Dark Matter searches at ATLAS

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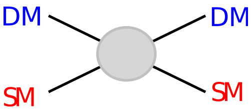
On behalf of the ATLAS Collaboration

Dark Interactions @ BNL

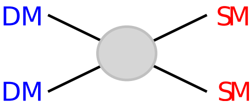
June 12, 2014

Dark Matter candidates and the LHC

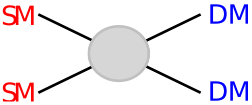
- Astrophysical measurements point to existence of invisible Dark Matter
  - Galactic rotation curves
  - Large-scale structure, galactic evolution, Bullet Cluster
  - Precision cosmology, including CMB measurements
- Dark Matter (DM) has no known interactions beyond gravity
- What if it couples to Standard Model (SM) particles very weakly?
  - Weakly Interacting Massive Particle (WIMP) interpretation
  - Could be produced in pairs at colliders (Dark Matter is stable)



Direct detection
(WIMP-nucleon scattering)



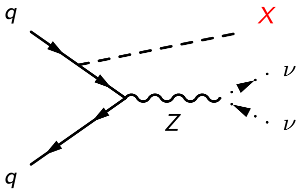
Indirect detection
(WIMP annihilation)



Collider searches
(WIMP pair production)

Mono-X searches

- A final state with only two DM particles is not detectable
  - Need something to balance it → missing transverse momentum, $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$
- Add a particle X, usually via Initial State Radiation (ISR)
  - X can be jets, photons, W/Z bosons, ...
  - Typically one ISR particle, creating mono-X + $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ topologies
- Irreducible standard model background: $Z \to \nu\nu + \mathrm{X}$



Mono-X interpretations

- Effective Field Theories (EFTs):
  - Mediator is beyond the energy scale of the LHC, and is integrated out
  - Leaves a suppression scale $\mathrm{M}^* = \mathrm{M}_{\mathrm{med}}/\sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}}$
  - Used to conduct generic, minimally model dependent searches
    - Potential EFT validity problems when used at colliders
  - Limits compared to direct detection experiments via $\sigma_{\mathrm{WIMP-nucleon}}$

Phys. Rev. D 82, 116010

Name	Coupling type	Operator	Coefficient
D1	Scalar	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D5	Vector	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D8	Axial vector	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5 q$	$1/M_*^2$
D9	Tensor	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D11	Gluon	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$

- Simplified models:
  - The massive mediator is not integrated out, giving extra parameters
  - UV-complete, addresses problems of questionable EFT validity at colliders

Mono-photon

$\sqrt{s} = 7\,\mathrm{TeV}$: PRL 110, 011802 (2013)

Event selection:

- Good quality photon, $p_T^{\gamma} > 150\,\mathrm{GeV}$
- 0 or 1 jet(s), $p_T^{\mathrm{jet}} > 30\,\mathrm{GeV}$
- Photon, jet, $\mathrm{E}_T^{\mathrm{miss}}$ all well separated
- Veto on electrons and muons
- $\mathrm{E}_T^{\mathrm{miss}} > 150\,\mathrm{GeV}$

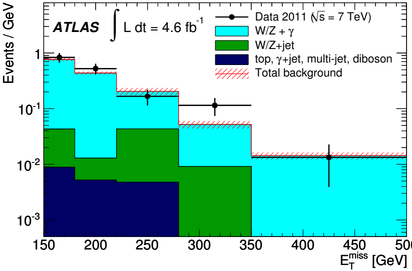
Main backgrounds:

- $Z \to \nu\nu + \gamma$: irreducible
  - Control region: $\gamma + \mu_{\geq 1}$
- $W \to \ell\nu + \gamma$: missed leptons, τ_{had}
  - Control region: $\gamma + \mu_{\geq 1}$
- $W/Z + e/\mathrm{jets}$: fake γ from e or jets
  - Dedicated fake regions

Main uncertainties:

- Photon/jet energy scale, $\mathrm{E}_T^{\mathrm{miss}}$
- Showering and hadronization
- Data statistics in $\mu_{\geq 1}$ control region
- Total uncertainty of 15%

$\gamma + \mu_{\geq 1}$ control region



Mono-photon

$\sqrt{s} = 7\,\mathrm{TeV}$: PRL 110, 011802 (2013)

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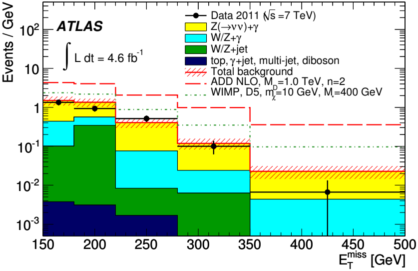
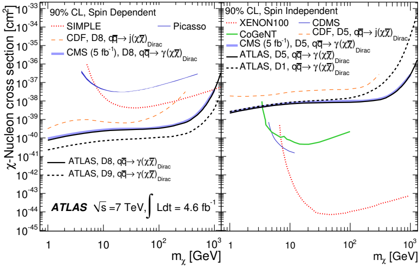
Limits:

- Good agreement between data and SM backgrounds
- Limits set on D1 (scalar), D5 (vector), D8 (axial vector), and D9 (tensor) EFTs
- Spin-independent plane: not very sensitive, comparable with CMS
- Spin-dependent plane: sensitive for full DM mass range, comparable with CMS

Signal region E_T^{miss}



$\sigma_{\mathrm{WIMP-nucleon}}$



Mono-$W/Z(\to qq)$

$\sqrt{s} = 8\,\text{TeV}$: PRL 112, 041802 (2014)

Event selection:

- Reconstruct W/Z as $R = 1.2$ Cambridge-Aachen (C-A) jet
- Require central C-A jet, p_{T}>250 GeV
- m_{jet} is under the W/Z mass peak
- 0 or 1 extra jet(s), $p_{\text{T}}^{\text{jet}} > 40\,\text{GeV}$
- Veto on electrons, muons, photons
- $\text{E}_{\text{T}}^{\text{miss}} > 350, 500\,\text{GeV}$

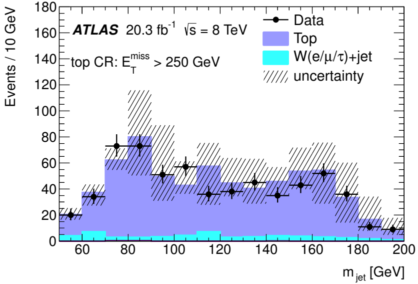
Main backgrounds:

- $Z \to \nu\nu + \text{jets}$: irreducible
  - Control region: C-A $+ \mu_{\geq 1}$
- $W \to \ell\nu + \text{jets}$: missed leptons, τ_{had}
  - Control region: C-A $+ \mu_{\geq 1}$

Main uncertainties:

- Limited control region statistics
- MC theoretical uncertainties
- C-A jet energy scale/resolution
- Total uncertainty of 7 to 13%

C-A top control region



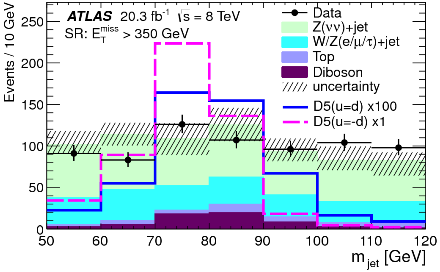
Mono-$W/Z(\to qq)$

$\sqrt{s} = 8\,\mathrm{TeV}$: PRL 112, 041802 (2014)

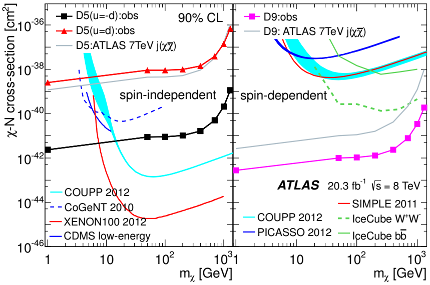
Limits:

- Good agreement between data and SM backgrounds
- Limits set on D5 (vector) and D9 (tensor) EFTs
  - Two cases: D5(u=-d) constructive and D5(u=d) destructive interference
- Spin-independent plane: sensitive mostly for $m_\chi < 10\,\mathrm{GeV}$
- Spin-dependent plane: powerful for all DM masses considered

Signal region E_T^{miss}



$\sigma_{\mathrm{WIMP-nucleon}}$



Mono-$Z(\to \ell\ell)$

$\sqrt{s} = 8\,\mathrm{TeV}$: arxiv:1404.0051 (submitted to PRD)

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Event selection:

- Good quality pair: e^+e^- or $\mu^+\mu^-$
- $M_{\ell\ell}$ is under the Z mass peak
- Dilepton system is central, balances $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ (magnitude and direction)
- Veto on third leptons
- Veto on jets, $p_{\mathrm{T}}^{\mathrm{jet}} > 25\,\mathrm{GeV}$
- $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}} > 150, 250, 350, 450\,\mathrm{GeV}$

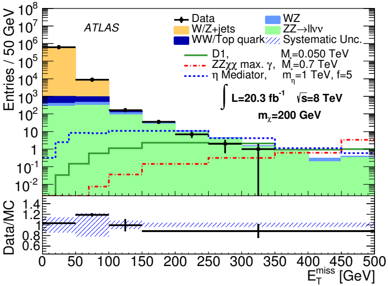
Main backgrounds:

- $ZZ \to \ell^+\ell^-\nu\nu$ $[\ell = e, \mu]$: irreducible
  - NLO MC (`POWHEG BOX 1.0`), normalized to `MCFM 6.2`
- $WZ \to \ell\nu\ell^+\ell^-$: missed lepton
  - NLO MC (`POWHEG BOX 1.0`)

Main uncertainties:

- Jet and electron energy scale
- Muon momentum scale
- MC theoretical uncertainties
- Total uncertainty of 34 to 175%

Signal region $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$



Mono-$Z(\to \ell\ell)$

$\sqrt{s} = 8\,\mathrm{TeV}$: arxiv:1404.0051 (submitted to PRD)

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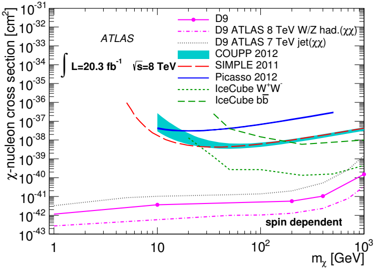
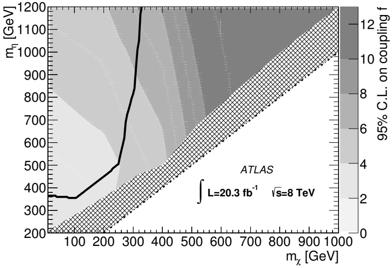
Limits:

- Good agreement between data and SM backgrounds
- Limits set on D1 (scalar), D5 (vector), and D9 (tensor) EFTs
- Spin-independent plane: not very sensitive, see backup
- Spin-dependent plane: powerful for all m_χ, comparable to mono-W/Z$\to$ qq
- Also considered simplified model of a scalar t-channel mediator η with coupling f
  - Black line: lower limit on f from relic density constraints

Spin-dependent $\sigma_{\mathrm{WIMP-nucleon}}$



Simplified model limits



Mono-jet

$\sqrt{s} = 7\,\mathrm{TeV}$: JHEP 04 (2013) 075

$\sqrt{s} = 8\,\mathrm{TeV}$: ATLAS-CONF-2012-147

Event selection:

- Require central leading jet
- 0 or 1 extra jet(s), $p_{\mathrm{T}}^{\mathrm{jet}} > 30\,\mathrm{GeV}$
- Second jet not aligned with $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$
- Veto on electrons and muons
- $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{jet1}} > 120, 220, 350, 500\,\mathrm{GeV}$

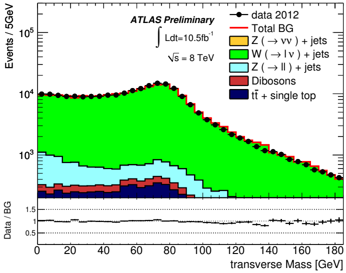
Main backgrounds:

- $Z \to \nu\nu + \mathrm{jets}$: irreducible
  - Control regions $[\ell = e, \mu]$: $W \to \ell\nu + \mathrm{jets}$, $Z \to \ell\ell + \mathrm{jets}$
- $W \to \ell\nu + \mathrm{jets}$: missed leptons, τ_{had}
  - Control regions $[\ell = e, \mu]$: $W \to \ell\nu + \mathrm{jets}$

Main uncertainties:

- Limited control region statistics
- Jet energy scale/resolution
- Lepton identification efficiencies
- Total uncertainty of 3.4 to 17%

$W \to \mu\nu + \mathrm{jets}$ control region



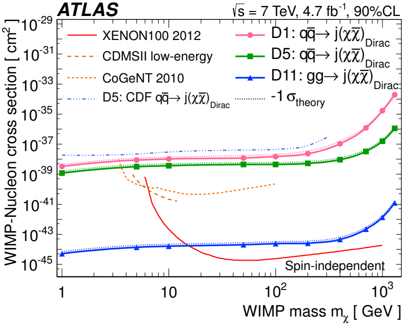
Mono-jet

$\sqrt{s} = 7\,\mathrm{TeV}$: JHEP 04 (2013) 075 $\sqrt{s} = 8\,\mathrm{TeV}$: ATLAS-CONF-2012-147

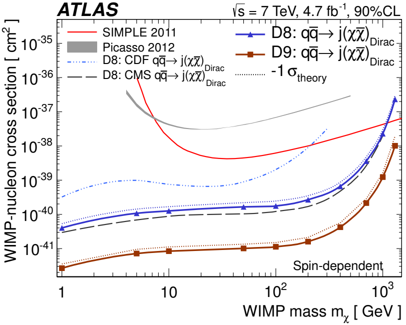
Limits: $(7\,\mathrm{TeV})$

- Good agreement between data and SM backgrounds
- Limits set on D1 (scalar), D5 (vector), D8 (axial), D9 (tensor), and D11 (gluon)
- Spin-independent plane: sensitivity varies, generally powerful for $m_\chi < 10\,\mathrm{GeV}$
- Spin-dependent plane: strong for all m_χ, weaker than $8\,\mathrm{TeV}$ mono-W/Z

Spin-independent $\sigma_{\mathrm{WIMP-nucleon}}$



Spin-dependent $\sigma_{\mathrm{WIMP-nucleon}}$



Mono-jet upgrade studies

$\sqrt{s} = 14\,\mathrm{TeV}$: ATL-PHYS-PUB-2014-007

Event selection:

	8 TeV	14 TeV
N_{jets}	1 or 2	
$p_{\mathrm{T}}^{\mathrm{jet}}$	$30\,\mathrm{GeV}$	$50\,\mathrm{GeV}$
$p_{\mathrm{T}}^{\mathrm{jet1}}$	$120\,\mathrm{GeV}$	$300\,\mathrm{GeV}$
$\Delta\phi$	$\Delta\phi(\mathrm{jet}_{12}, \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}) > 0.5$	
ℓ veto	Veto on e, μ	
$\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$	$400, 600, 800\,\mathrm{GeV}$	

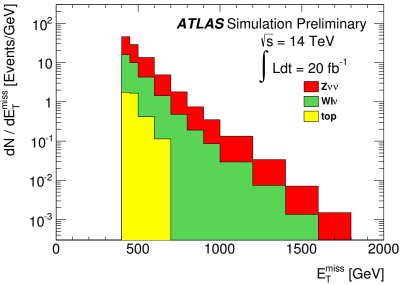
Main backgrounds:

- Pure MC study, both 8 and $14\,\mathrm{TeV}$
- $Z \to \nu\nu + \mathrm{jets}$: irreducible
- $W \to \ell\nu + \mathrm{jets}$: missed leptons, τ_{had}

Uncertainties considered:

- Two flat systematics considered:
  - 5%, reasonable in early Run-II
  - 1%, ultimate goal for HL-LHC
- Statistics varies with lumi choices

$14\,\mathrm{TeV}$ signal region



Mono-jet upgrade studies

$\sqrt{s} = 14\,\mathrm{TeV}$: ATL-PHYS-PUB-2014-007

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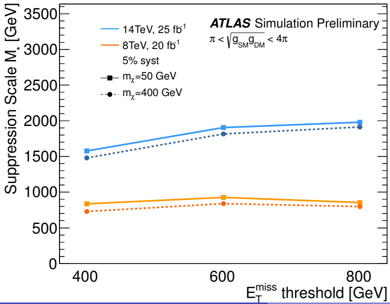
Sensitivity: EFT D5 (vector), valid assuming $\pi \lesssim \sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}} < 4\pi$

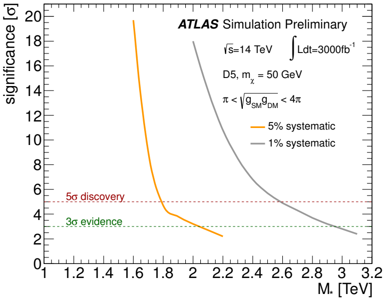
- Limits improve by factor of ~ 2 with first expected year of $14\,\mathrm{TeV}$ data
- Reducing systematics doesn't help too much yet - need more luminosity
- $\mathrm{E_T^{miss}}$ threshold limited by luminosity

$25\,\mathrm{fb}^{-1}$ limit strength



- 5σ discovery potential out to $\mathrm{M}^* \approx 2.5\,\mathrm{TeV}$ with full HL-LHC run
  - Aggressive 1% systematic
- Systematics dominated at $800\,\mathrm{GeV}$:
  - Limited impact of more data, need higher $\mathrm{E_T^{miss}}$ cuts

$3000\,\mathrm{fb}^{-1}$ discovery potential



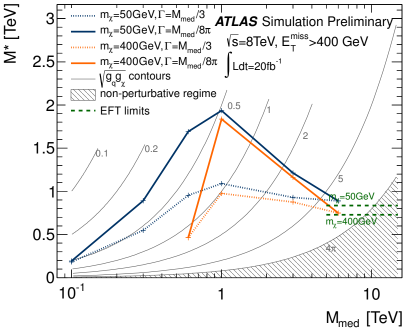
Mono-jet upgrade studies

$\sqrt{s} = 14\,\mathrm{TeV}$: ATL-PHYS-PUB-2014-007

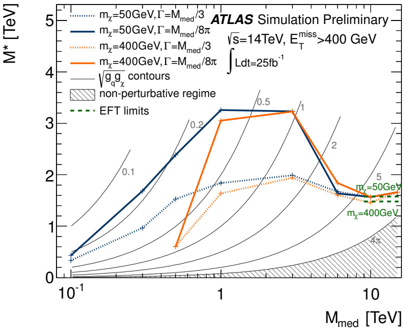
Sensitivity: Simplified Model Z′ (vector)

- Simplified Models give access to the resonance, provides much more information
  - EFT and Simplified Model limits meet at high mediator mass M_ξ
  - EFT limits are conservative for M_ξ above $\sim 1\,\mathrm{TeV}$, optimistic below that
- Limits improve by factor of 1.5 to 2.5 with first expected year of $14\,\mathrm{TeV}$ data

$8\,\mathrm{TeV}$ limits with $20\,\mathrm{fb}^{-1}$



$14\,\mathrm{TeV}$ limits with $25\,\mathrm{fb}^{-1}$



Summary

- Many independent astrophysical indications of Dark Matter
- If DM couples to the Standard Model, we can produce it in collisions
  - Complementary to direct and indirect detection experiments
- Mono-X + $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ searches provide access to a number of topologies which are sensitive to DM production at the LHC
  - ATLAS has studied X = photon, $W/Z \to qq$, $Z \to \ell\ell$, and jet
- Good agreement between data and SM expectations is observed
  - Limits are set on Effective Field Theories and Simplified Models
- Preliminary study of 14 TeV mono-jet sensitivity is promising
  - Suggests first year of data will increase sensitivity by a factor of ~ 2
  - Suggests ultimate HL-LHC 5σ discovery potential of up to $\mathrm{M}^* \approx 2.5\,\mathrm{TeV}$

Backup Slides

Mono-jet upgrade studies

$\sqrt{s} = 14\,\mathrm{TeV}$: ATL-PHYS-PUB-2014-007

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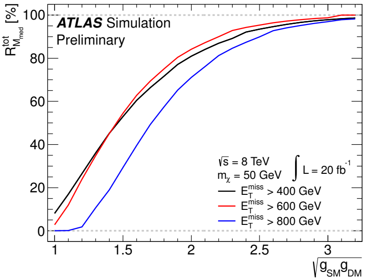
- Mono-X searches in ATLAS have used EFTs for minimal model dependence
- Over the past $\sim$ year, many concerns on validity have been raised
- Past ATLAS results used $\mathrm{M}^* > \mathrm{m}_\chi / 4\pi$
- More realistic constraint: $\mathrm{Q}_{\mathrm{tr}} < \mathrm{M}_{\mathrm{med}}$
  - EFT has integrated out $\mathrm{M}_{\mathrm{med}}$, but $\mathrm{M}_{\mathrm{med}} = \sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}} \mathrm{M}^*$
  - Typical theory assumption: $g_{\mathrm{SM}} = g_{\mathrm{DM}} = 1 \implies \mathrm{M}_{\mathrm{med}}^{g=1} = \mathrm{M}^*$
  - Without knowledge of DM properties, $0 \leq \sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}} < 4\pi$
- Can study the fraction of valid events, $R_{\mathrm{M}_{\mathrm{med}}}^{\mathrm{tot}}$, as a function of the coupling
  - Use $R_{\mathrm{M}_{\mathrm{med}}}^{\mathrm{tot}}$ to rescale the nominal EFT limits, $\mathrm{M}_{\mathrm{exp}}^*$
  - $\mathrm{M}_{\mathrm{valid}}^* = \left[R_{\mathrm{M}_{\mathrm{med}}}^{\mathrm{tot}}\right]^{1/[2(d-4)]} \mathrm{M}_{\mathrm{exp}}^*$, where $d = 6$ for D5
  - See arxiv:1402.1275 for detail on the rescaling procedure

Mono-jet upgrade studies

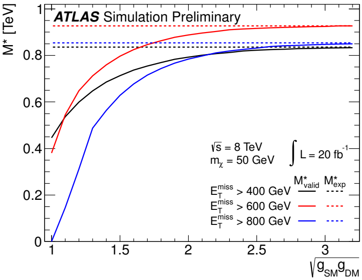
$\sqrt{s} = 14\,\mathrm{TeV}$: ATL-PHYS-PUB-2014-007

- The coupling phase space is $\sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}} \in [0, 4\pi)$, but $[1, \pi]$ is an interesting subset
  - $8\,\mathrm{TeV}$: $\sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}} = 1$ is $\sim 0\%$ valid, $\sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}} = \pi$ is $\sim 100\%$ valid
- Without knowledge of DM couplings, cannot make an absolute statement
  - Common theory assumption of $\sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}} = 1$ is particularly strict
  - Useage of EFT is valid for this scenario when $\pi \lesssim \sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}} < 4\pi$
- Rescaled limits for D5 depend on $\left[R^{\mathrm{tot}}_{\mathrm{M_{med}}}\right]^{\frac{1}{4}}$, so $\mathrm{M}^*_{\mathrm{valid}}$ quickly approaches $\mathrm{M}^*_{\mathrm{exp}}$

Fraction of valid events, $R^{\mathrm{tot}}_{\mathrm{M_{med}}}$



Rescaled limits on M^*



Mono-jet upgrade studies

$\sqrt{s} = 14\,\mathrm{TeV}$: ATL-PHYS-PUB-2014-007

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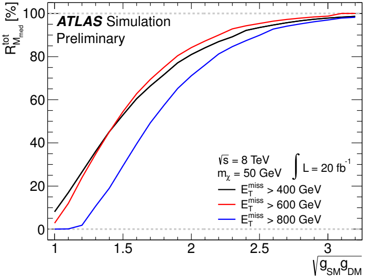
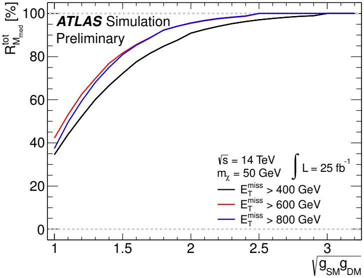
- Comparing 8 to 14 TeV collisions combines multiple effects
  - For a given $\mathrm{Q_{tr}}$ cut, validity is worse ($\mathrm{Q_{tr}}$ increases with $\sqrt{s}$)
  - However, limits are much stronger ($\mathrm{M}^*_{\mathrm{exp}}$ increases with $\sqrt{s}$)
- Net gain: fraction of valid events increases going from 8 to 14 TeV
  - Lower coupling values such as $\sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}} = 1$ are more reasonable at 14 TeV

8 TeV validity fraction, $R^{\mathrm{tot}}_{\mathrm{M_{med}}}$



14 TeV validity fraction, $R^{\mathrm{tot}}_{\mathrm{M_{med}}}$

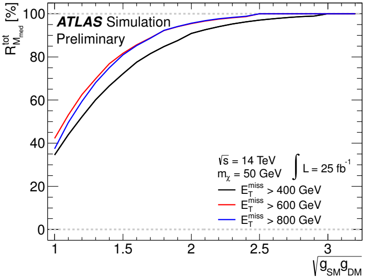


Mono-jet upgrade studies

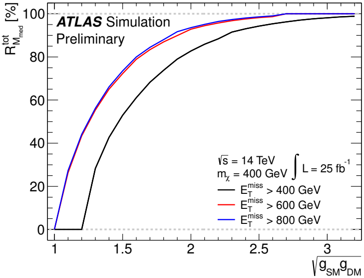
$\sqrt{s} = 14\,\mathrm{TeV}$: ATL-PHYS-PUB-2014-007

- Recall that $\mathrm{Q_{tr}}$ and m_χ are not independent quantities
  - $\mathrm{Q_{tr}} \geq 2\mathrm{m}_\chi$ to pair-produce DM particles at rest
  - Validity constraint is really $2\mathrm{m}_\chi \leq \mathrm{Q_{tr}} < \mathrm{M_{med}}$
- Increasing m_χ requires more momentum transfer, and thus decreases validity
  - Still 100% valid by $\sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}} \approx \pi$, as influence of DM mass decreases

$\mathrm{m}_\chi = 50\,\mathrm{GeV}$ validity fraction

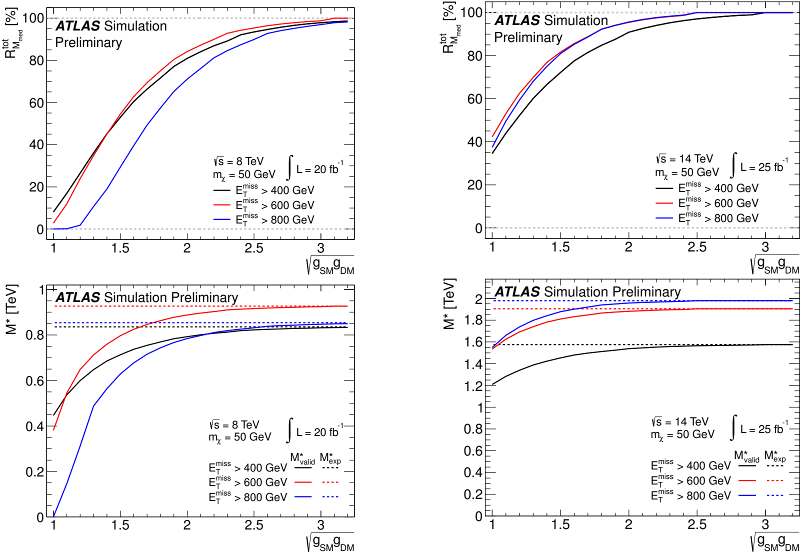


$\mathrm{m}_\chi = 400\,\mathrm{GeV}$ validity fraction



Mono-jet upgrade studies

$\sqrt{s} = 14\,\mathrm{TeV}$: ATL-PHYS-PUB-2014-007



Mono-jet upgrade studies

$\sqrt{s} = 14\,\mathrm{TeV}$: ATL-PHYS-PUB-2014-007

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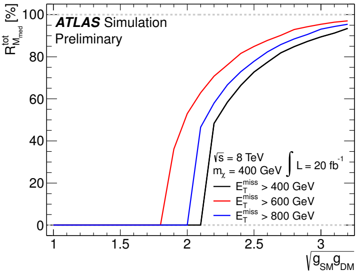
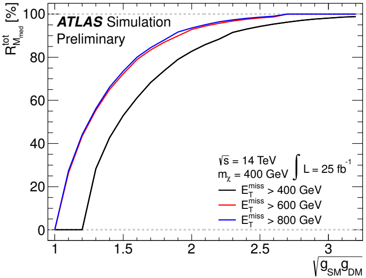
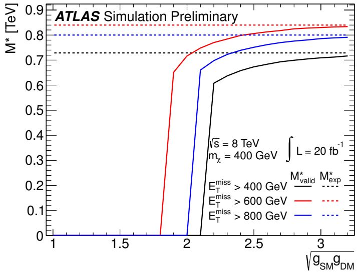
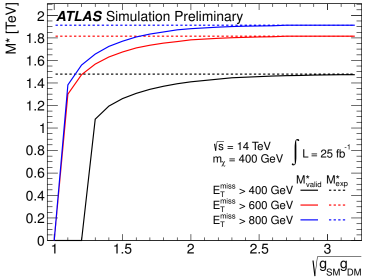








Mono-jet upgrade studies

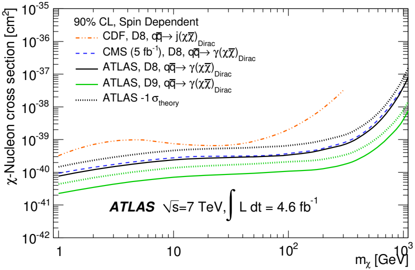
$\sqrt{s} = 14\,\mathrm{TeV}$: ATL-PHYS-PUB-2014-007

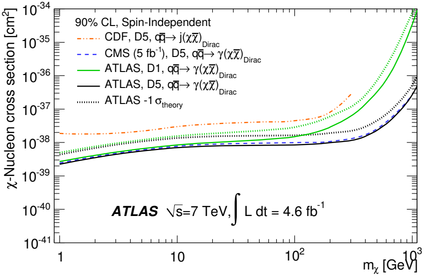
$\sqrt{s}$ [TeV]	m_χ [GeV]	$\mathrm{E}_\mathrm{T}^\mathrm{miss}$ cut [GeV]	$\mathrm{M}^*_\mathrm{exp}$ [TeV]	Validity fraction $R^\mathrm{tot}_{\mathrm{M}_\mathrm{med}}$ and rescaled limit $\mathrm{M}^*_\mathrm{valid}$ [%, TeV]					
				$\sqrt{g_\mathrm{SM} g_\mathrm{DM}} = 1$		$\sqrt{g_\mathrm{SM} g_\mathrm{DM}} = 2$		$\sqrt{g_\mathrm{SM} g_\mathrm{DM}} = \pi$	
8	50	400	0.84	8.1	0.45	81	0.79	98	0.83
8	50	600	0.93	2.8	0.38	84	0.89	100	0.93
8	50	800	0.85	0	0	71	0.78	98	0.85
8	400	400	0.73	0	0	0	0	91	0.71
8	400	600	0.84	0	0	53	0.72	96	0.83
8	400	800	0.80	0	0	0	0	94	0.79
14	50	400	1.6	35	1.2	91	1.5	100	1.6
14	50	600	1.9	42	1.5	95	1.9	100	1.9
14	50	800	2.0	37	1.5	95	2.0	100	2.0
14	400	400	1.5	0	0	83	1.4	99	1.5
14	400	600	1.8	0	0	93	1.8	100	1.8
14	400	800	1.9	0	0	94	1.9	100	1.9

Table 4 - EFT validity and rescaled limits

Mono-photon

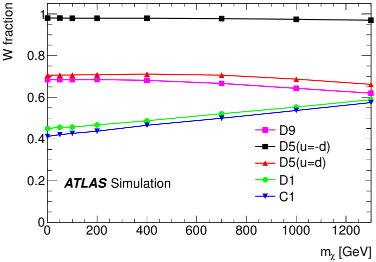
$\sqrt{s} = 7\,\mathrm{TeV}$: PRL 110, 011802 (2013)

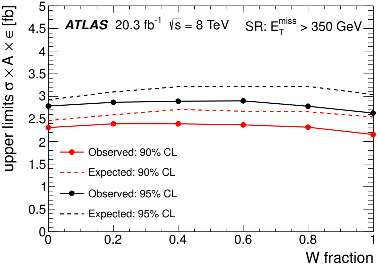


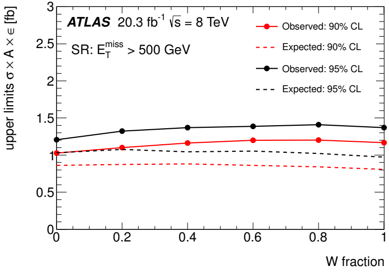


Mono-$W/Z(\rightarrow qq)$

$\sqrt{s} = 8\,\mathrm{TeV}$: PRL 112, 041802 (2014)

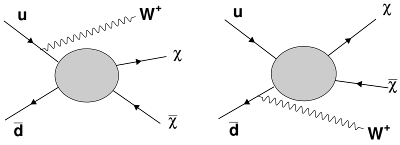


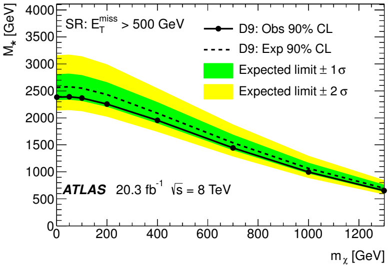


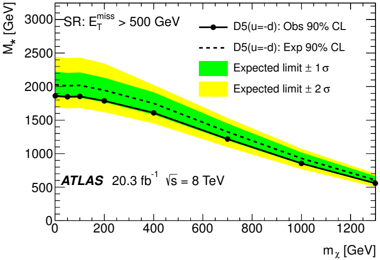


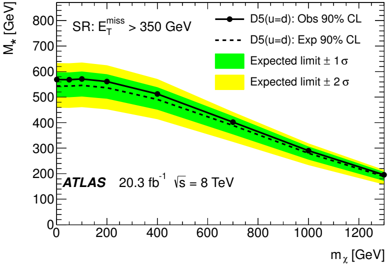
Mono-$W/Z(\to qq)$

$\sqrt{s} = 8\,\mathrm{TeV}$: PRL 112, 041802 (2014)



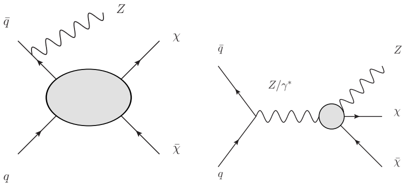




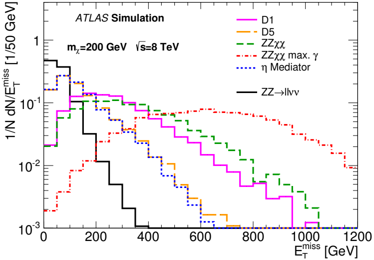


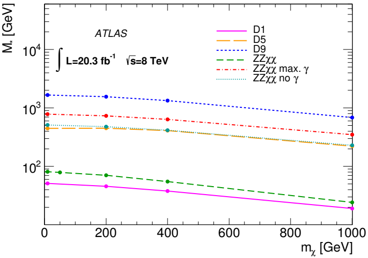
Mono-$Z(\to \ell\ell)$

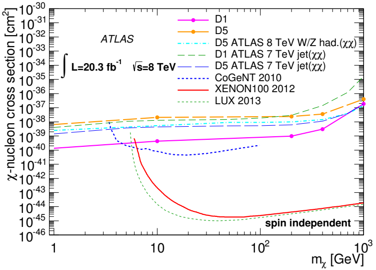
$\sqrt{s} = 8\,\mathrm{TeV}$: arxiv:1404.0051 (submitted to PRD)



Mono-X: not always only ISR emission!



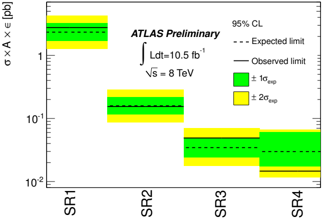


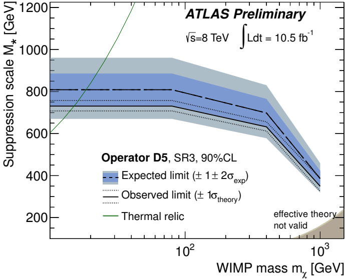


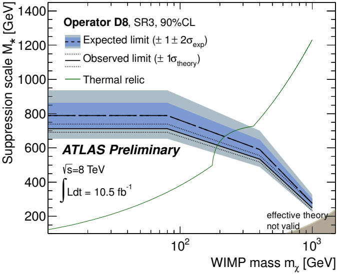
Mono-jet

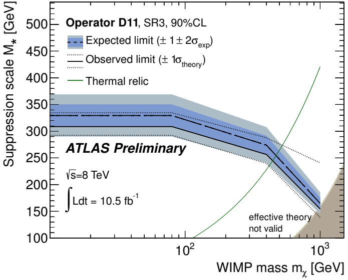
$\sqrt{s} = 7\,\text{TeV}$: JHEP 04 (2013) 075

$\sqrt{s} = 8\,\text{TeV}$: ATLAS-CONF-2012-147



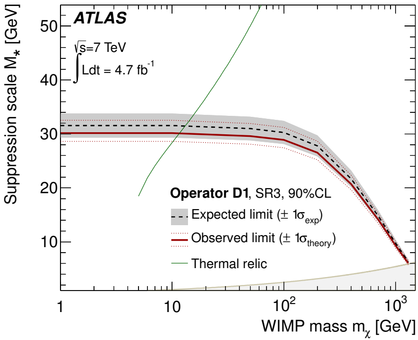


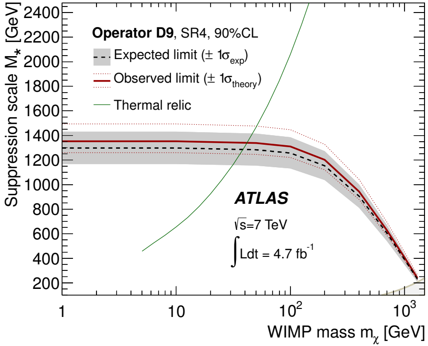




Mono-jet

$\sqrt{s} = 7\,\mathrm{TeV}$: JHEP 04 (2013) 075 $\sqrt{s} = 8\,\mathrm{TeV}$: ATLAS-CONF-2012-147

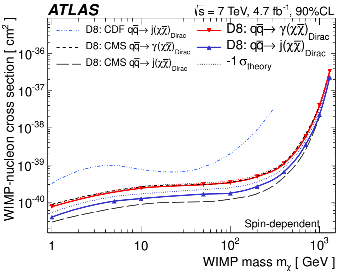


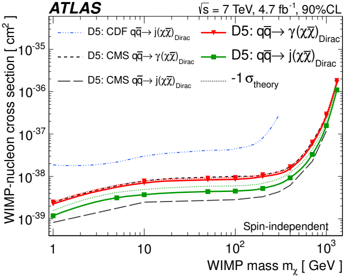


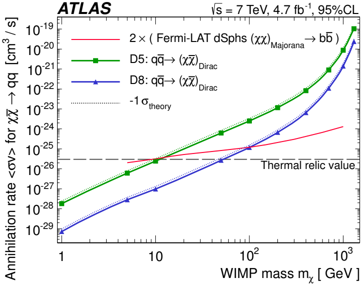
Mono-jet

$\sqrt{s} = 7\,\mathrm{TeV}$: JHEP 04 (2013) 075

$\sqrt{s} = 8\,\mathrm{TeV}$: ATLAS-CONF-2012-147

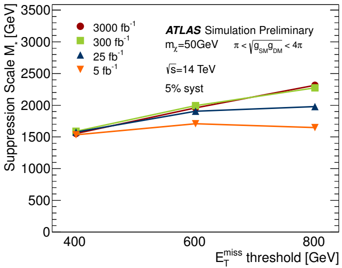


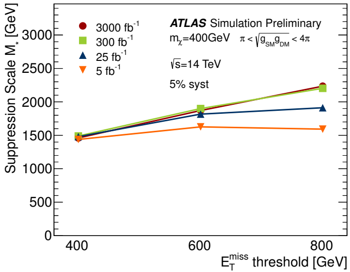


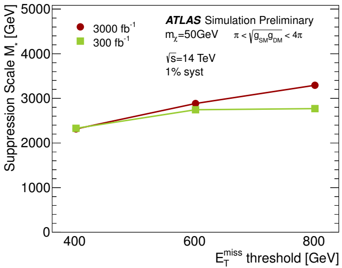


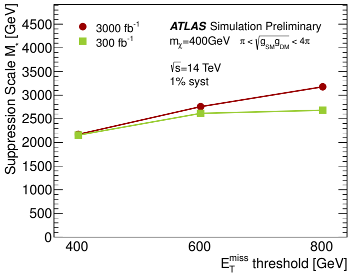
Mono-jet upgrade studies

$\sqrt{s} = 14\,\mathrm{TeV}$: ATL-PHYS-PUB-2014-007



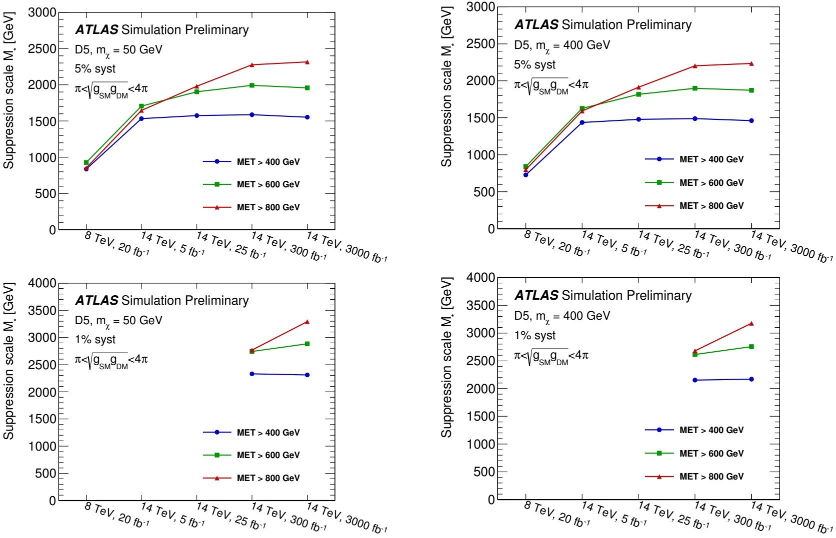






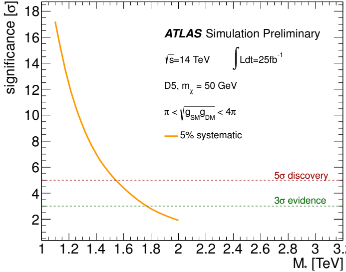
Mono-jet upgrade studies

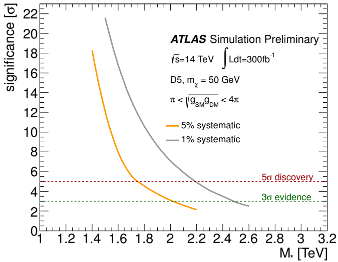
$\sqrt{s} = 14\,\mathrm{TeV}$: ATL-PHYS-PUB-2014-007

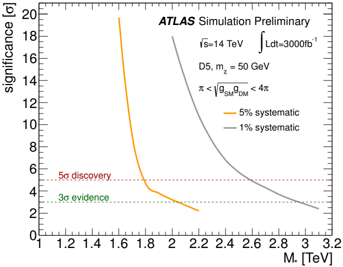


Mono-jet upgrade studies

$\sqrt{s} = 14\,\mathrm{TeV}$: ATL-PHYS-PUB-2014-007







Mono-jet upgrade studies

$\sqrt{s} = 14\,\mathrm{TeV}$: ATL-PHYS-PUB-2014-007