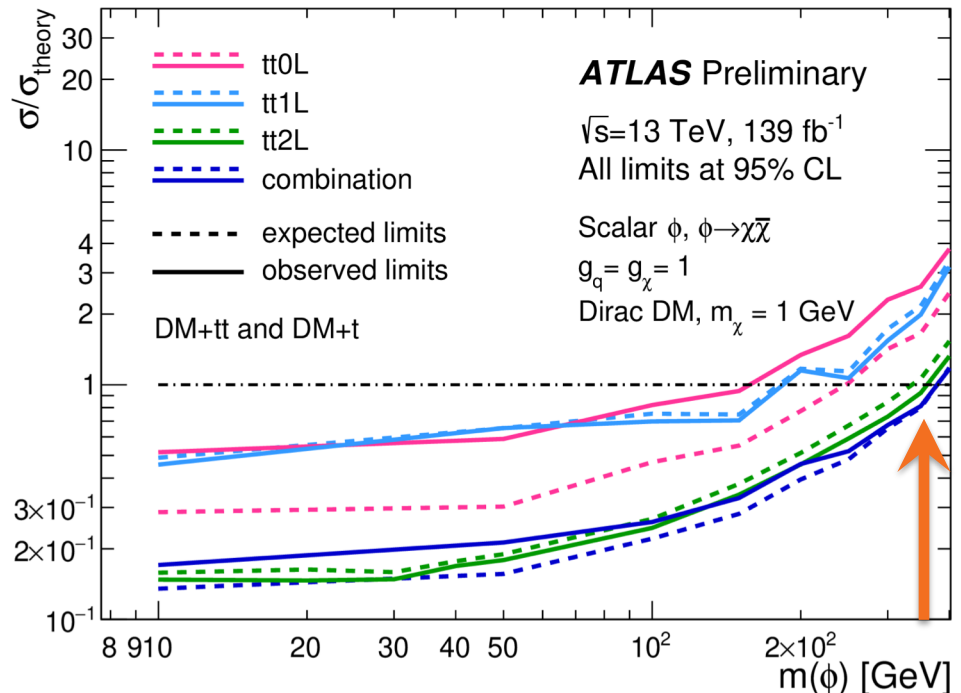
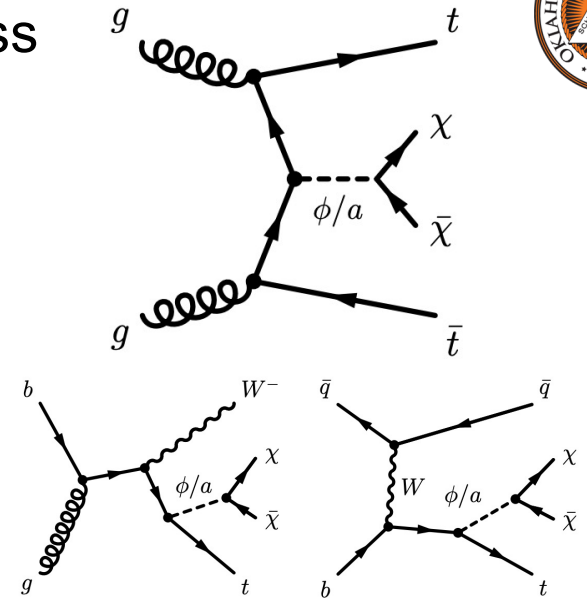
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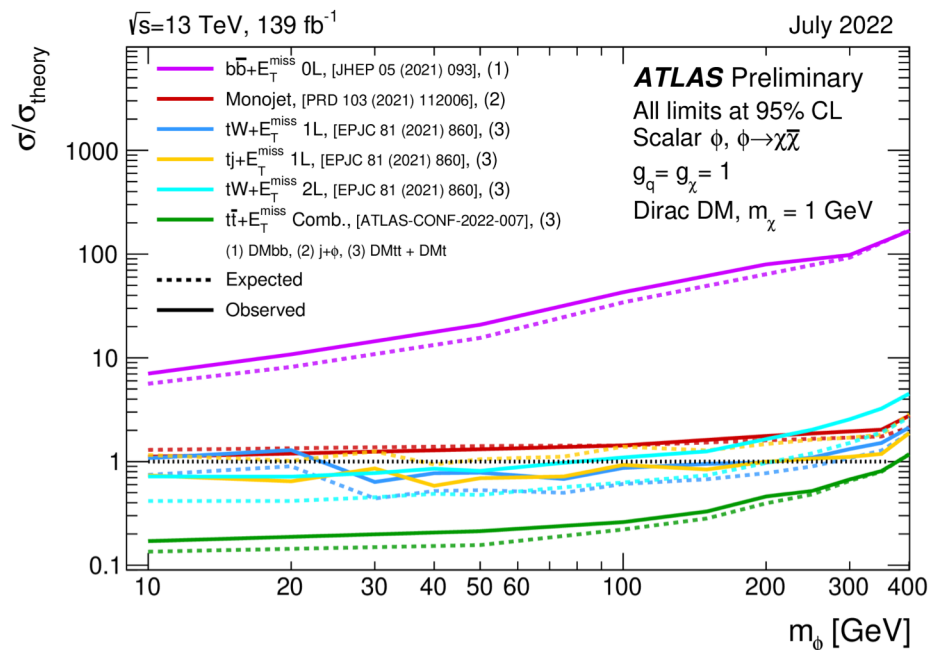
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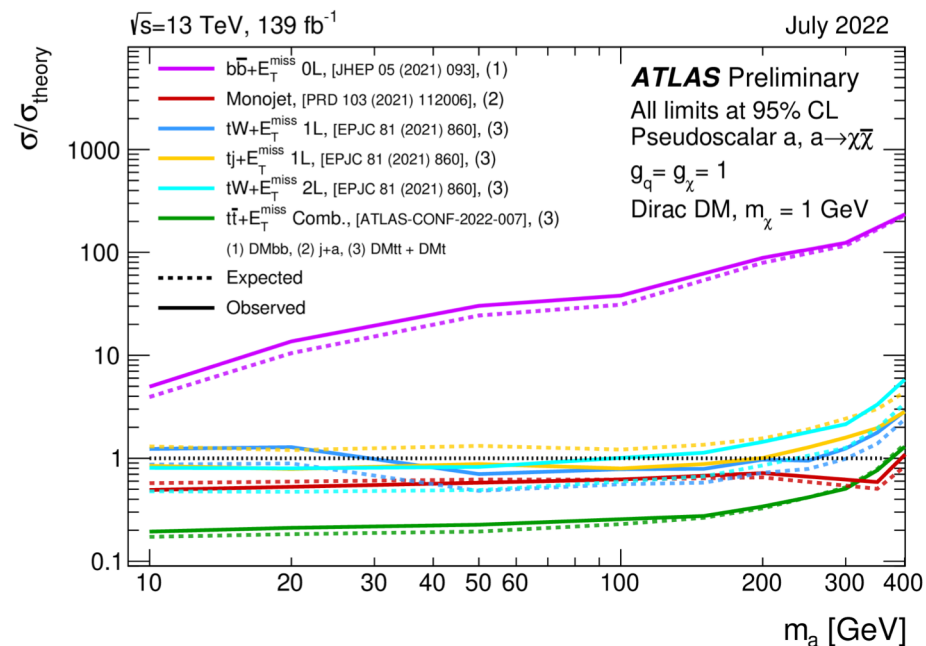


Summary Plots: Spin-0 Mediators

Limit on $\sigma/\sigma_{\text{theory}}$ assuming $g_\chi = g_q = 1$, $m_\chi = 1$ GeV



Scalar mediator
 \Rightarrow Exclude $m_\phi < 370$ GeV

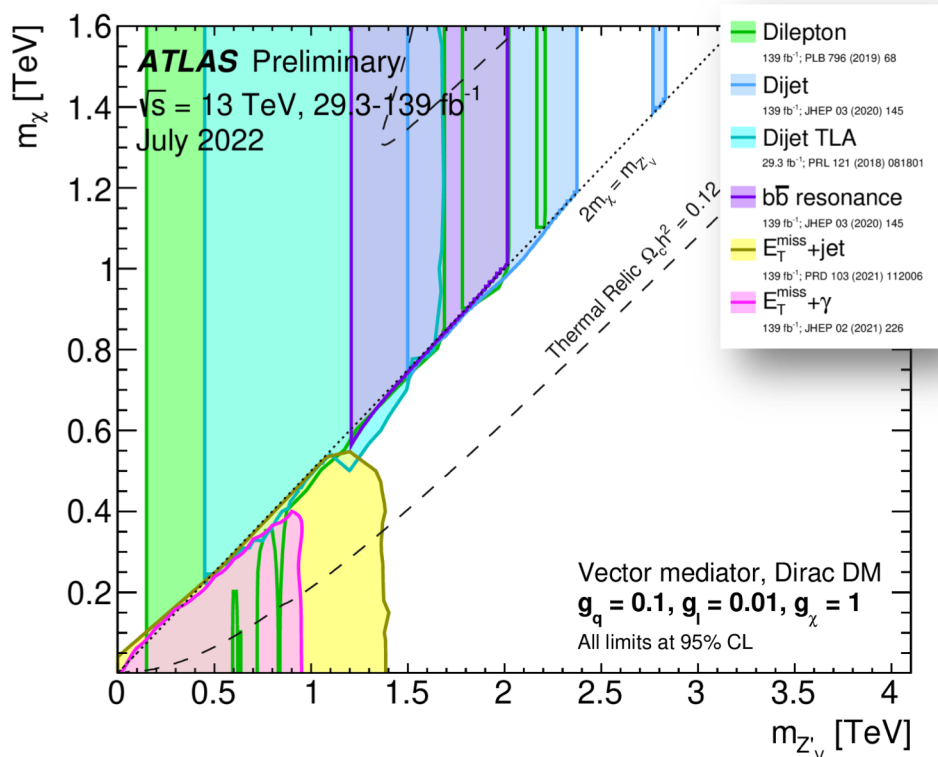


Pseudoscalar mediator
 \Rightarrow Exclude $m_a < 376$ GeV

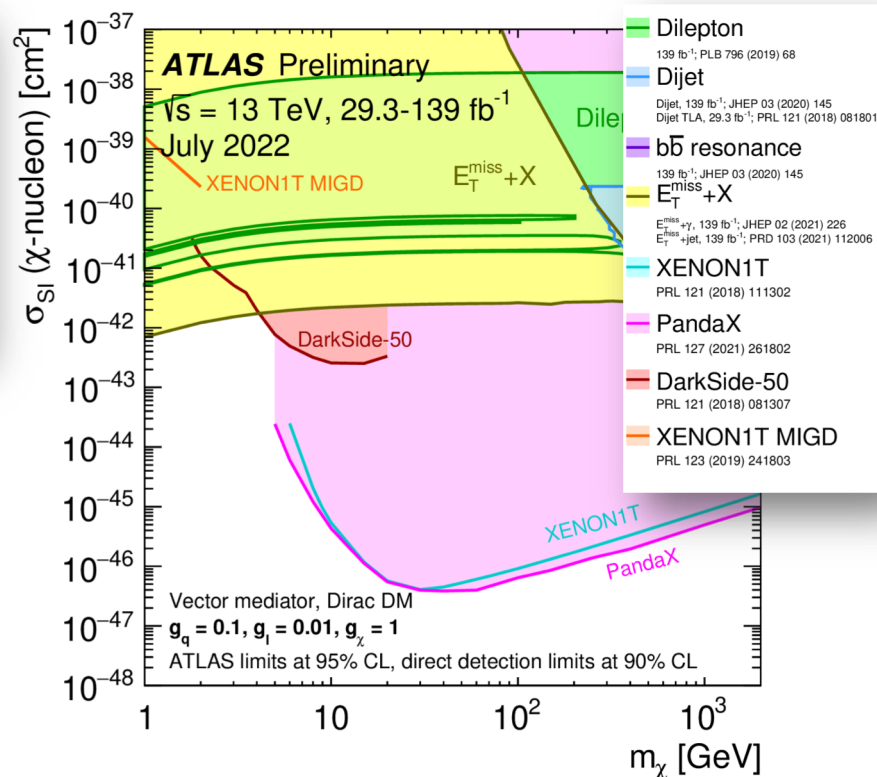
Summary Plots: Spin-1 Mediators

Leptophilic Vector mediator assuming $g_q=0.1, g_l=0.01, g_\chi=1$

95% CL limits on m_χ vs. $m_{V(A)}$



90% CL limits on WIMP-nucleon cross-section vs. m_χ

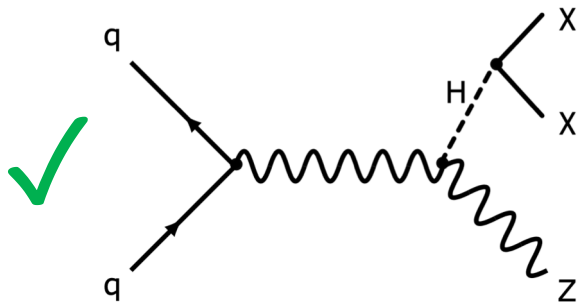


- Similar results for Axial-Vector
- Also results for leptophobic couplings $g_q=0.25, g_l=0, g_\chi=1$

New $H \rightarrow$ invisible Combination

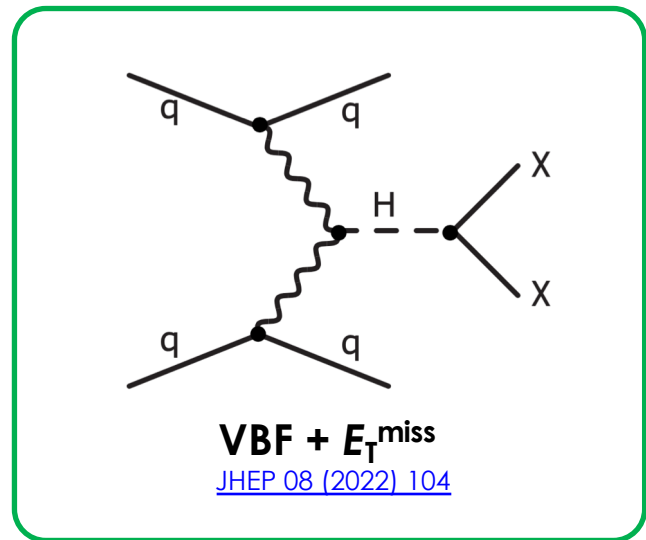
Assume SM production cross sections, but $H \rightarrow E_T^{\text{miss}}$

Look in main production topologies



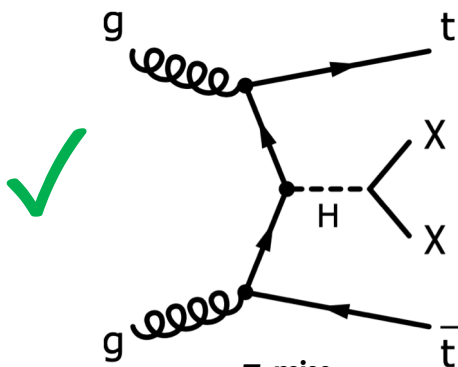
Z + E_T^{miss}

[Phys. Lett. B 829 \(2022\) 137066](#)



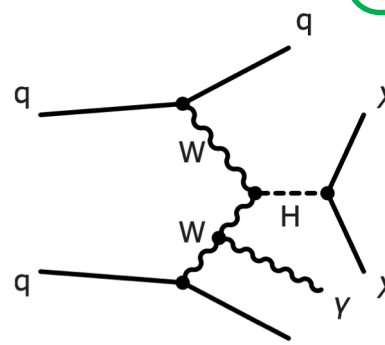
VBF + E_T^{miss}

[JHEP 08 \(2022\) 104](#)



$tt + E_T^{\text{miss}}$

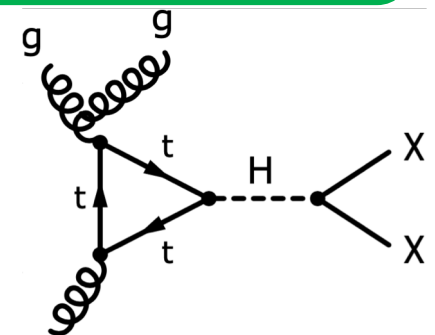
[2211.05426](#)



VBF + $\gamma + E_T^{\text{miss}}$

[Eur. Phys. J. C82 \(2022\) 105](#)

(see backup slides)



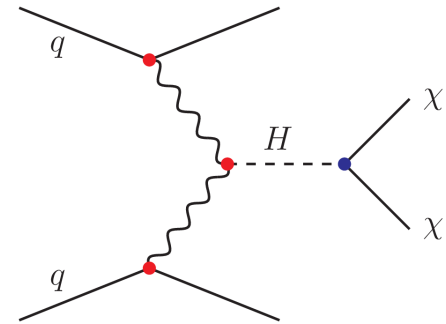
jet + E_T^{miss}

[Phys. Rev. D 103, 112006 \(2021\)](#)

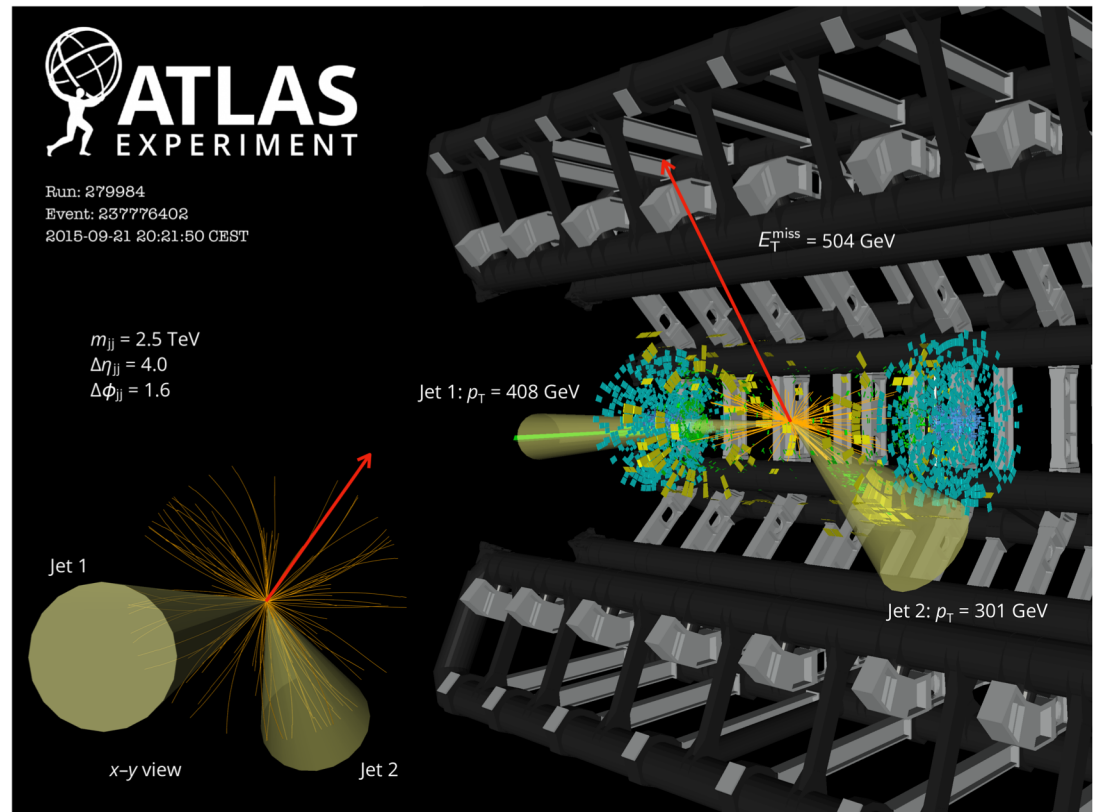
(see backup slides)

VBF + E_T^{miss}

Second highest rate and unique signature
 \Rightarrow most sensitive channel

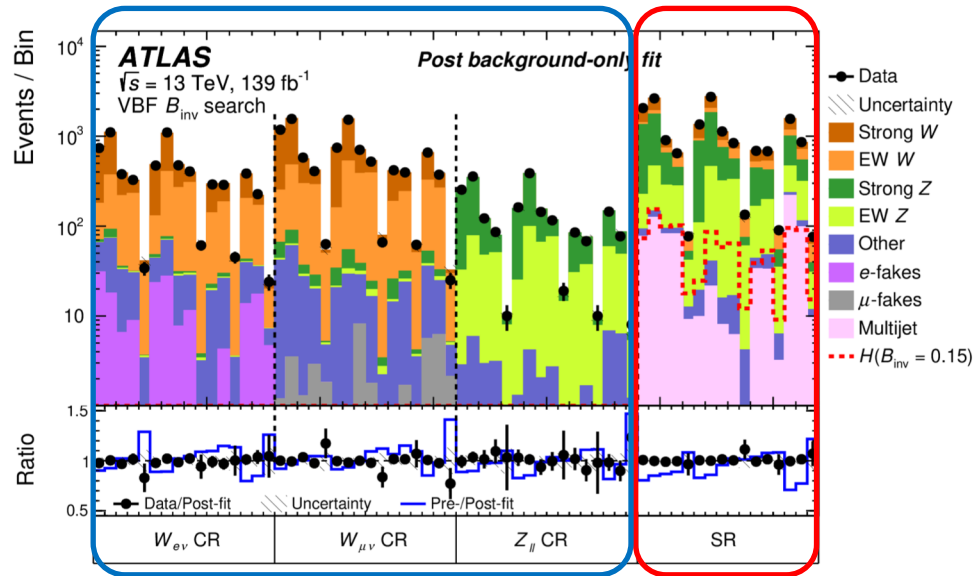
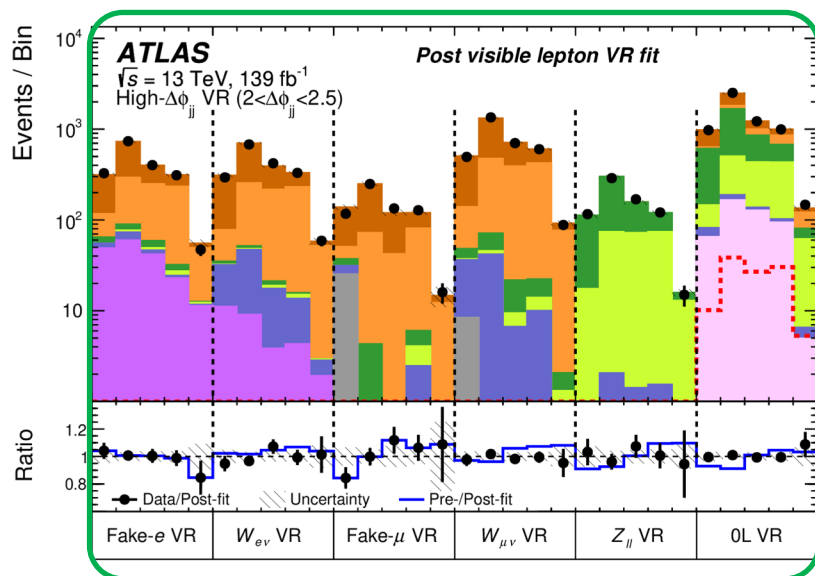


- E_T^{miss} + two forward jets in opposite hemisphere
 - Large $E_T^{\text{miss}} > 160$ GeV
 - Large $\Delta\eta_{jj} > 3.8$
 - Large $m_{jj} > 800$ GeV
 - $\Delta\phi < 2.0$
 \Rightarrow Reduce multijet
 - Veto e, μ, γ
 \Rightarrow Reduce other backgrounds
 - Allow up 3rd and 4th jet if compatible with VBF FSR



VBF + E_T^{miss}

Dedicated VRs and CRs to validate and constrain backgrounds
 16 SRs of varying purity and composition



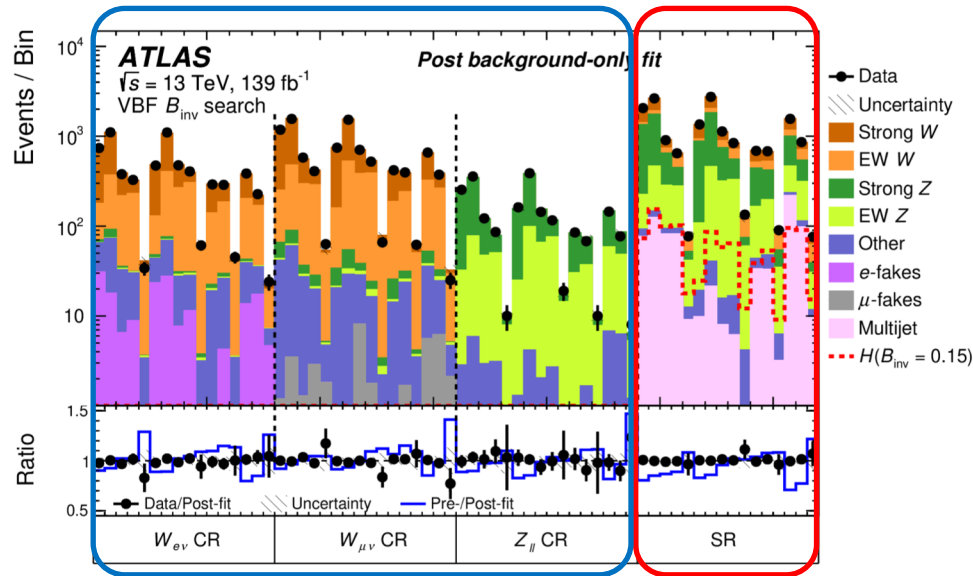
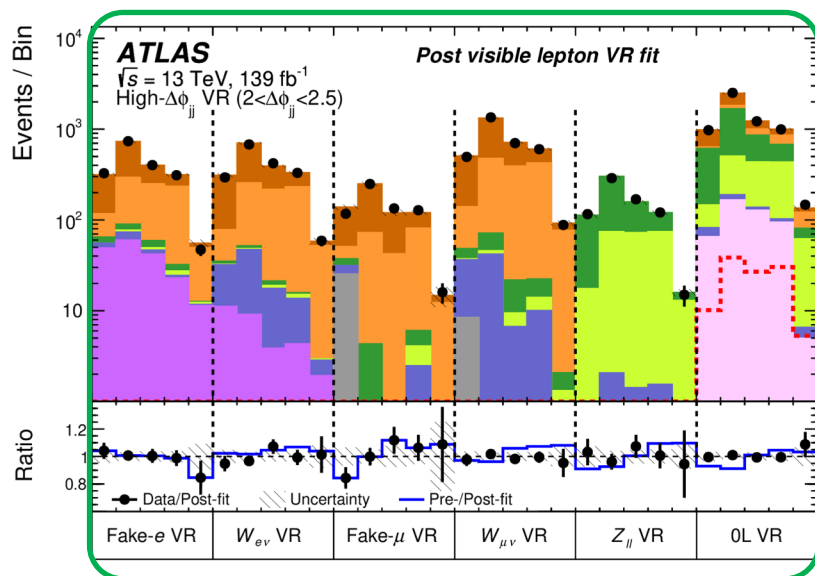
Data consistent with SM \Rightarrow Set limit @ 95%CL

- **Observed:** $B(H \rightarrow \text{inv}) < 0.145$
- **Expected:** $B(H \rightarrow \text{inv}) < 0.103$

\Rightarrow **Combine** with other Run 2 searches,
 plus previous Run 1 combination...

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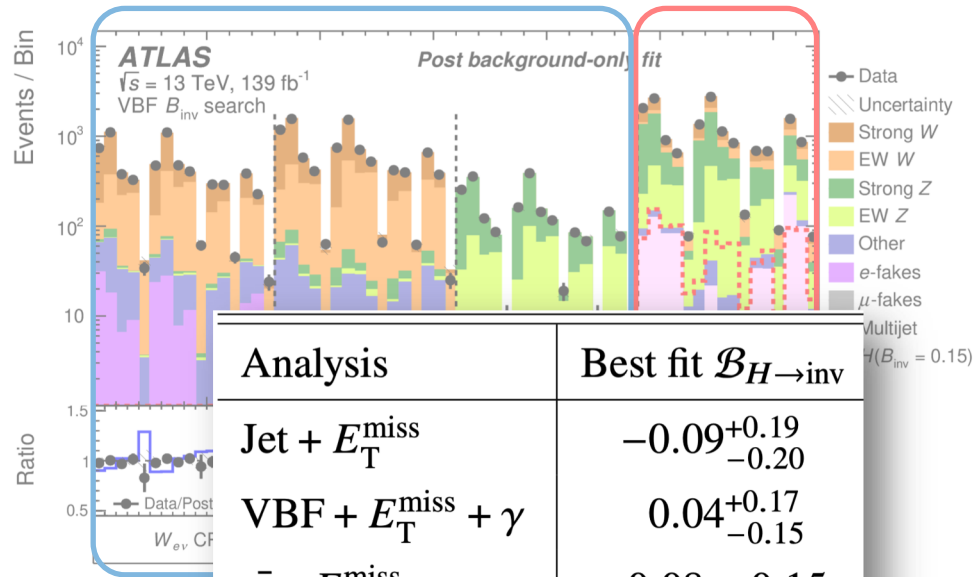
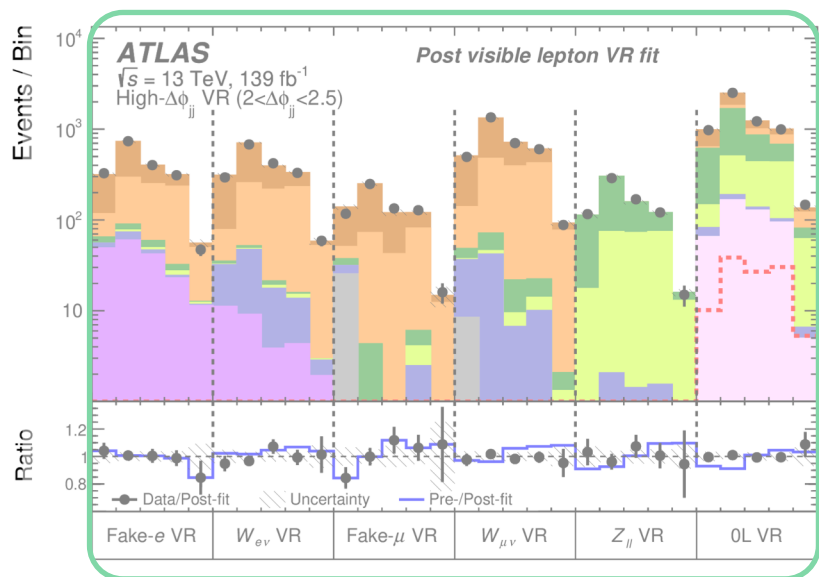
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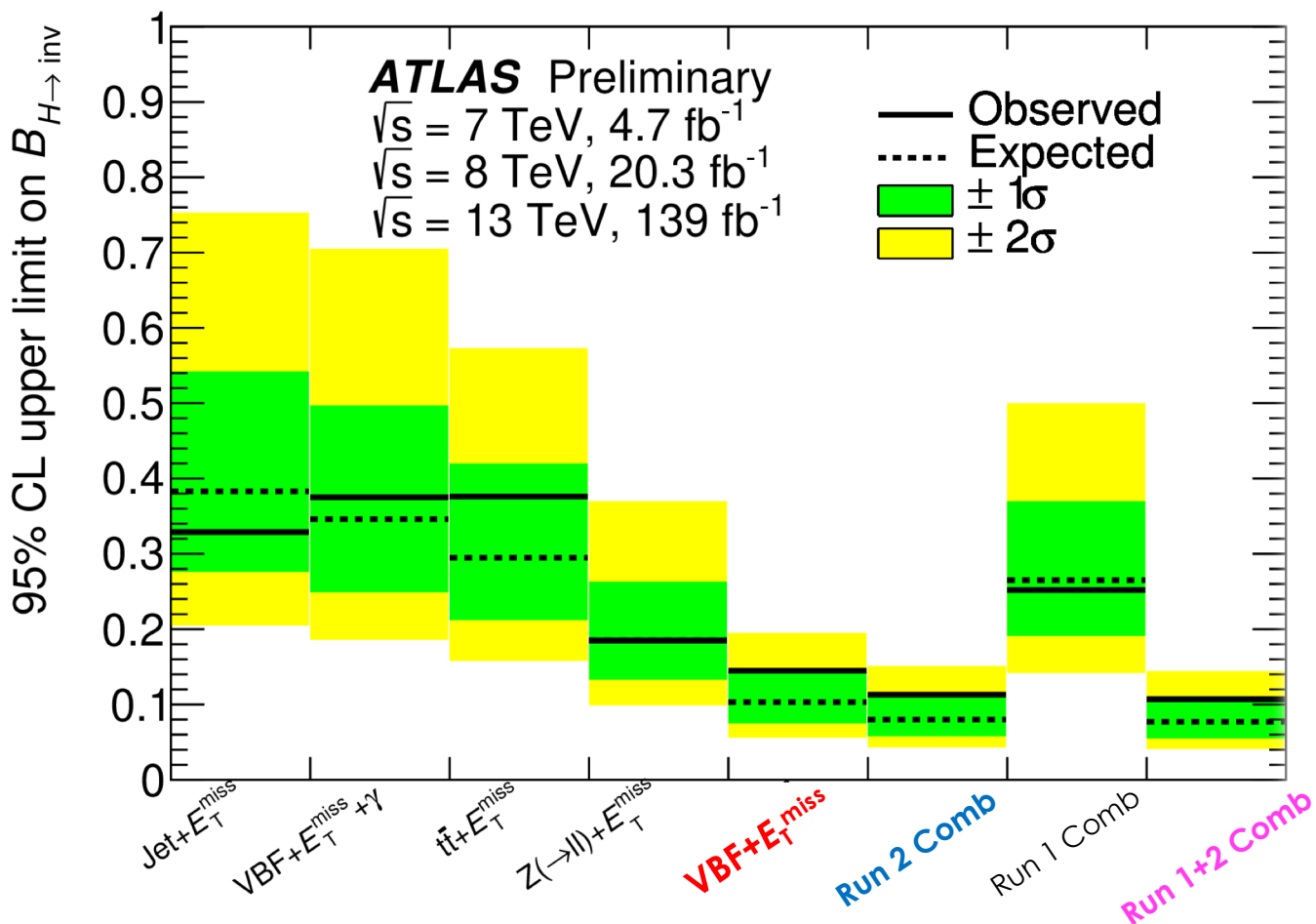
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Analysis	Best fit $\mathcal{B}_{H \rightarrow \text{inv}}$
Jet + E_T^{miss}	$-0.09^{+0.19}_{-0.20}$
VBF + $E_T^{\text{miss}} + \gamma$	$0.04^{+0.17}_{-0.15}$
$t\bar{t} + E_T^{\text{miss}}$	0.08 ± 0.15
$Z(\rightarrow \ell\ell) + E_T^{\text{miss}}$	0.00 ± 0.09
VBF + E_T^{miss}	0.05 ± 0.05
Run 2 Comb.	0.04 ± 0.04
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$
Run 1+2 Comb.	0.04 ± 0.04

$H \rightarrow \text{inv.}$ Combination

Upper limits on $B(H \rightarrow \text{inv.})$ at 95% CL



Sensitivity dominated by VBF+ E_T^{miss}

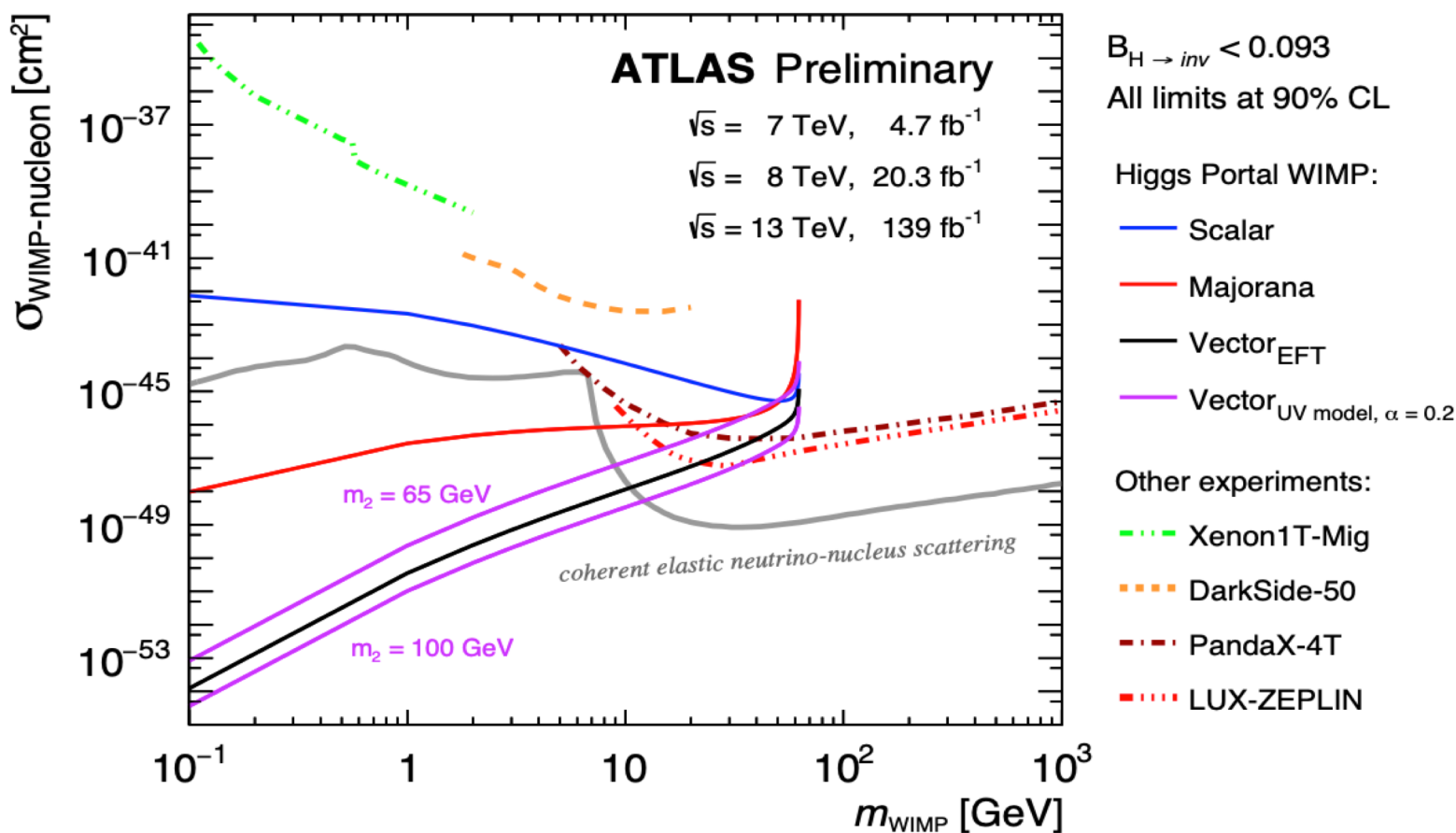
22% gain

+4% gain

$H \rightarrow \text{inv.}$ Combination

Interpret in models where **Higgs is portal** to DM WIMP

- Set limits on WIMP-nucleon cross section at 90% CL
- Complementary to direct detection experiments



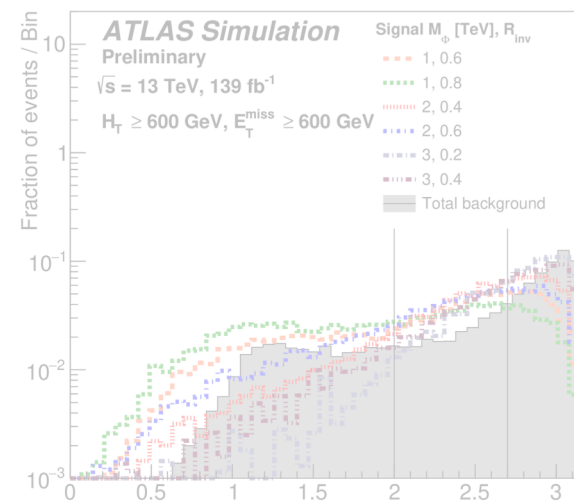
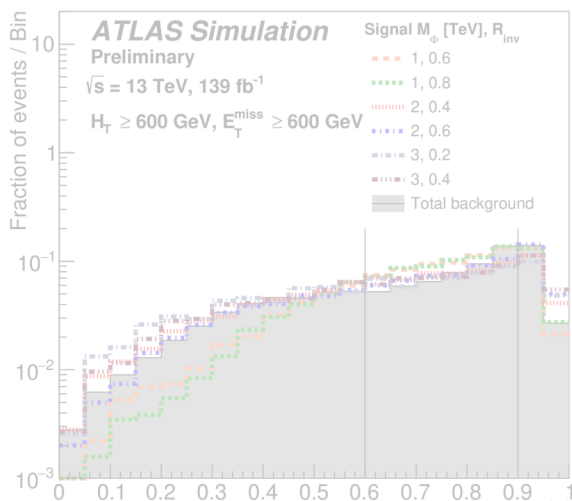
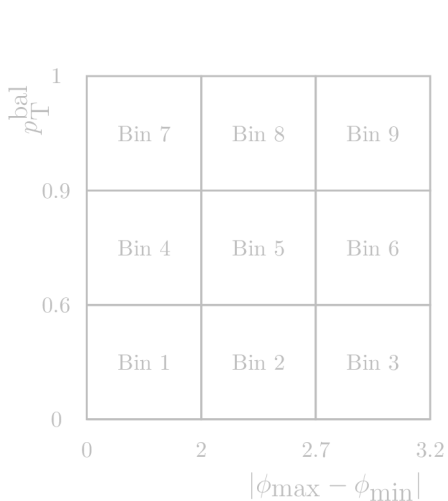
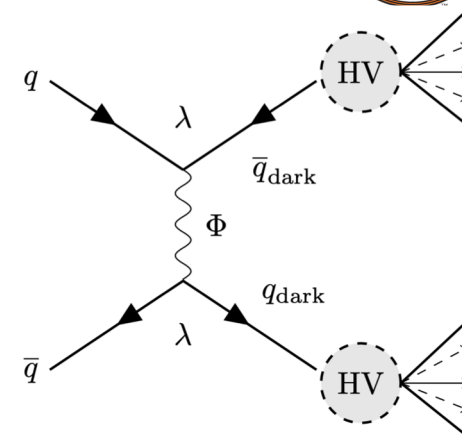
Dark matter to semi-visible jets

Sensitive to strongly coupled dark sector

- Scalar mediator (Φ) acts as portal
- Focus on t-channel (can probe high masses)

Signal: 2 semi-visible jets (SVJs)

- High $H_T = \sum_{\text{jets}} p_T$ and high E_T^{miss} close to a jet
- ≥ 1 additional jet to suppress dominant multijet background
- Veto e, μ , and ≥ 2 b -tags to suppress other backgrounds
- Fit 9-bin distribution of two discriminating variables



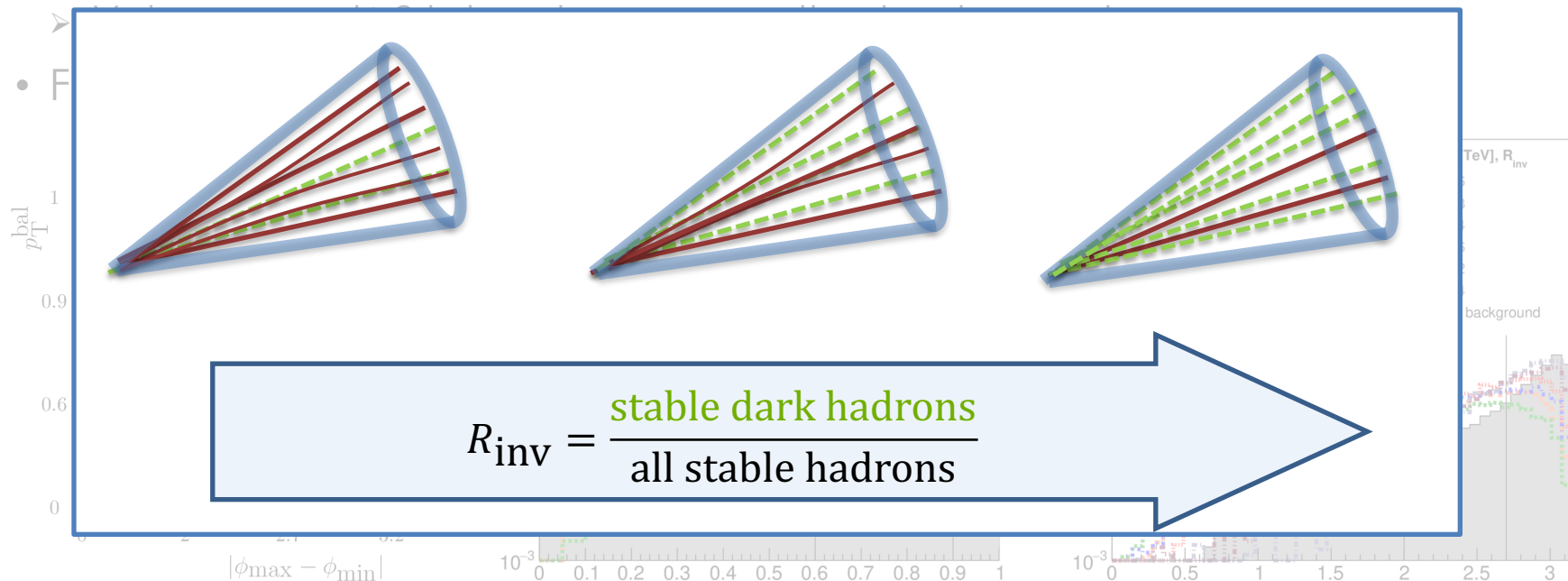
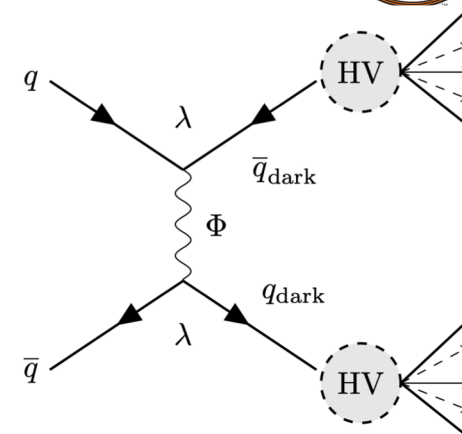
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- ≥ 1 additional jet to suppress dominant multijet background



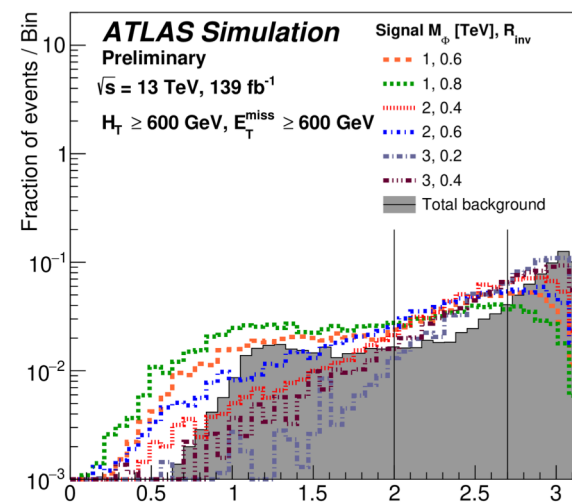
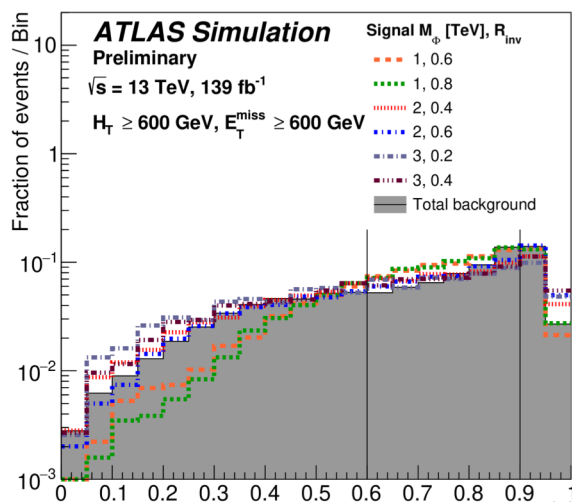
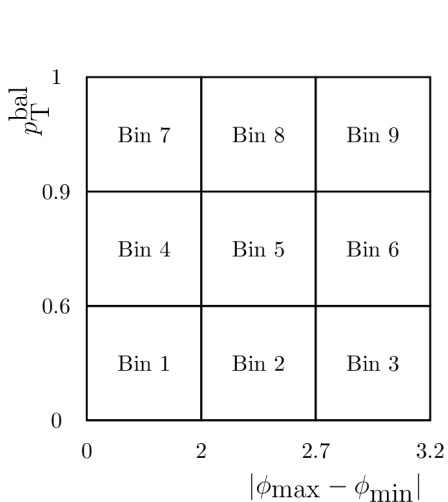
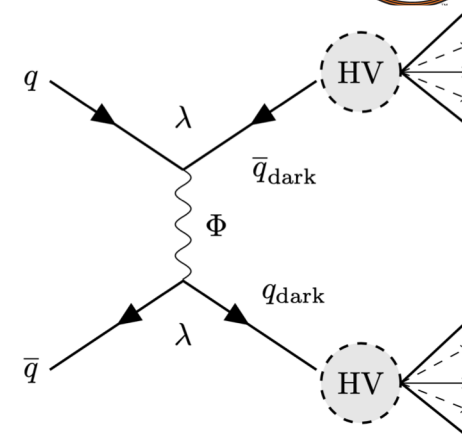
Dark matter to semi-visible jets

Sensitive to strongly coupled dark sector

- Scalar mediator (Φ) acts as portal
- Focus on t-channel (can probe high masses)

Signal: 2 semi-visible jets (SVJs)

- High $H_T = \sum_{\text{jets}} p_T$ and high E_T^{miss} close to a jet
- ≥ 1 additional jet to suppress dominant multijet background
- Veto e, μ , and ≥ 2 b -tags to suppress other backgrounds
- Fit 9-bin distribution of two discriminating variables



$$p_T^{\text{bal}} = \frac{|\vec{p}_T(j_1) + \vec{p}_T(j_2)|}{|\vec{p}_T(j_1)| + |\vec{p}_T(j_2)|}$$

$$|\phi_{\text{max}} - \phi_{\text{min}}|$$

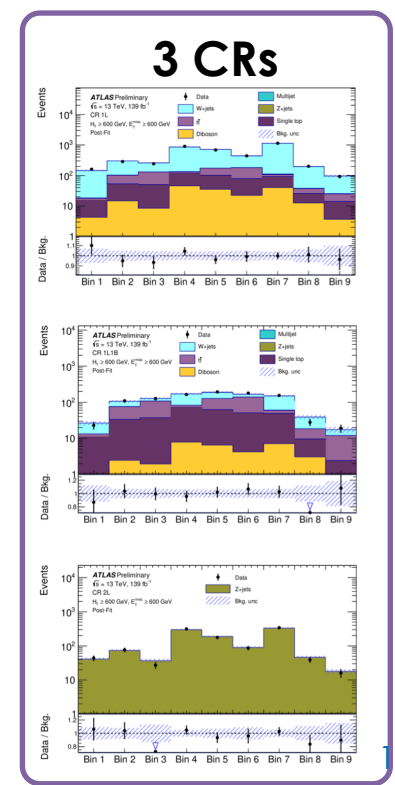
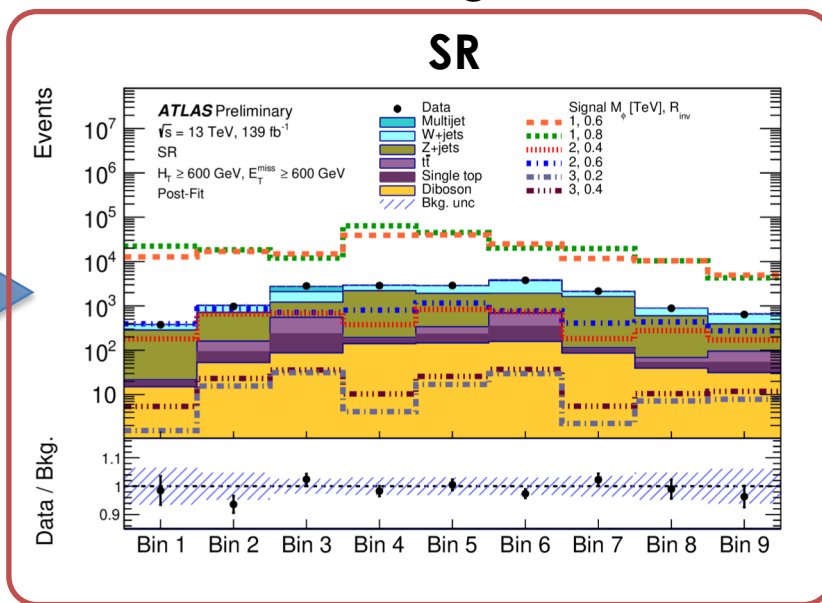
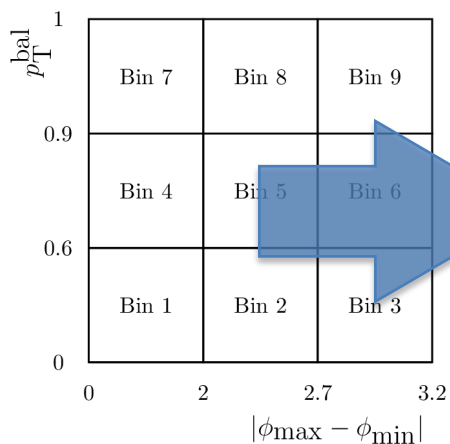
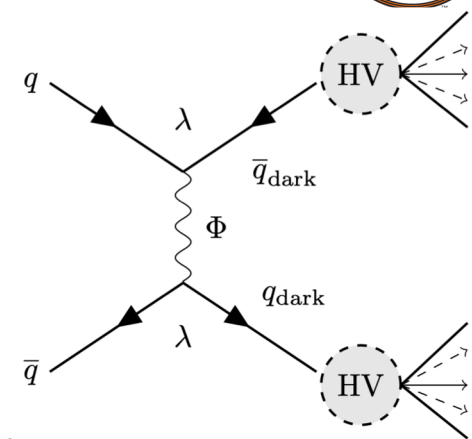
Dark matter to semi-visible jets

Sensitive to strongly coupled dark sector

- Scalar mediator (Φ) acts as portal
- Focus on t-channel (can probe high masses)

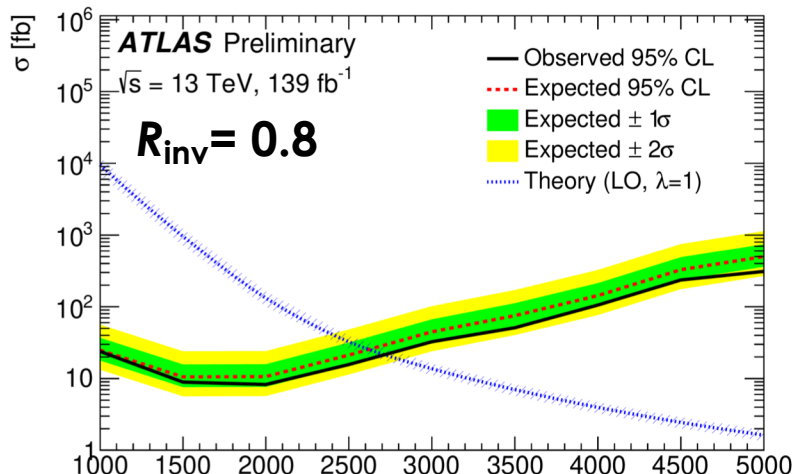
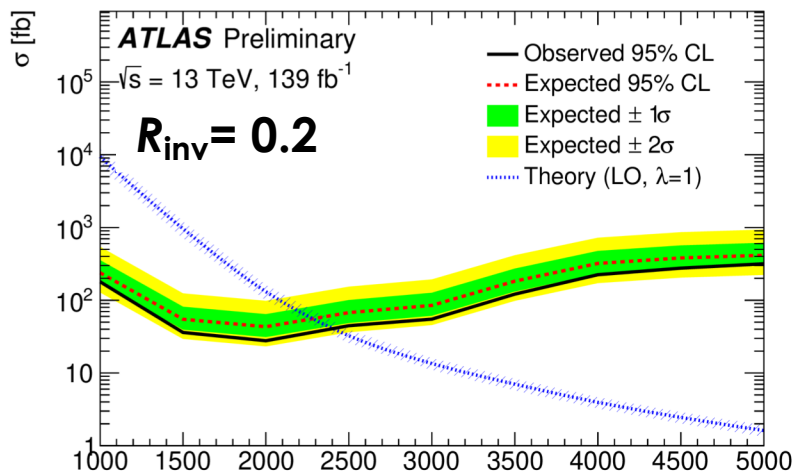
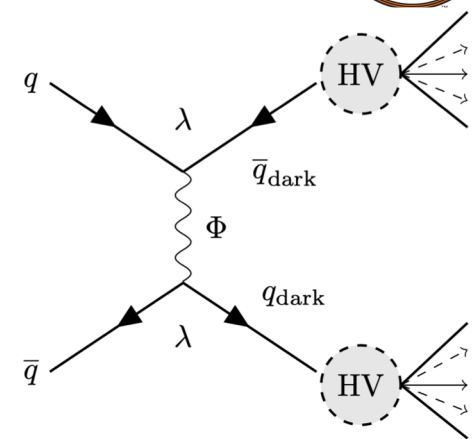
Signal: 2 semi-visible jets (SVJs)

- High $H_T = \sum_{\text{jets}} p_T$ and high E_T^{miss} close to a jet
- ≥ 1 additional jet to suppress dominant multijet background
- Veto e, μ , and ≥ 2 b -tags to suppress other backgrounds
- Fit 9-bin distribution of two discriminating variables



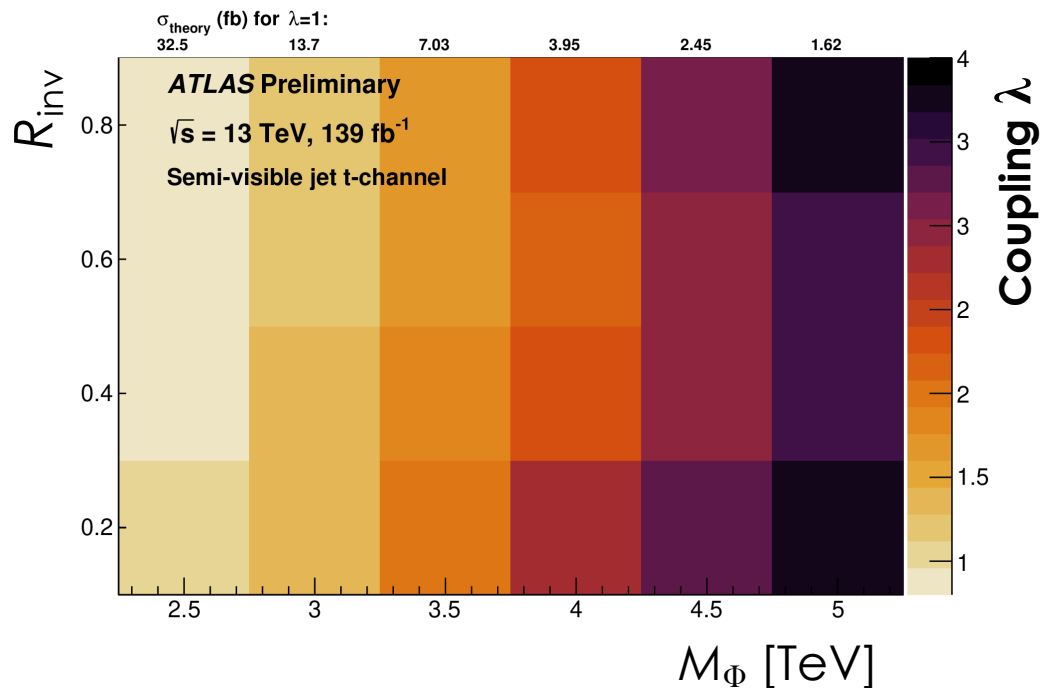
Dark matter to semi-visible jets

Set limits on cross-section and coupling vs. M_Φ and R_{inv}



M_Φ [GeV]

95% CL upper limits on λ

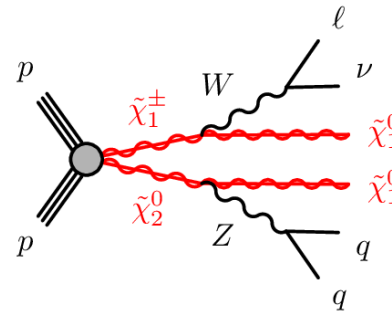
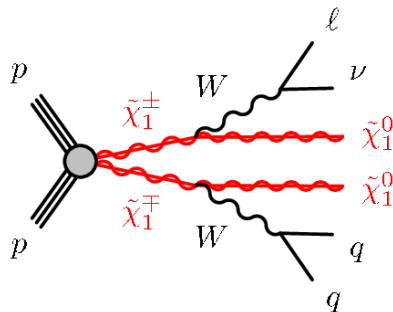


Searches for Electroweakinos

Three searches for direct neutralino/chargino production

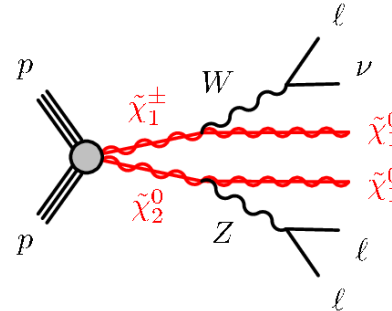
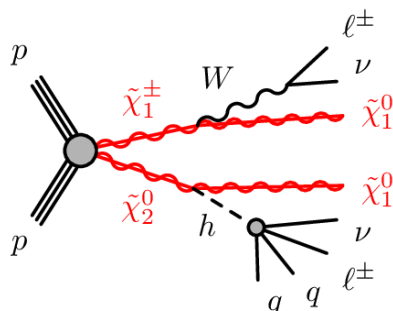
- **Lepton+jet**

[ATLAS-CONF-2022-059](#)



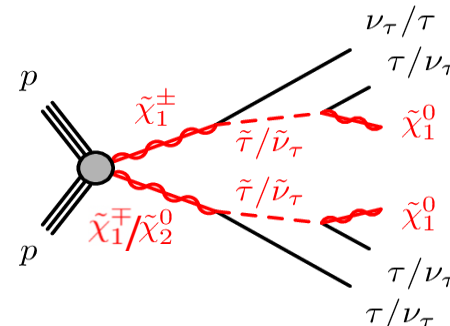
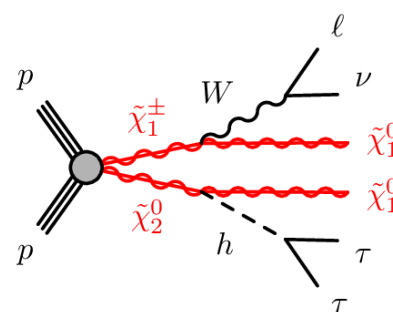
- **Same-sign/trilepton**

[ATLAS-CONF-2022-057](#)



- **Di-tau**

[ATLAS-CONF-2022-042](#)

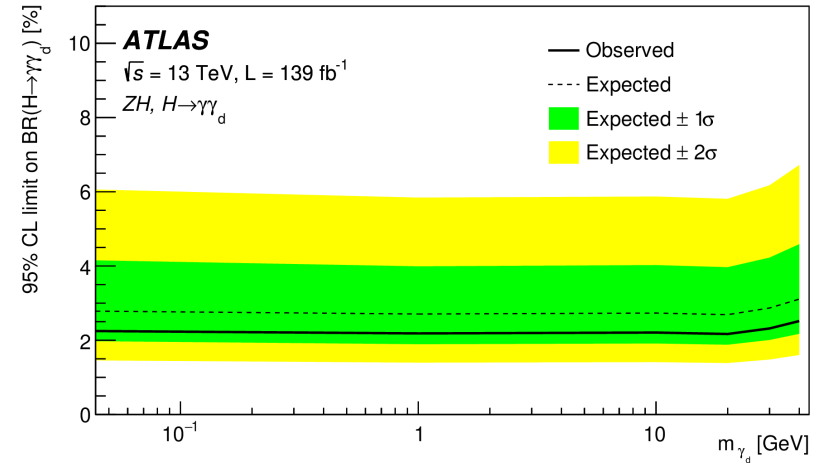
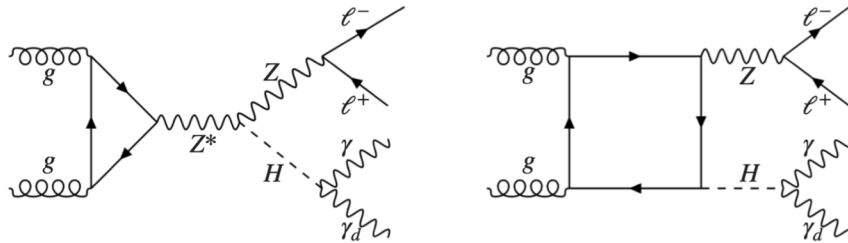


See talk by Tomohiro Yamazaki on SUSY searches
(BSM session after the coffee break)

Many more new results...

Higgs decaying to dark photons ($ZH \rightarrow \ell\ell\gamma\gamma_d$)

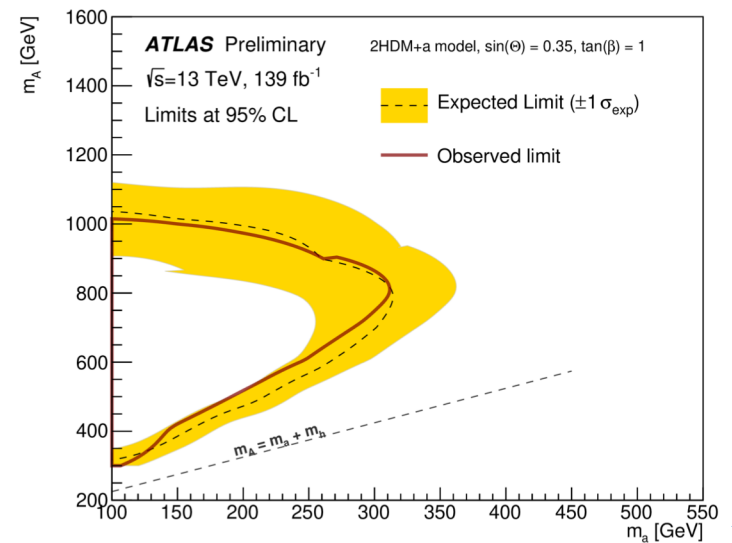
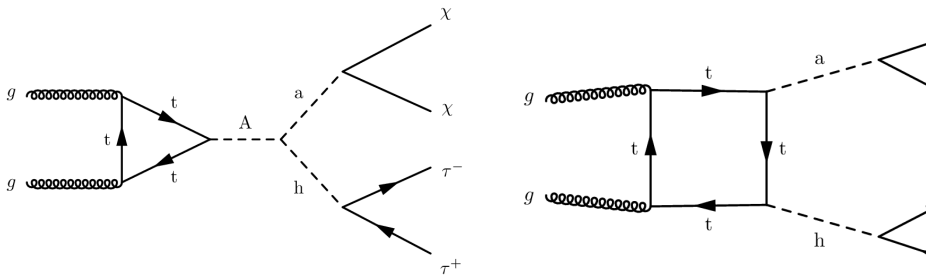
[2212.09649](#) (Submitted to JHEP)



Higgs+DM with $H \rightarrow \tau\tau$

[ATLAS-CONF-2022-069](#)

- Interpret in 2HDM+ a
- Set limits on heavy Higgs masses

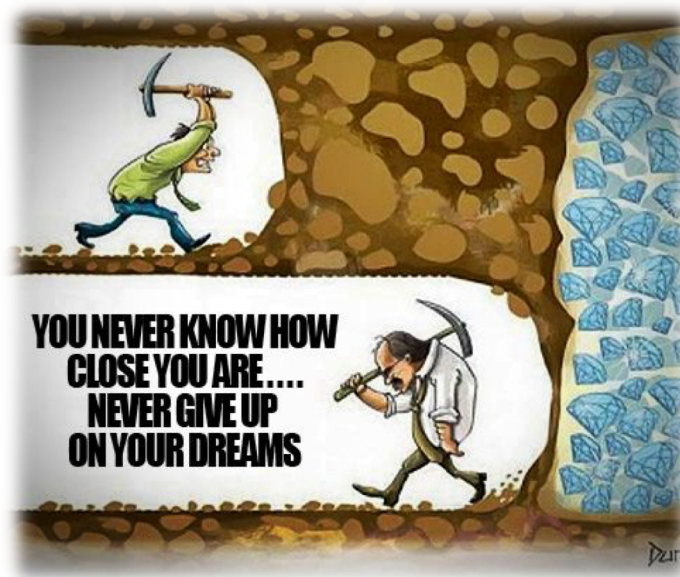


Conclusion

Many new DM results from ATLAS!

- Complementary to direct and indirect detection experiments
- Probing a wide range of final states and models
 - Complete list of ATLAS dark matter results (many more not shown today):
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/>
 - Also see related talks by Tomohiro Yamazaki, Neza Ribaric, and Anna Ivina
- Significant gains from previous results
 - Larger data set + improved analysis tools + re-optimized selections + improved background modeling

Unfortunately, still no signs of dark matter at the LHC



... But much more data to analyze in Run 3!!!

Thank you!

And special thanks to:



DOE for supporting this research



The ATLAS Collaboration

- Complete list of ATLAS dark matter results:
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/>



The HEP2023 Organizers!

Bonus Material

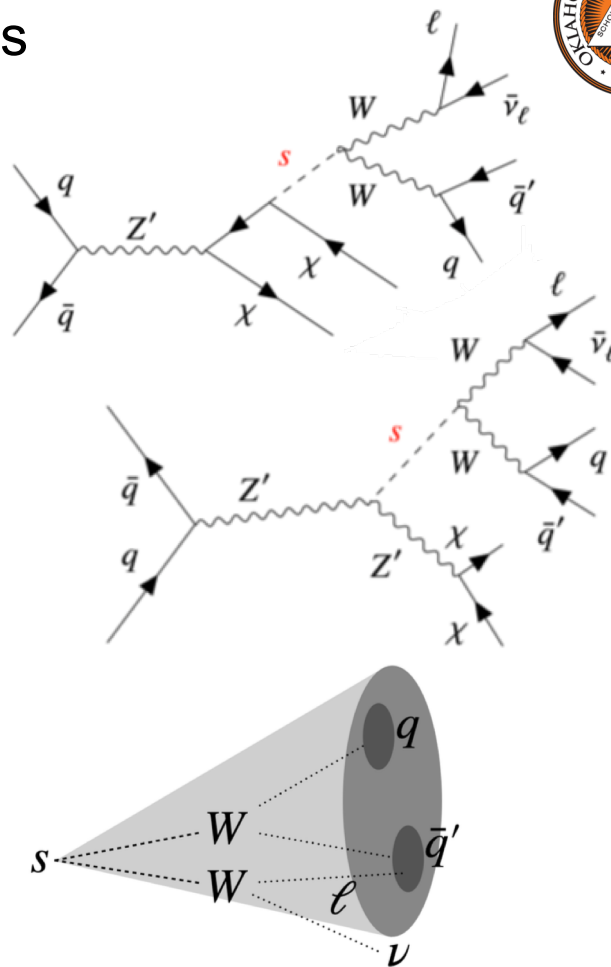
$S(WW) + E_T^{\text{miss}}$

Search for **dark Higgs** ($\rightarrow WW \rightarrow \ell \nu qq$)

- Interpreted in **two-mediator** model with vector $Z' \rightarrow \chi\chi$ and scalar $S \rightarrow WW$

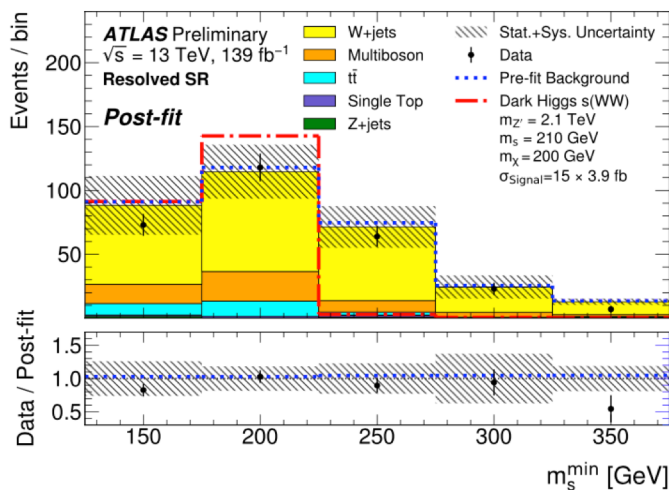
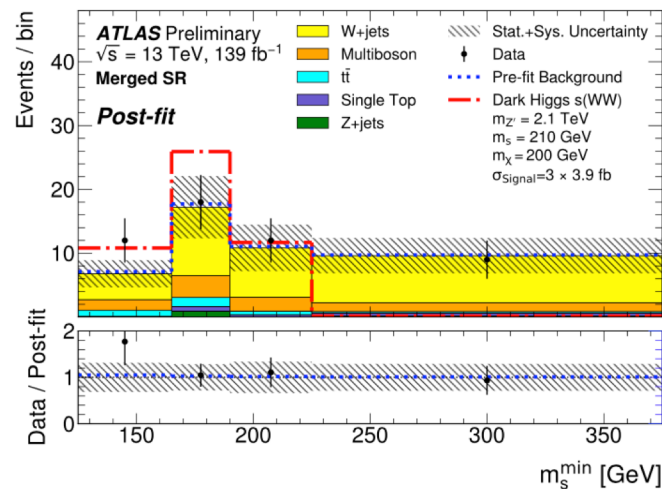
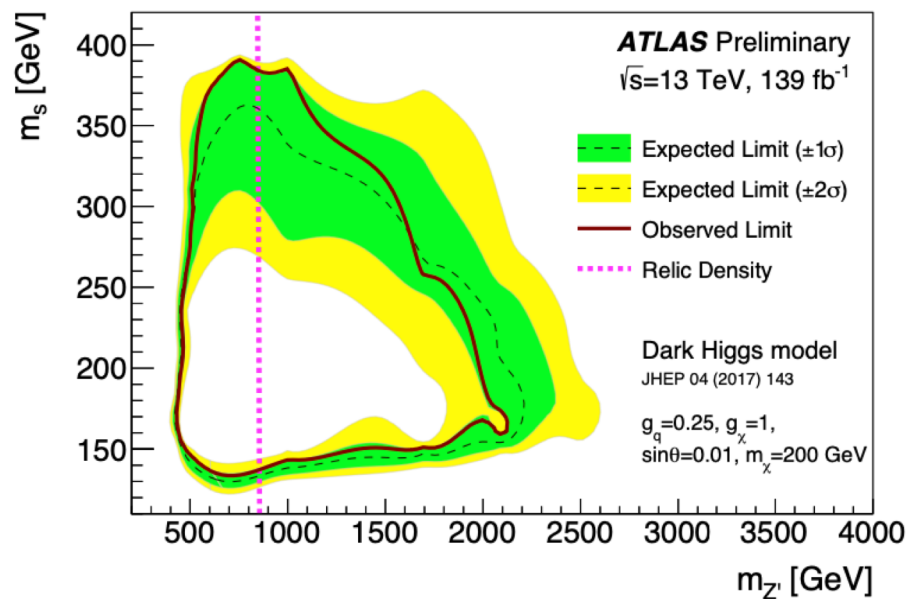
Select events with

- $E_T^{\text{miss}} > 200$ GeV
- 1 high- p_T lepton (e/μ)
- Two categories for $W \rightarrow qq$
 - Merged: large- R jet with 2-prong substructure
 - ✧ Use “track-assisted reclustering” (TAR) to remove overlapping leptons
 - Resolved: two small- R jets
- CRs to constrain dominate W +jets and $t\bar{t}$ backgrounds



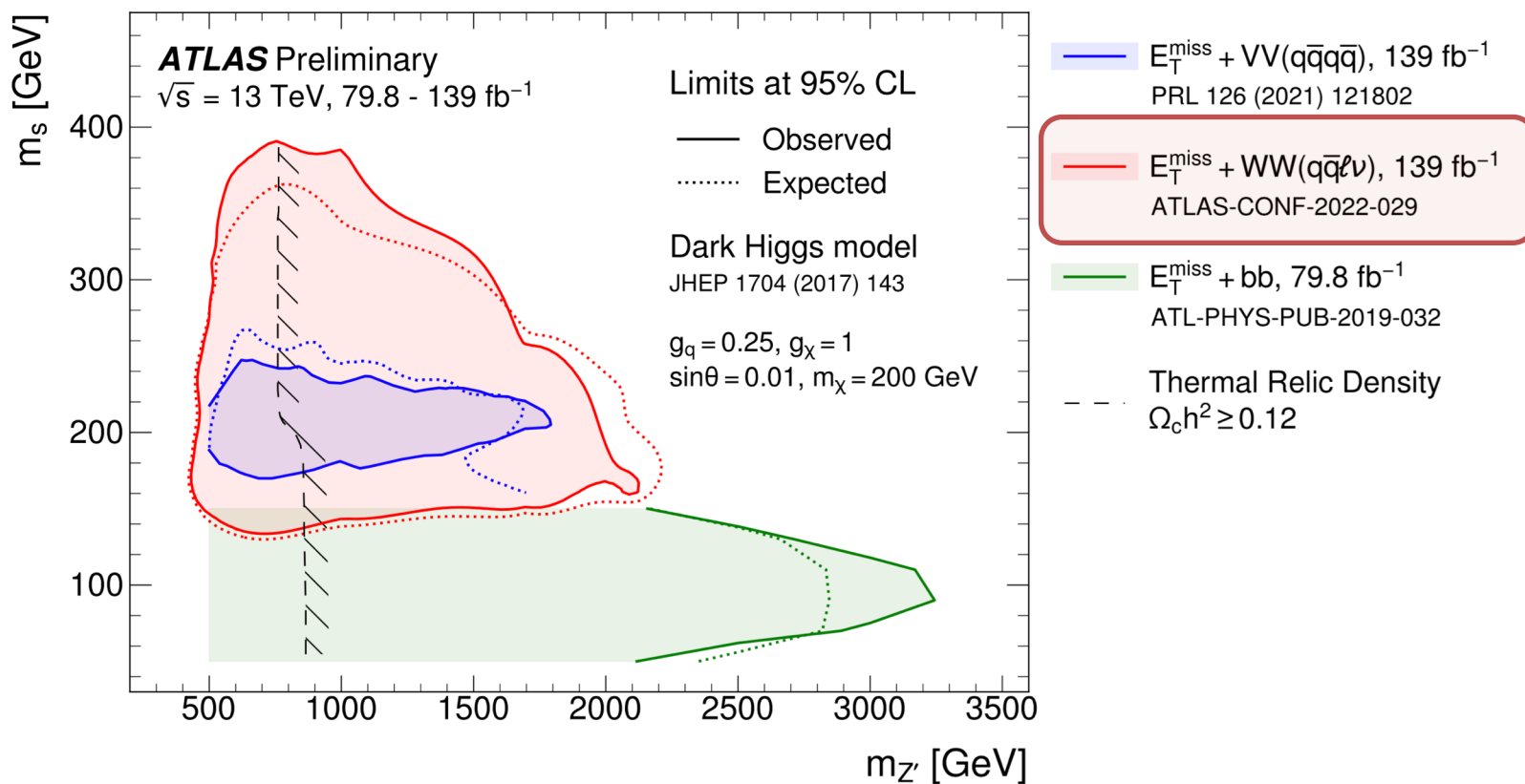
$S(WW) + E_T^{\text{miss}}$

- Reconstruct $S \rightarrow WW \rightarrow qq\ell\nu$ up to ambiguity from missing neutrino
- Fit m_s^{min} distribution in Merged and Resolved SRs
- No significant excess \Rightarrow Set limits on mediator masses



Dark Higgs Summary Plot

July 2022

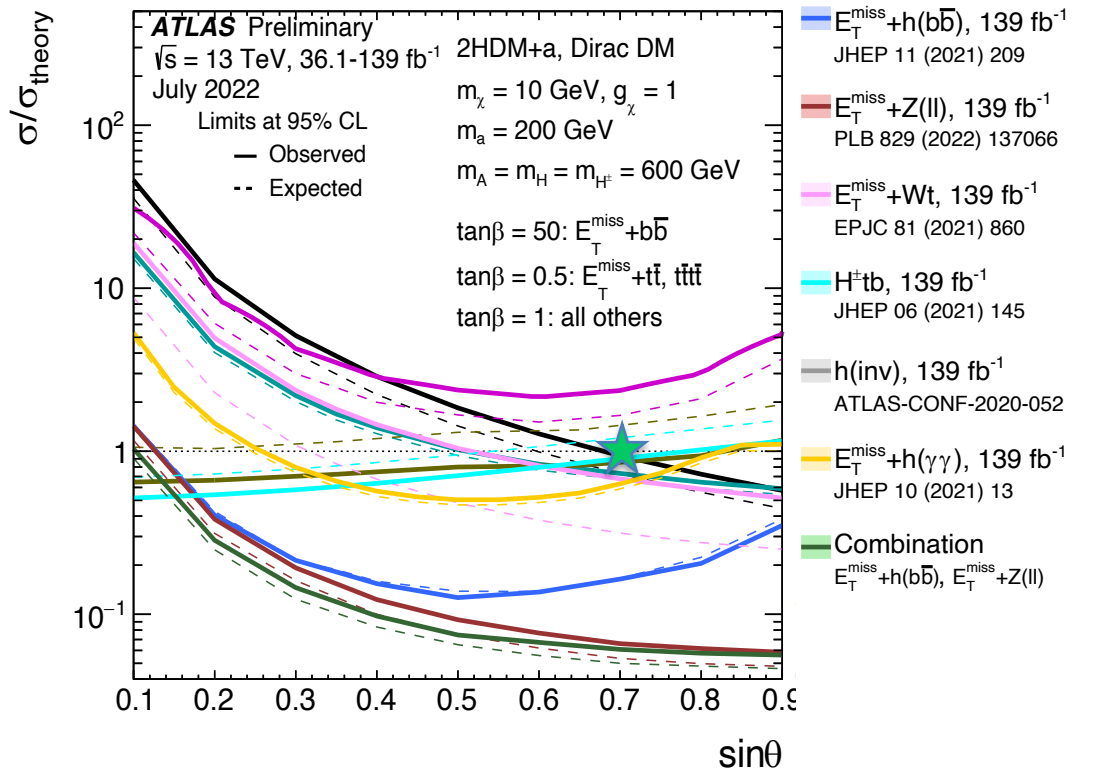
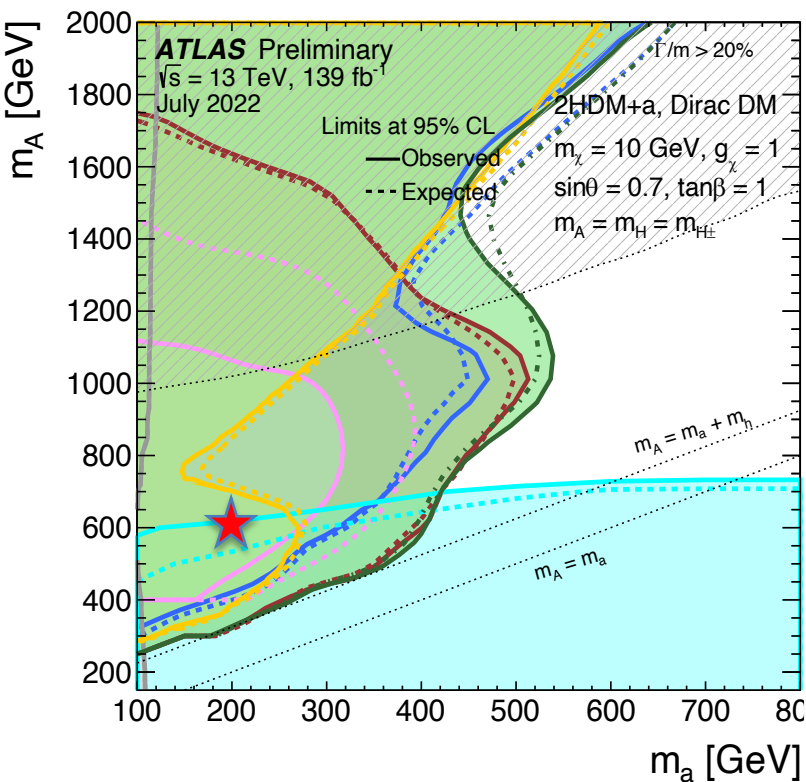


2HDM+*a* Summary Plots

95% CL exclusion limits:

- m_A vs. m_a ($m_A = m_H = m_{H^\pm}$)
 - $m_\chi = 10$ GeV
 - $g_\chi = 1$
 - $\sin\theta = 0.7$
 - $\tan\beta = 1$

- $\sigma/\sigma_{\text{th}}$ vs. $\sin\theta$
 - $m_\chi = 10$ GeV
 - $m_a = 200$ GeV
 - $m_A = m_H = m_{H^\pm} = 600$ GeV



- $E_T^{\text{miss}} + t\bar{t}$, 36.1 fb⁻¹
EPJC 78 (2018) 18, JHEP 06 (2018) 18
- $E_T^{\text{miss}} + b\bar{b}$, 36.1 fb⁻¹
EPJC 78 (2018) 18
- $E_T^{\text{miss}} + Z(q\bar{q})$, 36.1 fb⁻¹
JHEP 10 (2018) 180
- $t\bar{t}t$, 36.1 fb⁻¹
JHEP 09 (2017) 088
- $E_T^{\text{miss}} + h(b\bar{b})$, 139 fb⁻¹
JHEP 11 (2021) 209
- $E_T^{\text{miss}} + Z(\text{ll})$, 139 fb⁻¹
PLB 829 (2022) 137066
- $E_T^{\text{miss}} + Wt$, 139 fb⁻¹
EPJC 81 (2021) 860
- $H^\pm tb$, 139 fb⁻¹
JHEP 06 (2021) 145
- $h(\text{inv})$, 139 fb⁻¹
ATLAS-CONF-2020-052
- $E_T^{\text{miss}} + h(\gamma\gamma)$, 139 fb⁻¹
JHEP 10 (2021) 13
- Combination
 $E_T^{\text{miss}} + h(b\bar{b})$, $E_T^{\text{miss}} + Z(\text{ll})$

Searches for Electroweakinos

Three searches for direct neutralino/chargino production

• Lepton+jet

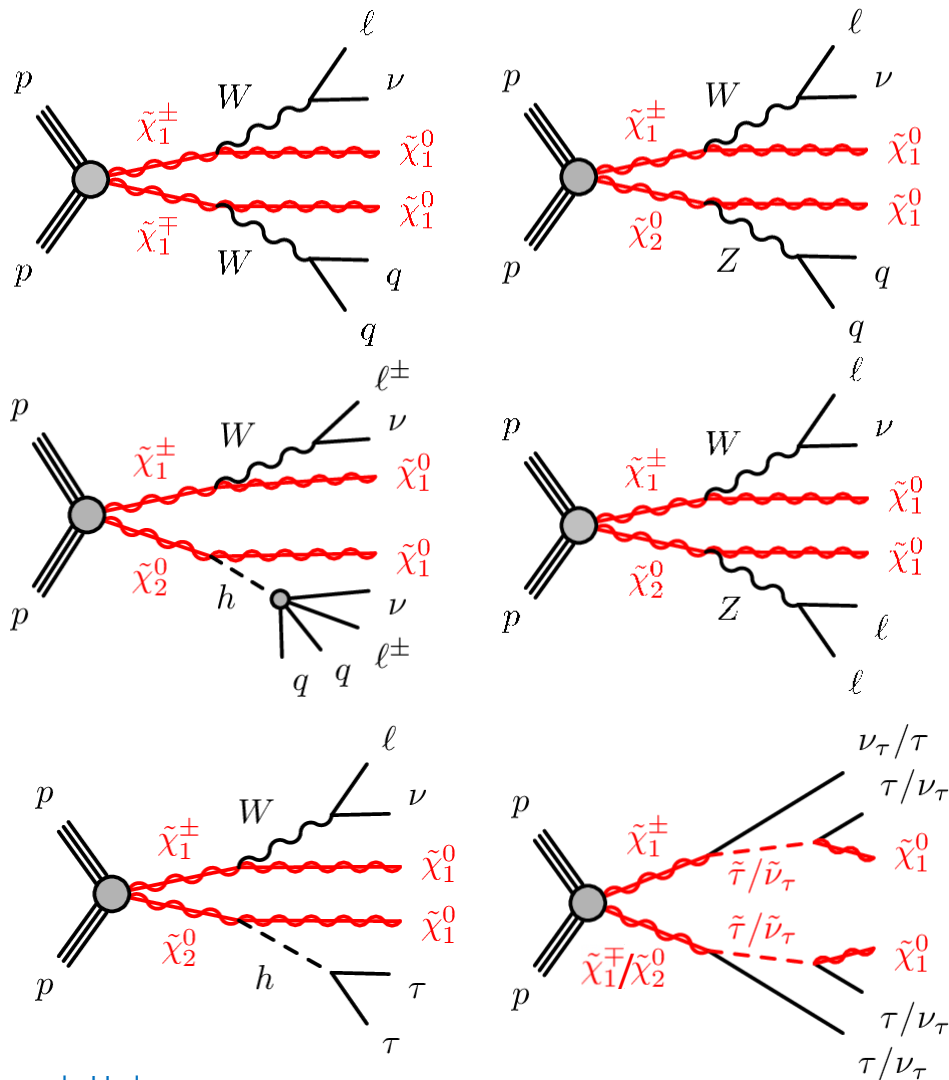
- $E_T^{\text{miss}} > 200 \text{ GeV}$, $\sigma(E_T^{\text{miss}}) > 12$
- 1 isolated e or μ
- 1-3 small-R jets and large-R jet w/ W or Z-tag

• Same-sign/trilepton

- $E_T^{\text{miss}} > 50 \text{ GeV}$, $\sigma(E_T^{\text{miss}}) > 6$
- 2 same-sign e/ μ or 3 leptons
- ≥ 1 jet, 0 b-tags

• Di-tau

- $\geq 2 \tau \rightarrow$ hadronic candidates
- 0 b-tags
- + SR-specific criteria

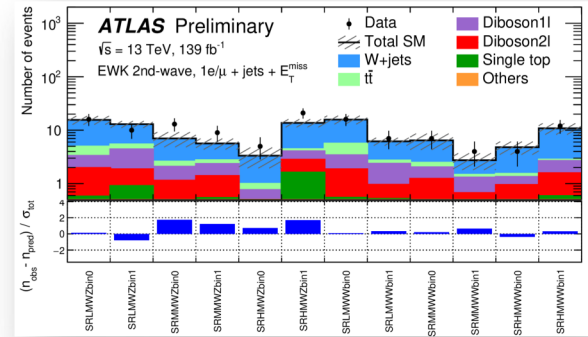


Searches for Electroweakinos

Split into multiple SRs (also CRs and VRs) to target different signals (and backgrounds)

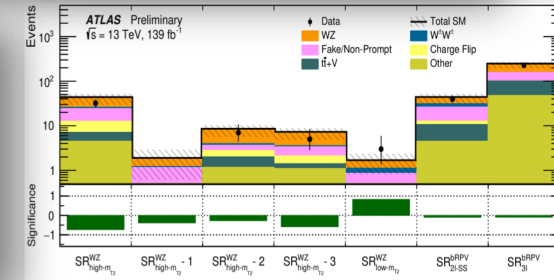
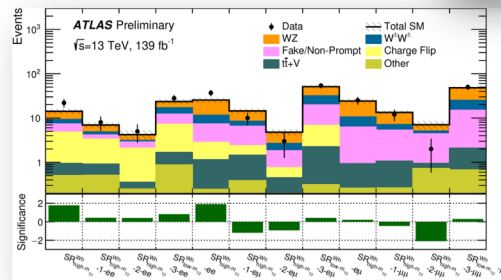
• Lepton+jet

- 12 SRs used for WW and WZ channels
- Main splitting criteria: W/Z-tag, $m_T(\ell + E_T^{\text{miss}})$, m_{eff}



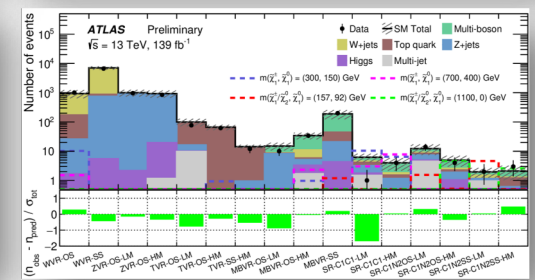
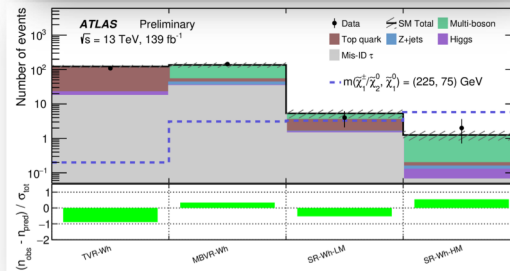
• Same-sign/trilepton

- 12 SRs for Wh, 5 SRs for WZ
- Main criteria: E_T^{miss} , $\sigma(E_T^{\text{miss}})$, Lepton number/flavor, m_{T2} , m_T^{min}



• Di-tau

- 4 SRs for Wh, 16 SRs for intermediate stau channels
- Main criteria: E_T^{miss} , N_τ , $\Delta\phi(\tau_1, \tau_2)$, $\Delta R(\tau_1, \tau_2)$, $m(\tau_1, \tau_2)$, m_{T2} , $m_{T\text{sum}}$



$$m_{T2} = \min_{\mathbf{q}_T} \left[\max \left(m_{T1}(\mathbf{p}_{T1}, \mathbf{q}_T), m_{T2}(\mathbf{p}_{T2}, \mathbf{p}_T^{\text{miss}} - \mathbf{q}_T) \right) \right]$$

$$m(\mathbf{p}, \mathbf{q}) = \sqrt{2(p_T q_T - \mathbf{p}_T \cdot \mathbf{q}_T)}$$

Electroweakino Limits

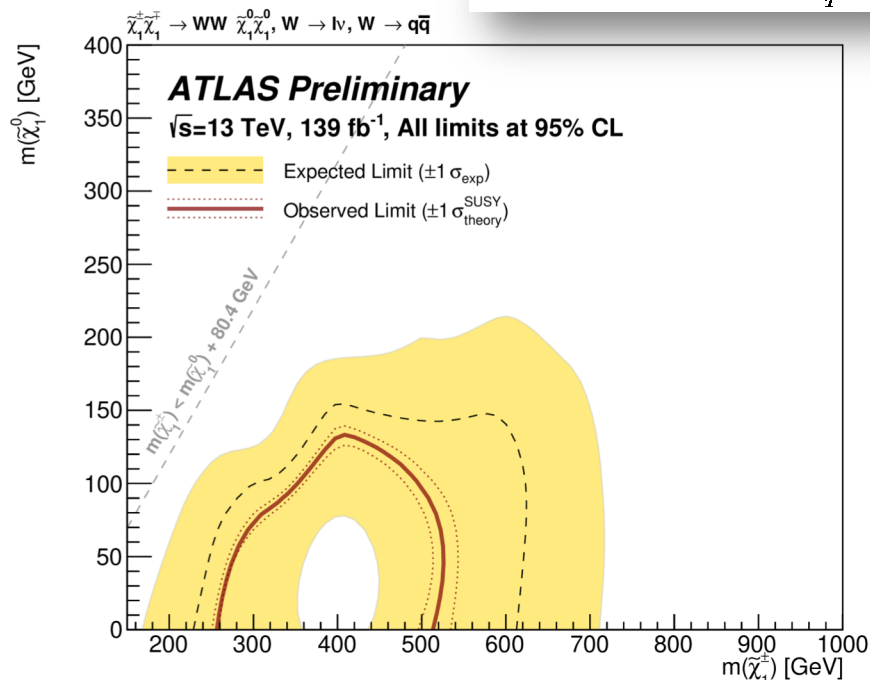
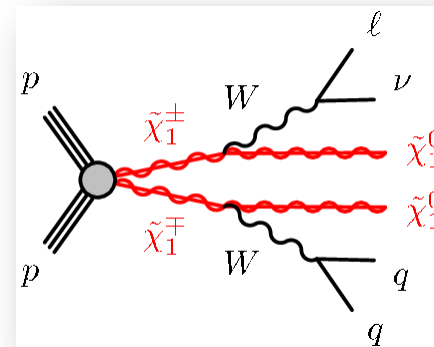
No significant deviations from SM

⇒ Set limits on DM particle masses in simplified models for various decays

$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production decaying via intermediate WW

- **Lepton+jet**

- Exclude $m(\tilde{\chi}_1^\pm) \approx [260, 420]$ GeV for massless LSP
- Exclude LSP mass below 130 GeV for $m(\tilde{\chi}_1^\pm) \approx 400$ GeV



Electroweakino Limits

No significant deviations from SM

⇒ Set limits on DM particle masses in simplified models for various decays

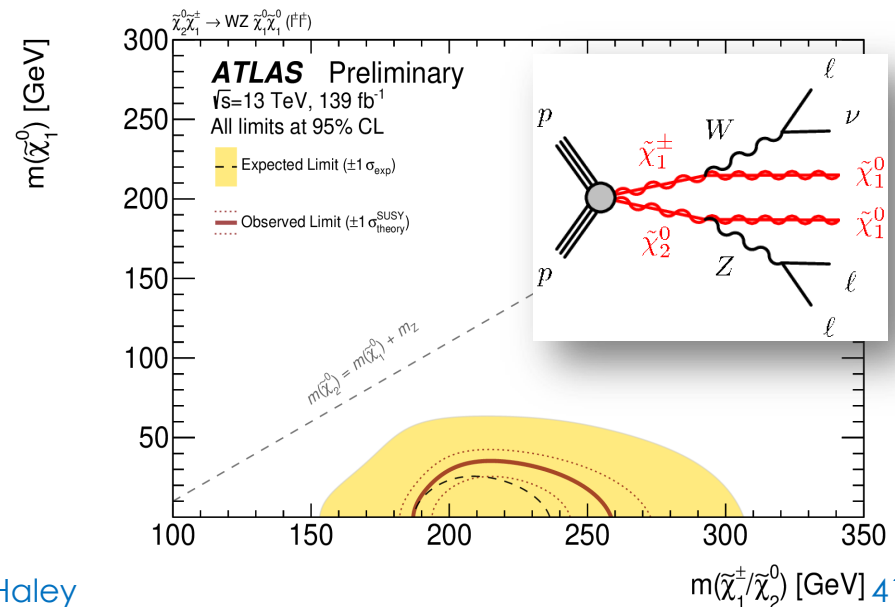
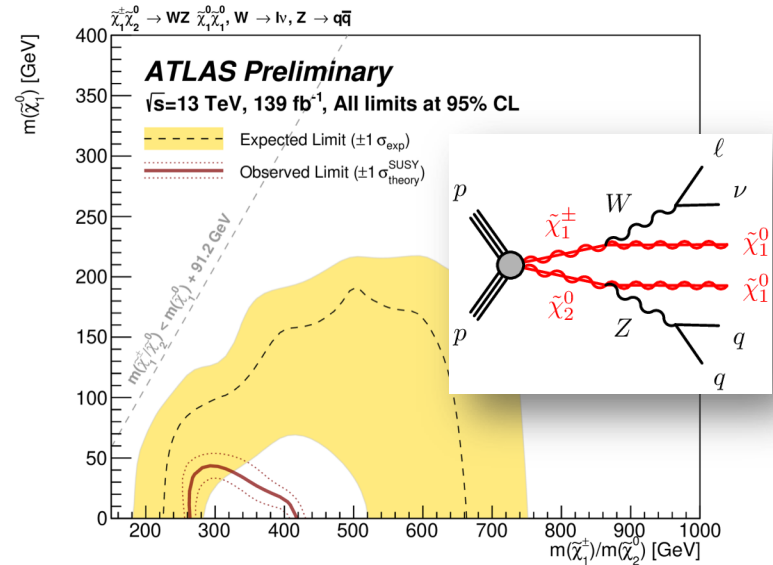
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production decaying via intermediate WZ

• Lepton+jet

- Exclude $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0) \approx [260,420]$ GeV for massless LSP
- Exclude LSP mass below 40 GeV for $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0) \approx 80$ GeV

• Same-sign/trilepton

- Exclude $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0) \approx [190,260]$ GeV for massless LSP
- Exclude LSP mass below 30 GeV for $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0) \approx 210$ GeV



Electroweakino Limits

No significant deviations from SM
 \Rightarrow Set limits on DM particle masses in simplified models for various decays

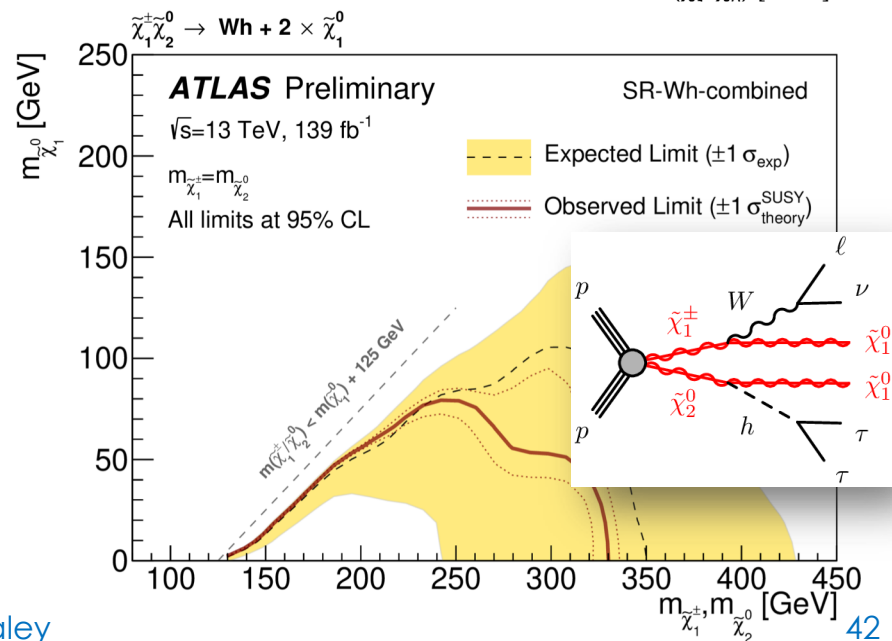
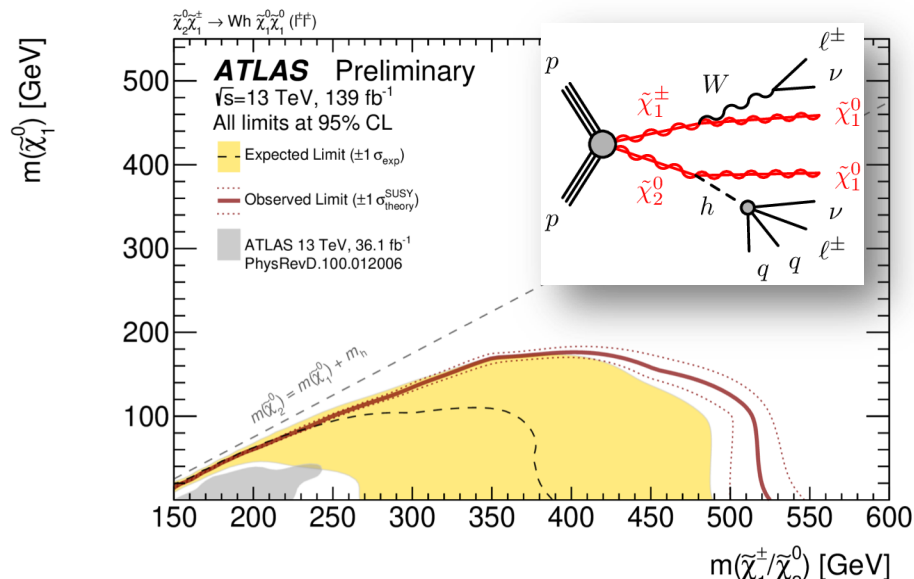
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production decaying via intermediate Wh

• Same-sign/trilepton

- \triangleright Exclude $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0) < 520$ GeV for massless LSP
- \triangleright Exclude LSP mass below 170 GeV for $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0) \approx 400$ GeV

• Di-tau

- \triangleright Exclude $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0) \approx [80, 330]$ GeV for massless LSP
- \triangleright Exclude LSP mass below 70 GeV for $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0) \approx 240$ GeV



Much more SUSY

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2022

ATLAS Preliminary

$\sqrt{s} = 13$ TeV

Model	Signature	$\int \mathcal{L} dt$ [fb $^{-1}$]	Mass limit	Reference								
Inclusive Searches	$q\bar{q}, \bar{q} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 e, μ mono-jet	2-6 jets 1-3 jets	E_T^{miss} E_T^{miss}	139 139	\tilde{q} [1x, 8x Degen.] \tilde{q} [8x Degen.]	1.0 0.9	1.85	$m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5$ GeV	210.14293 2102.10874		
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 e, μ	2-6 jets	E_T^{miss}	139	\tilde{g}	Forbidden	1.15-1.95	2.3	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{g}) = 1000$ GeV	210.14293 210.14293	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$	1 e, μ	2-6 jets	E_T^{miss}	139	\tilde{g}			2.2	$m(\tilde{\chi}_1^0) = 600$ GeV	2101.01629	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	E_T^{miss}	139	\tilde{g}			2.2	$m(\tilde{\chi}_1^0) < 700$ GeV	CERN-EP-2022-014	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}WZ\tilde{\chi}_1^0$	0 e, μ	7-11 jets	E_T^{miss}	139	\tilde{g}			1.97	$m(\tilde{\chi}_1^0) < 600$ GeV	2008.06032	
		SS e, μ	6 jets	E_T^{miss}	139	\tilde{g}		1.15		$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV	1909.08457	
		$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ SS e, μ	3 b 6 jets	E_T^{miss} E_T^{miss}	79.8 139	\tilde{g} \tilde{g}		1.25	2.25	$m(\tilde{\chi}_1^0) < 200$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV	ATLAS-CONF-2018-041 1909.08457
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e, μ	2 b	E_T^{miss}	139	\tilde{b}_1 \tilde{b}_1		0.68	1.255	$m(\tilde{\chi}_1^0) < 400$ GeV 10 GeV < $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20$ GeV	2101.12527 2101.12527	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow b\tilde{h}\tilde{\chi}_1^0$	0 e, μ 2 τ	6 b	E_T^{miss} E_T^{miss}	139 139	\tilde{b}_1 \tilde{b}_1	Forbidden	0.23-1.35		$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	1908.03122 2103.08189	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 e, μ	≥ 1 jet	E_T^{miss}	139	\tilde{t}_1			1.25	$m(\tilde{\chi}_1^0) = 1$ GeV	2004.14060, 2102.03799	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 e, μ	3 jets/1 b	E_T^{miss}	139	\tilde{t}_1	Forbidden	0.65		$m(\tilde{\chi}_1^0) = 500$ GeV	2012.03799	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	139	\tilde{t}_1	Forbidden		1.4	$m(\tilde{\tau}_1) = 800$ GeV	2108.07665	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, μ 0 e, μ	2 c mono-jet	E_T^{miss} E_T^{miss}	36.1 139	\tilde{t}_1 \tilde{t}_1			0.85	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5$ GeV	1805.01649 2102.10874	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	1-2 e, μ	1-4 b	E_T^{miss}	139	\tilde{t}_1			0.067-1.18	$m(\tilde{\chi}_2^0) = 500$ GeV	2006.05880	
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, μ	1 b	E_T^{miss}	139	\tilde{t}_2	Forbidden		0.86	$m(\tilde{\chi}_1^0) = 360$ GeV, $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40$ GeV	2006.05880	
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	Multiple ℓ /jets $ee, \mu\mu$	≥ 1 jet	E_T^{miss} E_T^{miss}	139 139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$			0.96	$m(\tilde{\chi}_1^0) = 0$, wino-bino $m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_2^0) = 5$ GeV, wino-bino	2106.01676, 2108.07586 1911.12606	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW	2 e, μ		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$			0.42	$m(\tilde{\chi}_1^0) = 0$, wino-bino	1908.08215	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	Multiple ℓ /jets		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	Forbidden		1.06	$m(\tilde{\chi}_1^0) = 70$ GeV, wino-bino	2004.10894, 2108.07586	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e, μ		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$			1.0	$m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^{\pm}) + m(\tilde{\chi}_1^0))$	1908.08215	
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	139	$\tilde{\tau}$	$[\tilde{\tau}_L, \tilde{\tau}_{R,1}]$	0.16-0.3	0.12-0.39	$m(\tilde{\chi}_1^0) = 0$	1911.06660	
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ $ee, \mu\mu$	0 jets ≥ 1 jet	E_T^{miss} E_T^{miss}	139 139	$\tilde{\ell}$ $\tilde{\ell}$			0.7	$m(\tilde{\chi}_1^0) = 0$	1908.08215 1911.12606	
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ 4 e, μ 0 e, μ	≥ 3 b 0 jets ≥ 2 large jets	E_T^{miss} E_T^{miss} E_T^{miss}	36.1 139 139	\tilde{H} \tilde{H} \tilde{H}		0.13-0.23	0.29-0.88	$BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$	1806.04030 17103.11684 2108.07586	
	Long-lived particles	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$		0.21	0.66	Pure Wino Pure higgsino	2201.02472 2201.02472
Stable \tilde{g} R-hadron		pixel dE/dx		E_T^{miss}	139	\tilde{g}			2.05		CERN-EP-2022-029	
Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$		pixel dE/dx		E_T^{miss}	139	\tilde{g}	$(\tau(\tilde{g}) = 10$ ns)		2.2	$m(\tilde{\chi}_1^0) = 100$ GeV	CERN-EP-2022-029	
$\tilde{U}, \tilde{L} \rightarrow t\tilde{G}$		Displ. lep		E_T^{miss}	139	\tilde{e}, μ $\tilde{\tau}$			0.7	$\tau(\tilde{L}) = 0.1$ ns $\tau(\tilde{L}) = 0.1$ ns	2011.07812 2011.07812	
	pixel dE/dx		E_T^{miss}	139	$\tilde{\tau}$		0.34	0.36	$\tau(\tilde{L}) = 10$ ns	CERN-EP-2022-029		
RPV	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0, \tilde{\chi}_1^{\pm} \rightarrow Z\ell\ell$	3 e, μ		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_1^0$	$[BR(Z\tau)=1, BR(Ze)=1]$	0.625	1.05	Pure Wino	2011.10543	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\nu\nu$	4 e, μ	0 jets	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	$[A_{33} \neq 0, A_{22} \neq 0]$	0.95	1.55	$m(\tilde{\chi}_1^0) = 200$ GeV	2103.11684	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0 \rightarrow qq\tilde{\chi}_1^0$	4-5 large jets		E_T^{miss}	36.1	\tilde{g}	$[m(\tilde{\chi}_1^0) = 200$ GeV, 1100 GeV]		1.3	1.9	Large A'_{11}	1804.03568
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple		E_T^{miss}	36.1	\tilde{t}	$[A'_{23} = 2e-4, 1e-2]$	0.55	1.05	$m(\tilde{\chi}_1^0) = 200$ GeV, bino-like	ATLAS-CONF-2018-003	
	$\tilde{u}, \tilde{t} \rightarrow b\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow bbs$	$\geq 4b$		E_T^{miss}	139	\tilde{t}		Forbidden	0.95	$m(\tilde{\chi}_1^0) = 500$ GeV	2010.01015	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	2 jets + 2 b		E_T^{miss}	36.7	\tilde{t}_1	$[qq, bs]$	0.42	0.61		1710.07171	
	2 e, μ 1 μ	2 b DV		E_T^{miss}	36.1 136	\tilde{t}_1 \tilde{t}_1			1.0	0.4-1.45	$BR(\tilde{t}_1 \rightarrow b\tilde{e}/b\mu) > 20\%$ $BR(\tilde{t}_1 \rightarrow q\mu) = 100\%$, $\cos\theta_0 = 1$	1710.05544 2003.11956
	1-2 e, μ	≥ 6 jets		E_T^{miss}	139	$\tilde{\chi}_1^0$		0.2-0.32		Pure higgsino	2106.09609	

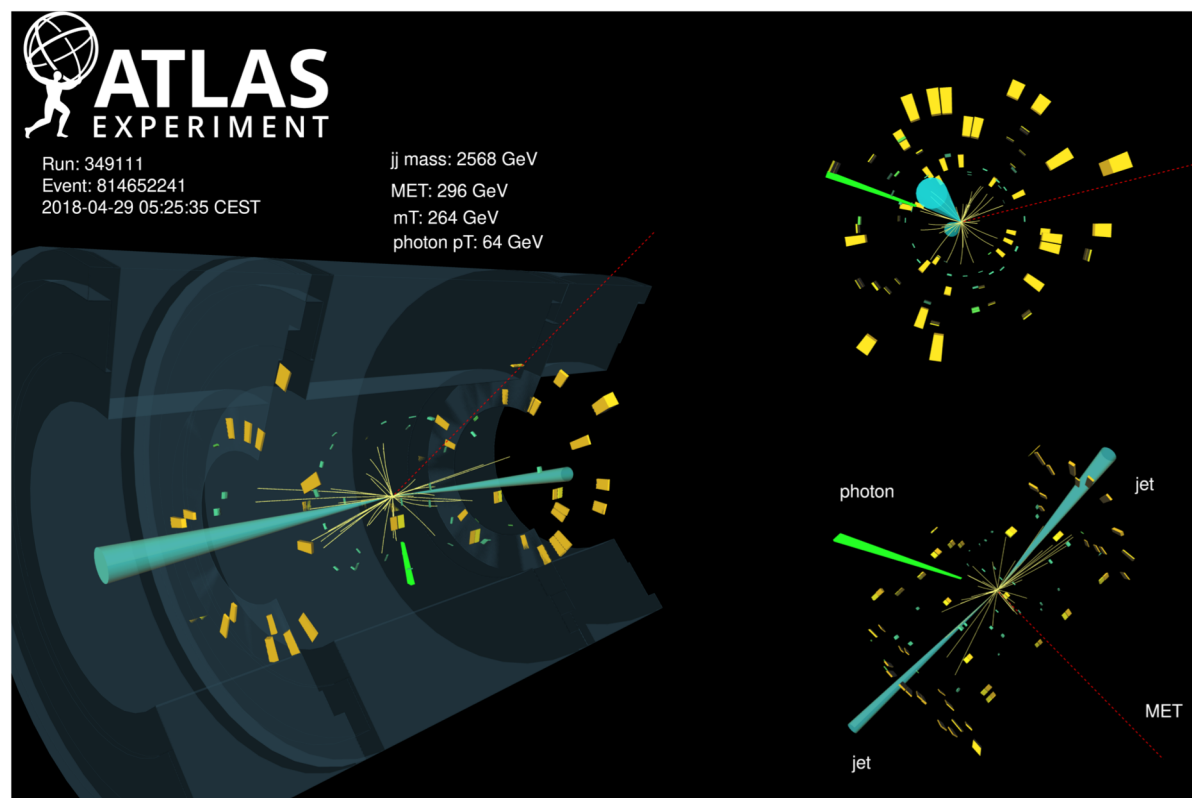
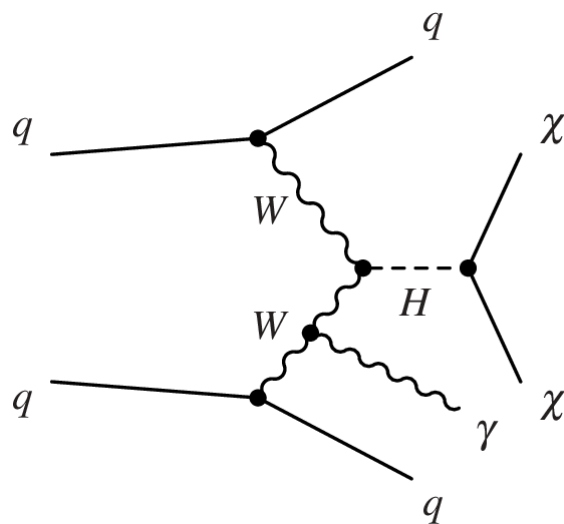
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10⁻¹ 1 Mass scale [TeV]

VBF + γ + E_T^{miss}

Similar to VBF, but require a high- p_T photon

- Smaller cross section, but much higher signal purity
- Higher signal efficiency and background rejection

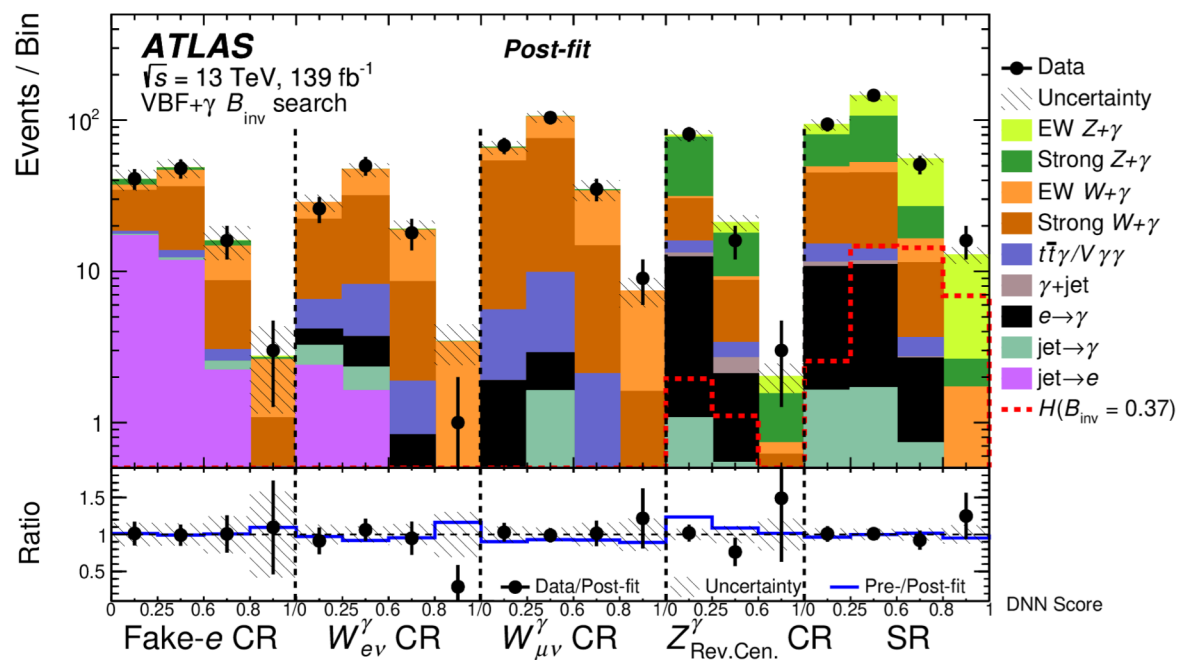


VBF + γ + E_T^{miss}

Similar to VBF, but require a high- p_T photon

- Smaller cross section, but much higher signal purity
- Looser selection, then use Deep Neural Net (DNN) to improve sensitivity

- Limit on $B(H \rightarrow \text{inv})$
@ 95% CL:
Observed: > 0.37
Expected: > 0.34



$E_T^{\text{miss}} + tW$

Dominant single-top final state for 2HDM+a

Target events with 0 or 1 lepton from top decay and hadronic W decay

- W-tagged large-R jet or two small-R jets
- Combined with previous 2 lepton analysis

- Six CRs to constrain main backgrounds (t , tt , W/Z +jets, ttZ)

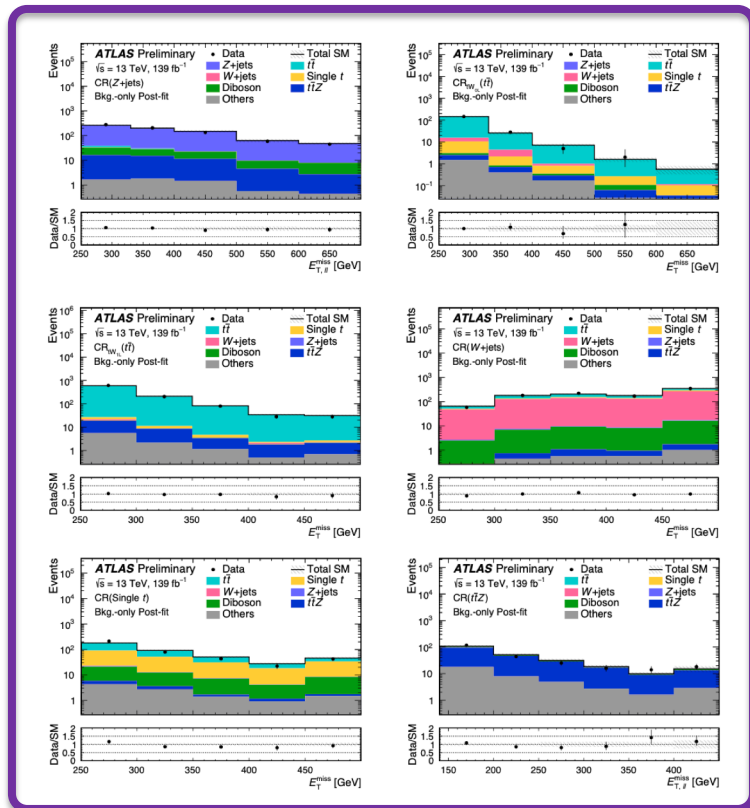
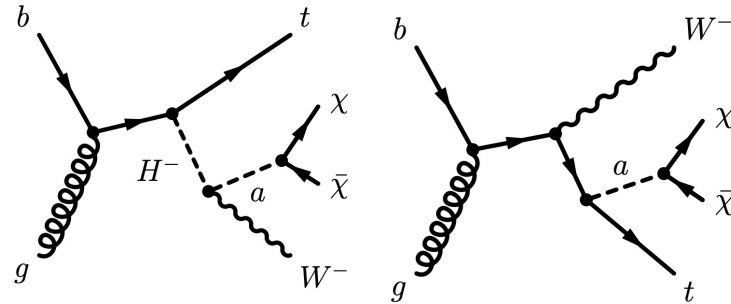
- Three SRs (binned in E_T^{miss})

- $tW \rightarrow \text{had had} / \text{had lep} / \text{lep had}$

Interpret in 2HDM+a model

- Set **limits on m_{H^\pm} vs. m_a** and $\tan\beta$

- Also other 2HDM+a results in summary note (ATL-PHYS-PUB-2022-036)



$E_T^{\text{miss}} + tW$

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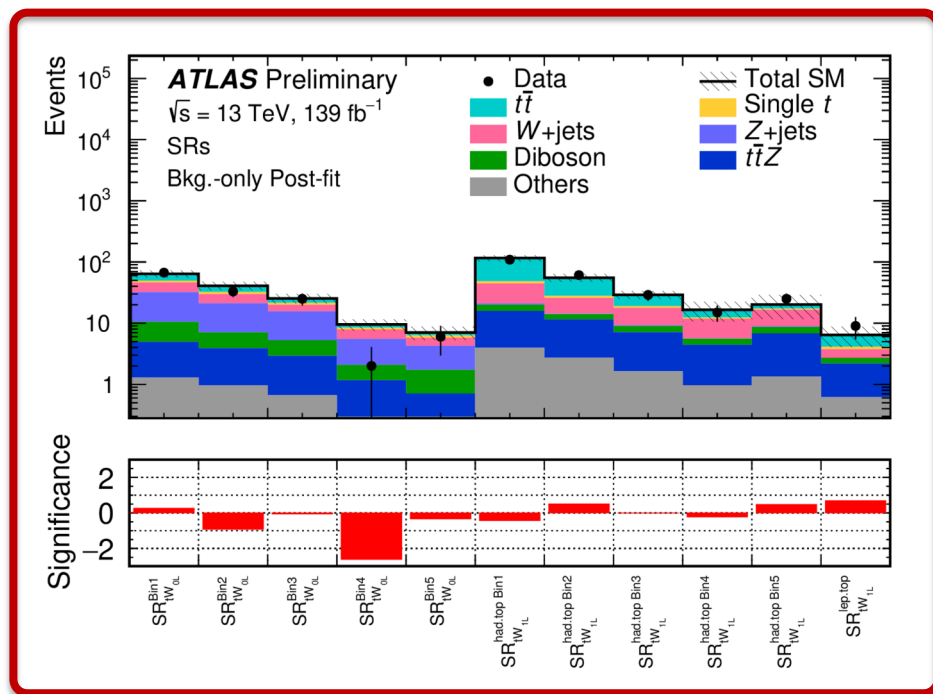
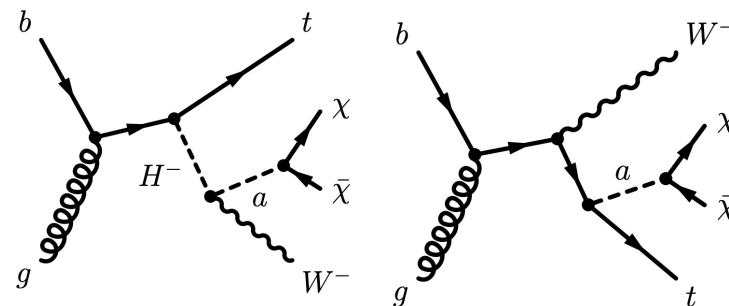
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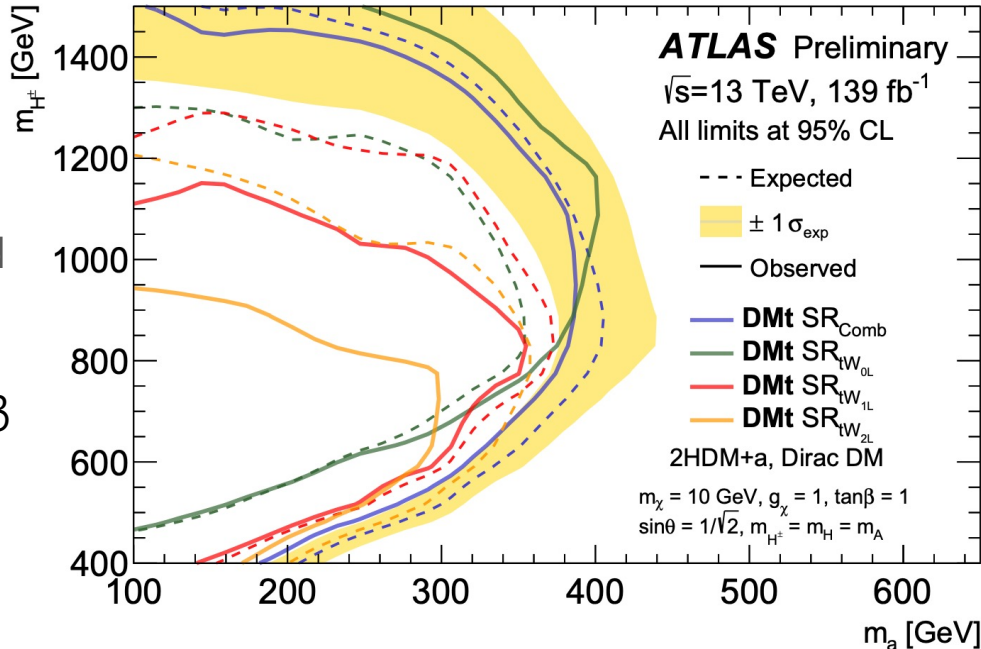
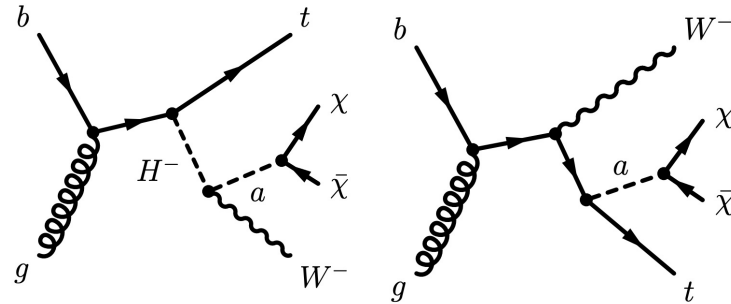
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- Also other 2HDM+a results in summary note (ATL-PHYS-PUB-2022-036)

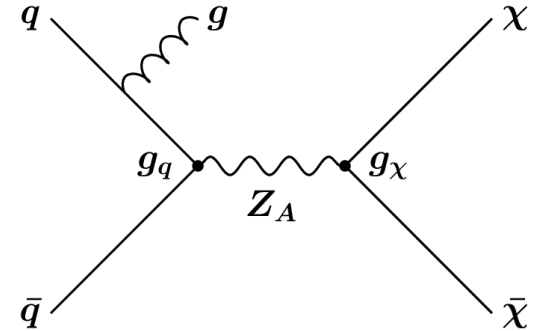


$E_T^{\text{miss}} + \text{jet}$

Sensitive to Pseudo-scalar and Axial-vector mediators

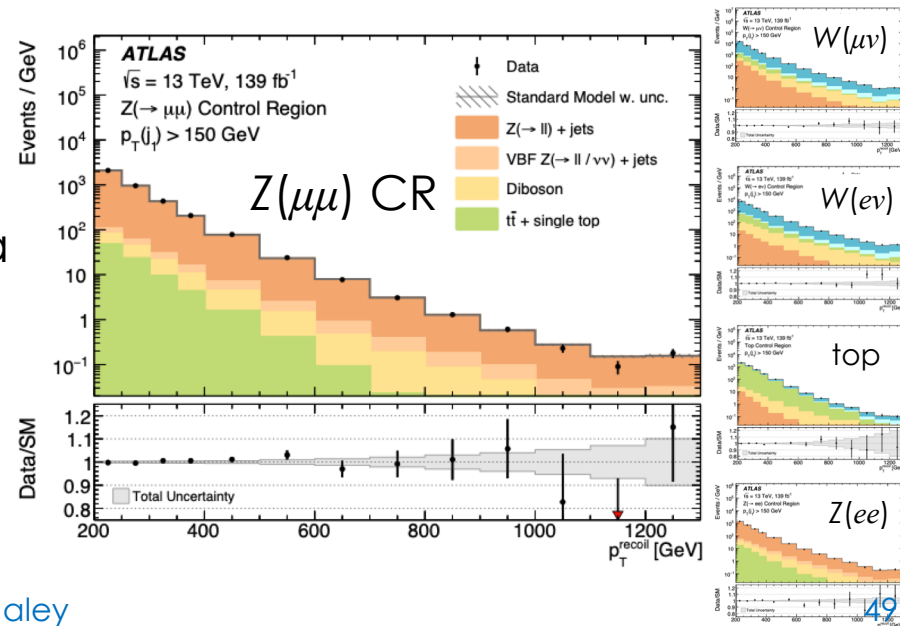
Select events with:

- Large missing momentum: $E_T^{\text{miss}} > 200 \text{ GeV}$
- High- p_T jet from initial state radiation: $p_T^{\text{jet}} > 150 \text{ GeV}$
- Veto events with e, μ, τ, γ



Main backgrounds from W/Z +jets (90%), plus top

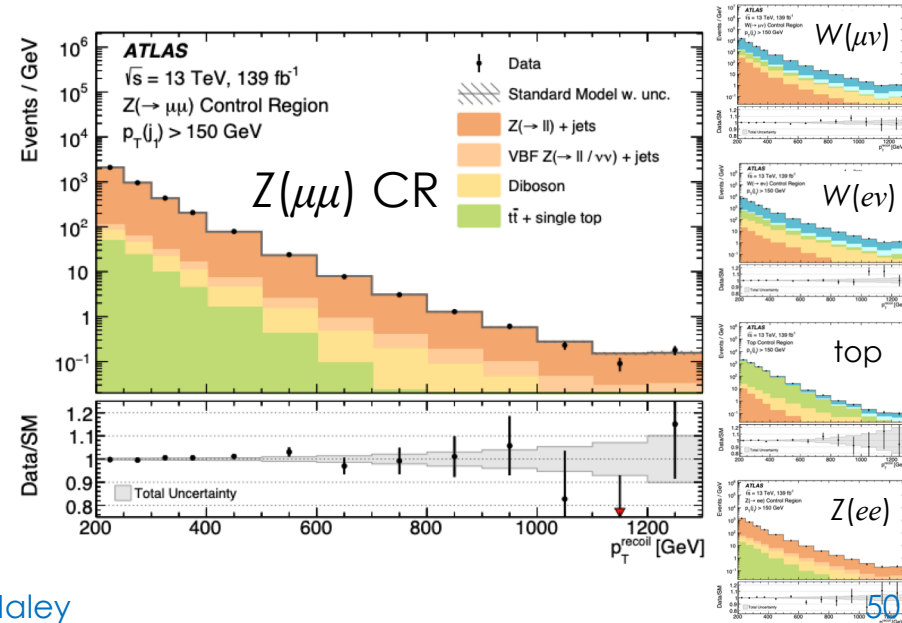
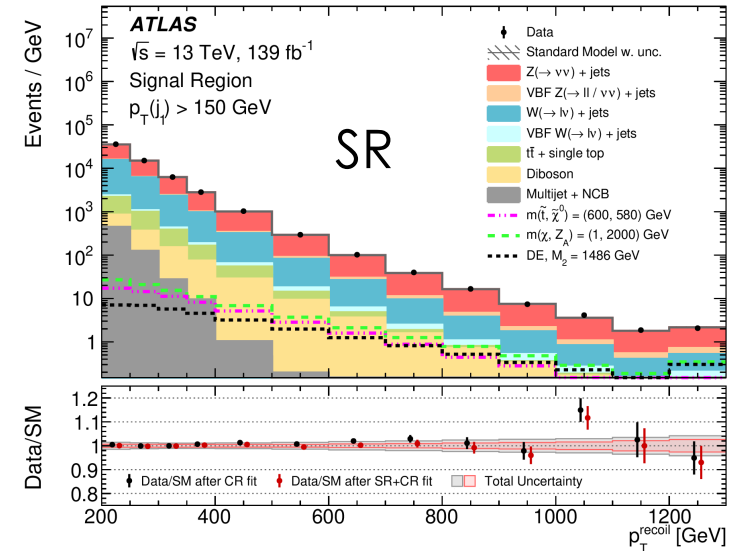
- Shapes modeled by state-of-the-art Monte Carlo simulation
 - NNLO QCD + NLO EW
- Normalization determined from data
 - Four W/Z +jets Control Regions (CRs) enriched in $W(e\nu), W(\mu\nu), Z(ee), Z(\mu\mu)$
 - One top CR enriched in $t\bar{t}$ + single top



$E_T^{\text{miss}} + \text{jet}$

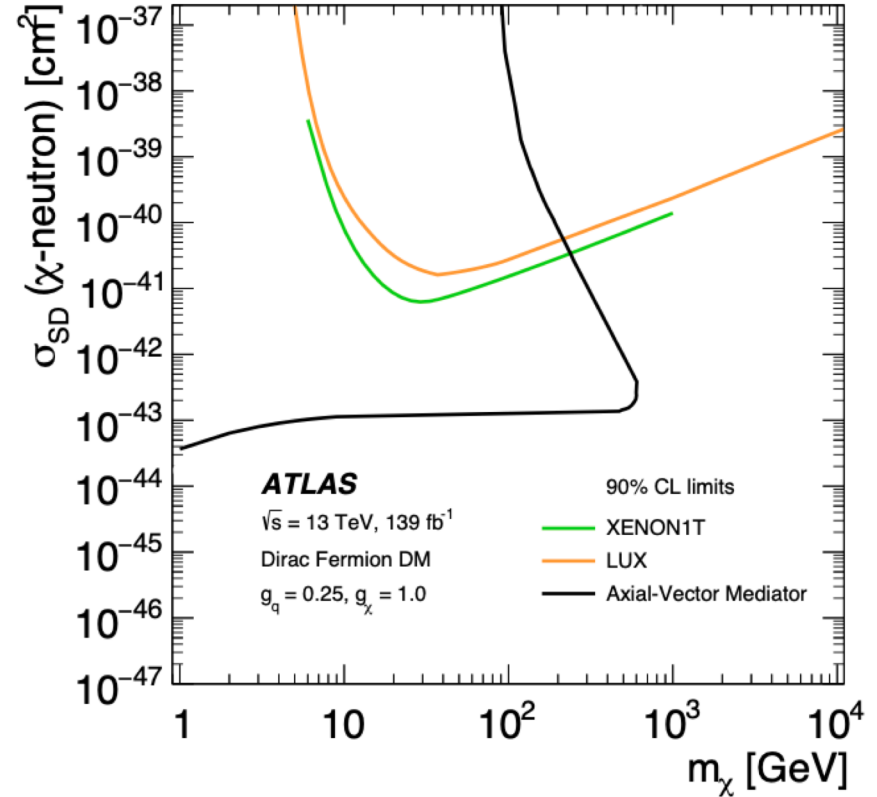
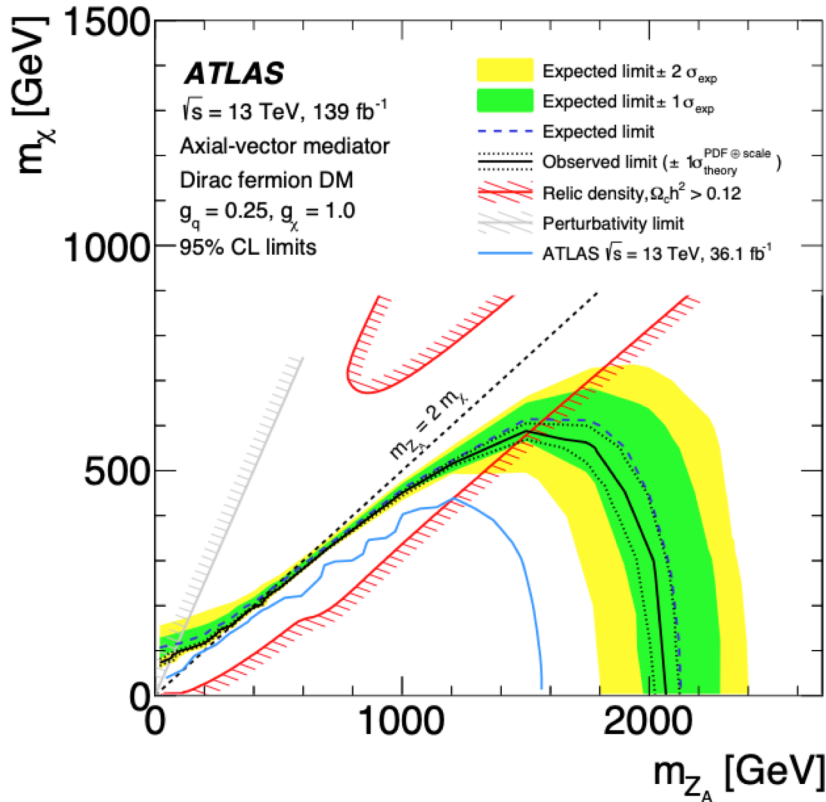
Perform profile likelihood fit

- Simultaneous fit in five CRs and one Signal Region (SR)
- Fit $p_T^{\text{recoil}} = |\mathbf{p}_T|$ of system recoiling against hadronic activity
(In SR: $p_T^{\text{recoil}} \equiv E_T^{\text{miss}}$)
- 1.5-4.2% total uncertainty on background prediction
- Fit consistent with SM
⇒ Set limits on DM production cross-section and parameters



$E_T^{\text{miss}} + \text{jet}$

Limits on Axial-Vector Mediator:



See paper for additional limits on pseudo-scalar model, squark production, large extra-dimensions, and invisible Higgs

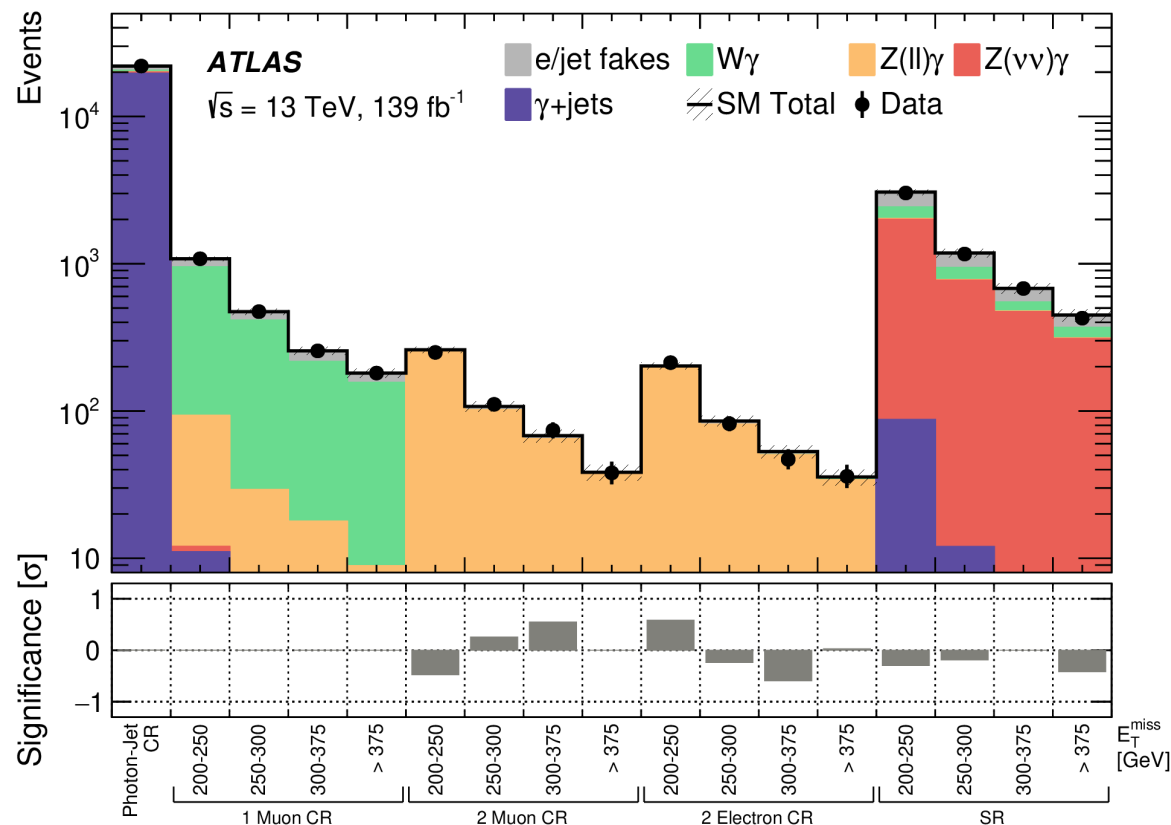
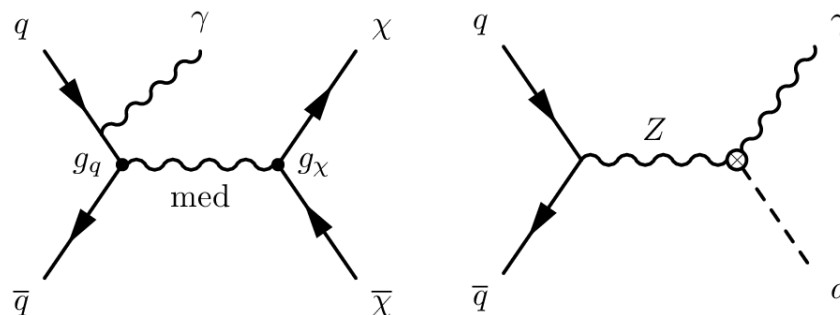
$$E_T^{\text{miss}} + \gamma$$

Select events with

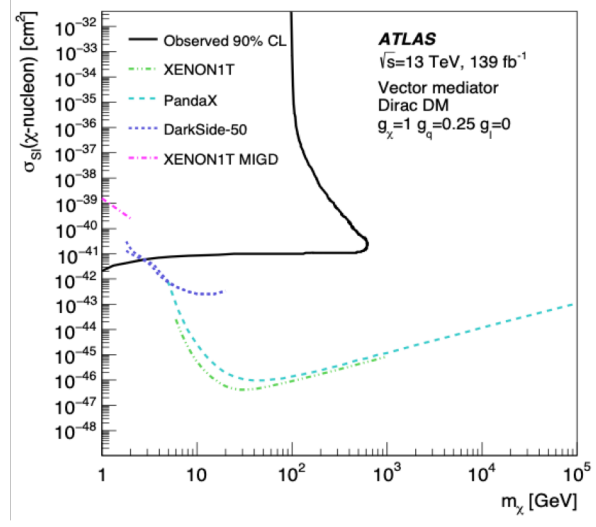
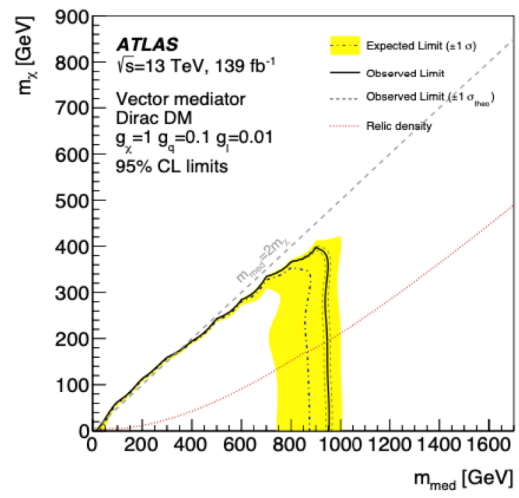
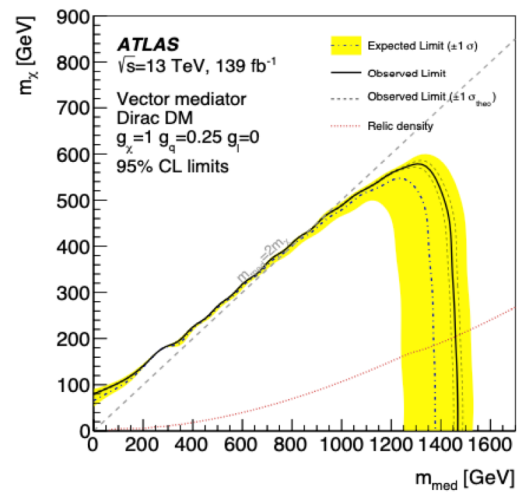
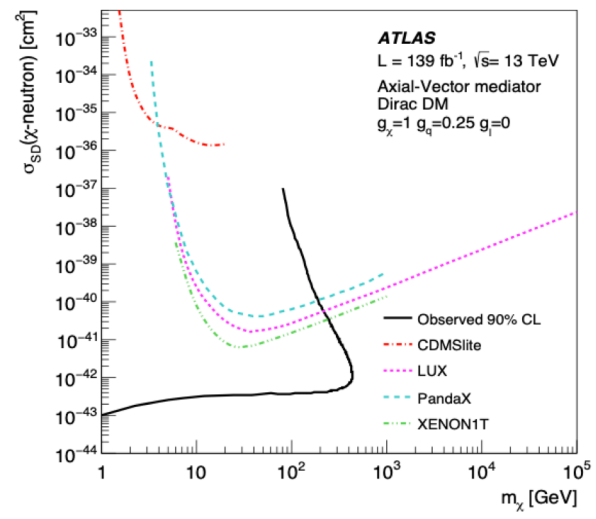
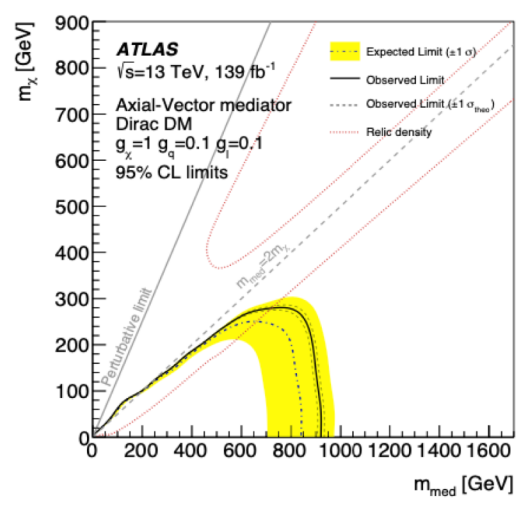
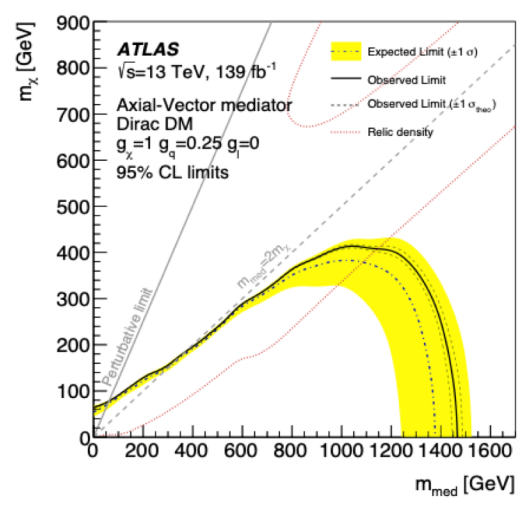
- Isolated photon, $p_T^\gamma > 150 \text{ GeV}$
- $E_T^{\text{miss}} > 200 \text{ GeV}$, E_T^{miss} signif. > 8.5
- No leptons
- Up to one jet

Fit SR and 4 CRs
in bins of E_T^{miss}

- Normalization of main backgrounds from fit to data



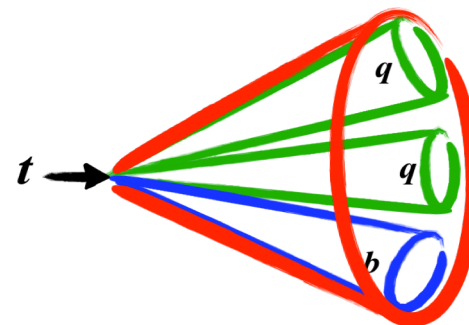
$$\gamma + E_T^{\text{miss}}$$



top-tagging

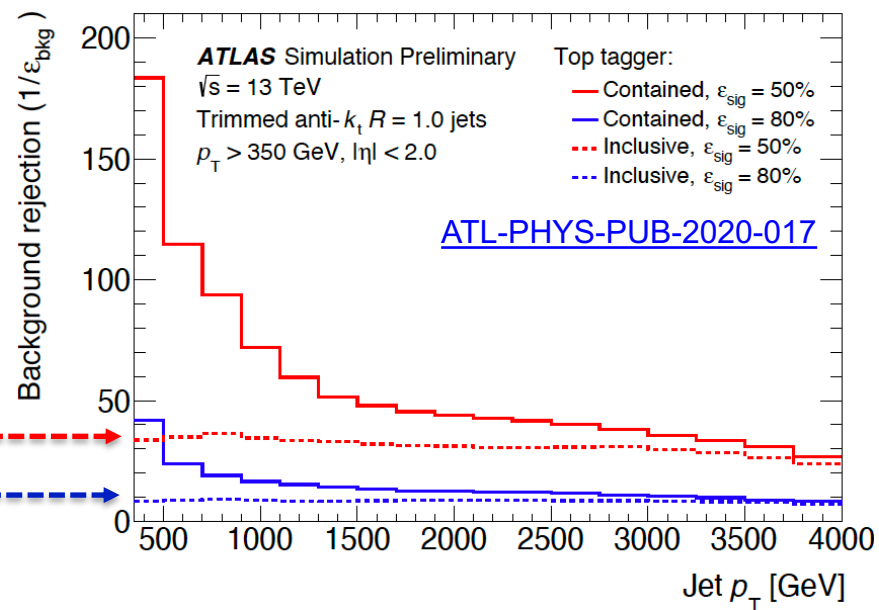
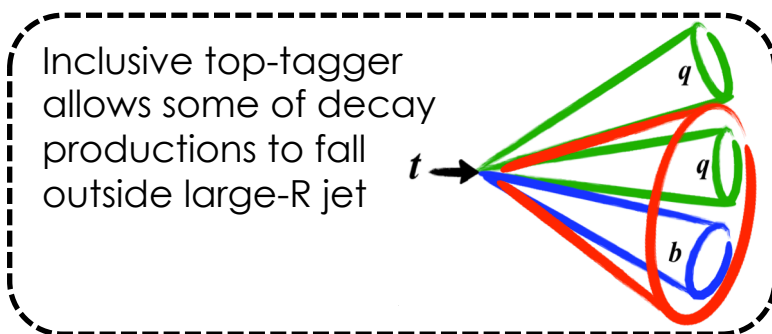
Identify high- p_T **top** quarks (“boosted-tops”)

- **Large-radius jet** with highly collimated **sub-jets**, including one **b-jet**



⇒ Deep Neural Network top-tagger

- Uses kinematics (jet mass, p_T , etc.) and dispersion of jet constituents (N-subjettiness, splitting scales, and energy correlation functions)



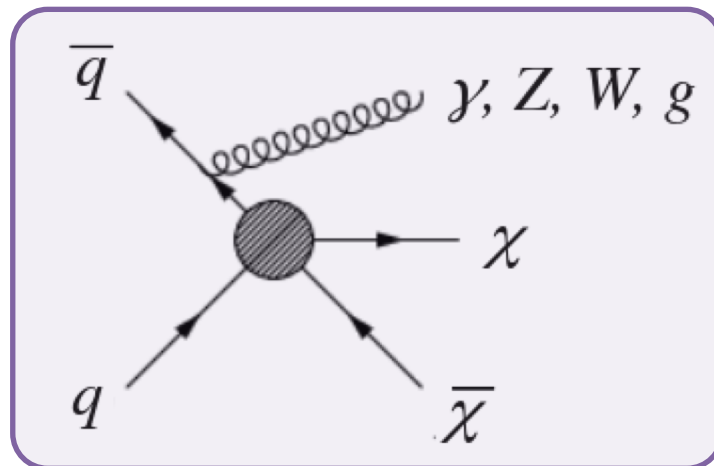
(Some analyses define their own custom taggers, but idea is the same)

Collider Strategy

- Resonance searches: $\chi \rightarrow jj/bb/tt/\ell\ell$

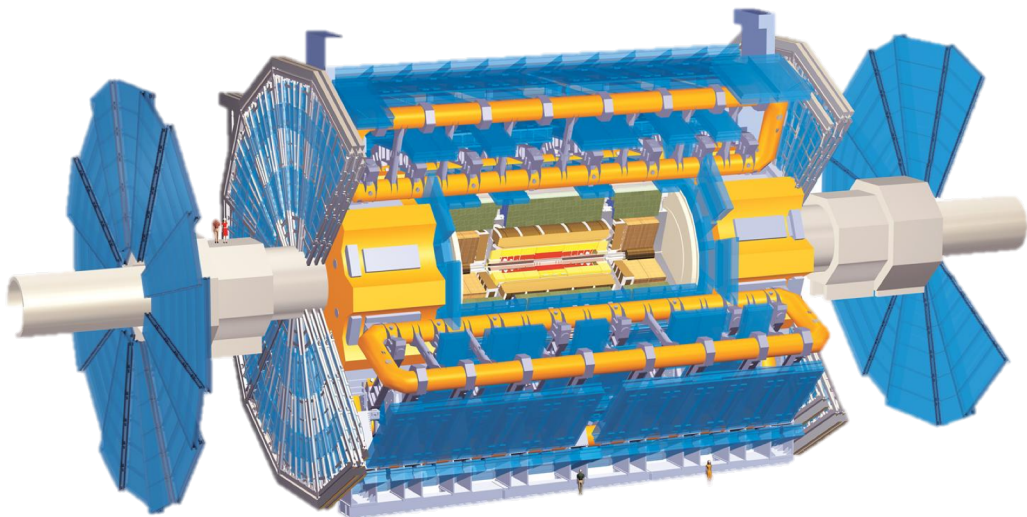
- $E_T^{\text{miss}} + X$

- DM particles escape detection
 $\Rightarrow |\mathbf{p}_T^{\text{miss}}| \equiv E_T^{\text{miss}}$
- Recoil against SM object(s)
 $\Rightarrow X = \text{jet}, \gamma, W, Z, H/S, tt/bb, tW, \dots$



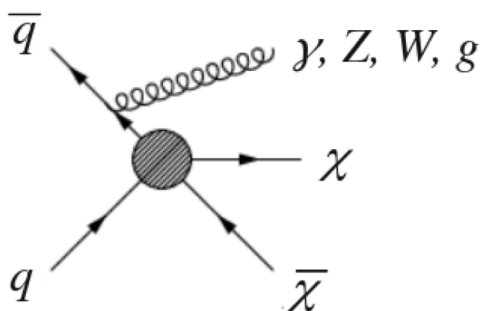
This talk:

- A selection of the **most recent ATLAS** dark matter searches
 $\Rightarrow E_T^{\text{miss}} + X$
- All results using the full Run 2 dataset
 $\Rightarrow 139 \text{ fb}^{-1}$ of pp collisions at $\sqrt{s} = 13 \text{ TeV}$



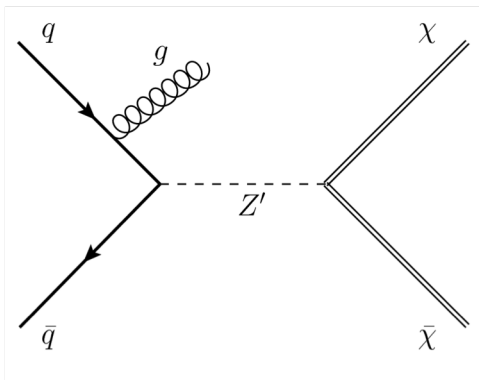
Interpreting DM Production

Effective field theory (EFT)



Name	Operator	Type of interaction
D1	$\frac{m_q}{M_*^3} \bar{\chi} \chi \bar{q} q$	Scalar, WIMP-quark
D5	$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q$	Vector
D8	$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q$	Axial-vector
D9	$\frac{1}{M_*^2} \bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q$	Tensor
D11	$\frac{\alpha_s}{(4M_*)^3} \bar{\chi} \chi G_{\mu\nu} \bar{G}_{\mu\nu}$	Scalar, WIMP-gluon
C1	$\frac{m_q}{M_*^2} \chi^\dagger \chi \bar{q} q$	Scalar, WIMP-quark
C5	$\frac{\alpha_s}{4M_*^2} \chi^\dagger \chi G_{\mu\nu} \bar{G}_{\mu\nu}$	Scalar, WIMP-gluon

- Only two parameters: DM mass (m_χ) & interaction scale (M_* or Λ)
- Good approximation if momentum transfer is less than mediator mass (m_V)



Simplified models

- Valid for higher momentum transfer
- But more parameters: $m_\chi, m_V, g_q, g_\chi, \Gamma$

VBF + E_T^{miss}

Dedicated VRs and CRs to validate and constrain backgrounds
 16 SRs of varying purity and composition

Interpret in models
 where **Higgs is portal**
 to DM WIMP

- Set limits on WIMP-nucleon cross section at 90% CL
- Complementary to direct detection experiments

