

EFT Validity in ATLAS

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Outline

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- 3 Validity treatment in ATLAS
 - Truncation procedure
 - Validity scans
 - Presenting results with truncation
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Introduction to EFT validity in mono-X searches

- EFTs useful for mono-X searches due to minimal model dependence
- Past validity constraints shown to be insufficient by many papers
 - Already demonstrated in Thomas' talk
 - Even if EFT limits are often conservative, the resulting constraints are not robust and may lead to non-perturbative couplings
- Consider the more realistic requirement: $Q_{\text{tr}} \ll M_{\text{med}}$
 - Cannot quantify *much less than*, use minimal constraint: $Q_{\text{tr}} < M_{\text{med}}$
- Particularly important for comparing to direct detection experiments
 - Very different energy scales: Q_{tr} of $\mathcal{O}(\text{TeV})$ vs $\mathcal{O}(\text{keV})$

Recovering M_{med} as a function of M_*

- EFT has integrated out M_{med} , but it can be retrieved as a function of M_* and couplings (and occasionally other factors)
 - Must assume a UV completion, involves unknown coupling values
- Common simple mediator completion for D5, D8, D9:

$$\sigma(pp \rightarrow \chi\chi + \text{jet}) \propto \frac{g_q^2 g_\chi^2}{(Q_{\text{tr}}^2 - M_{\text{med}}^2)^2 + \Gamma_{\text{med}}^2 M_{\text{med}}^2}$$

$$\xrightarrow{M_{\text{med}} \gg Q_{\text{tr}}, \Gamma_{\text{med}}} \frac{g_q^2 g_\chi^2}{M_{\text{med}}^4} \xrightarrow{\text{EFT}} \frac{1}{M_*^4} \therefore \boxed{M_{\text{med}}^{\text{D5,D8,D9}} = \sqrt{g_q g_\chi} M_*}$$

- Completions for other operators possible with additional assumptions
 - D1, C1: chirally suppressed operators
 - D11, C5: gluon operators
 - Details of these completions on following slides

Chirally suppressed operator completion

- Quark mass dependence in EFT formula comes from Yukawa coupling
 - Assume Yukawa coupling for the completion too (self-consistency)
- For C1, remember VEV from trilinear scalar vertex, $\nu_\lambda = \zeta_\lambda M_{\text{med}}$

D1

$$\frac{m_q}{M_*^3} = \frac{y_q g_\chi}{M_{\text{med}}^2}$$

$$M_{\text{med}}^{\text{D1}} = \sqrt{y_q g_\chi} \cdot \sqrt{M_*^3 / m_q}$$

C1

$$\frac{m_q}{M_*^2} = \frac{y_q \lambda_\chi \nu_\lambda}{M_{\text{med}}^2}$$

$$M_{\text{med}}^{\text{C1}} = y_q \lambda_\chi \zeta_\lambda \cdot M_*^2 / m_q$$

- Experimental challenge: what value of m_q to use?
 - Heavier quarks in sample → increased xsec → improved limits
 - Heavier quarks in sample → reduced validity → stronger truncation
 - ATLAS used the value of the heaviest quark produced in the sample
 - Samples may involve many quarks, but are dominated by heaviest quark
 - Self consistent approach regardless of if the two effects balance

Gluon operator completion

- Three dimensions to resolve in this case, follow example in this paper
 - Assume mediator is resolved, gluon-gluon-mediator vertex is not (Λ_s)
- For C5, remember VEV from trilinear scalar vertex, $\nu_\lambda = \zeta_\lambda M_{\text{med}}$

D11

$$\frac{\alpha_s}{4M_*^3} = \frac{\alpha_s g_\chi}{M_{\text{med}}^2 \Lambda_s}$$

$\Lambda_s > M_{\text{med}}$ (resolved mediator)

Let $\Lambda_s = b \cdot M_{\text{med}}$, $b > 1$

$$\frac{1}{4M_*^3} = \frac{g_\chi}{b M_{\text{med}}^3}$$

$$M_{\text{med}} = \sqrt[3]{\frac{4g_\chi}{b}} M_*$$

Let $a = 4b^{-1}$, $0 < a < 4$

$$M_{\text{med}}^{\text{D11}} = \sqrt[3]{a g_\chi} M_*$$

C5

$$\frac{\alpha_s}{4M_*^2} = \frac{\alpha_s \lambda_\chi \nu_\lambda}{M_{\text{med}}^2 \Lambda_s}$$

$\Lambda_s > M_{\text{med}}$ (resolved mediator)

Let $\Lambda_s = b \cdot M_{\text{med}}$, $b > 1$

$$\frac{1}{4M_*^2} = \frac{\lambda_\chi \zeta_\lambda}{b M_{\text{med}}^2}$$

$$M_{\text{med}} = \sqrt{\frac{4\lambda_\chi \zeta_\lambda}{b}} M_*$$

Let $a = 4b^{-1}$, $0 < a < 4$

$$M_{\text{med}}^{\text{C5}} = \sqrt{a \lambda_\chi \zeta_\lambda} M_*$$

Operator UV completion summary

Operator(s)	Relation between M_{med} and M_*	Coupling term range
D1	$M_{\text{med}} = \sqrt{y_q g_\chi} \sqrt{M_*^3/m_q}$	$0 < \sqrt{y_q g_\chi} < 4\pi$
C1	$M_{\text{med}} = y_q \lambda_\chi \zeta_\lambda M_*^2/m_q$	$0 < y_q \lambda_\chi \zeta_\lambda < (4\pi)^2 \zeta_\lambda$
D5, D8, D9	$M_{\text{med}} = \sqrt{g_q g_\chi} M_*$	$0 < \sqrt{g_q g_\chi} < 4\pi$
D11	$M_{\text{med}} = \sqrt[3]{a g_\chi} M_*$	$0 < \sqrt[3]{a g_\chi} < \sqrt[3]{16\pi}$
C5	$M_{\text{med}} = \sqrt{a \lambda_\chi \zeta_\lambda} M_*$	$0 < \sqrt{a \lambda_\chi \zeta_\lambda} < 4\sqrt{\pi \zeta_\lambda}$

- The above is for a particular set of assumptions on the UV completion
 - Changing these assumptions leads to different matching conditions
- Each operator has a range of couplings which are permissible
 - Covers no coupling between SM and DM through to perturbativity limit
 - Scanning over this range provides an idea of the possible validity effects
- C1,C5: must choose value for VEV scale factor, $\zeta_\lambda = v_\lambda/M_{\text{med}}$
 - Typically use $\zeta_\lambda = 1$ for simplicity
 - Assumption can be varied by adjusting the coupling range considered

History of EFT validity in ATLAS

- ATLAS has studied the impact of EFT validity in several publications:
 - First studied for simple D5 scenario in 14 TeV monojet PUB note
 - D1, D9, and C1 investigated by 8 TeV HF+DM paper
 - D5, D8, and D9 studied by 8 TeV mono-photon paper
 - D1, D5, D8, D9, D11, C1, C5 considered in 8 TeV mono-jet paper
- Two methods for truncating/rescaling limits have been studied
 - Provide compatible results when sufficient statistics are available
- Some nomenclature for what will be used (from [this paper](#)):
 - $R_{M_{\text{med}}}^{\text{tot}}$: the fraction of events passing the validity criterion
 - M_*^{exp} : the limit on M_* before validity is considered
 - M_*^{valid} : the limit on M_* after validity, $M_*^{\text{valid}} = [R_{M_{\text{med}}}^{\text{tot}}]^{1/2(d-4)} M_*^{\text{exp}}$
 - $d = 6$ for {D5,D9,C1,C5}, $d = 7$ for {D1,D11}

Truncation method 1: cross-section truncation

1. Construct the Q_{tr} distribution for a given MC sample
2. Scan over M_* and compare to the Q_{tr} distribution, determining $R_{M_{\text{med}}}^{\text{tot}}$ for each value of M_*
3. Rescale the nominal expected/observed limit on the cross-section of each signal sample, $\sigma_{\text{exp}}(M_*)$, so that it corresponds to only the valid events: $\sigma_{\text{valid}}(M_*) = \sigma_{\text{exp}}(M_*) \cdot R_{M_{\text{med}}}^{\text{tot}}(M_*)$.
4. Determine the point where σ_{valid} and the experimental limit on the visible cross-section σ_{vis} meet, and take the corresponding M_* value as the truncated limit on the suppression scale M_*^{valid} .

This method was used for 8 TeV papers, cross-check for the 14 TeV note

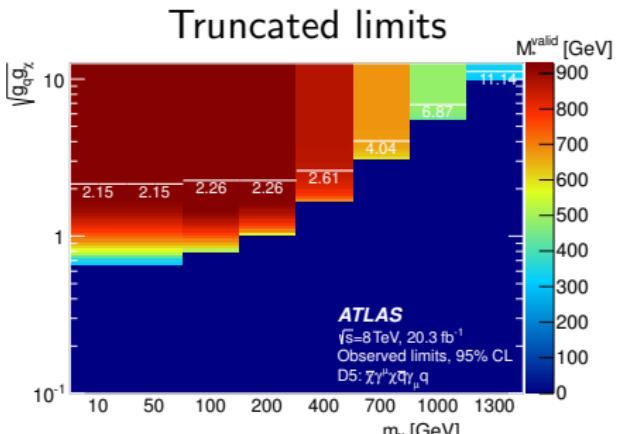
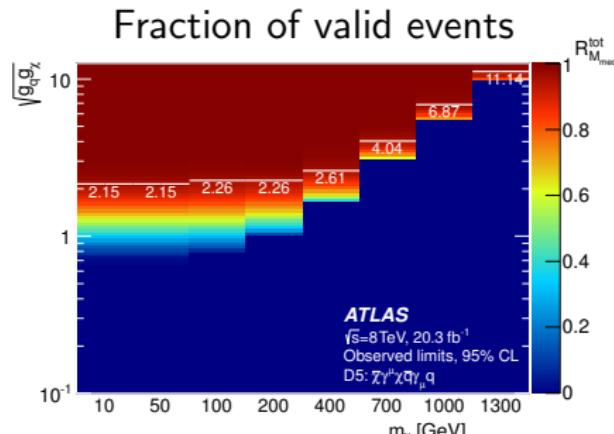
Truncation method 2: iterative rescaling

1. Start with the nominal expected/observed limit on M_* assuming 100% validity, named M_*^{exp} .
2. For each step i , obtain the relative fraction of valid events $R_{M_{\text{med}}}^i$ satisfying $Q_{\text{tr}} < M_{\text{med}}^{\text{in}}$ with respect to all events passing the previous iteration. $M_{\text{med}}^{\text{in}}$ is the mediator mass limit obtained in the previous step, which depends on M_*^{in} . For the first step, $M_*^{\text{in}} = M_*^{\text{exp}}$.
3. Rescale M_* : $M_*^{\text{out}} = [R_{M_{\text{med}}}^i]^{1/2(d-4)} M_*^{\text{in}}$
4. Go to step 2, using the current M_*^{out} as the new M_*^{in} , repeating until the fraction of valid events at a given step $R_{M_{\text{med}}}^i$ reaches 0 or 1.
5. Calculate the total validity fraction $R_{M_{\text{med}}}^{\text{tot}} = \prod_i R_{M_{\text{med}}}^i$ and the final rescaled limit on the suppression scale $M_*^{\text{valid}} = [R_{M_{\text{med}}}^{\text{tot}}]^{1/2(d-4)} M_*^{\text{exp}}$.

This method was used for 14 TeV note, cross-check for the 8 TeV papers

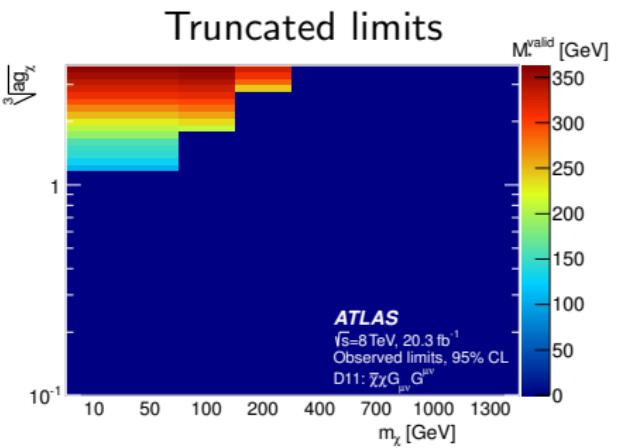
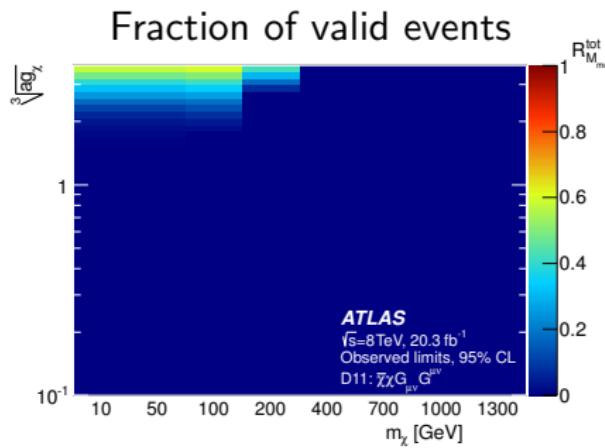
EFT validity dependencies

- EFT validity depends on multiple factors
 - Increasing the DM mass increases Q_{tr} , reducing validity ($Q_{\text{tr}} \geq 2m_\chi$)
 - Larger coupling values for fixed M_* increases M_{med} , increasing validity
 - Higher E_T^{miss} thresholds (typical of higher signal regions) are somewhat correlated with Q_{tr} , although this effect has much less impact
- Scan over m_χ and coupling value to resolve these dependencies
 - White lines and numbers are where $M_*^{\text{valid}}/M_*^{\text{exp}} > 99\%$



EFT validity dependencies, continued

- Both Q_{tr} and $M_* - M_{med}$ relation depend heavily on the operator
- Previous slide of D5 showed reasonable validity over large region
- D11 shows the worst operator validity seen in 8 TeV mono-jet studies
 - No points where $M_*^{\text{valid}}/M_*^{\text{exp}} > 99\%$ for the given assumptions
 - Truncated limits are zero for all coupling values at high m_χ

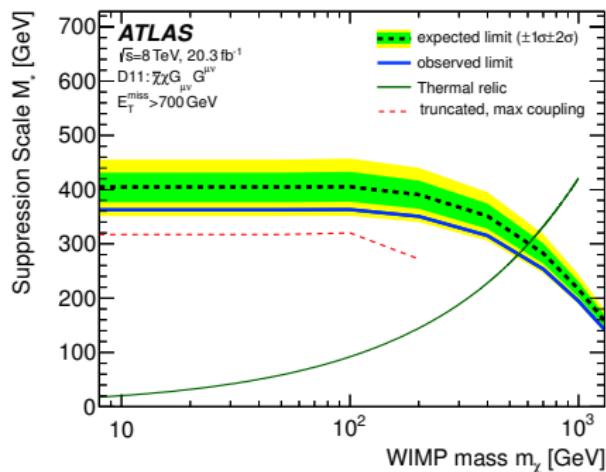
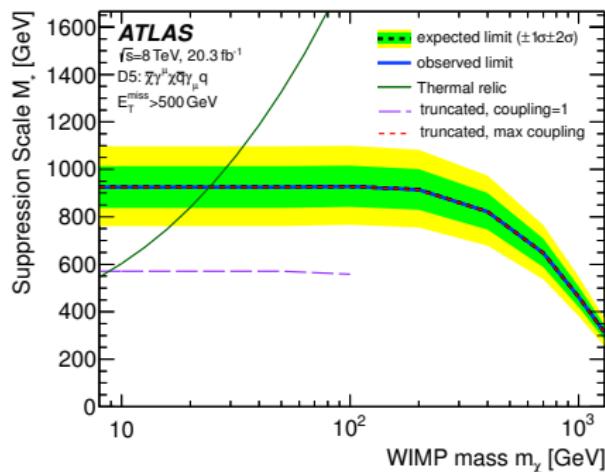


Validity presentation considerations

- Presentation of EFT validity results provides a dilemma
 - Nominal limits may violate assumptions made during model building
 - Truncated limits also contain many assumptions as detailed
- What coupling value should be assumed for the validity calculation?
 - No real answer until SM-DM coupling is observed and scale is known
 - Until then, consider the so-called natural scale of coupling=1
 - Also consider the best case for colliders (max coupling) as upper bound
 - Only these two scenarios are considered to avoid overcrowding plots

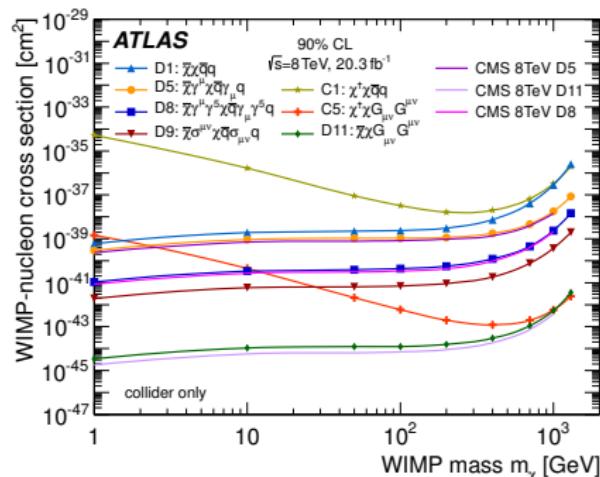
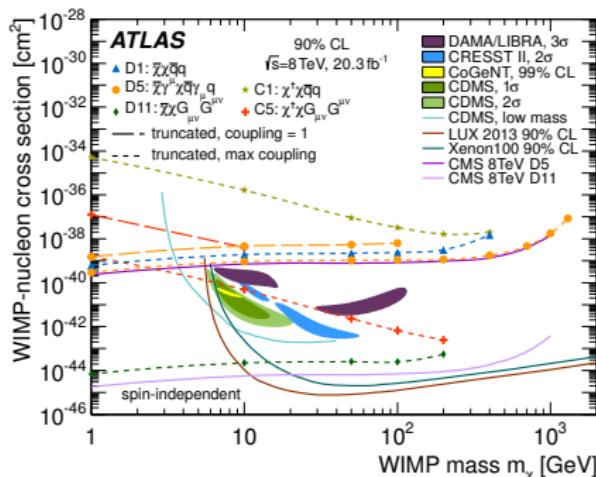
M_* limits for mono-jet including validity

- Ignoring validity, nominal results demonstrate benchmark sensitivity
 - For pure collider plots, such as limits on M_* , focus on nominal values
 - Truncated limits can be added on top, so long as not too crowded
 - Truncated lines not shown where the model is completely invalid
- Comparison of D5 and D11 shows large differences



$\sigma_{\text{WIMP-nucleon}}$ limits for mono-jet requiring validity

- Comparing to other experiment types highlights Q_{tr} differences
 - Must enforce validity when comparing to WIMP-nucleon experiments
 - Nominal results are not shown on the same plot as in/direct detection
- Difference between truncation and nominal clear in some cases
 - Lines disappear as m_χ grows and validity drops
 - Left is with truncation applied, right is nominal limits



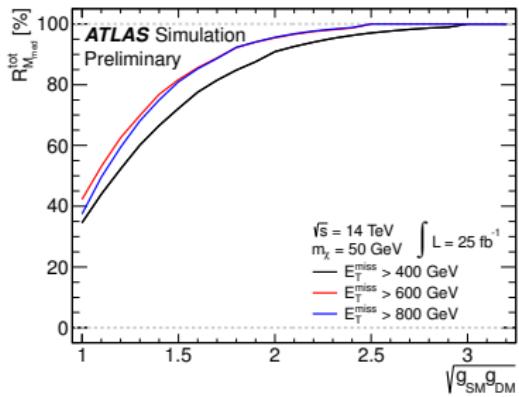
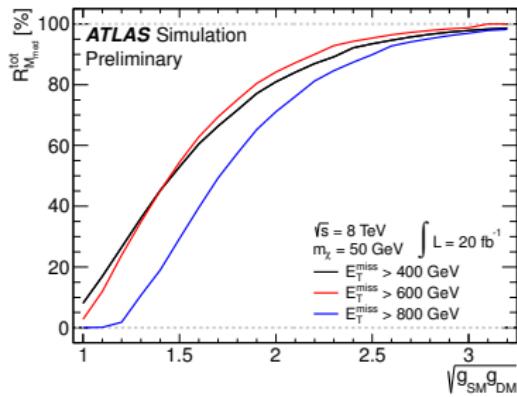
Summary

- EFTs used by ATLAS and CMS useful for minimal model dependence
 - However, they come with limitations on the model validity
 - Can ignore validity and use models purely as collider benchmarks
 - Cannot ignore validity if comparing to in/direct detection results
- Derived a set of UV matching conditions for all operators of interest
 - Simple mediator completion operators: D5, D8, D9
 - Chirally suppressed operators: D1, C1
 - Gluon operators: D11, D5
- Two truncation procedures exist and provide compatible results
 - Enable studies of validity dependencies on operator, m_χ , coupling
- ATLAS now has four publications involving EFT validity
 - M_* limit plots moving toward both nominal and truncated limits
 - Comparison to in/direct detection moving toward only truncated limits
- Must remember EFT validity procedure also contains assumptions
 - $Q_{\text{tr}} \ll M_{\text{med}}$ vs $Q_{\text{tr}} < M_{\text{med}}$, UV completion choice, coupling value, ...
- EFT models remain a good benchmark for collider searches
- Simplified models provide a better long-term answer

Backup Slides

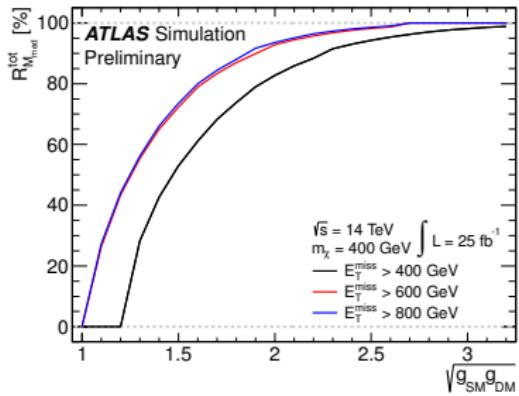
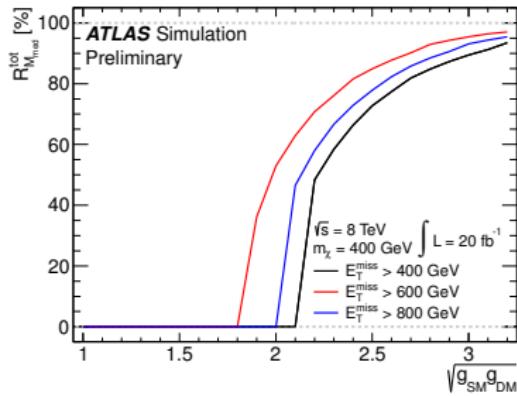


8 vs 14 TeV for m_χ of 50 GeV

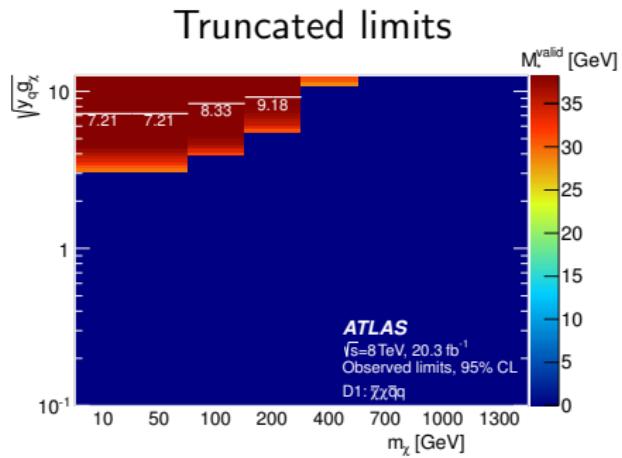
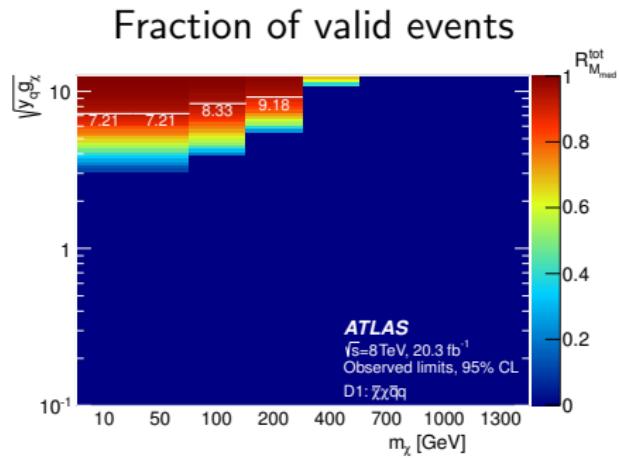




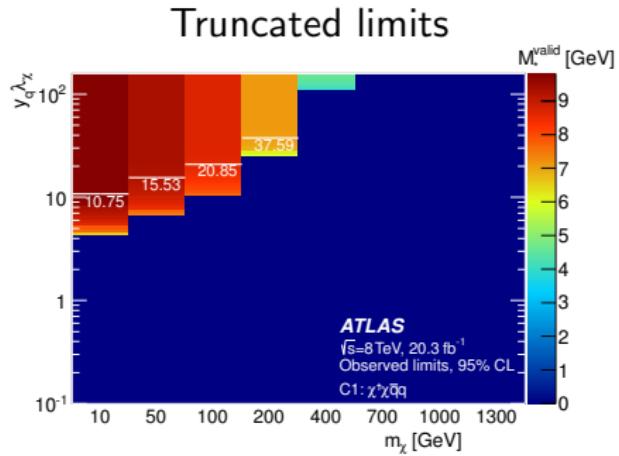
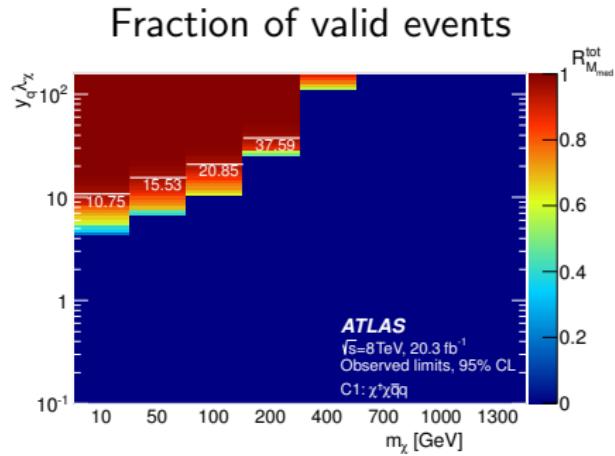
8 vs 14 TeV for m_χ of 400 GeV



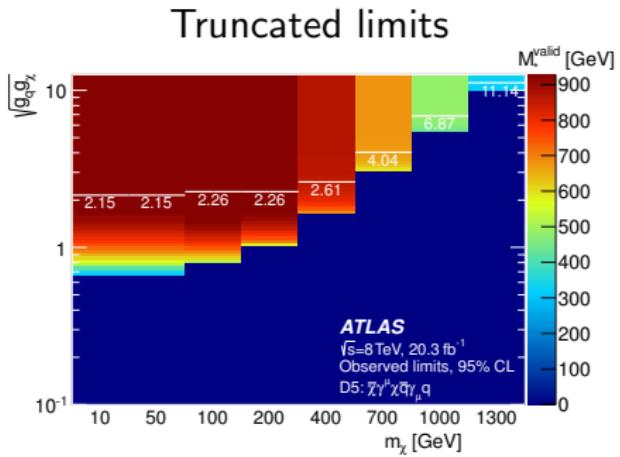
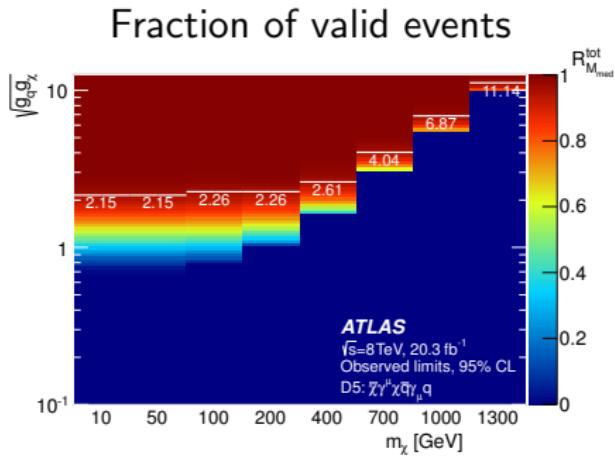
D1 validity scan



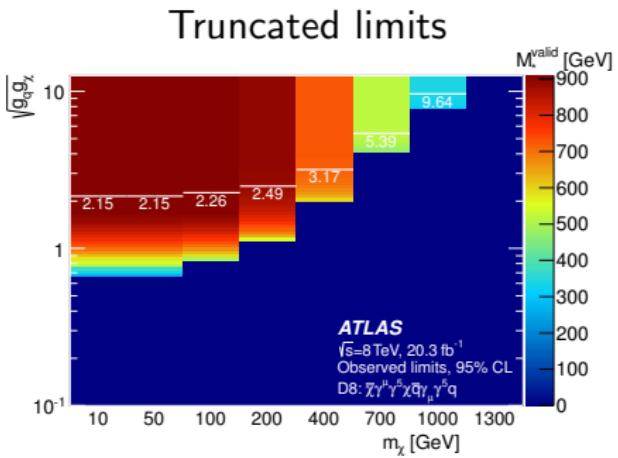
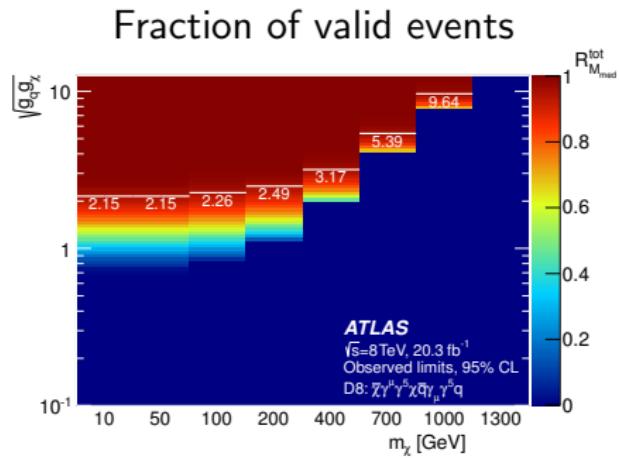
C1 validity scan



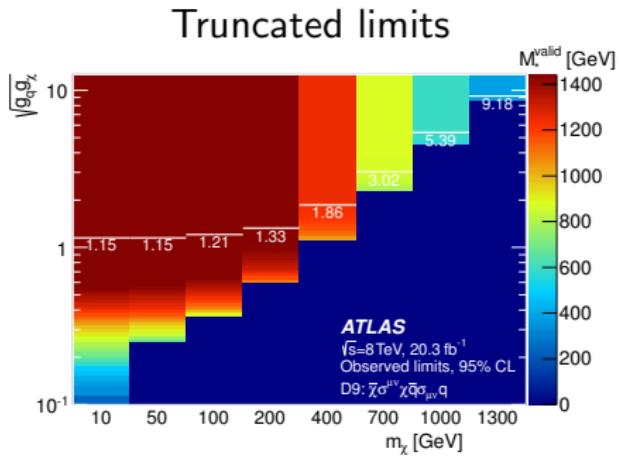
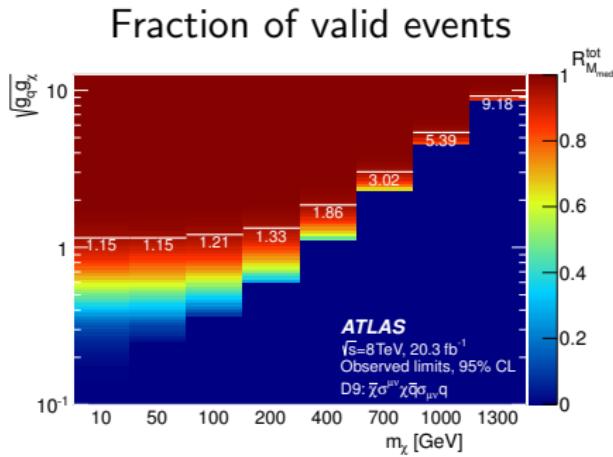
D5 validity scan



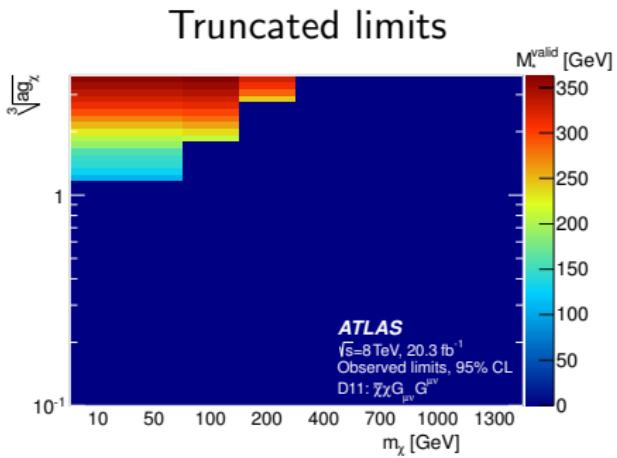
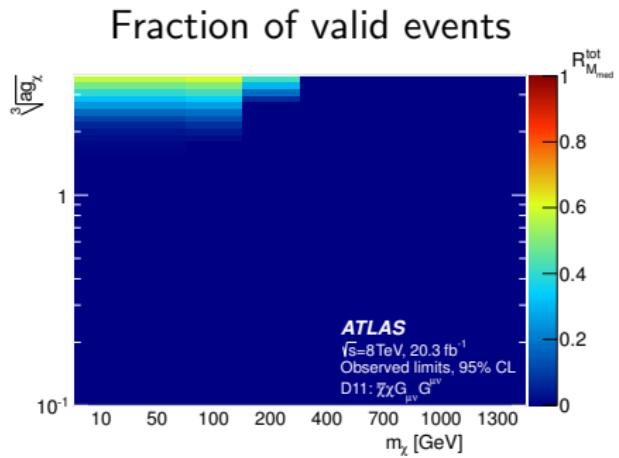
D8 validity scan



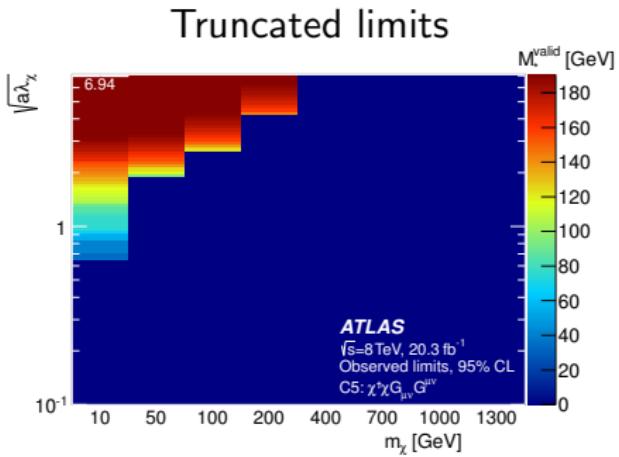
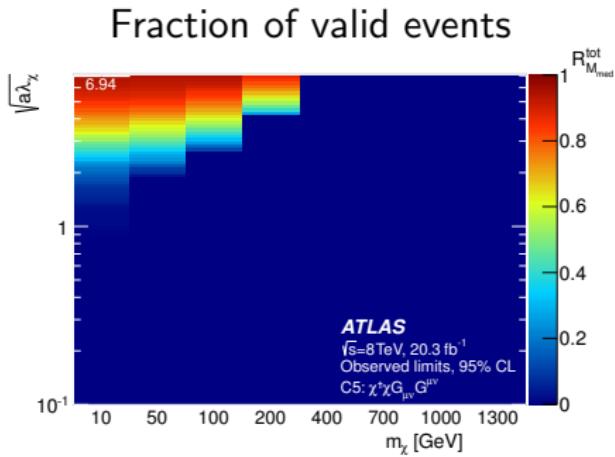
D9 validity scan



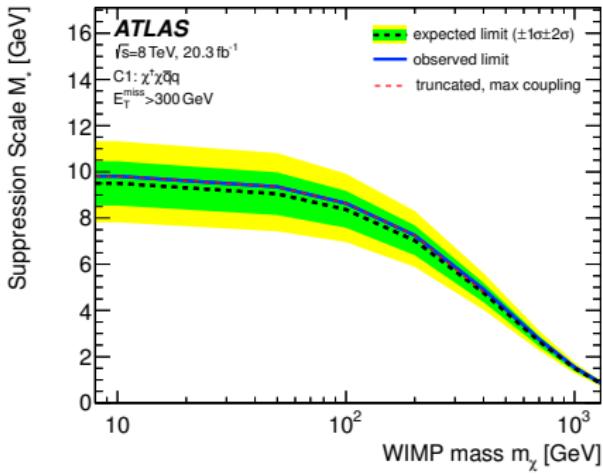
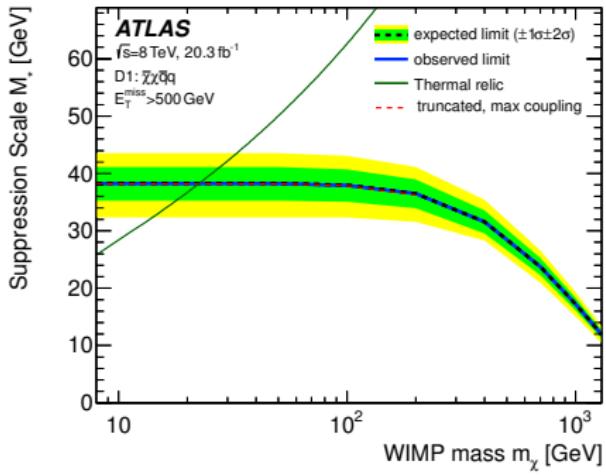
D11 validity scan



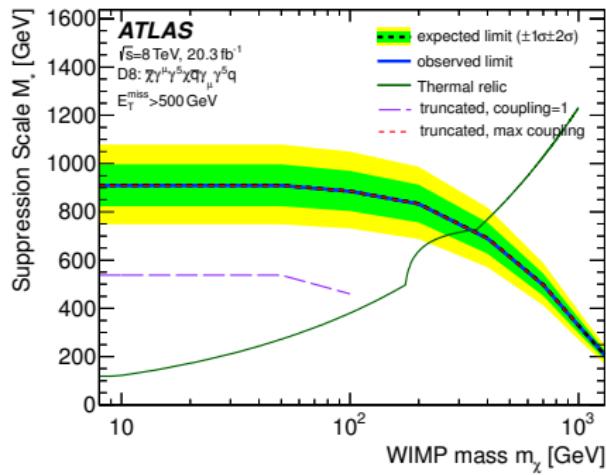
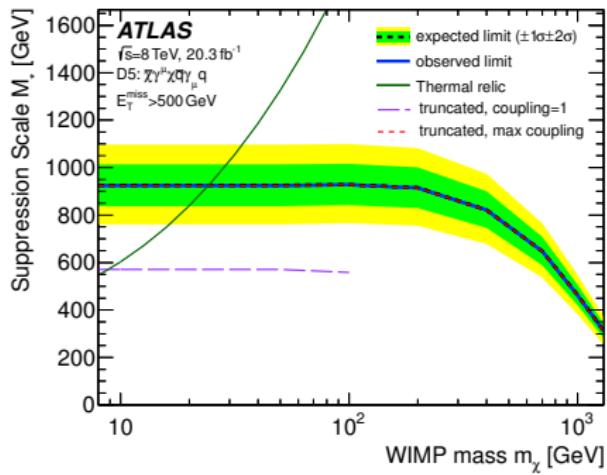
C5 validity scan

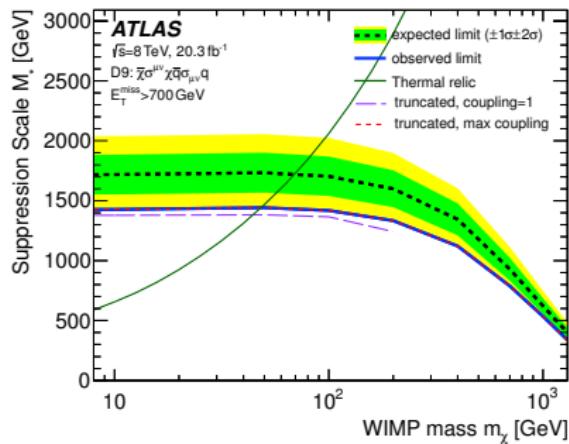


D1,C1 M_* limits

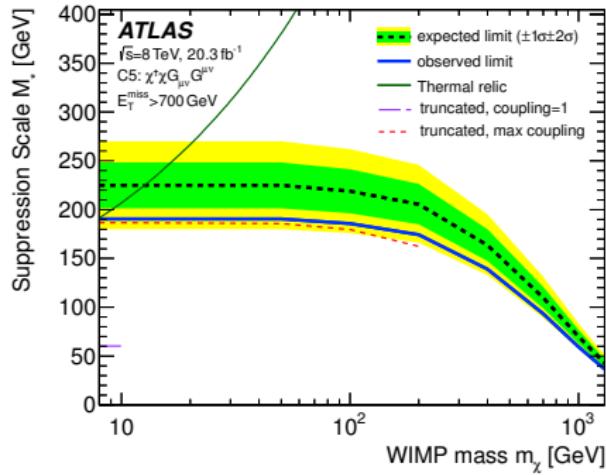
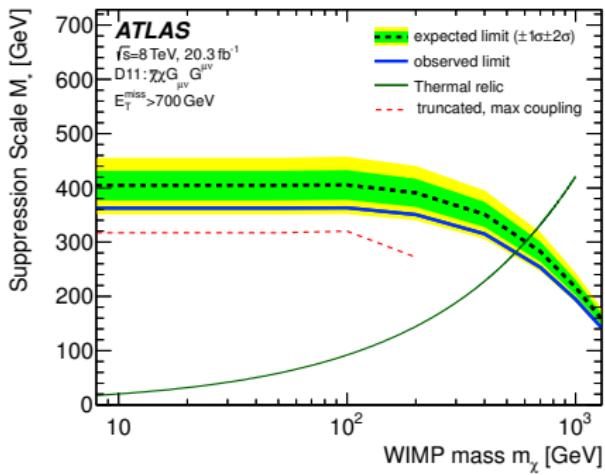


D5,D8 M_* limits



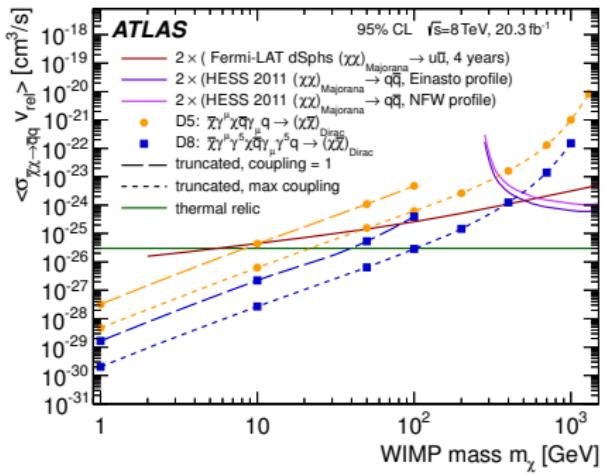
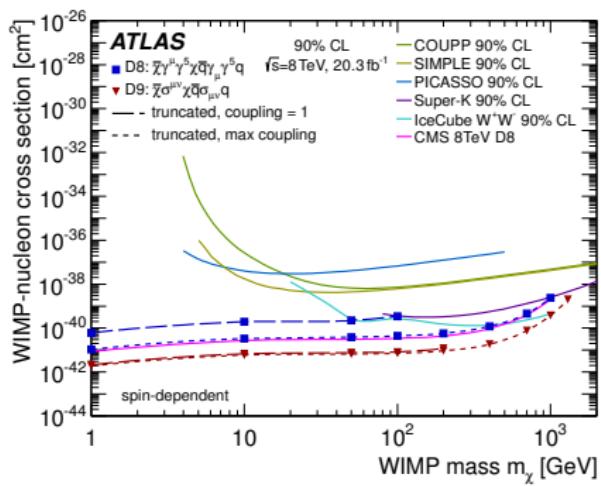
D9 M_* limits

D11,C5 M_* limits



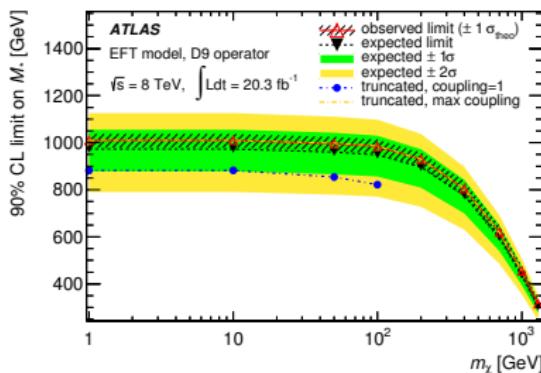
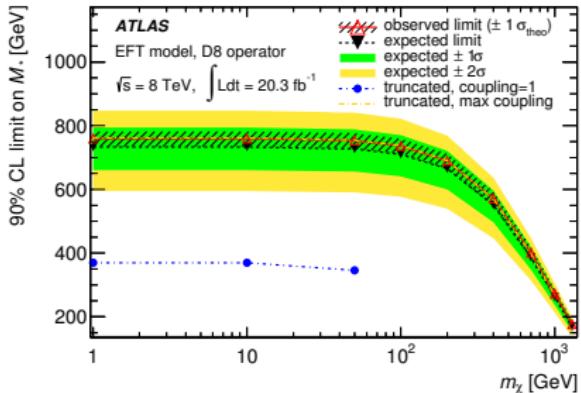
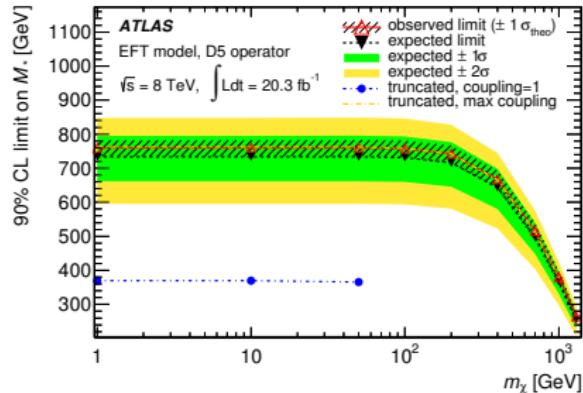


Comparisons to other experiments

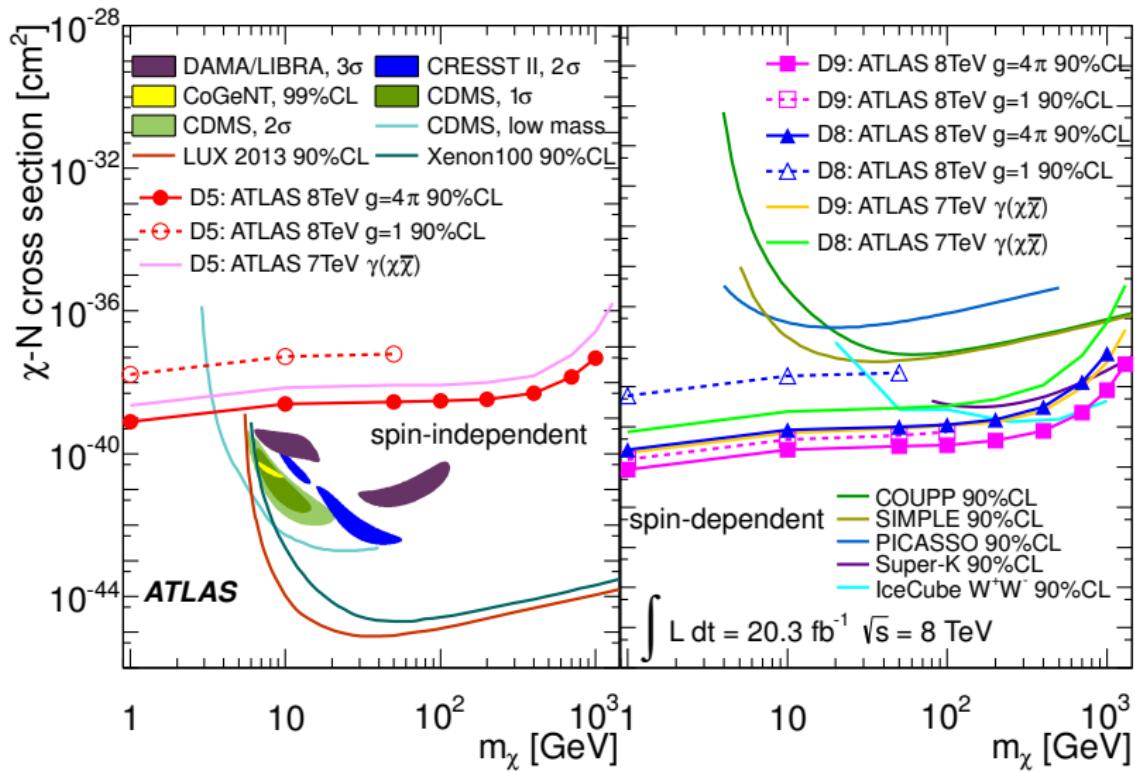




Mono-photon M_* limits

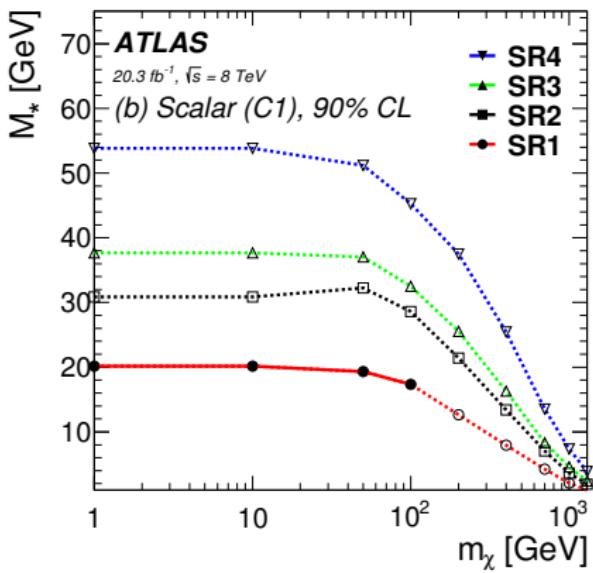
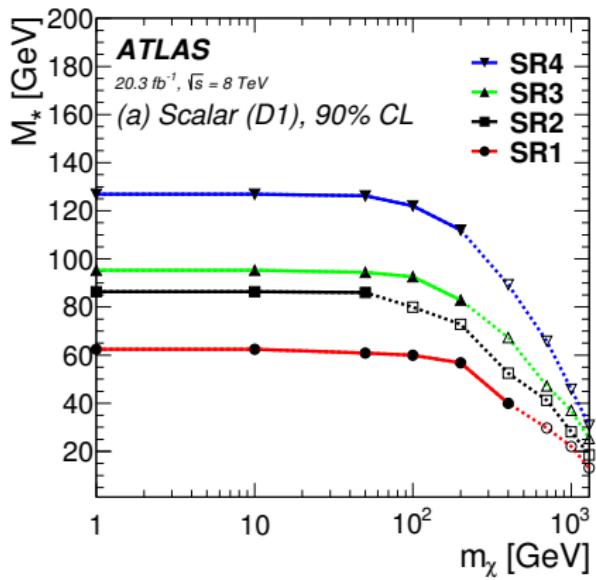


Mono-photon comparison to other experiments

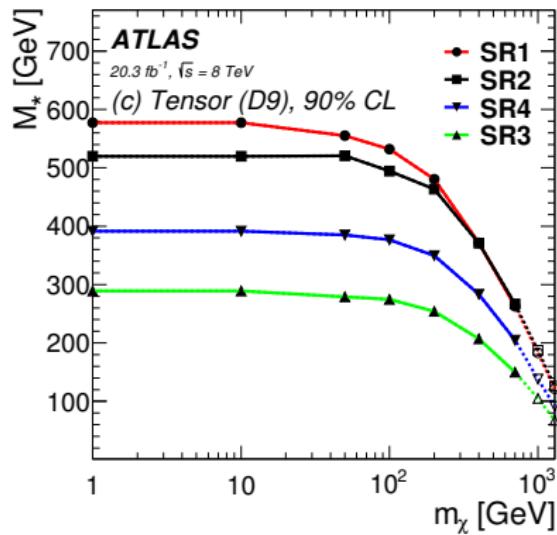




HF+DM M_* scalar operator limits



HF+DM M_* tensor operator limits





HF+DM comparison to other experiments

