Search for dark matter in events with a Z boson and missing transverse momentum in *pp* collisions at $\sqrt{s} = 8 TeV$ with the ATLAS detector

The Crazy Kids at ATLAS

Dark Matter?

- Evidence for existence from astrophysical observations: gravitational lensing, galaxy rotation curves…
- Particle nature and non-gravitational interactions (if any) are unknown
- Proposed explanations include axions, WIMPs and gravitational corrections such as MoND and TeVeS

WIMPs

- Weakly Interacting Massive Particles
- No EM or strong interactions (explains absence of luminosity)
- SUSY provides a candidate particle in the lightest neutralino – a mixture of the bino, neutral wino and the higgsinos.
- This is stable if R-parity ($(-1)^{3(B-L)+2S}$) is conserved.
- Would not be directly observable by detectors
- Instead detect through missing transverse energy

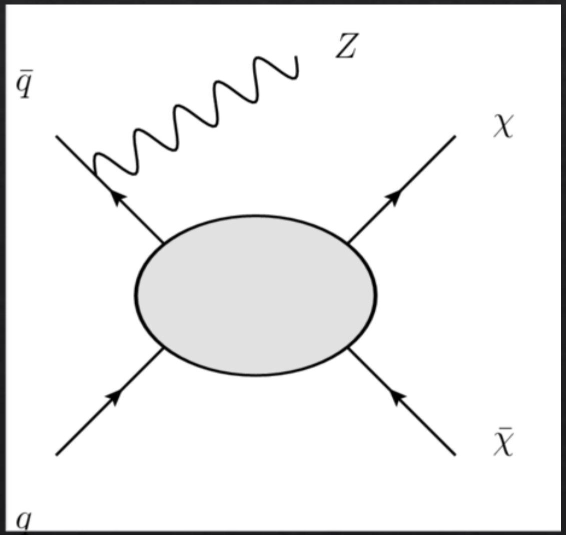
Leptonic Z boson decay with E_T^{miss}

- Search conducted in the $pp \rightarrow Z + \chi\bar{\chi}$ channel with the Z decaying leptonically ($Z \rightarrow l^+ l^-$).
- WIMP (χ) detected through missing transverse energy.
- Other sources of E_T^{miss} include neutrinos and detector uncertainties.
- Leptonic decay has smaller branching ratio but cleaner than hadronic decay.

Theoretical Models

Effective field theory (EFT) approach

- The nature of the intermediate state mediating the parton-WIMP interaction is unknown.
- If we assume it is heavy compared to the interaction energies (not always true!) we can model this by constructing an effective field theory, defined by a mass scale, M_*, and m_χ.
- Z boson produced through initial state radiation.



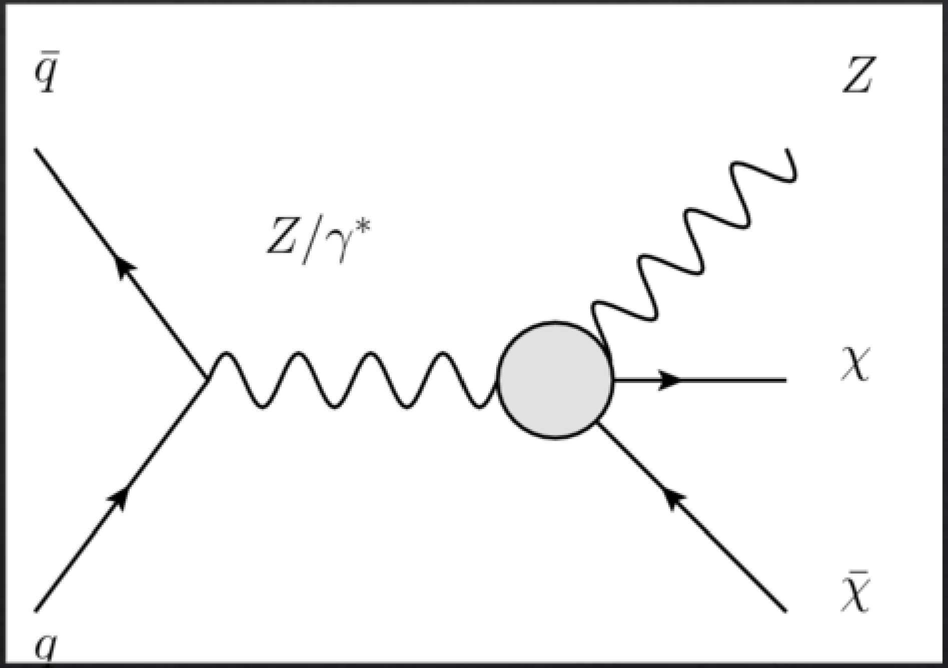
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

A list of all possible EFT operators for a Dirac fermion or scalar boson χ. The D1, D5 and D9 operators were considered in this search.

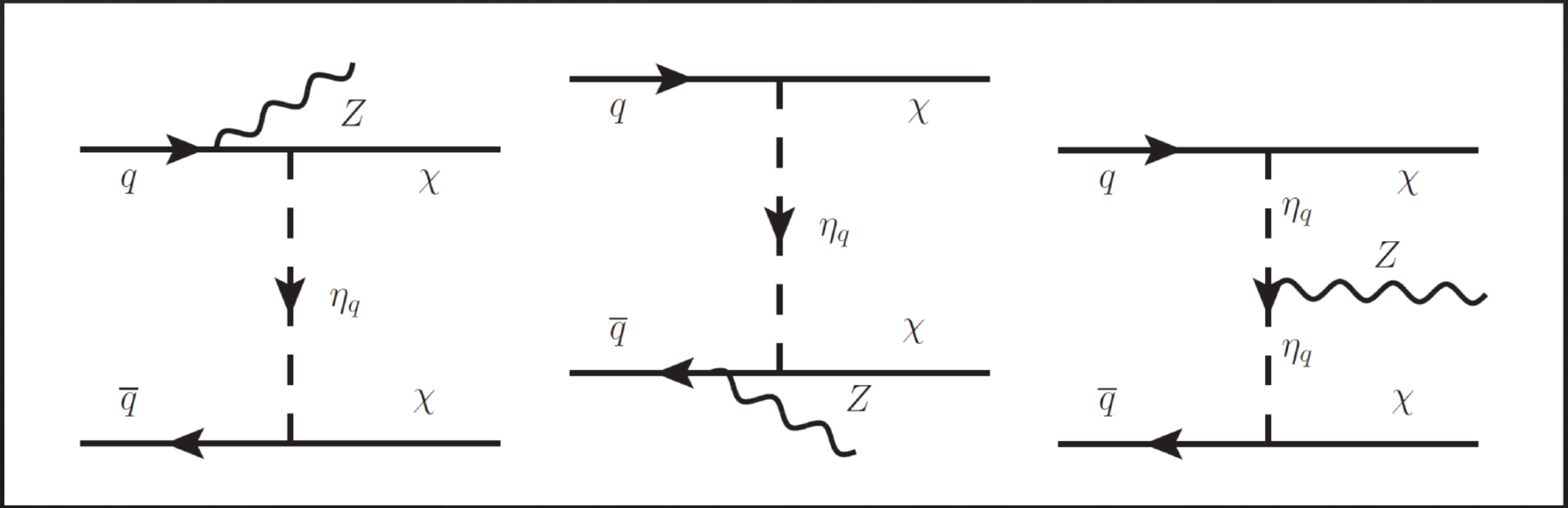
Direct dark matter-electroweak interaction

- EFTs with dimension-5 and -7 electroweak boson-WIMP interaction were also considered.
- The dimension-7 operator also allows $Z\gamma^*\chi\bar{\chi}$ interactions. The relative contribution of the Z and γ^* diagrams is a free parameter of the theory.
- Not previously investigated at LHC.



Scalar-mediator model

- Finally a model with a specific scalar mediator (η) is considered. η is assumed to be a colour triplet, electroweak doublet and have a hypercharge of 1/3.
- Corresponds to SUSY with a neutralino (χ) and squark (η) interaction if the gluino is too heavy to be produced at the LHC.

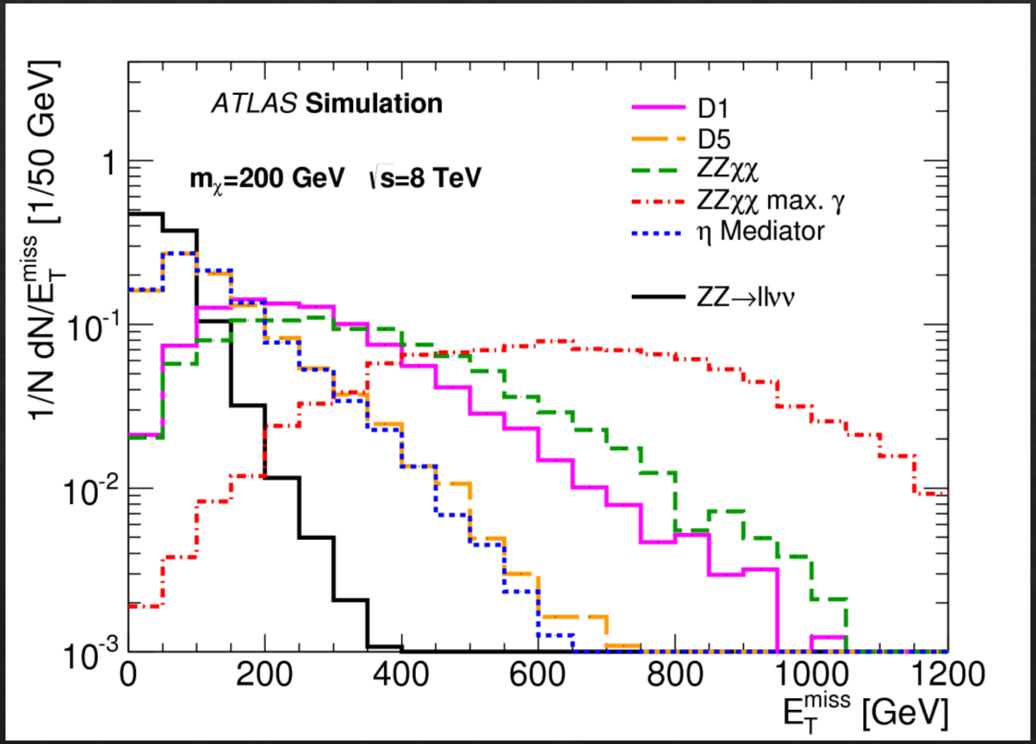


Requirements

- Electrons required to have $|\eta| < 2.47$, $E_T > 20\ GeV$, fulfil medium object requirements and be isolated
- Muons required to have $|\eta| < 2.5$, $p_T > 20\ GeV$, fit impact parameters and be isolated
- Anti-k_T jet algorithm used to identify jets
- Other criteria (eg delta-ray electrons)
- Trigger limits
- Four signal regions considered: E_T^{miss} = 150, 250, 350 and 450 GeV

Background

- Supress $t\bar{t}$ decay events by removing jets with $p_T > 25GeV$
- Dominant background is $ZZ \rightarrow l^+l^-\nu\bar{\nu}$ which is irreducible estimated by MC
- Subdominant $WZ \rightarrow l\,\nu\,l^+l^-$ background (also by MC)
- Minor backgrounds use data driven techniques
  - WW, $t\bar{t}$, Wt and $Z \rightarrow \tau^+\tau^-$ $(e\mu)$
  - $Z + jets$ (ABCD and extrapolation)
  - $W + jets$ (reversing electron isolation)



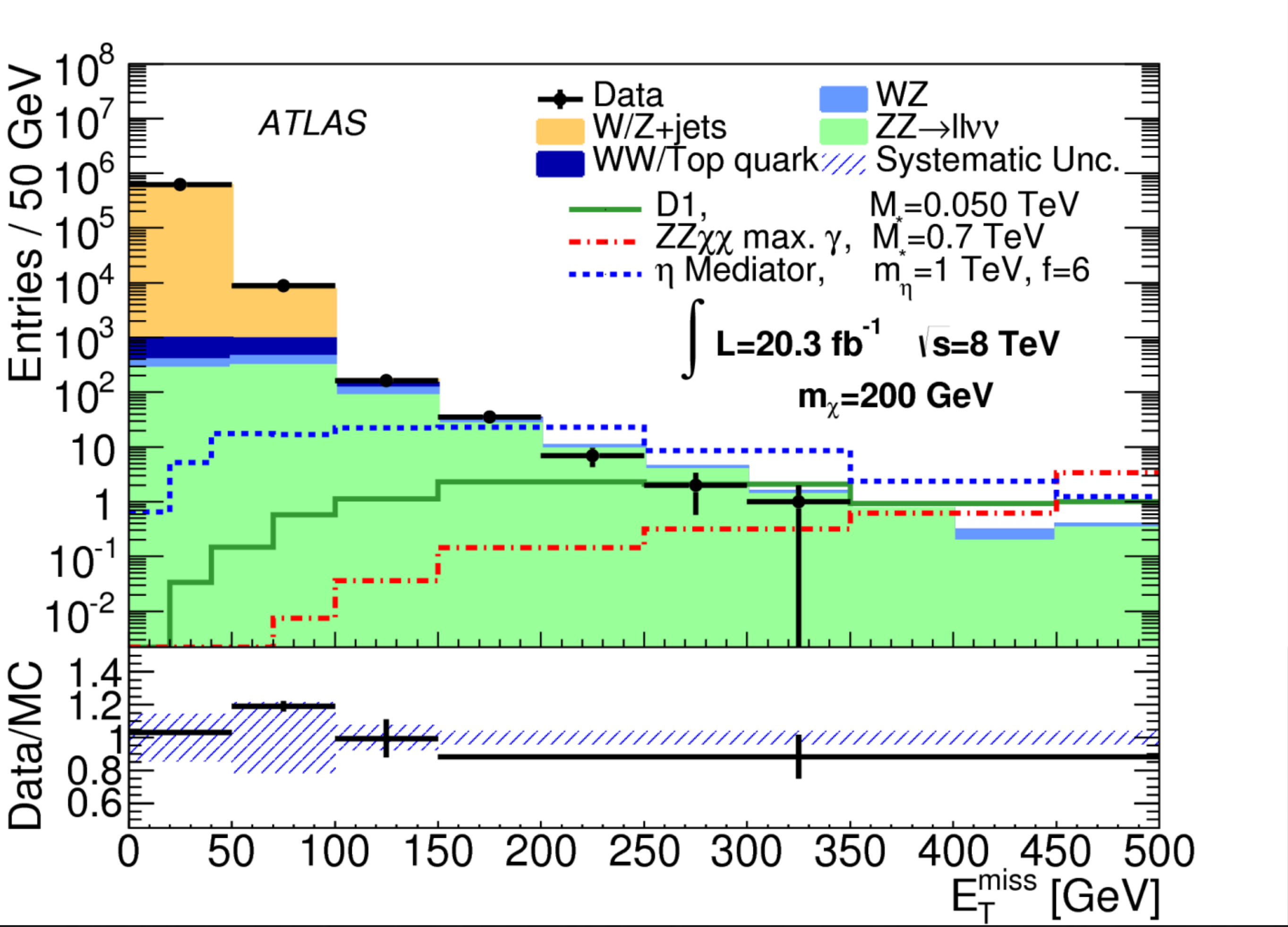
Uncertainty

Uncertainty Source	E_T^{miss} threshold [GeV]			
	150	250	350	450
Statistical [%]	2	6	13	24
Experimental [%]	3	6	9	8
Theoretical [%]	36	37	37	38
Luminosity [%]	3	3	3	3
Total [%]	36	38	40	46

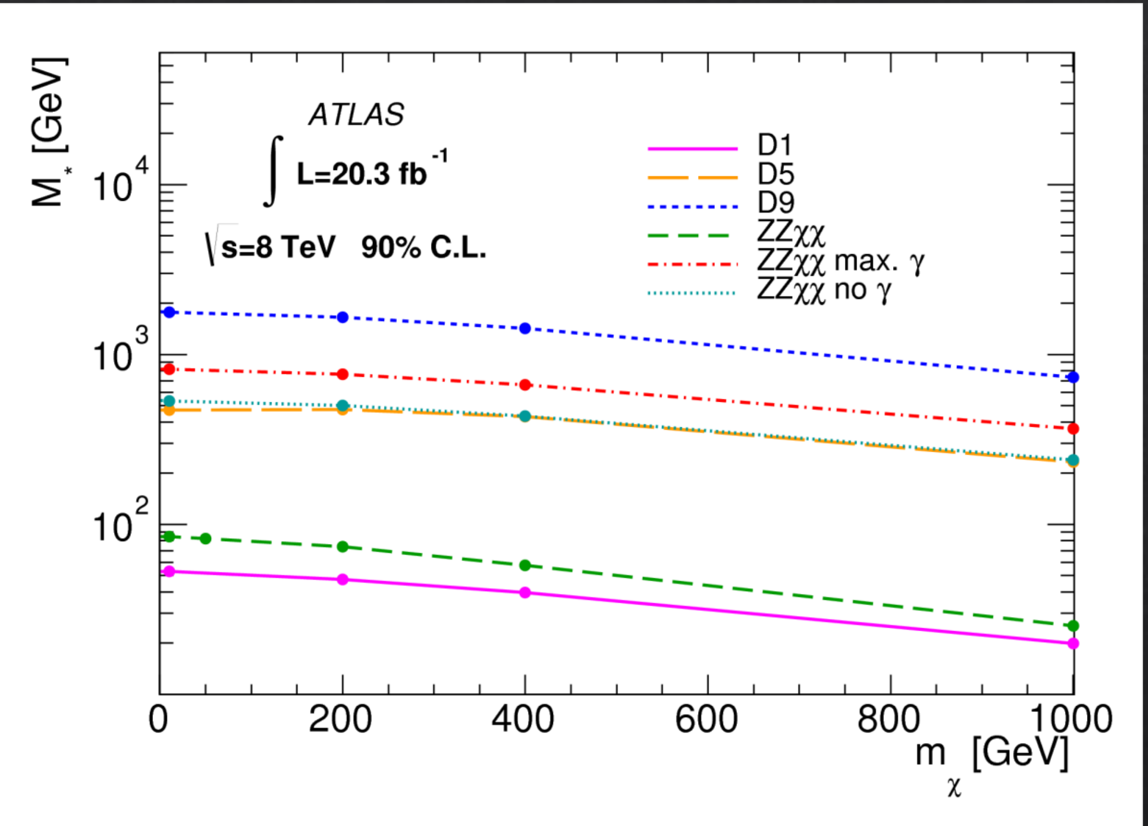
Results Table

Process	$E_{\mathrm{T}}^{\mathrm{miss}}$ threshold [GeV] 150	250	350	450
ZZ	41 ± 15	6.4 ± 2.4	1.3 ± 0.5	0.3 ± 0.1
WZ	8.0 ± 3.1	0.8 ± 0.4	0.2 ± 0.1	0.1 ± 0.1
WW, $t\bar{t}$, $Z \rightarrow \tau^+\tau^-$	1.9 ± 1.4	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$
Z+jets	0.1 ± 0.1	–	–	–
W+jets	0.5 ± 0.3	–	–	–
Total	52 ± 18	7.2 ± 2.8	1.4 ± 0.9	$0.4^{+0.7}_{-0.4}$
Data	45	3	0	0

E_T^{miss} Distributions



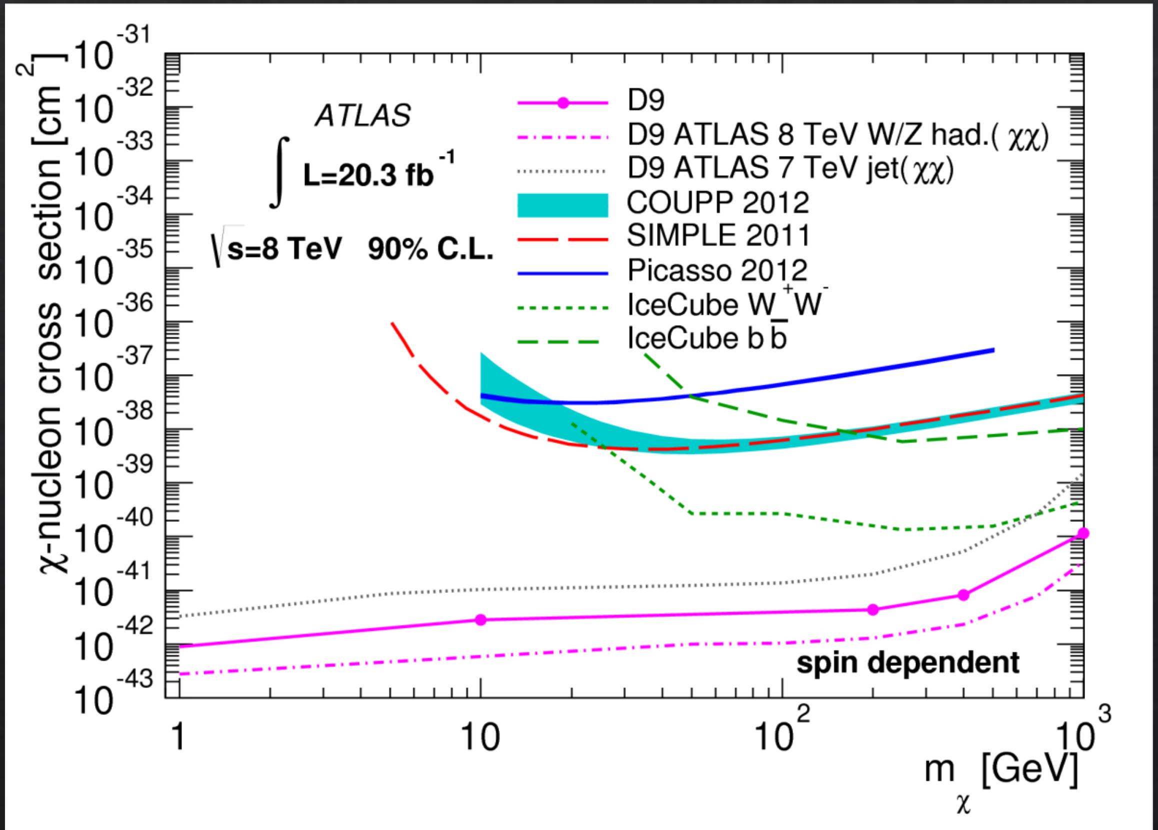
Mass scale lower limits

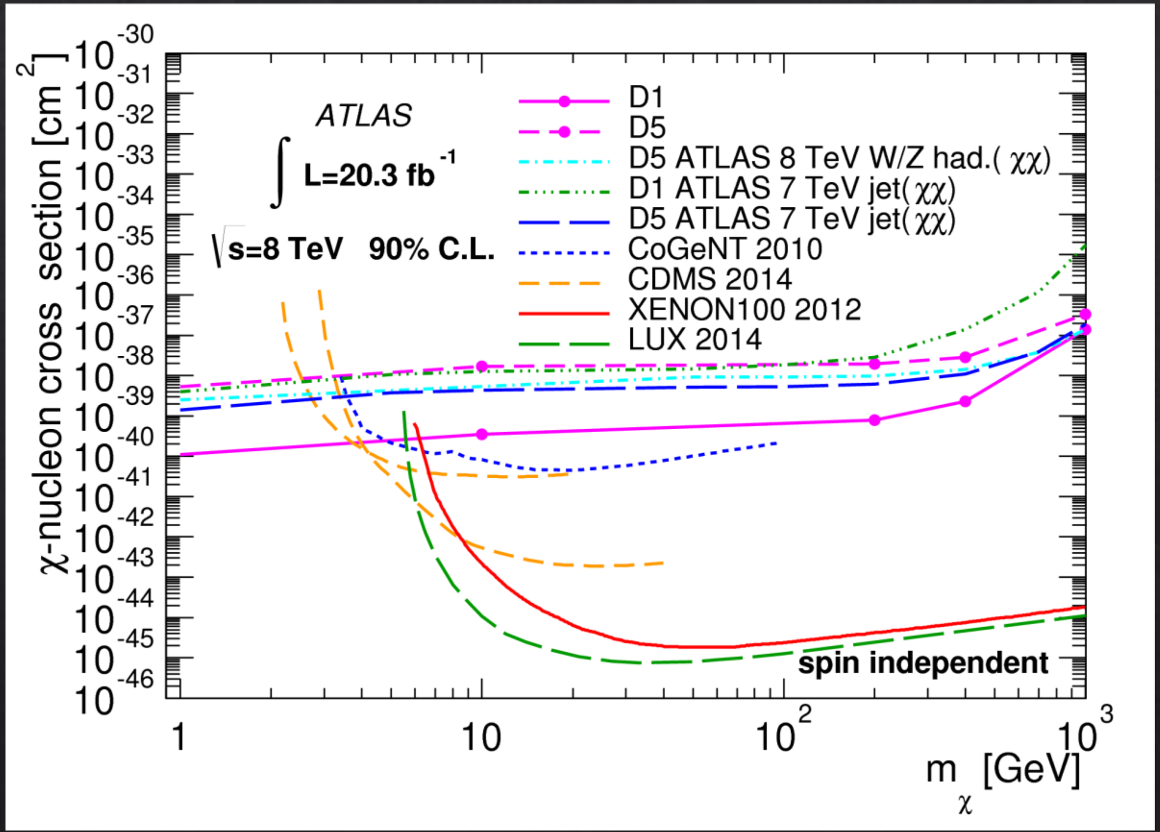


Observed 90% C.L. lower on the mass scale M^*. Values below the corresponding line are excluded.

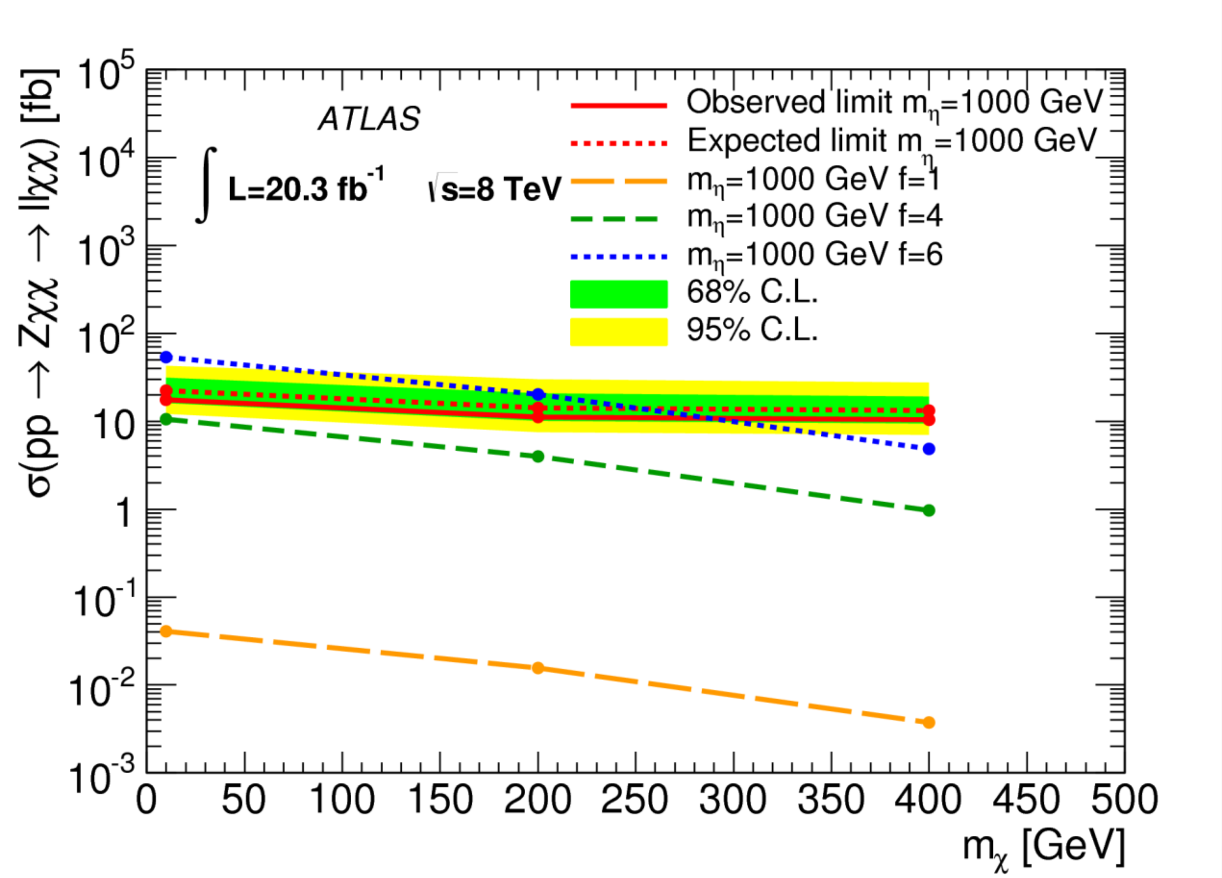
And here are some other graphs…

EFT cross-section upper limits



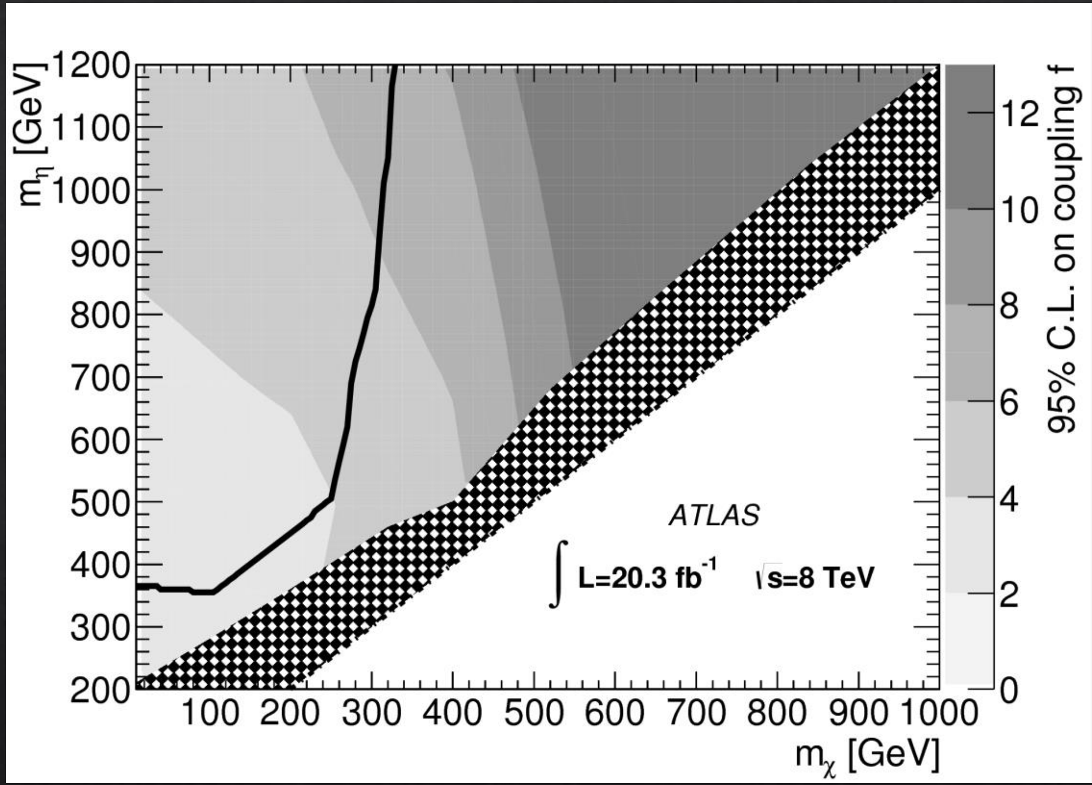


Scalar-mediated model cross-section upper limits



Observed limits on the cross-section of the scalar-mediator theory multiplied by the branching ratio of $Z \to l^+ l^-$.

Scalar-mediated model coupling constant upper limits



Observed 95% upper limits on the coupling constant for the scalar-mediator theory. The cross-hatching show the theoretically accessible region outside the range covered by this analysis. Lower limits from relic abundance calculations are sufficiently high that the upper left region can now be excluded.

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