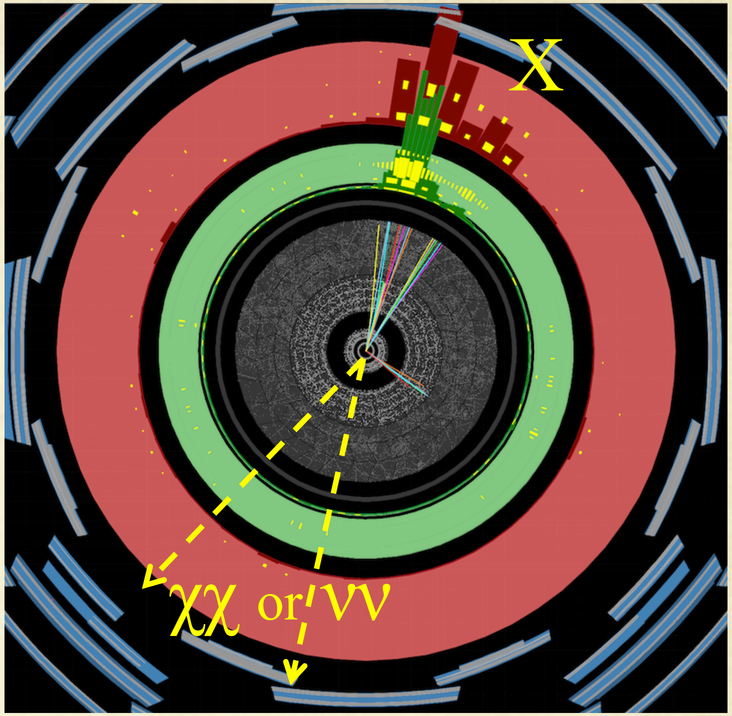
Searches for dark matter with the ATLAS detector

Christophe Clément – Stockholm University
for the ATLAS collaboration

Topical Meeting from Higgs to Dark Matter – Geilo Norway – 2014

Dark Matter Search with Mono-X Signatures

- Mono-Photon
- Mono-Top
- Heavy flavour + E_T(miss)
- Mono- W/Z hadronic
- Mono- W leptonic
- Mono- Z leptonic
- (Mono-Jet)
- (Invisible Higgs)



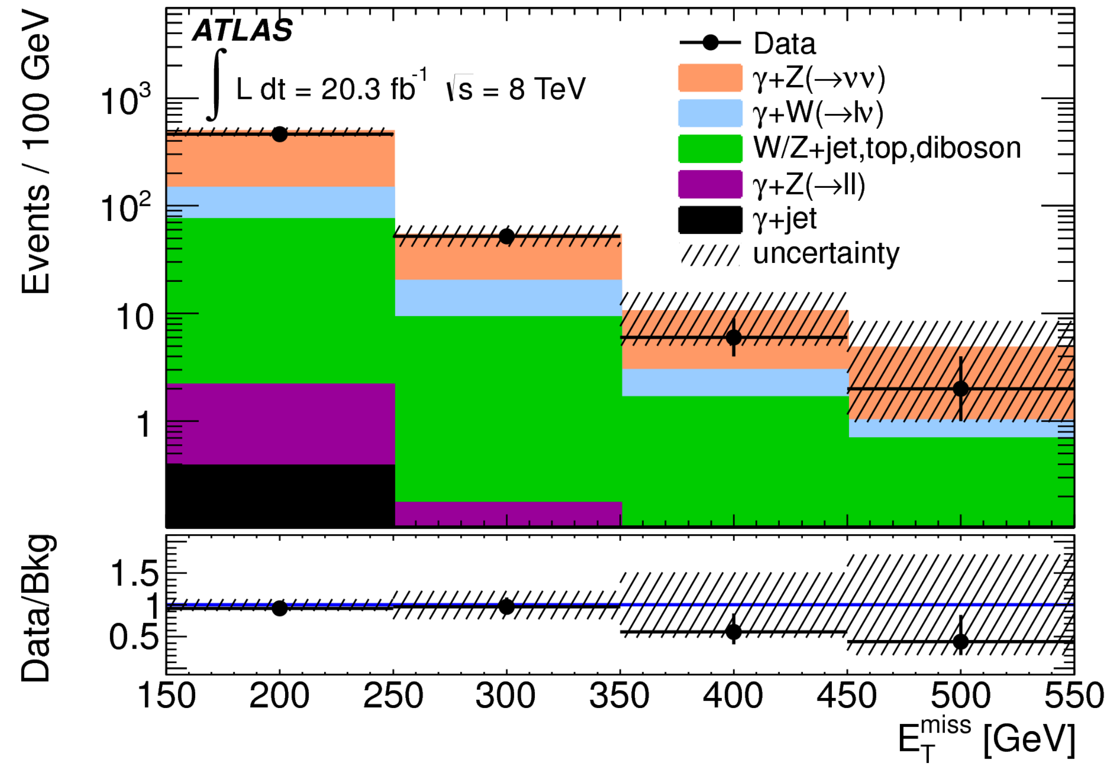
Display of a high p_T jets recoiling against missing transverse energy E_T(miss).

$$\mathbf{E}_T(miss) = -\sum_{jet} \mathbf{p}_T^{jet} - \sum_{leptons} \mathbf{p}_T^{lepton} - \sum_{photon} \mathbf{p}_T^{photon} - \ldots$$

Mono-Photon Signal Region

- $p_T(\gamma)$ >125 GeV with $|\eta|<1.37$
- E_T(miss) > 150 GeV
- $\Delta\varphi(\gamma, \mathbf{E_T}(\text{miss})) > 0.4$
- Allow up to one jet
- Veto events with e/μ (7/6 GeV)

Signal region



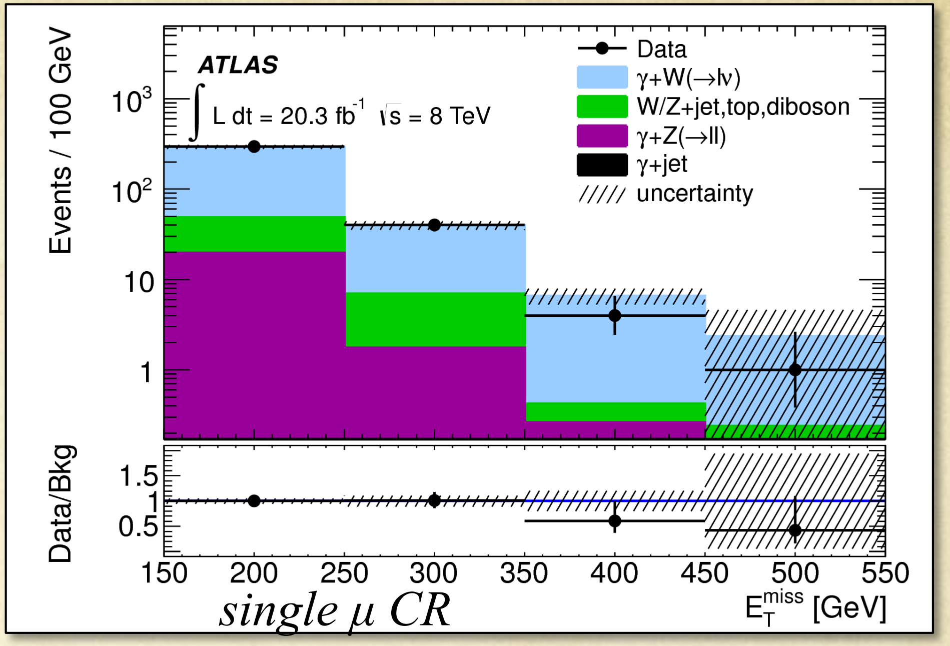
ATLAS Paper Submitted to PRD arXiv:1411.1559v1 [hep-ex]
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2014-06/

Leading backgrounds

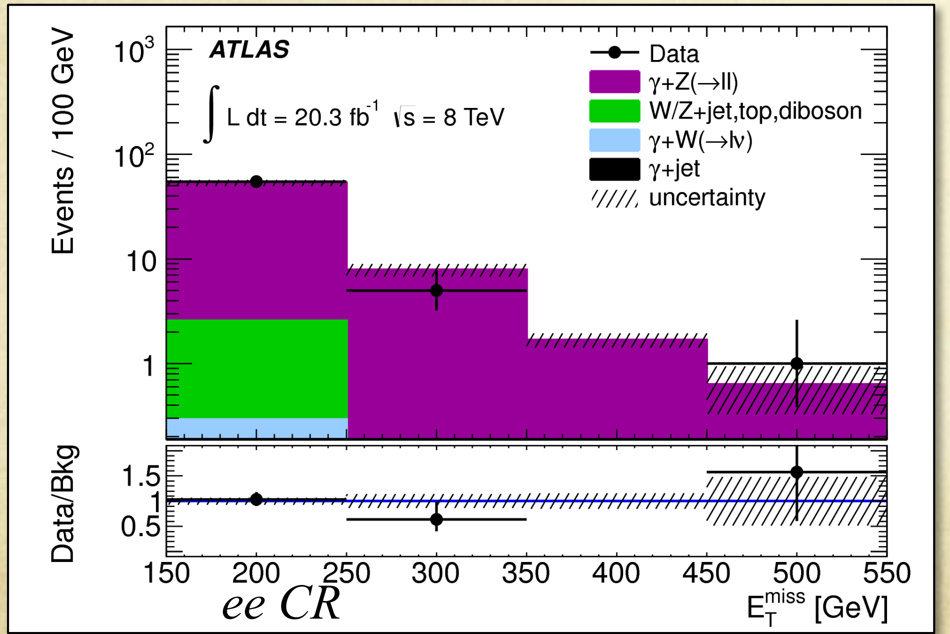
$(Z \rightarrow \bar{\nu}\nu) + \gamma$

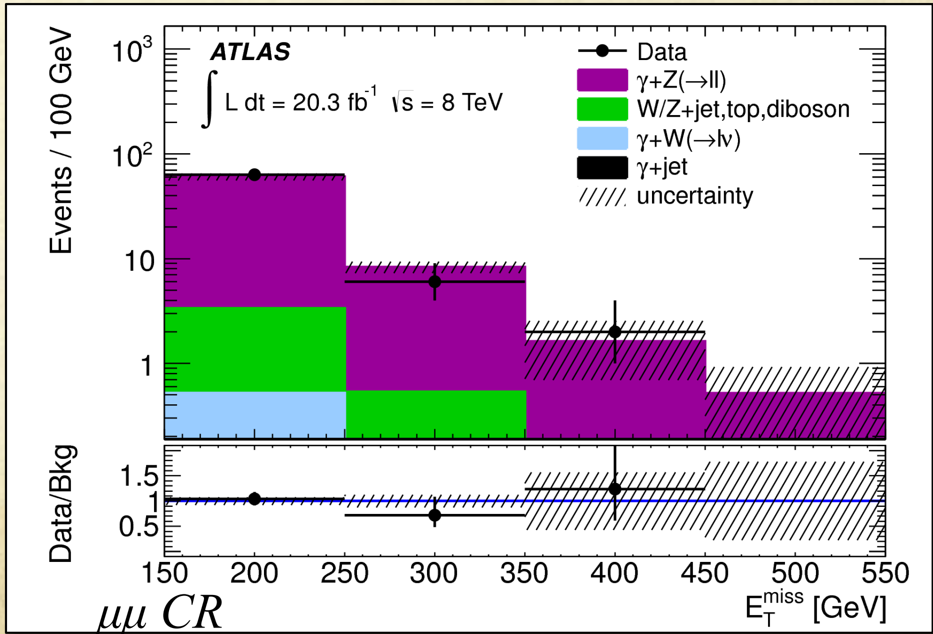
$W\gamma,\ Z\gamma$ unidentified leptons

Additional smaller backgrounds
Top, diboson, γ+jet, multijet.



Shape of E_T(miss) in $Z\gamma, W\gamma$ from simulation,
Normalisation from fit in control regions.

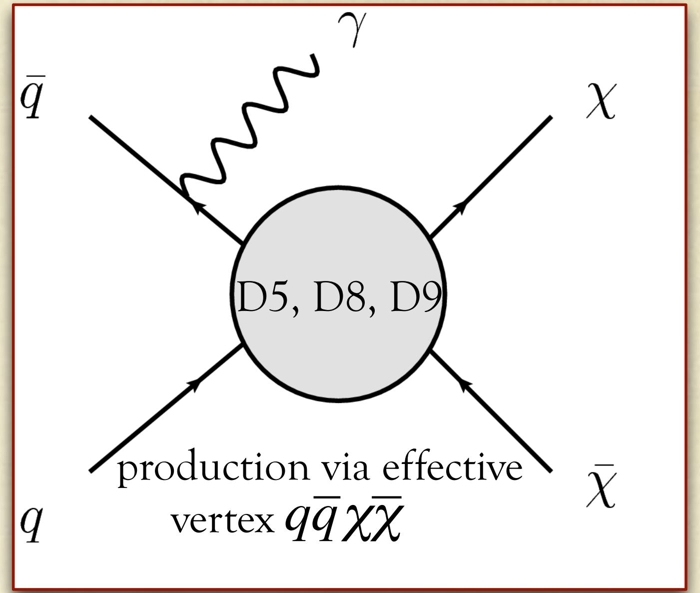




Mono-Photon Interpretation in Effective Field Theory

EFT Operators
D5 (vector interaction)
D8 (axial-vector)
D9 (tensor)

Interaction described by parameters
m_χ and suppression scale $M^* = (m_V/\sqrt{g_f g_\chi})$



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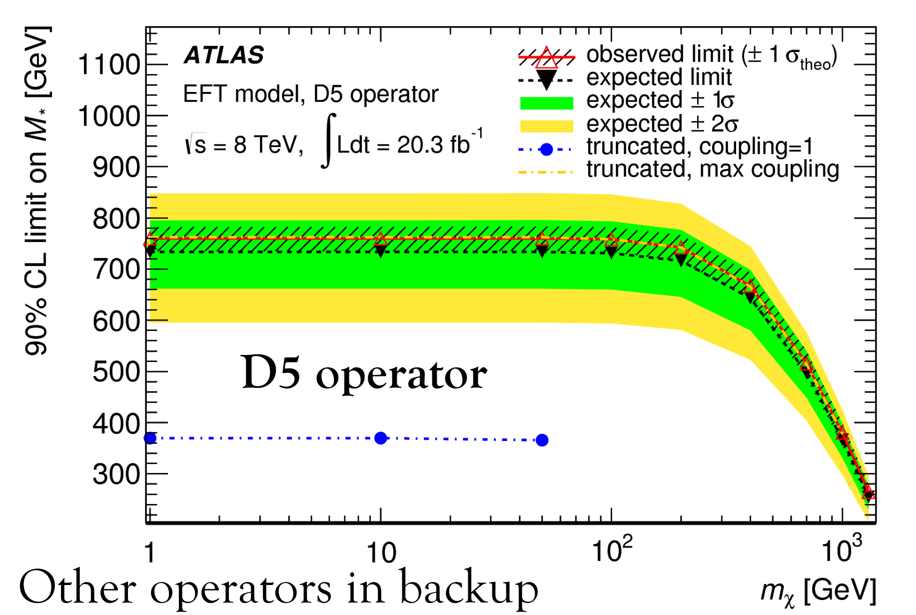
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2014-06/

Mono-Photon – Results – Effective Theory



Other operators in backup

Limits on M* up to 760 GeV(D5, D8) and 1010 GeV for D9.

Validity of EFT

Q_{tr} (momentum transfer) < m_V = M* $\sqrt{g_f g_\chi}$

Truncation

Reestimated the limits using only simulated signal events for which $Q_{tr} < m_V$ under two assumptions for the coupling:

i) Coupling $\sqrt{g_f g_\chi}=1$

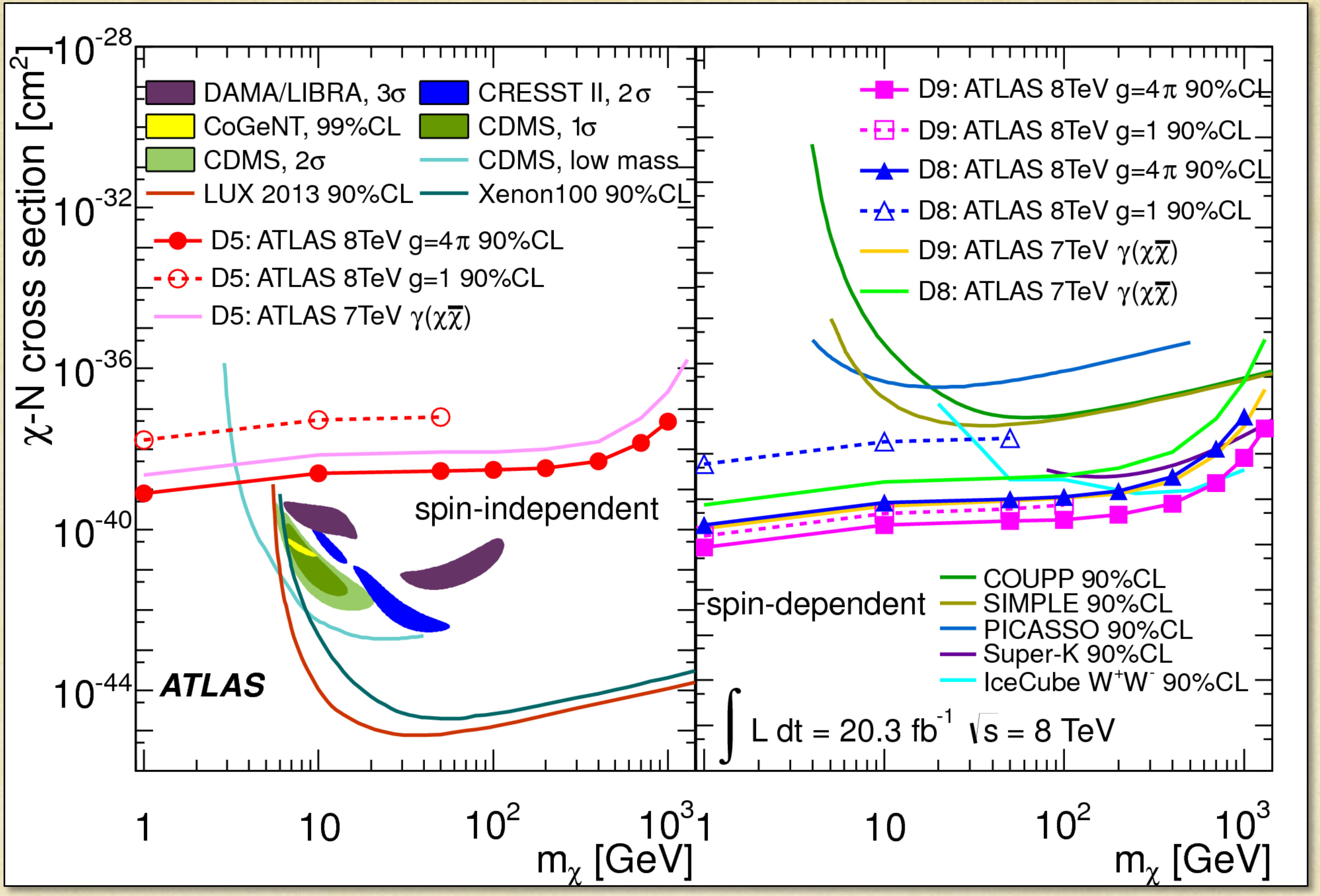
ii) Maximum coupling $\sqrt{g_f g_\chi}= 4\pi$

Effect of truncation is small for max coupling

But strong on for D5 and D8 and $\sqrt{g_f g_\chi}=1$ (still small for D9).

Effect of truncation strongly dependent on operator considered and signal region.

Effect nucleon-dark matter cross section studied



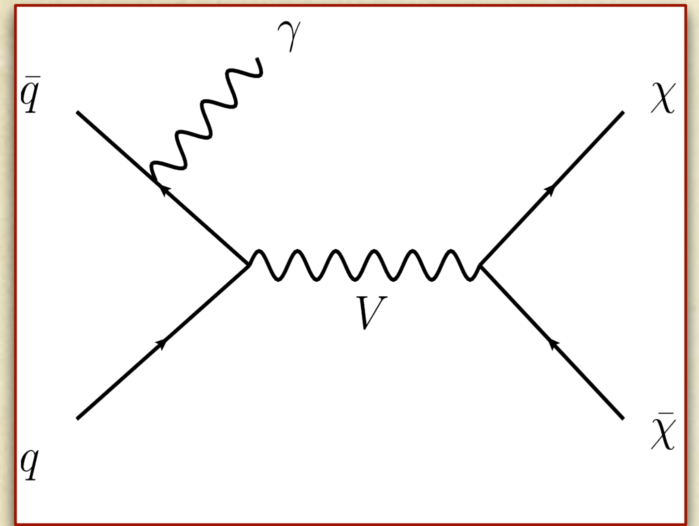
10^{-38} to 10^{-39} cm^2

10^{-39} to $10^{-40.5}$ cm^2

ATLAS mono-photon

Effect of truncation on the limits is shown.

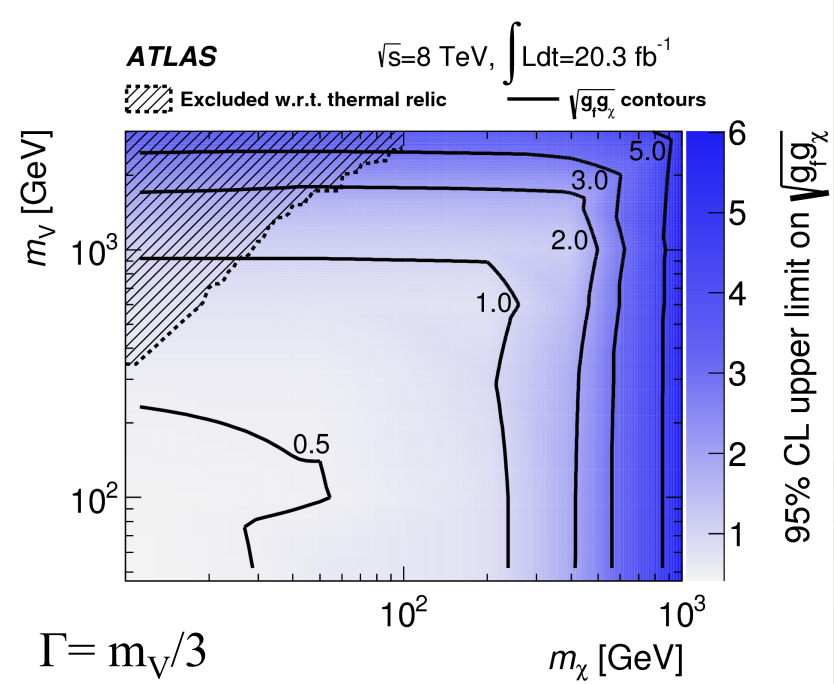
Mono-Photon Limits on Simplified Model : Z'-like mediator



Model parameters m_χ , m_V , Γ, and $\sqrt{g_f g_\chi}$

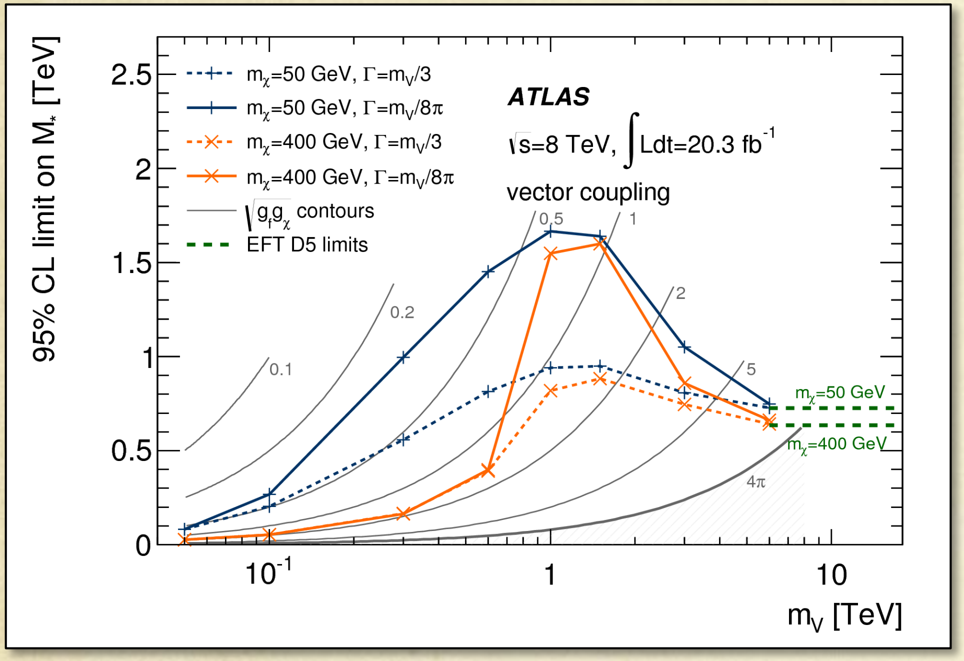
Investigated $\Gamma = m_V/3$, $m_V/8\pi$.

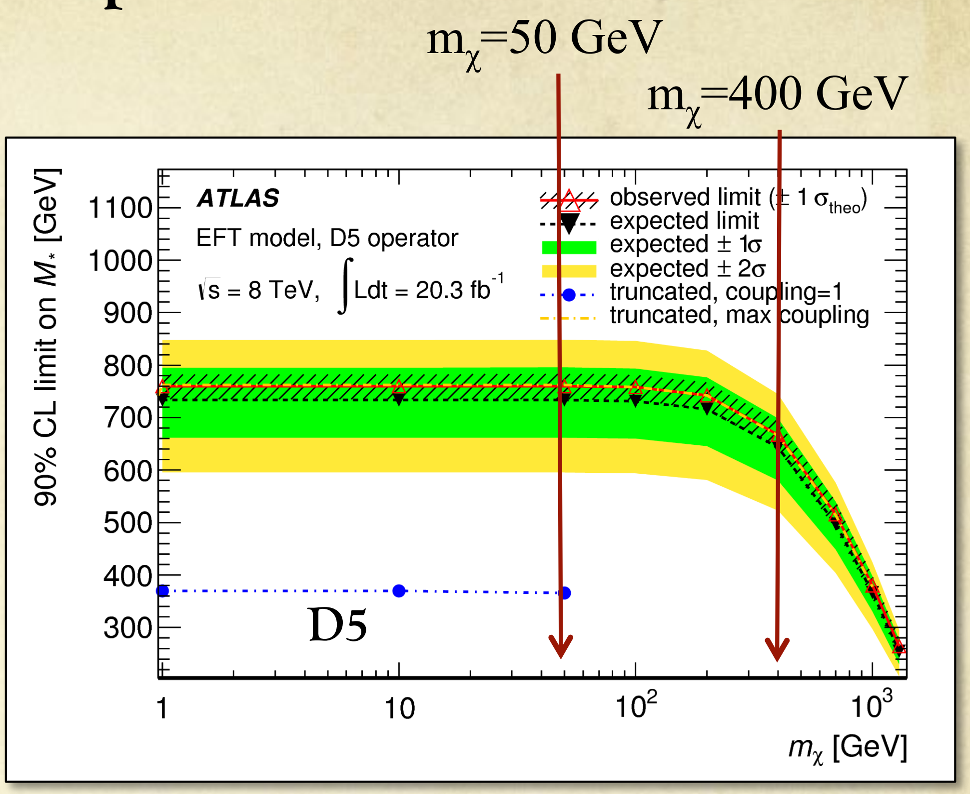
Upper limits on the coupling strength in the plane m_χ , m_V .



$\Gamma = m_V/3$

Simplified models and EFT compared



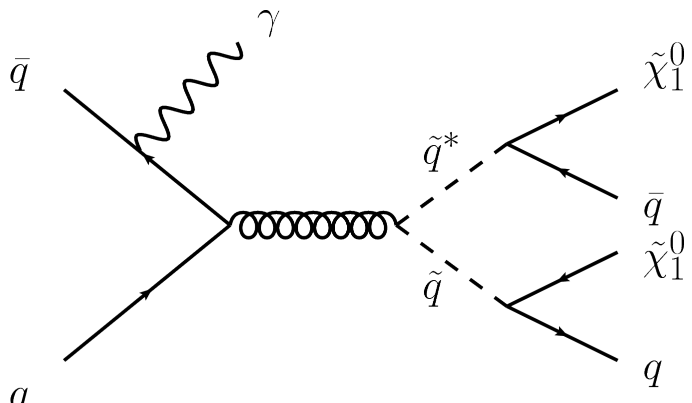


Limits on M* derived from simplified models and EFT limits on M* , $m_V = M^* \sqrt{g_f g_\chi}$

i) At high values of m_V EFT becomes valid, agreement b/w the two approaches

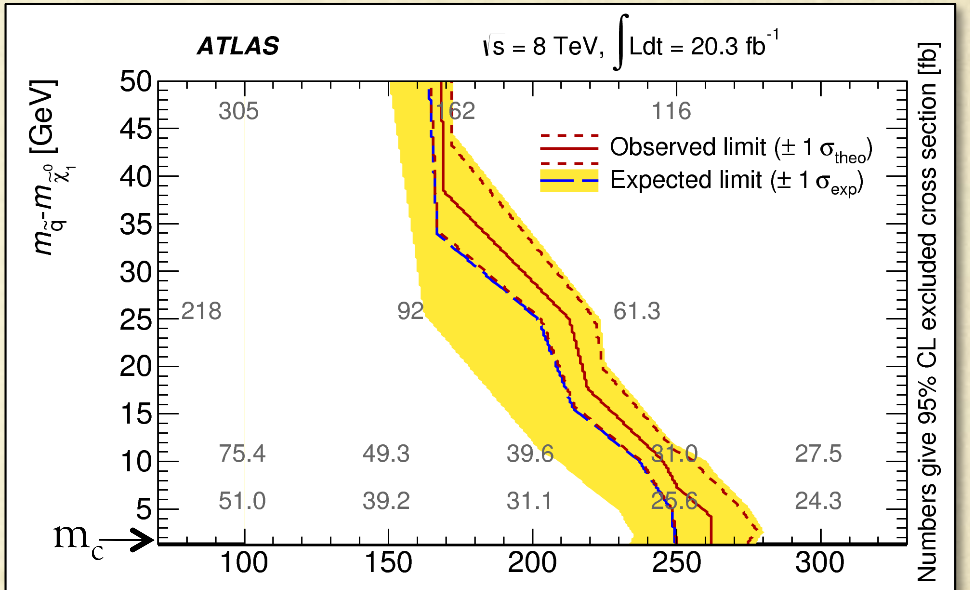
ii) EFT limits are conservative quite a bit lower than the production limit

Mono-Photon and SUSY compressed spectra



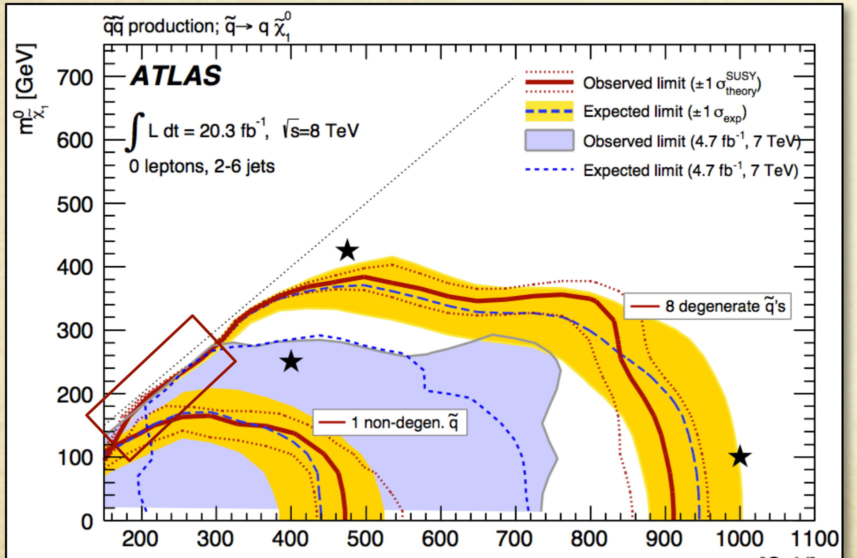
Compressed squark-neutralino1

Upper limit on $\sigma(pp \to \tilde{q}\tilde{q}^*\gamma + X)$



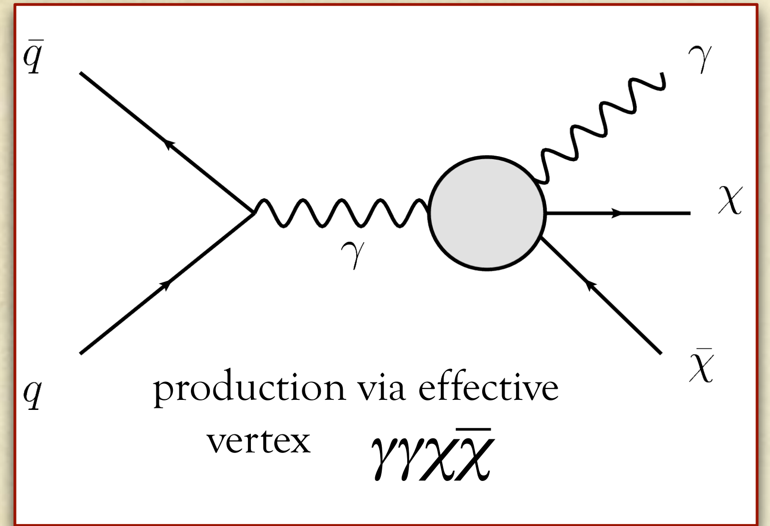
8 degenerate $\tilde{q}$'s

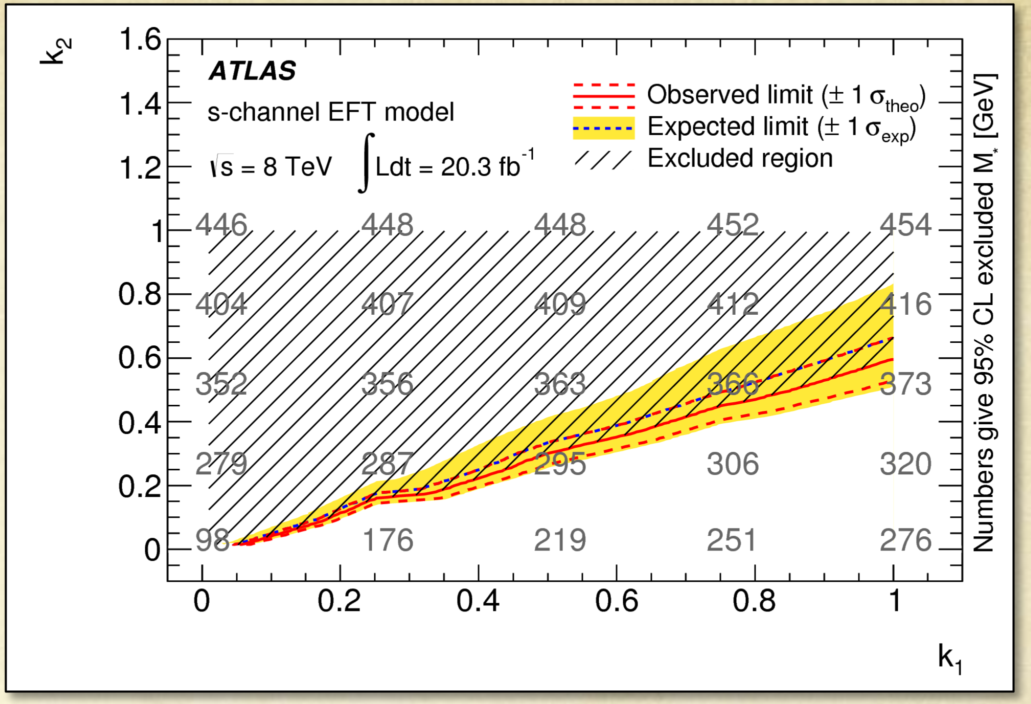
Exclude compressed models up to m_{squark}=250 GeV



"Standard SUSY search" 2-6 jets + E_T(miss)
JHEP09(2014)176

$\gamma\gamma\chi\bar{\chi}$ Interpretation





k_1 and k_2 control strength of the couplings to the U(1) and SU(2)

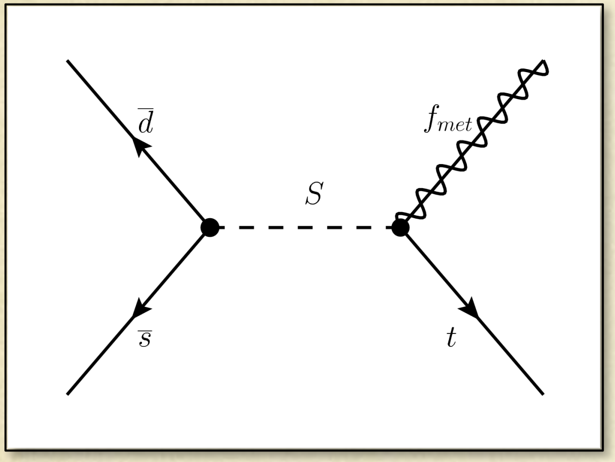
Alternative DM model hypothesizes interactions between the WIMPs and SM gauge bosons.
A. Nelson et al., Phys. Rev. D 89, 056011 (2014)

Model can be used to describe the peak observed in the Fermi- LAT data (C. Weniger, JCAP 1208, 007 (2012)),

- Lower limits on M* from ATLAS data

- Excluded region based on M* values needed to explain the Fermi-LAT line.

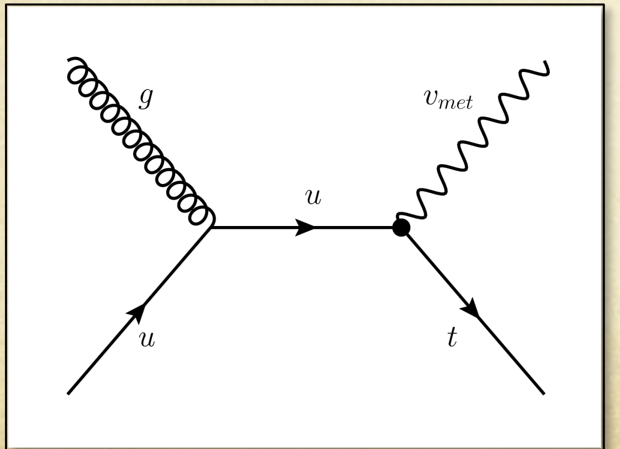
Single-Top + Missing Energy – Mono-Top

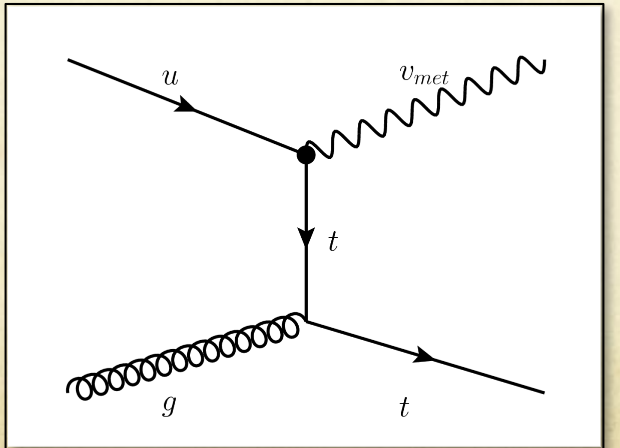


Simplified models

Charged (+2/3), coloured scalar resonance S decay into top + spin-1/2 colour singlet fermion f_{met} (encountered in SU5, SUSY RPV and other models).

Non-resonant production of top + neutral, color singlet spin-1 boson v_{met} (encountered in SUSY RPC and other models)

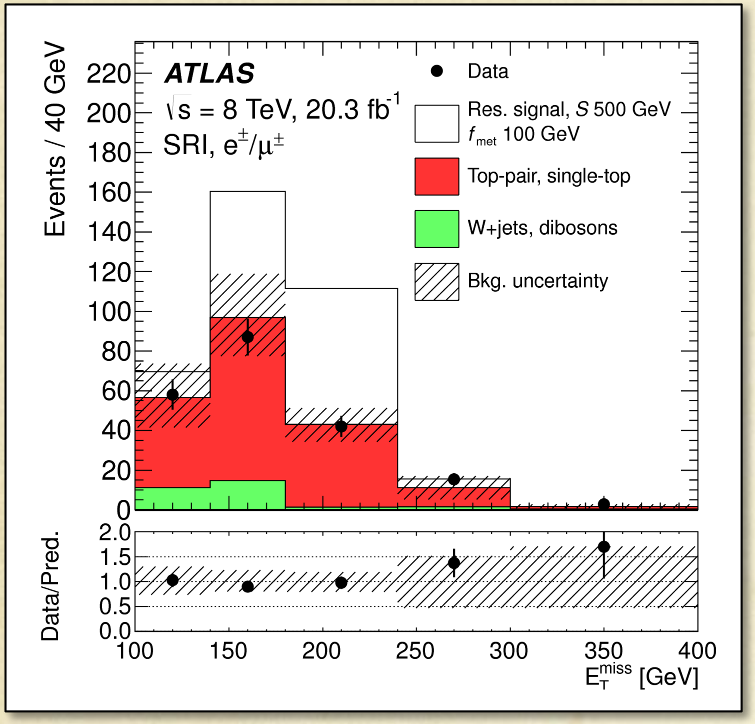


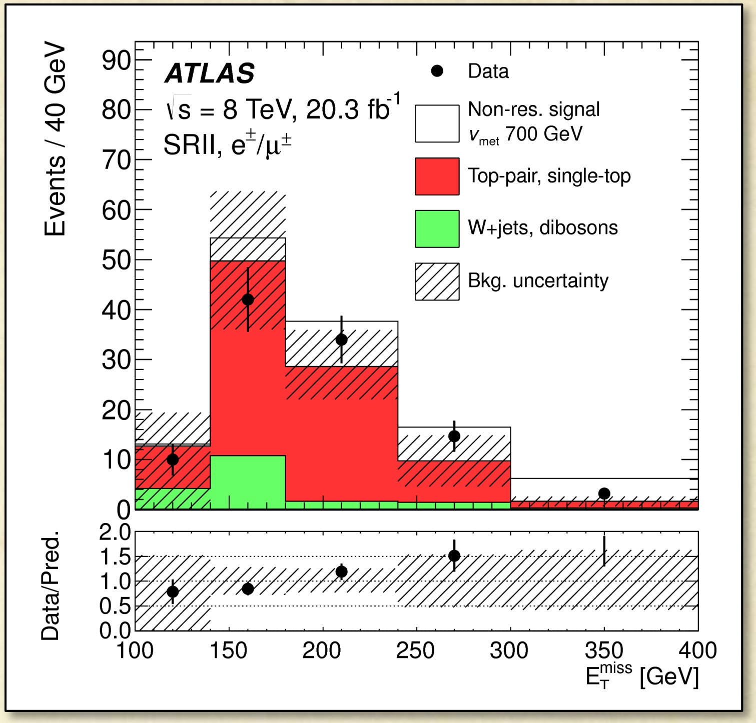


Submitted to EPJC
http://arxiv.org/abs/1410.5404

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2013-11/

Mono-Top Signal Region Results





Signal region definition

One isolated lepton e/μ with p_T>30 GeV

Exactly one jet, b-tagged p_T>25 GeV

E_T(miss)>35 GeV

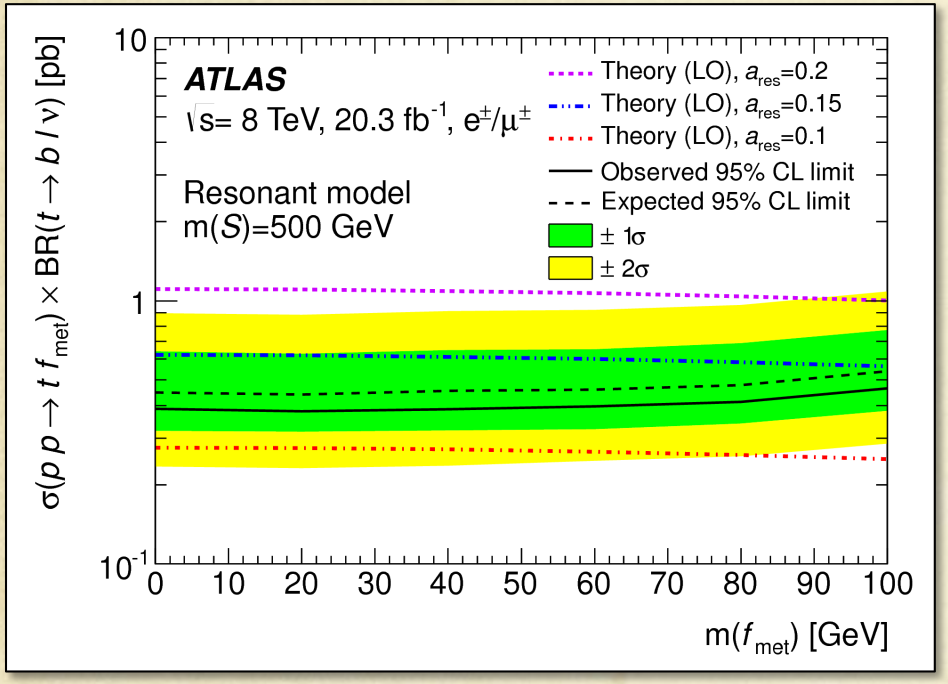
m_T + E_T(miss) > 60 GeV

SR-I Resonant model m_T>210 GeV & $|\Delta\varphi(l,b)|<1.2$

SR-II Non-Resonant model m_T>250 GeV & $|\Delta\varphi(l,b)|<1.4$

$$m_T = \sqrt{2 p_T E_T(miss)(1-\cos\varphi_{lv})}$$

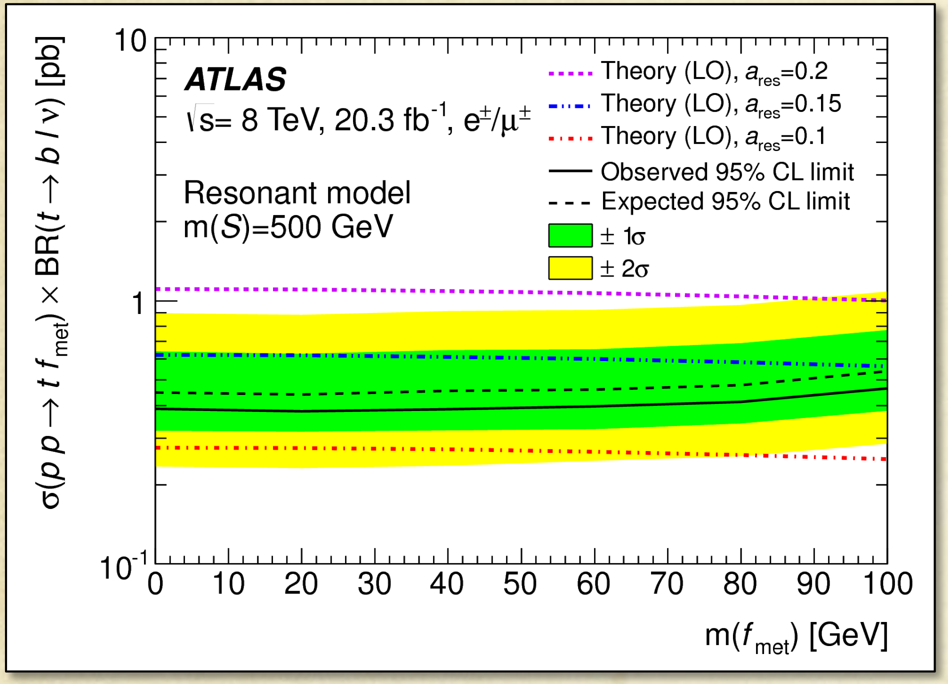
Results for Single-Top + E_T(miss)

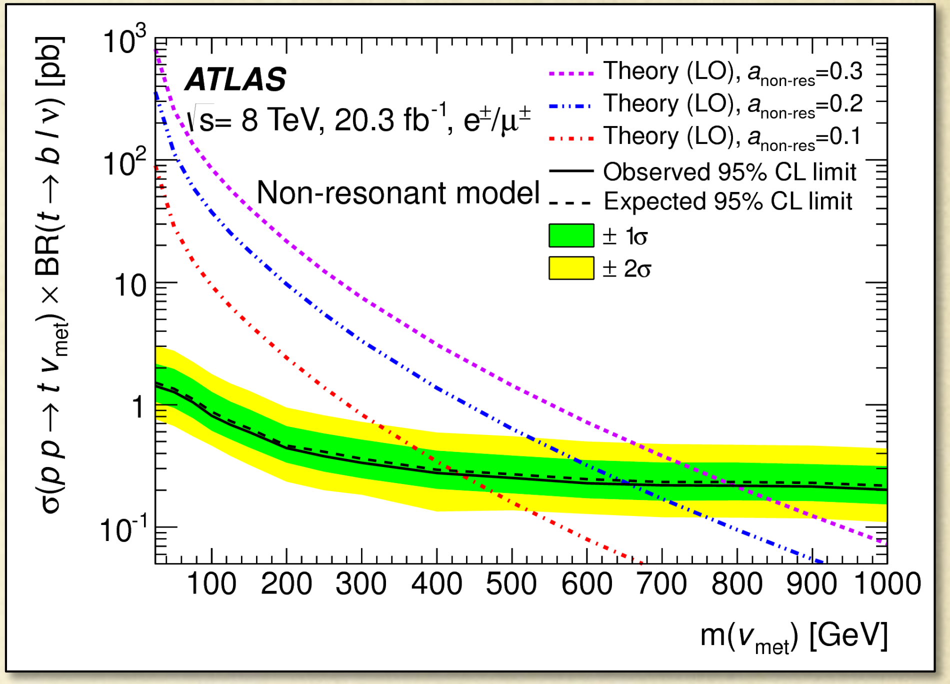


Upper limit on visible cross section for 500 GeV spin-0 resonance.

Effective coupling strengths > a_{res} = 0.15 are excluded for a mass of the invisible spin-1/2 state between 0 GeV and 100 GeV.

Results for Mono-Top + E_T(miss)





Upper limit on visible cross section for 500 GeV spin-0 resonance.

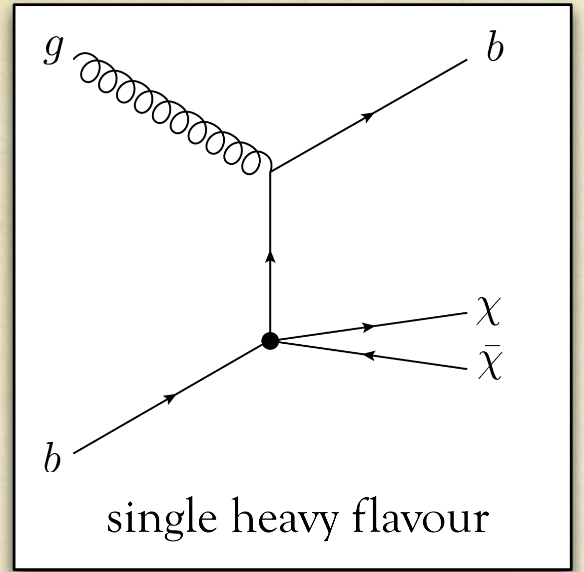
Effective coupling strengths > a_{res} = 0.15 are excluded for a mass of the invisible spin-1/2 state between 0 GeV and 100 GeV.

Upper limit on visible cross section for non-resonant production

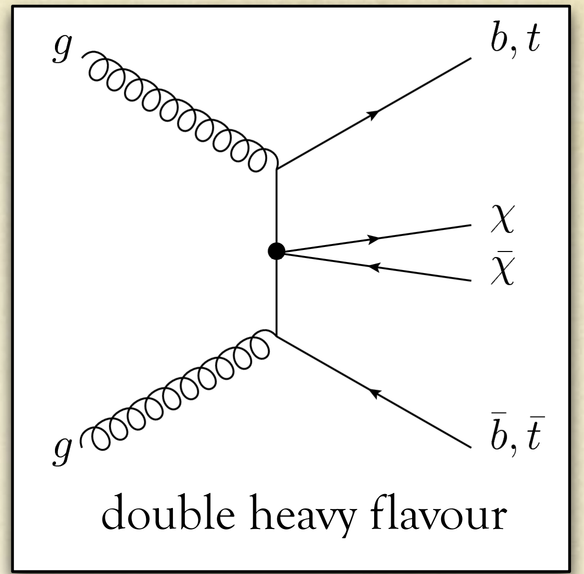
Effective coupling above $a_{non\text{-}res}$ = 0.1, 0.2, and 0.3 excluded for a mass of the spin-1 state up to 432 GeV, 657 GeV, and 796 GeV, respectively.

Heavy Flavour + Missing Energy Signatures

Effective Field Theory



single heavy flavour



double heavy flavour

Scalar interaction

$$\mathcal{O}_{\text{scalar}} = \sum_q \frac{m_q}{M_*^N} \bar{q} q \bar{\chi} \chi$$

N=3 for Dirac DM D1
N=2 for complex scalar C1
Also sensitive to tensor D9

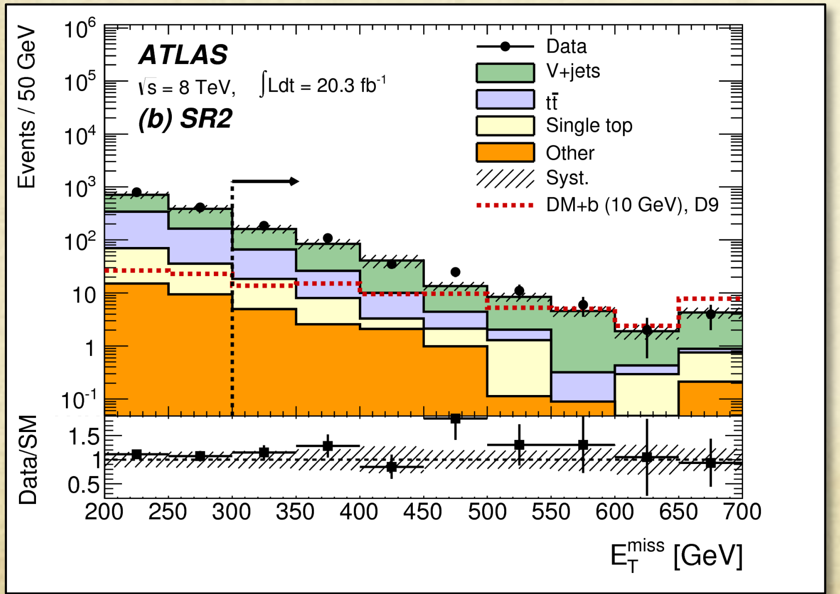
$$\mathcal{O}_{\text{tensor}} = \sum_q \frac{1}{M_*^2} \bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q$$

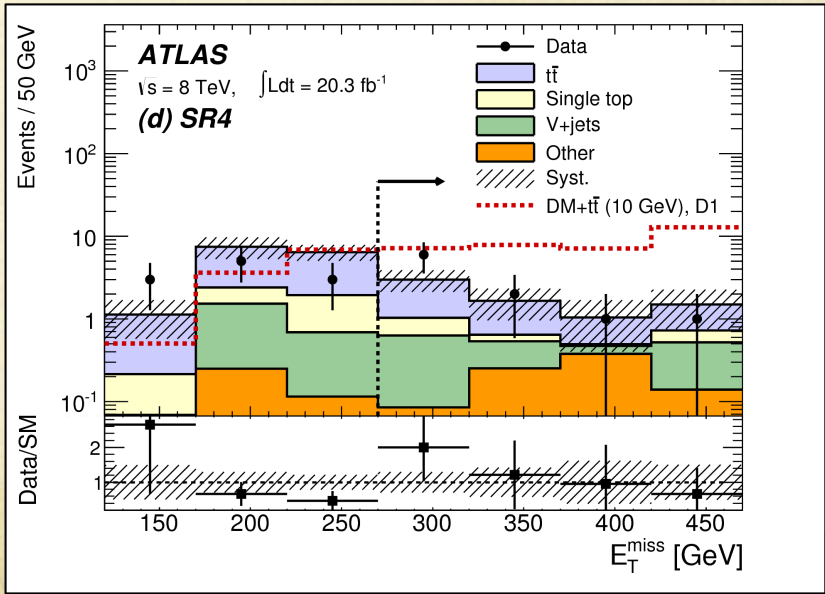
Models proposed in
T. Lin et al., Phys. Rev. D 88, 6,063510 (2013)

ATLAS paper submitted to EPJC arXiv:1410.4031
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2014-01/

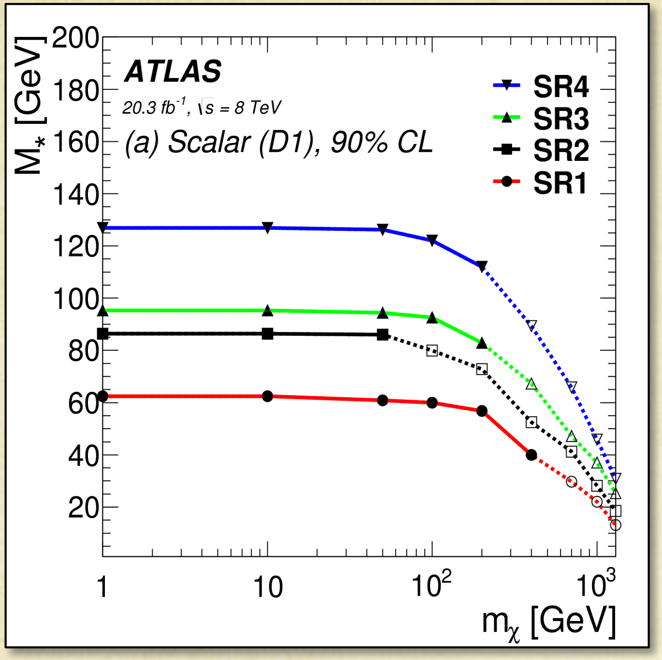
Four Signal regions

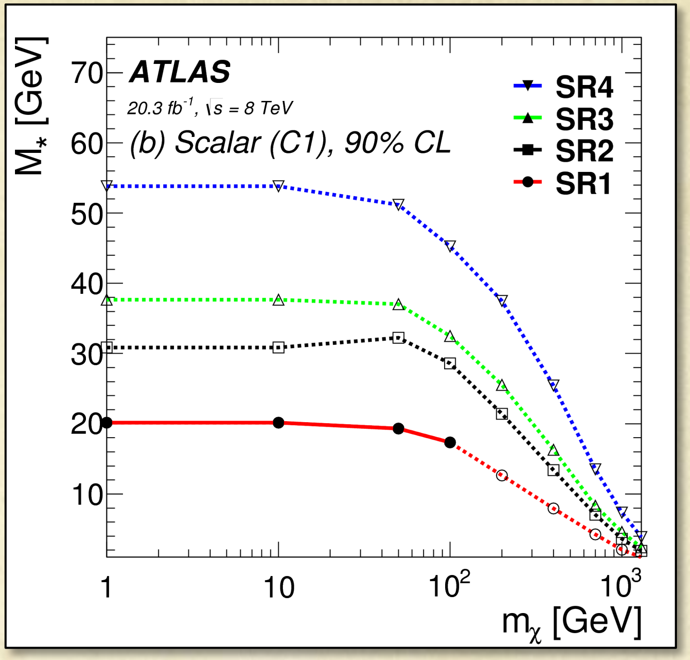
	SR1	SR2	SR3	SR4
	b-quarks		top-quarks	
	1-2 jets	3-4 jets	hadronic tops	one semileptonic top
E_T(miss)	300 GeV	300 GeV	200 GeV	270 GeV
Others	angles	angles	angles Razor	angles, one lepton, topness, am$_{T2}$, ET(miss) significance



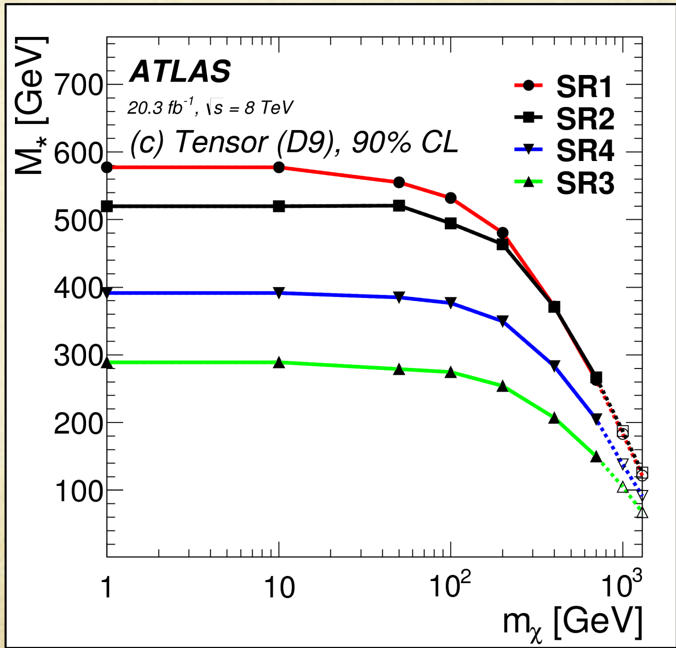


Lower limits on the suppression scale M*

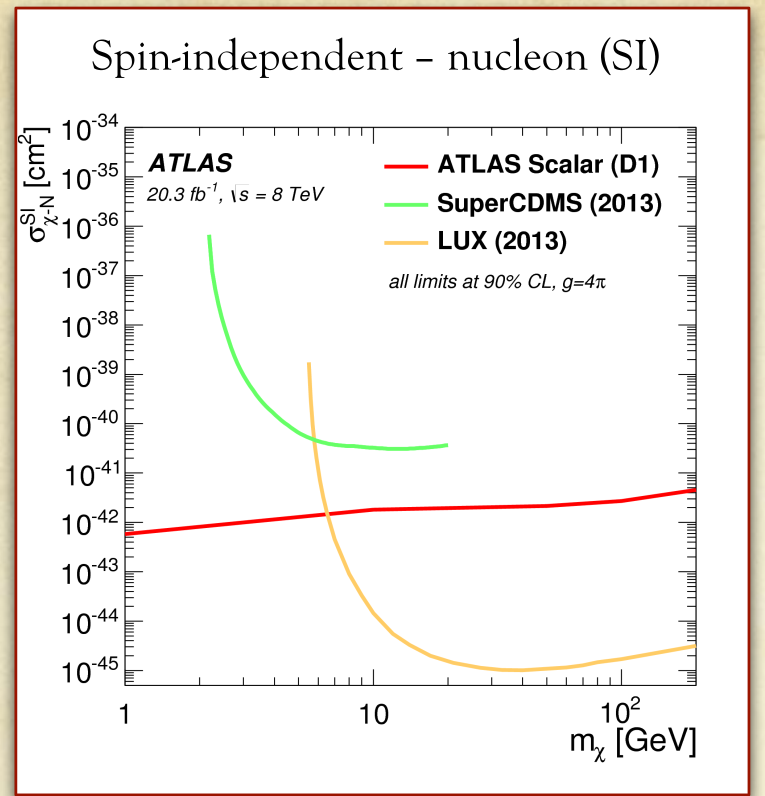


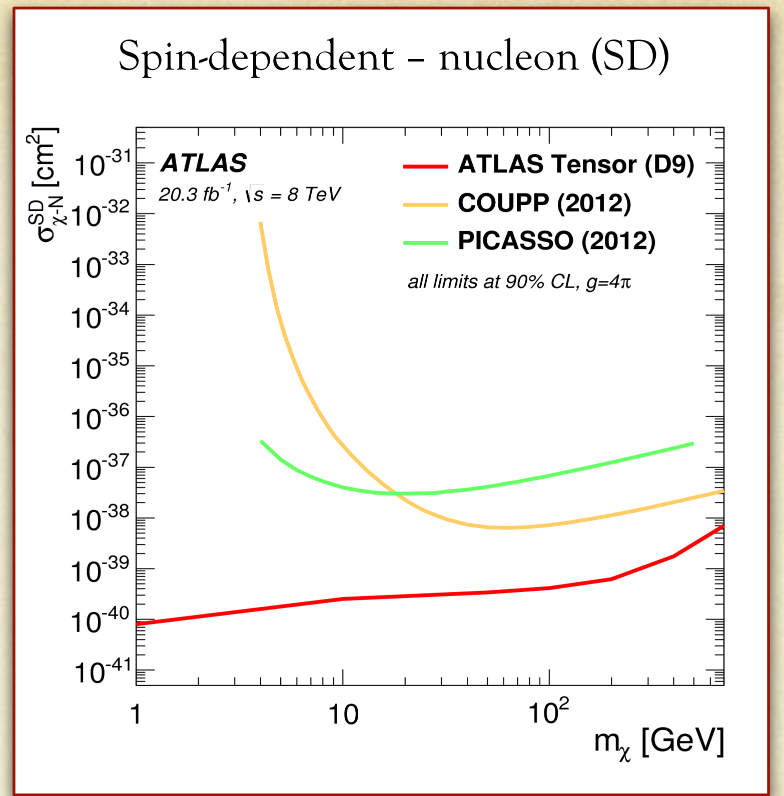


Best limits on the D1 and C1 operators from SR4, Best limit on D9 from SR1.



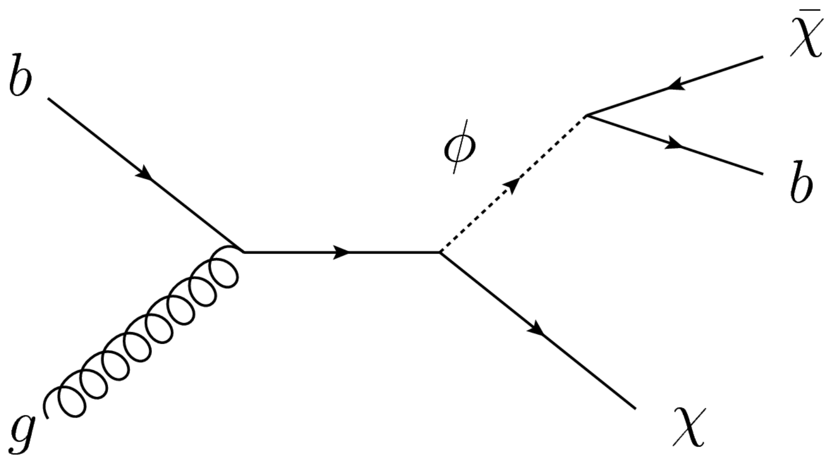
Truncated limits obtained by keeping only signal events where the EFT is valid, derived under the condition $Q_{tr}<m_V$ and for a maximum coupling of 4π.





- m_χ restricted to range with more than 90% of signal events fullfilling EFT validity condition.
- First ATLAS limits on the scalar operator C1

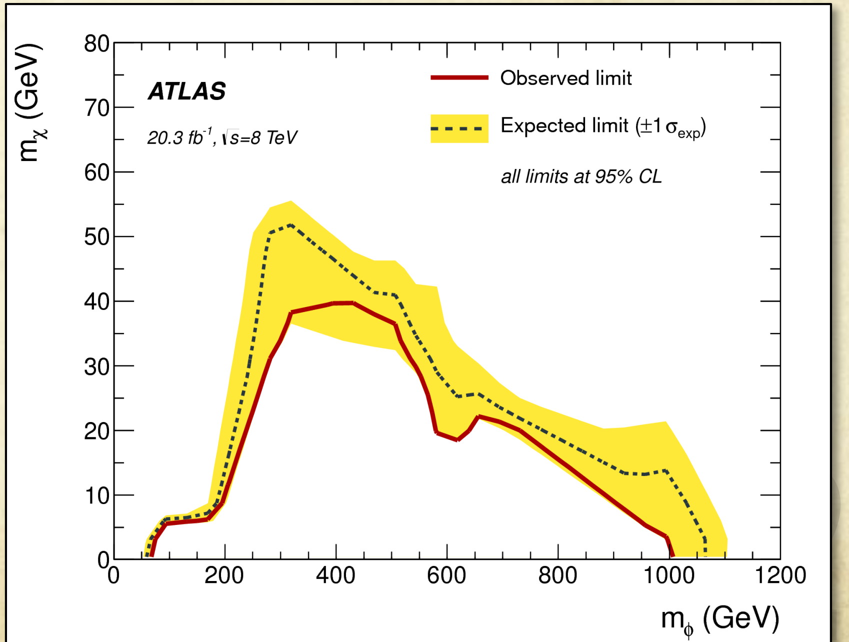
bottom-Flavoured Dark Matter **b-FDM**



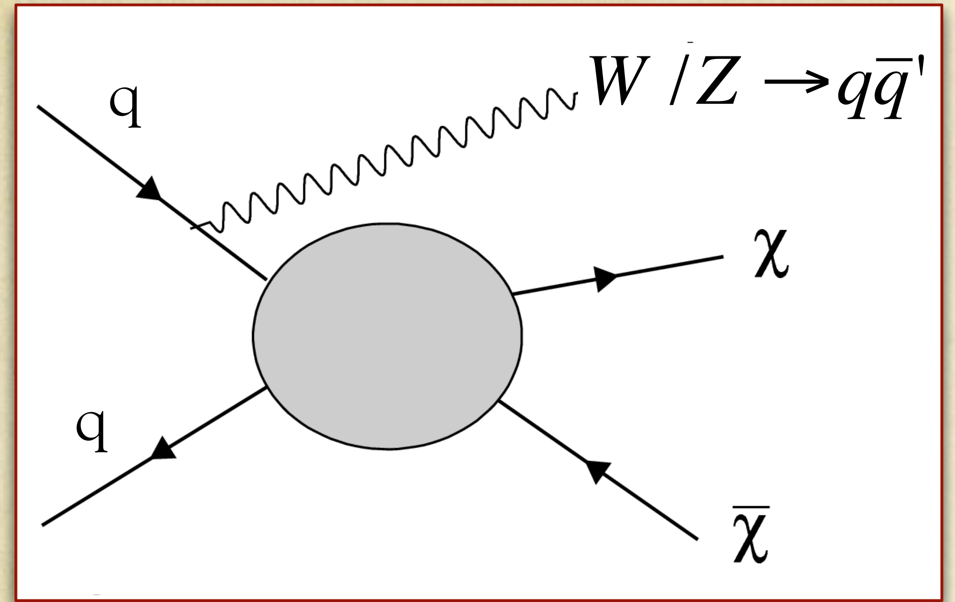
Model proposed to explain excess of γ-rays from the galactic centre, recently observed by Fermi satellite, and interpreted as a signal for DM annihilation.

Limits set in the parameter space of (m_{Φ},m_{χ}).

For m_{χ}=35 GeV as suggested for FERMI signal for galatic center, mediator mass between 300 and 500 GeV are excluded at 95% CL.



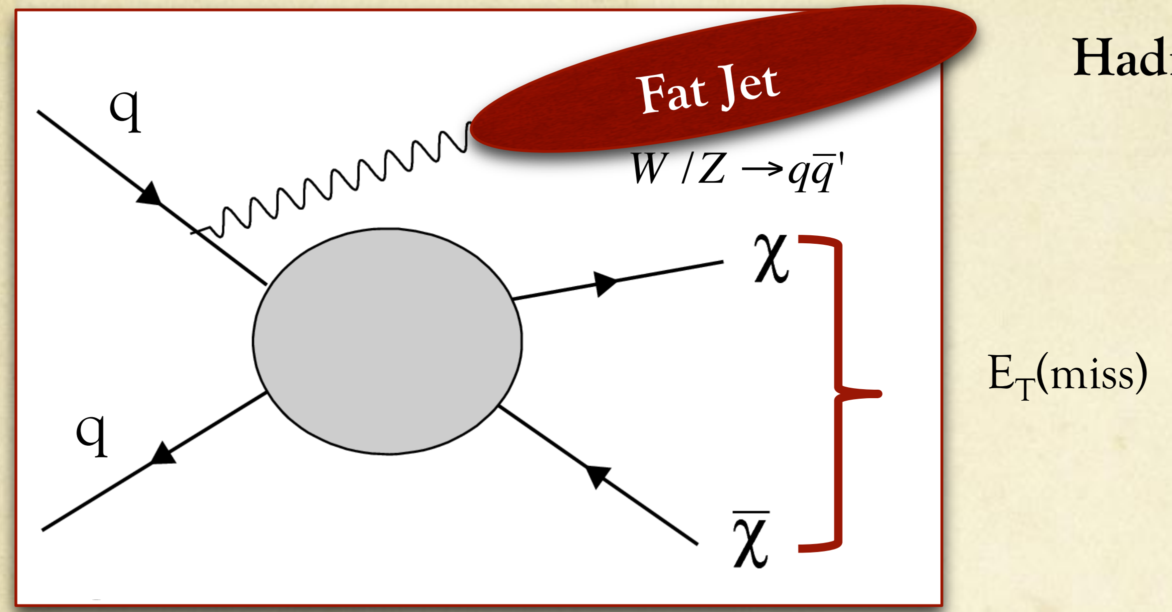
Mono-W/Z Searches – hadronic W/Z decay



Hadronic W/Z decay observed as massive jet.

Phys. Rev. Lett. 112, 041802 (2014)

Mono-W/Z Searches – hadronic W/Z decay



Hadronic W/Z decay observed as massive jet.

With W production, sensitive to the sign of **DM coupling** to the up- and down-quarks:

- Constructive interference if C(u)=-C(d)
- Destructive interference if C(u)=C(d)

=> Several order of magnitudes variation on the WIMP-nucleon cross section

Phys. Rev. Lett. 112, 041802 (2014)

Mono-W/Z →Hadrons – Selections & Backgrounds

"Fat Jet" capturing the hadronic W/Z decay

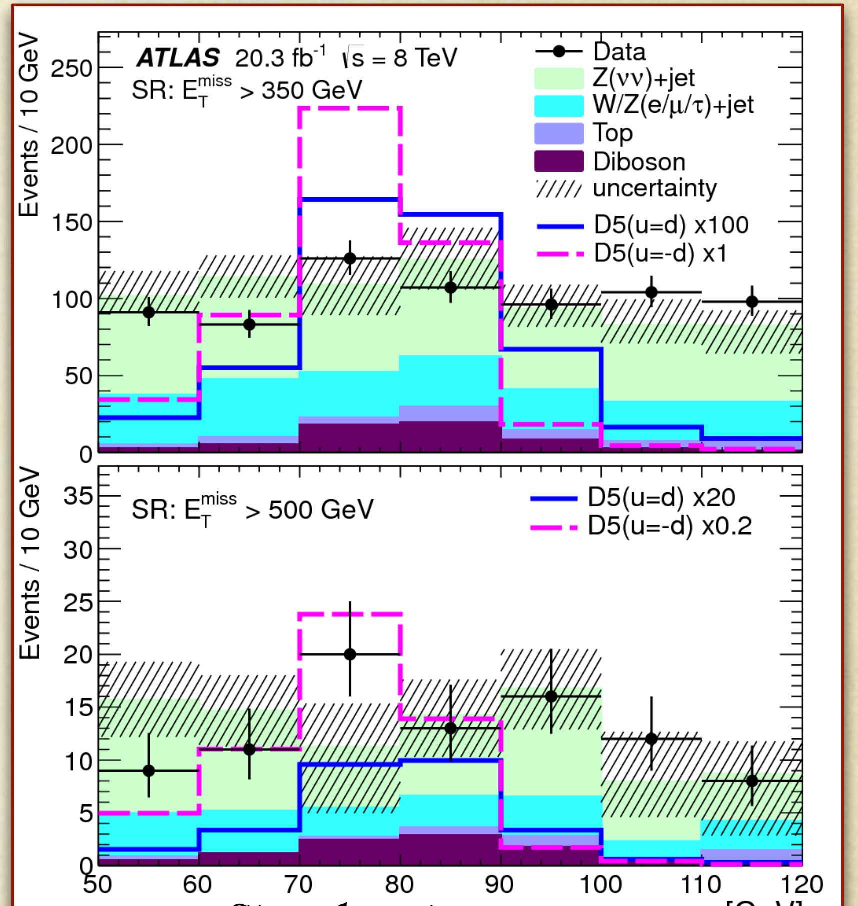
- large R=1.2 Cambridge-Aachen jet p_T>250GeV,
- $|\eta|$<1.2
- $\sqrt{y} = \min(p_{T1},p_{T2})\Delta R/m_{jet} > 0.4$
- $50 < m_{jet} < 120$ GeV

Veto

Leptons, photons, light jets

Signal Regions:

E_T(miss) > 350, 500 GeV



Signal regions

Main backgrounds, from data control regions

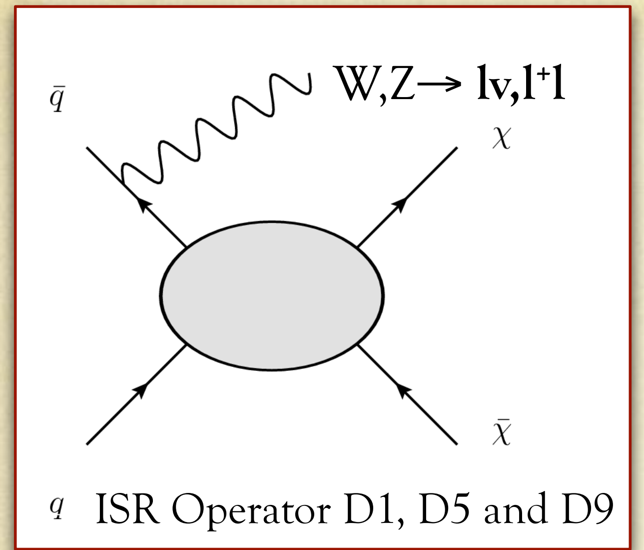
$(Z \rightarrow \bar{\nu}\nu) + jets$

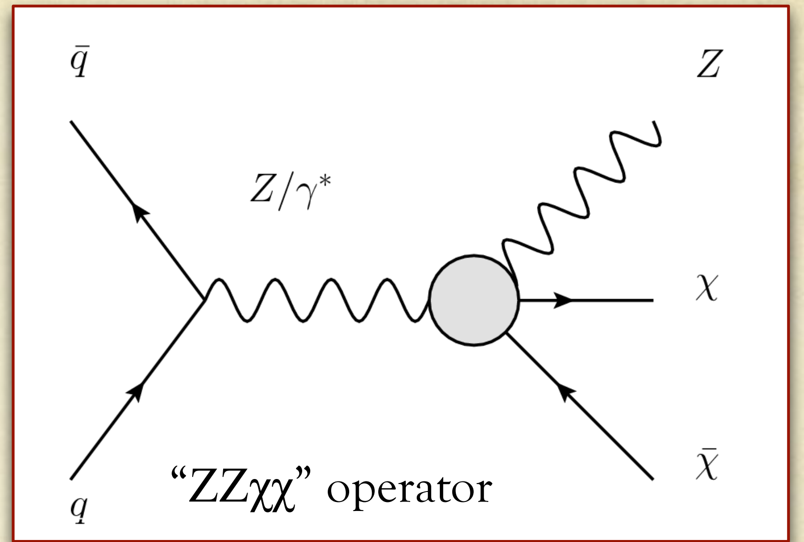
$W/Z + jets$ with misidentified lepton(s)

Secondary backgrounds

Top and diboson production from Monte Carlo simulation.

Mono-Z→ l^+l^- and Mono-W→ lν – Selections





Mono-Z Signal Region e^+e^-, $\mu^+\mu^-$

- p_T> 20 GeV, $m_{ll} \in$ [76, 106] GeV
- $|\eta_{ll}|$ <2.5

Back to back & balanced

- $\Delta\varphi(E_T(miss), p_T ll)$ >2.5
- $|p_T ll - E_T(miss)|/p_T ll < 0.5$
- E_T(miss)>150, 250, 350, 450 GeV

Mono-W Signal Region eν, μν

- e-channel p_T> 125 GeV
- μ-channel p_T> 45 GeV

Balanced

- e-channel E_T(miss)> 125 GeV
- μ-channel E_T(miss)> 45 GeV

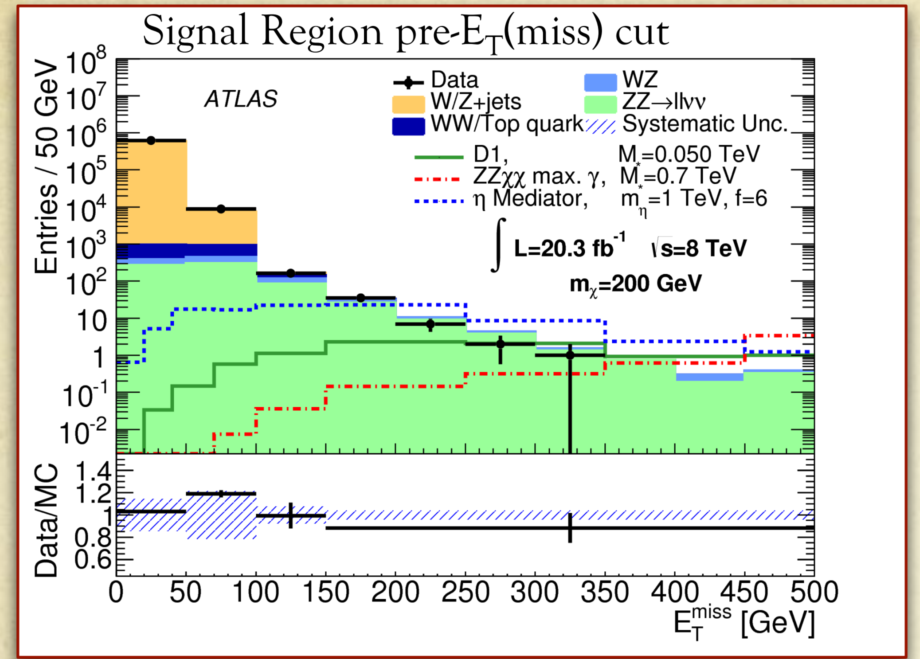
Final

$$m_T = \sqrt{2 p_T E_T(miss)(1-\cos\varphi_{lv})} > m_{T\,\min}$$

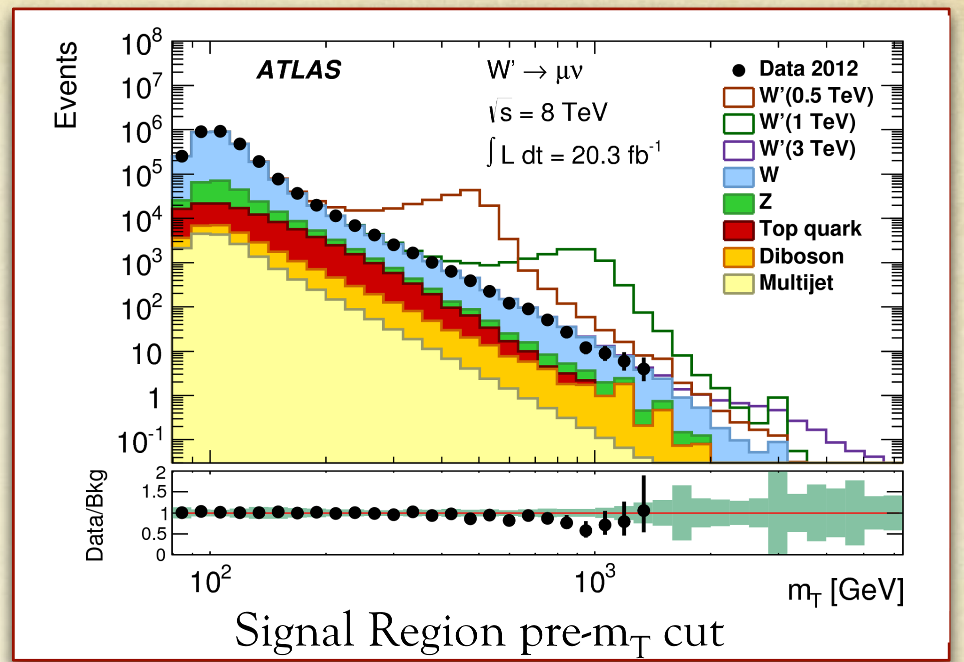
where the optimal value of $m_{T\min}$ is optimised for each model.

Mono-Z Phys. Rev. D 90, 012004 (2014)
Mono-W arXiv:1407.7494 [hep-ex] accepted by JHEP

Mono-Z→ l^+l



Mono-W→ lν



Signal Regions

E_T(miss)>150, 250, 350, 450 GeV

Irreducible backgrounds

$ZZ \rightarrow \ell^+\ell^-\bar{\nu}\nu$

$W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$

From MC with NLO generator

Reducible backgrounds

WW, top, Z→ττ from eμ data

Z+jets and W+jets from data CR.

Signal Regions

$m_T > m_{T\,\min} = 252$ GeV and higher bins

Main backgrounds

Tail of the m_T distribution in W+jets

Z+jets with one non-reconstructed lepton

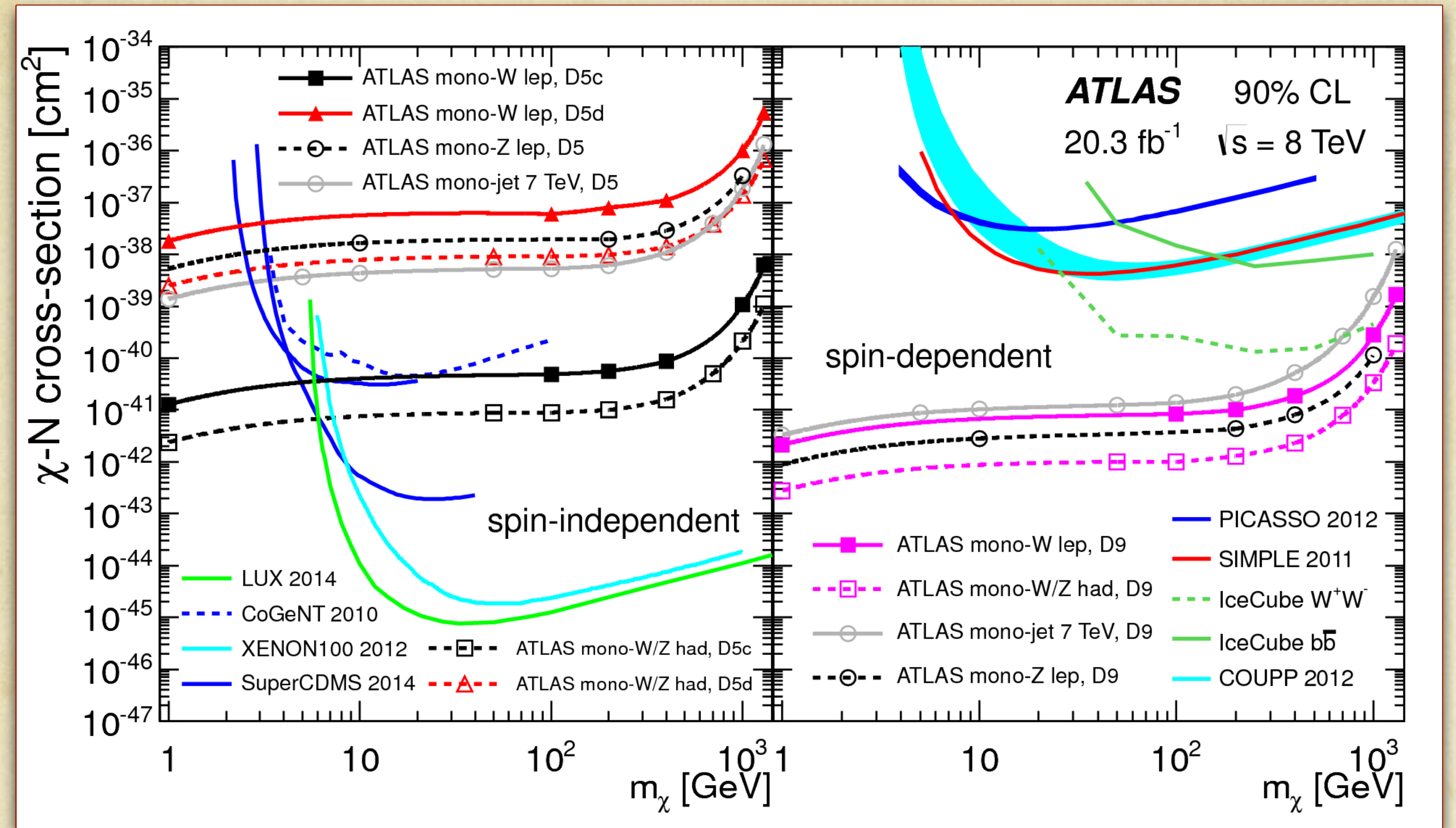
From NLO event generators+NNLO cross sections+higher order EW corrections

K-factors per mass bin.

Additional backgrounds

top, diboson <10 %, from simulation.

Dark Matter mono-X Summary



Sensitivity of the signal regions at low m_χ is independent on m_χ.

Powerful spin-dependent limits over entire mass range

Powerful spin-independent at low mass.

Mono-W/Z hadronic more performant that mono-Photon

Conclusions

New limits from ATLAS on Dark Matter production using multiple final states.

Particularly powerful in *spin-dependent case at all masses* and *low mass spin-independent*.

Same type of signals allows to probe so called-compressed spectra, demonstrated in the mono-photon analysis.

Limits set in context of Effective Field Theory (exhaustive set of operator available)

Some limits in the context of simplified models as well, but no global picture nor systematic approach yet.

Backup

Invisible Higgs

Monojet 10 fb^{-1}

Mono-Photon: Additional limit plots on Dark with EFT operators

Mono-Top: Limits on coupling strength

Mono Heavy flavour: Detailed signal region definition

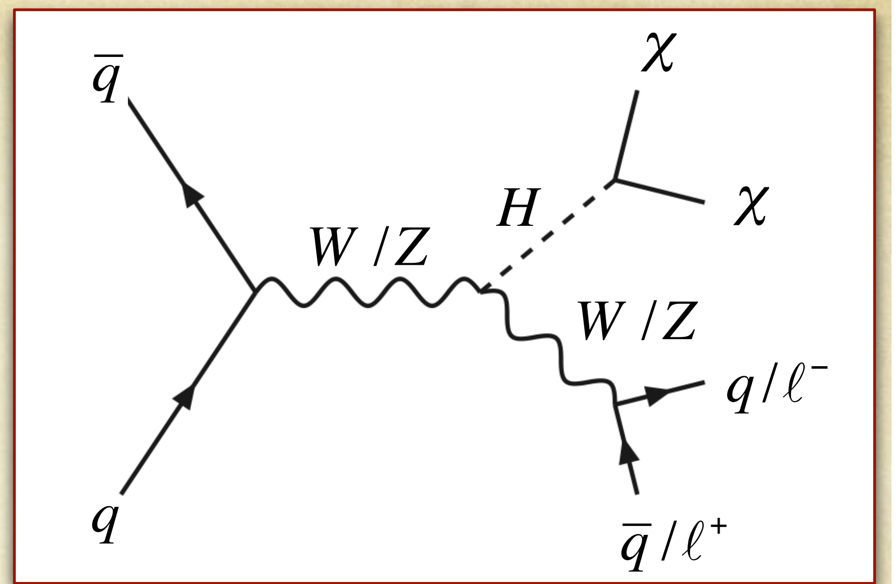
Mono Heavy flavour: Condition for

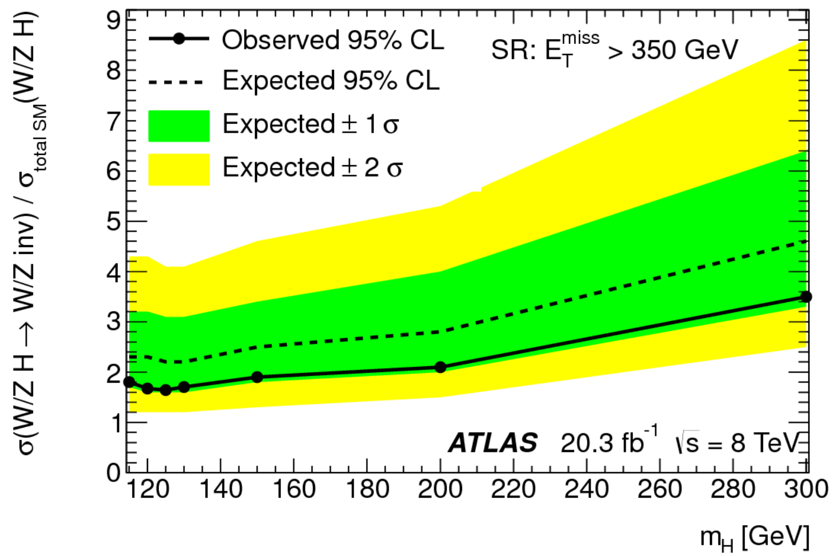
Invisible Higgs Search $H \rightarrow \chi\bar{\chi}$

DM particles search with $m_\chi < m_H/2$

1) Reinterpretation of mono-W/Z hadronic
Phys. Rev. Lett. 112, 041802 (2014)

2) Dedicated search with $Z \rightarrow \ell^+\ell^-$
Phys. Rev. Lett. 112, 201802 (2014)
Selections close but not identical to that of mono-Z with leptonic decay.

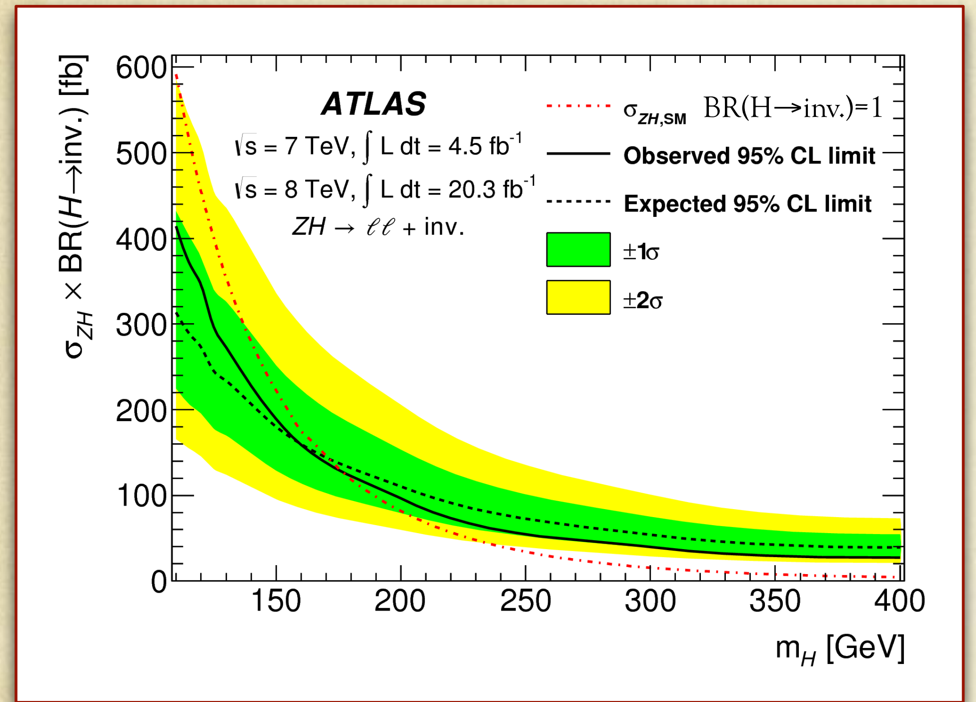


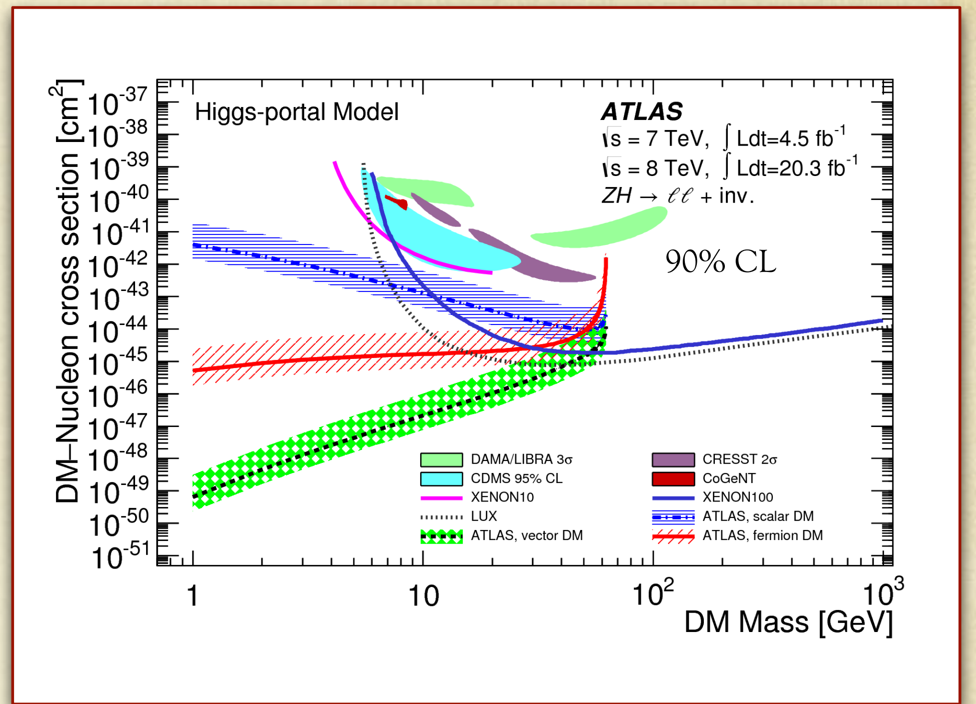


mono-W/Z hadronic reinterpretation

σ (W/Z+H →W/Z+inv.) / $\sigma_{W/Z+H}$ <1.6
for a Higgs mass of 125 GeV.

Invisible Higgs search $pp \rightarrow (Z \rightarrow \ell^+\ell^-)(H \rightarrow \chi\bar{\chi})$





95% CL upper limits on σ_{ZH} × BR(H →inv.) in the mass range 110<m_H< 400 GeV

Upper limit of BR(H→inv.)=0.75 at 95% CL (Expected limit of 0.62 at 95% CL)

Higgs-portal DM scenario
Higgs boson is mediator between DM and SM.

Upper limit on the DM–nucleon scattering cross section.

DM candidate=
Scalar, vector or a Majorana fermion.

Mono-Jet Based on L=10.5 fb^{-1}

One jet recoiling against missing energy

"Mono-jet"

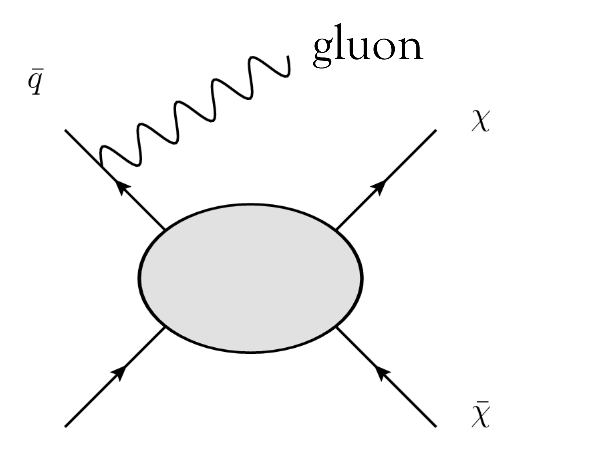
- Leading jet with $|\eta|<2.5$
- $\leq$ 2 jets with p_T>30 GeV and $|\eta|<4.5$
- Veto events with leptons

Back to back & balanced configuration

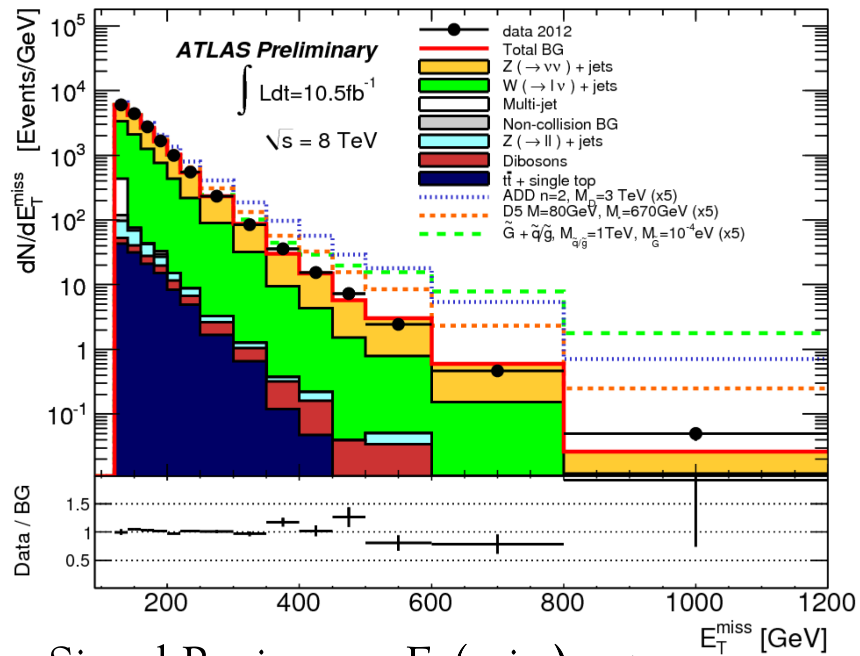
- $\Delta\phi$ (jet, E_T(miss)) > 0.5
- Same cut value on the jet p_T and E_T(miss)

Signal Regions

p_T(jet1), E_T(miss)> 120, 220, 350, 500 GeV



ISR Operator D1, D5 and D9



Signal Region pre-E_T(miss) cut

Leading backgrounds

$(Z \rightarrow \bar{\nu}\nu) + jets$

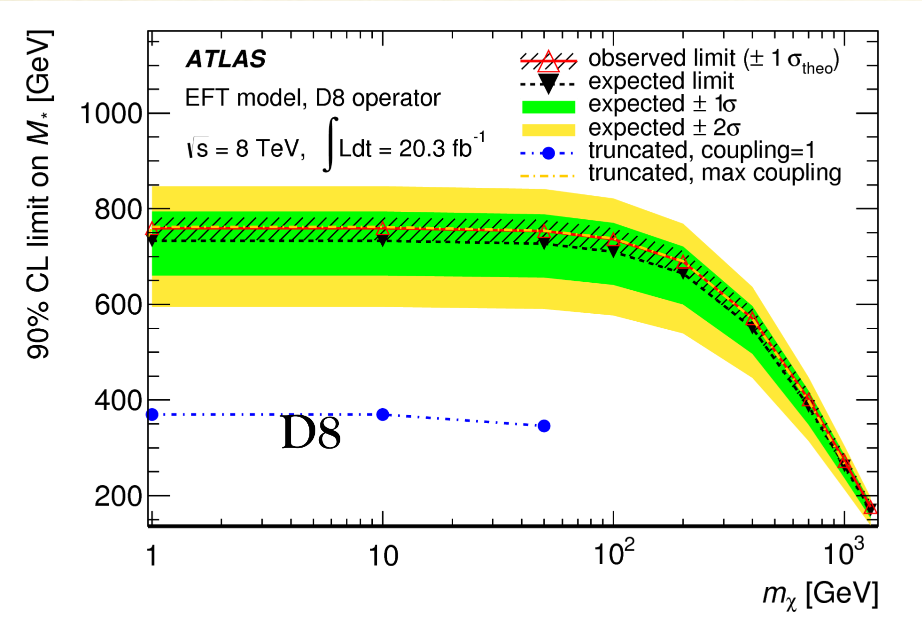
$W/Z + jets$

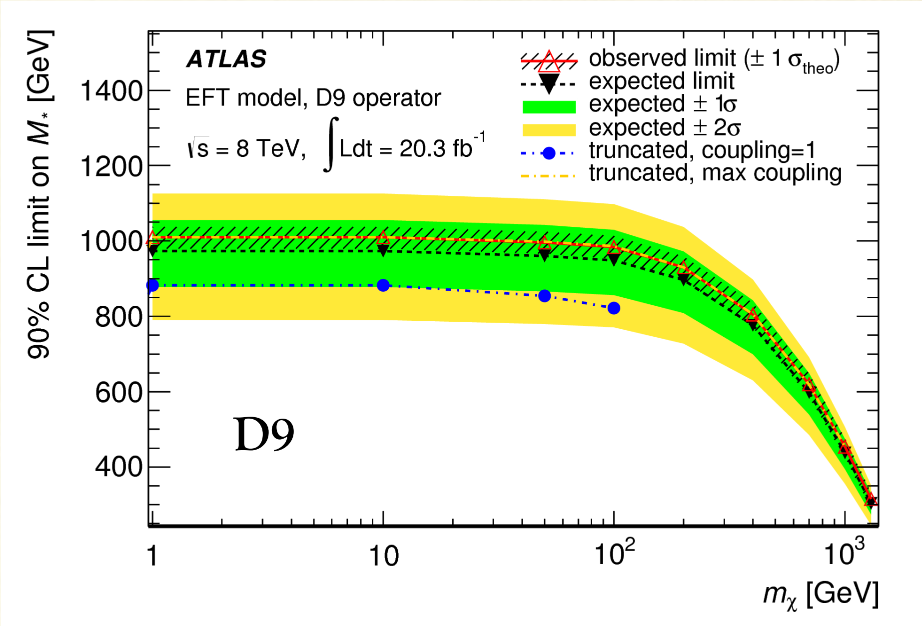
derived from a data W/Z control region with leptons

ATLAS CONF Note

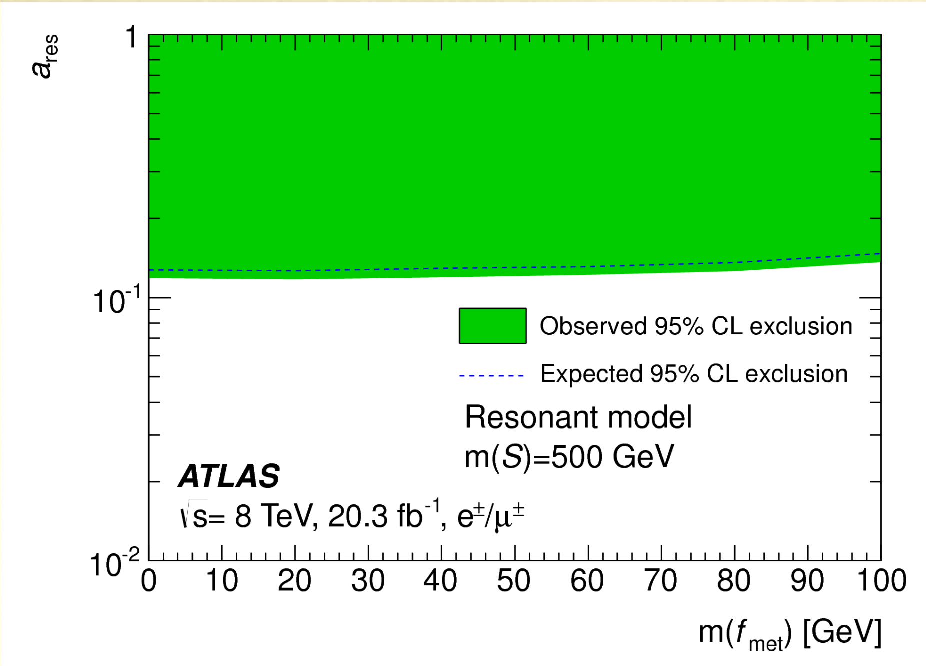
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-147/

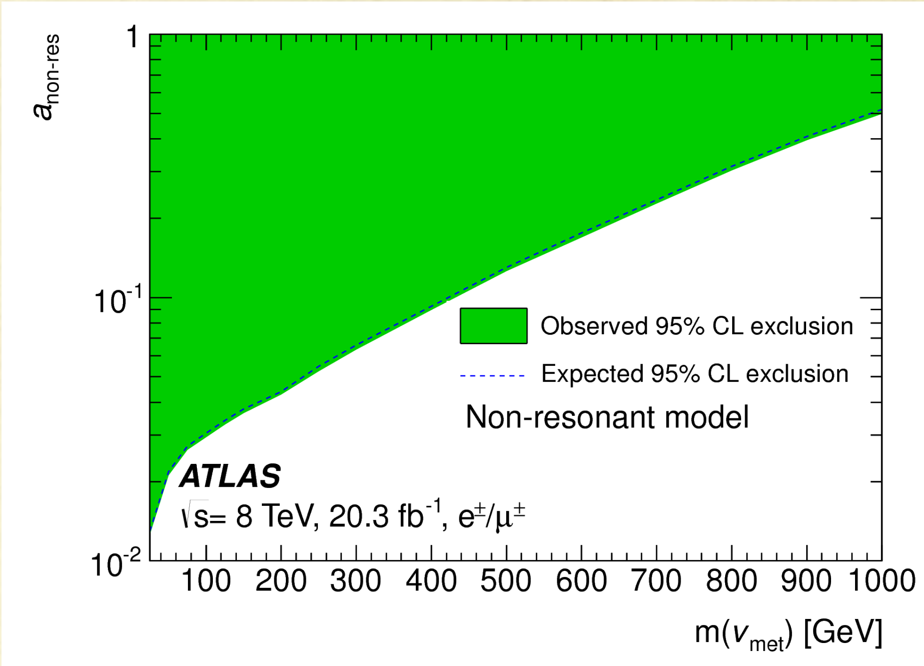
Extra plots on Dark Matter /mono-photon with EFT





Limits on Couplings for Single-Top + E_T(miss)





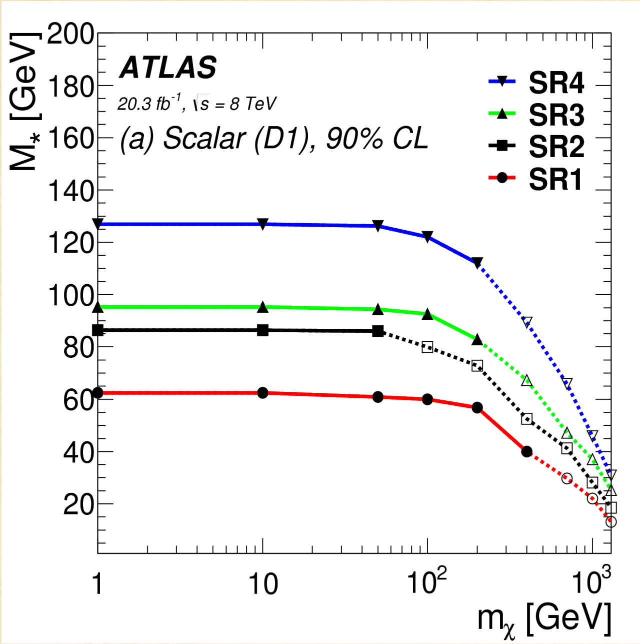
Heavy Flavour + Missing Energy Signatures

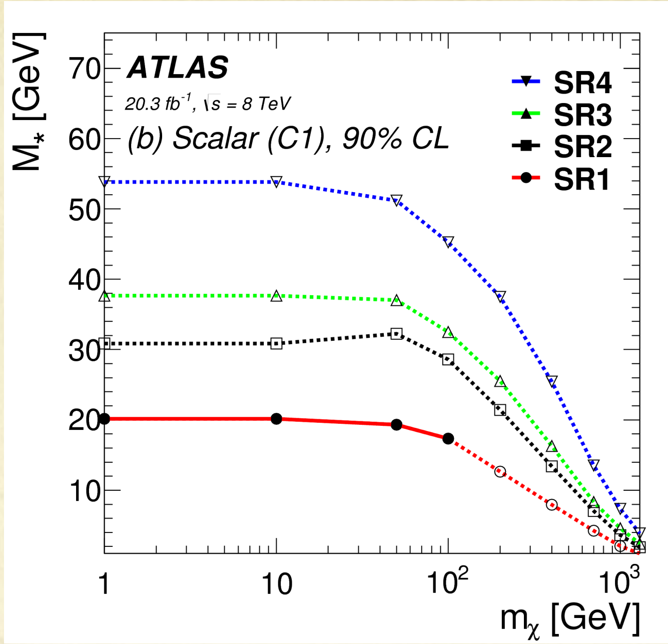
Detailed signal region definitions

	SR1	SR2	SR3	SR4
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}}$	5 jets || 4jets(1b)	$E_{\mathrm{T}}^{\mathrm{miss}}$ || 1 lepton (no τ)
Jet multiplicity n_j	1–2	3–4	≥5	≥4
b-jet multiplicity n_b	>0 (60% eff.)	>0 (60% eff.)	>1 (70% eff.)	>0 (70% eff.)
Lepton multiplicity n_ℓ	0	0	0	1 ℓ ($\ell = e, \mu$)
$E_{\mathrm{T}}^{\mathrm{miss}}$	>300 GeV	>300 GeV	>200 GeV	>270 GeV
Jet kinematics	$p_{\mathrm{T}}^{b_1} > 100$ GeV	$p_{\mathrm{T}}^{b_1} > 100$ GeV $p_{\mathrm{T}}^{j_2} > 100$ (60) GeV	$p_{\mathrm{T}}^{j} > 25$ GeV	$p_{\mathrm{T}}^{b_1} > 60$ GeV $p_{\mathrm{T}}^{1\text{-}4} = 80, 70, 50, 25$ GeV
Three-jet invariant mass				$m_{jjj} < 360$ GeV
$\Delta \ i\left(j_i, E_{\mathrm{T}}^{\mathrm{miss}}\right)$	$> 1.0,\ i = 1, 2$	$> 1.0,\ i = 1 - 4$	-	$> 0.6,\ i = 1, 2$
Angular selections	-	-	$\Delta \ i\left(b_1, E_{\mathrm{T}}^{\mathrm{miss}}\right) \geq 1.6$	$\Delta \ i\left(\ell, E_{\mathrm{T}}^{\mathrm{miss}}\right) > 0.6$ $\Delta R\left(\ell, j_1\right) < 2.75$ $\Delta R\left(\ell, b\right) < 3.0$
Event shape	-	-	Razor R >0.75	*topness* >2
am_{T2}	-	-	-	>190 GeV
$m_{\mathrm{T}}^{\ell + E_{\mathrm{T}}^{\mathrm{miss}}}$	-	-	-	>130 GeV
$E_{\mathrm{T}}^{\mathrm{miss}} / \sqrt{H_{\mathrm{T}}^{4j}}$	-	-	-	>9 $\sqrt{\mathrm{GeV}}$

SR4 taken from already existing signal region
in stop search "tNbC_mix "
ATLAS Collaboration (2014), arXiv:1407.0583 [hep-ex]

Conditions for Truncations Mono-Heavy flavour.





Conditions for truncations.

Qtr< M_{med}=M* $\sqrt{g_q g_\chi}$

Qtr< $4\pi(M^{3*}/mq)^{1/2}$ (D1)

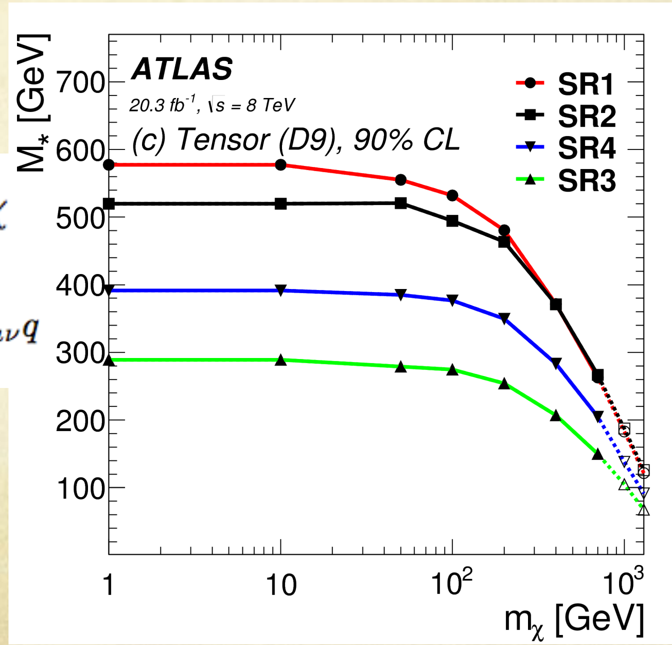
Qtr< $4\pi M^{2*}/mq$ (C1)

Qtr< $4\pi M^*$ (D9)

$$\mathcal{O}_{\rm scalar} = \sum_q \frac{m_q}{M_*^N}\bar{q}q\bar{\chi}\chi$$

$$\mathcal{O}_{\rm tensor} = \sum_q \frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$$

M_{med} = M* $\sqrt{g_f g_\chi}$



Effective operators

J. Goodman et al., Phys. Rev. D.82.116010
arXiv:1008.1783

Dirac fermions WIMPS

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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

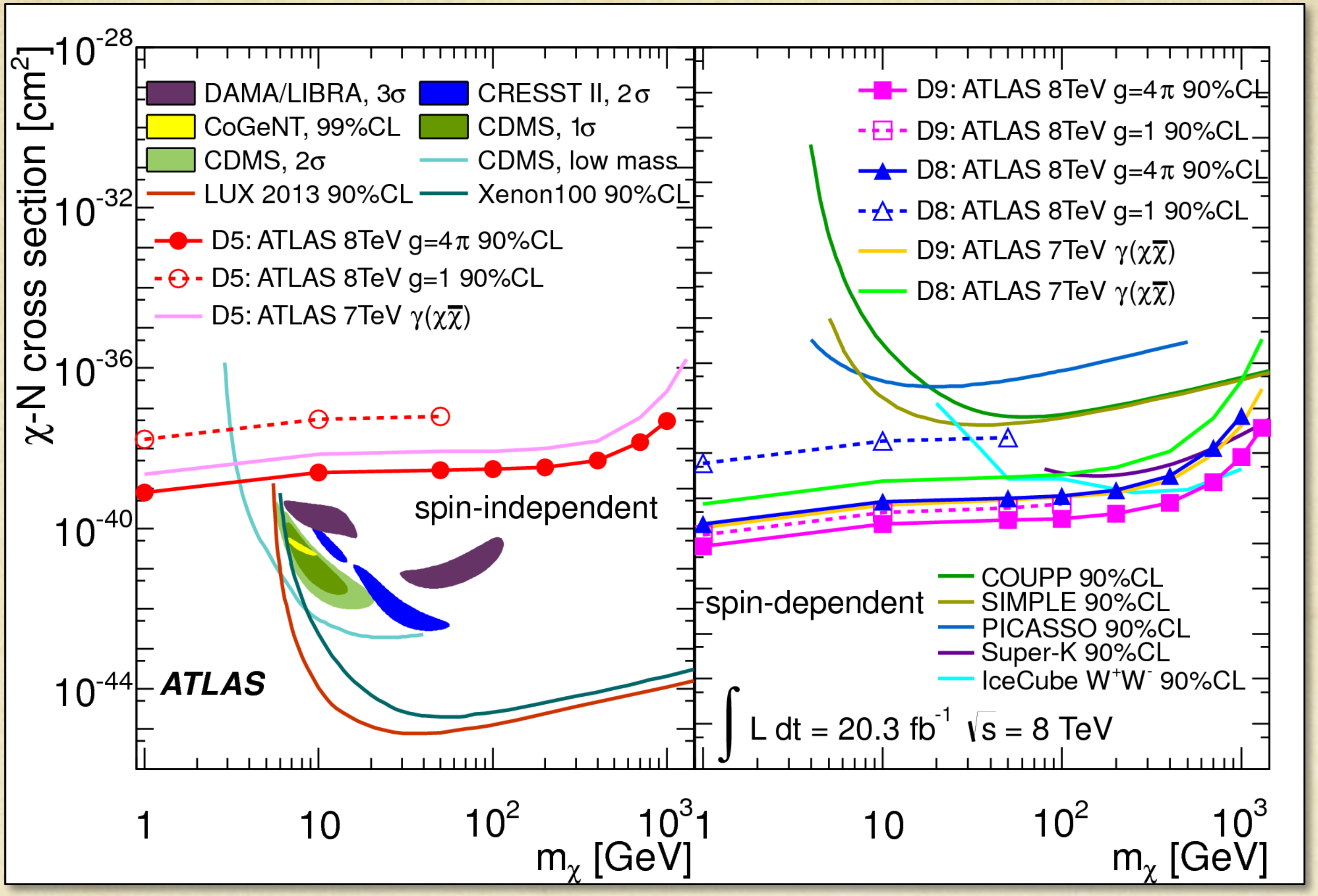
Complex scalar

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	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

Real scalar

TABLE I: Operators coupling WIMPs to SM particles. The operator names beginning with D, C, R apply to WIMPS that are Dirac fermions, complex scalars or real scalars respectively.

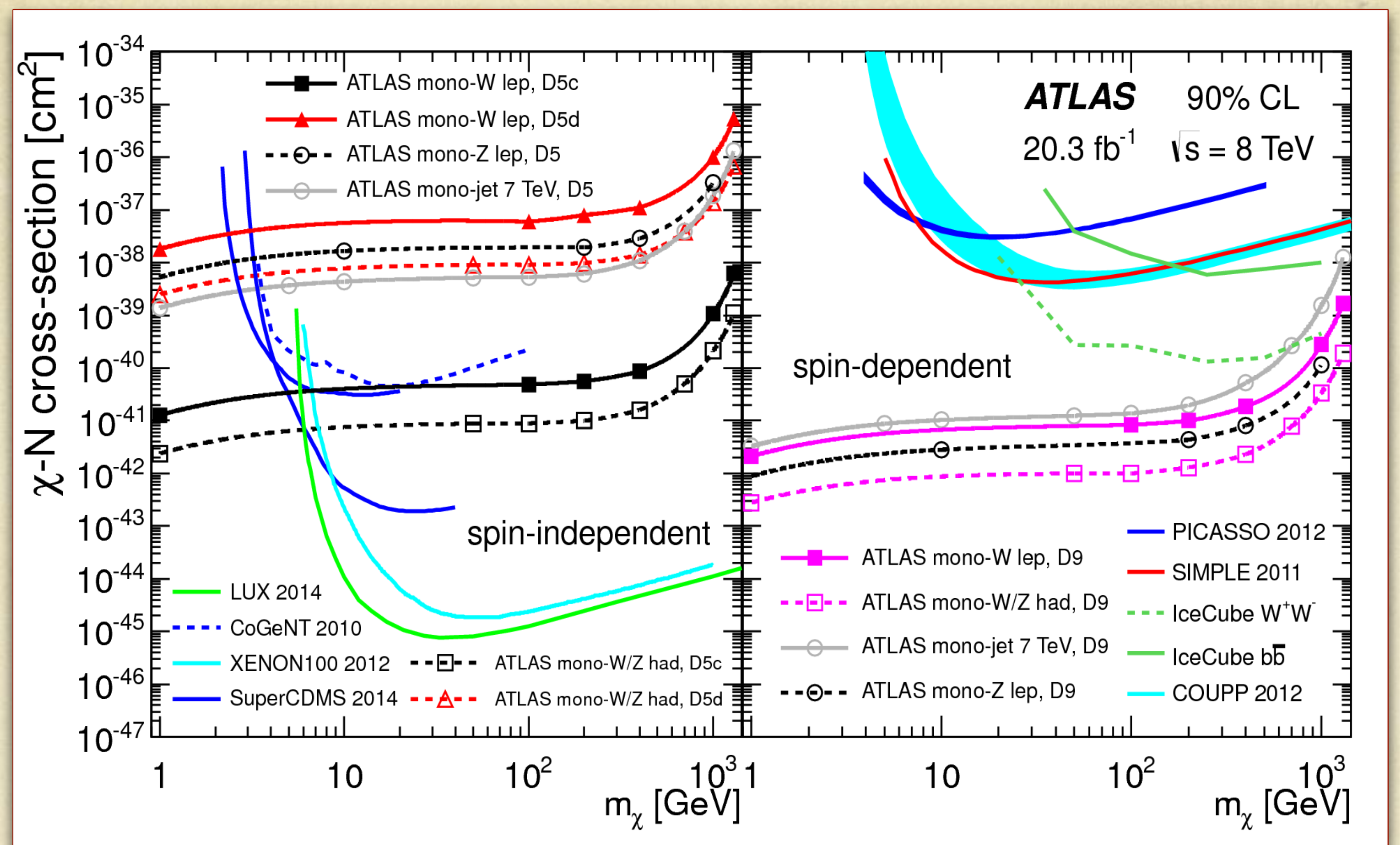
D5 from ATLAS mono-photon



-38 to -39

-39 to -40.5

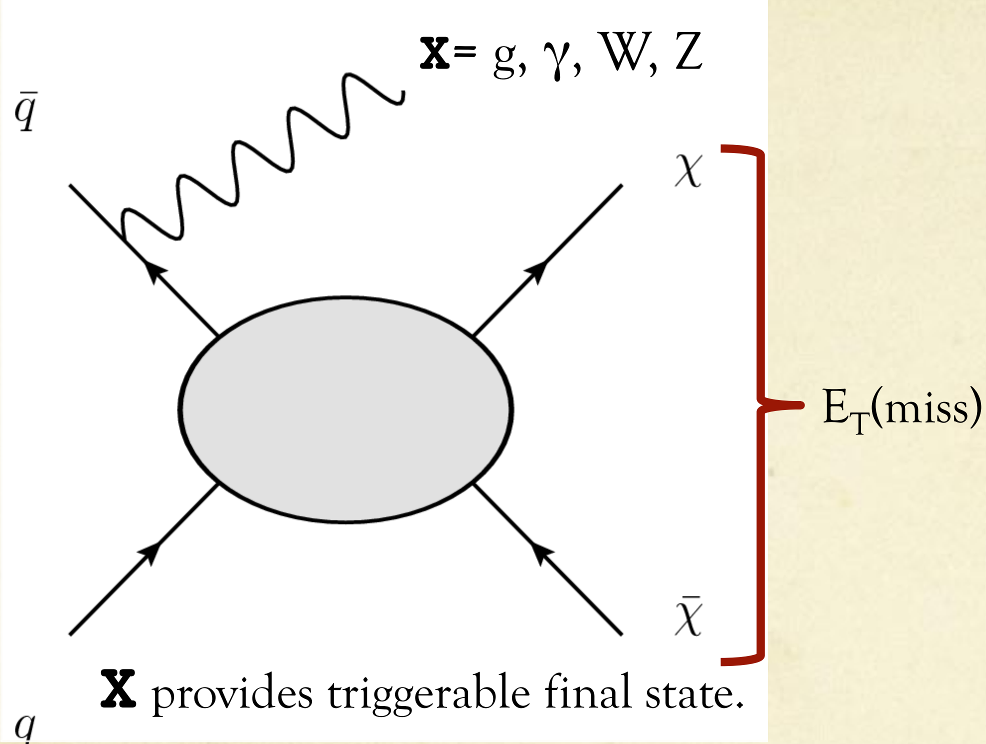
Mono-W/Z Leptonic and hadronic



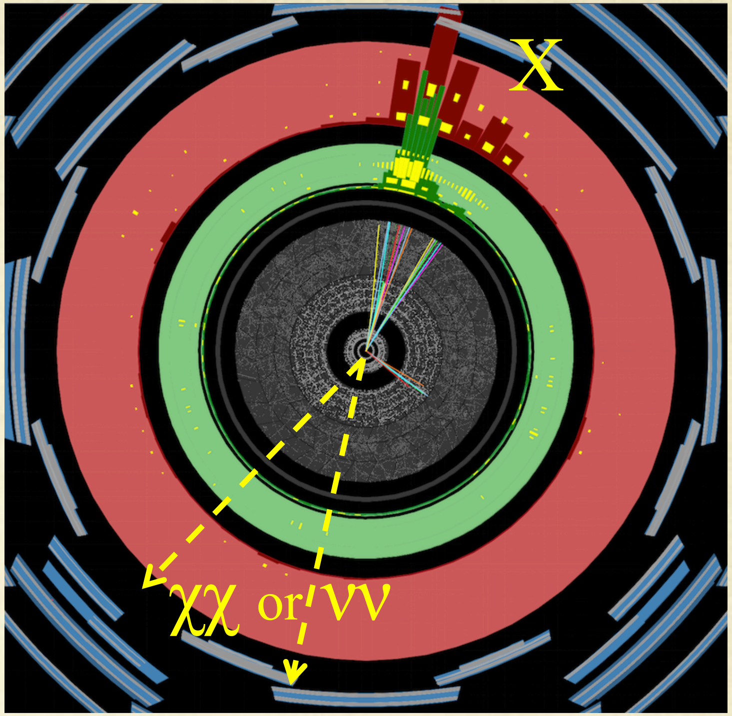
best is mono W/Z hadronic construtive -41.5
or
-38.5 monojet 7 TeV

best is mono W/Z hadronic construtive -42.5

Dark Matter Search with Mono-X Signatures



Effective Theory (EFT) approach for interpretation with m_χ and M* and DM.



Display of a high p_T jets recoiling against missing transverse energy E_T(miss).