Dark Matter Searches in ATLAS

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On behalf of the ATLAS Collaboration

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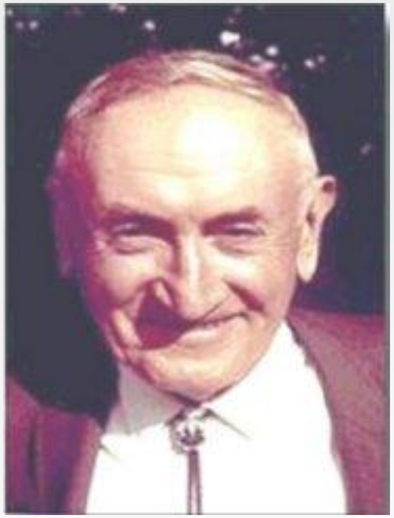
Mitchell 2015, College Station, Texas

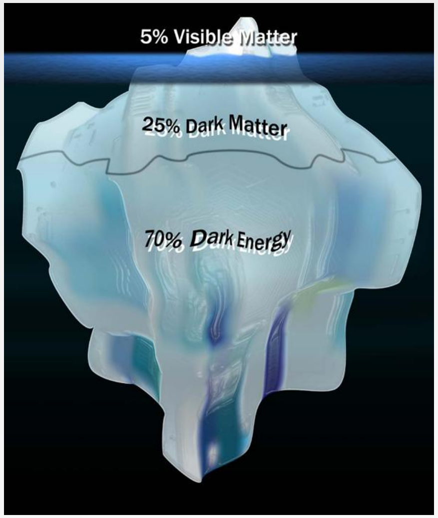
Dark Matter – Historical Perspective

- 82 year old cosmological mystery
- Dark matter was first observed by astronomer Fritz Zwicky
  - While studying velocity dispersions of galaxies in the Coma cluster
  - Estimated 400 times more gravitational mass than visible mass
- Idea neglected for almost 40 years
- Carefully measured by Vera Rubin
  - Galaxy rotation problem
  - Estimated factor of 10 more dark mass than visible mass
- Modern observations
  - CMB, gravitational lensing, galactic collisions, Milky way, and many others

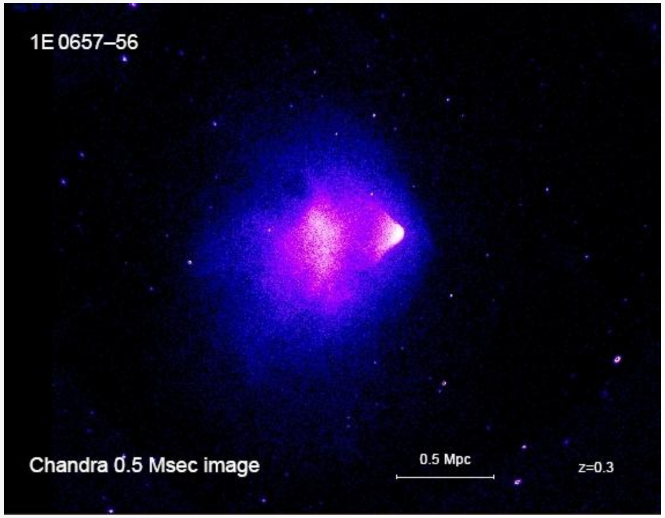


Dark Matter Today

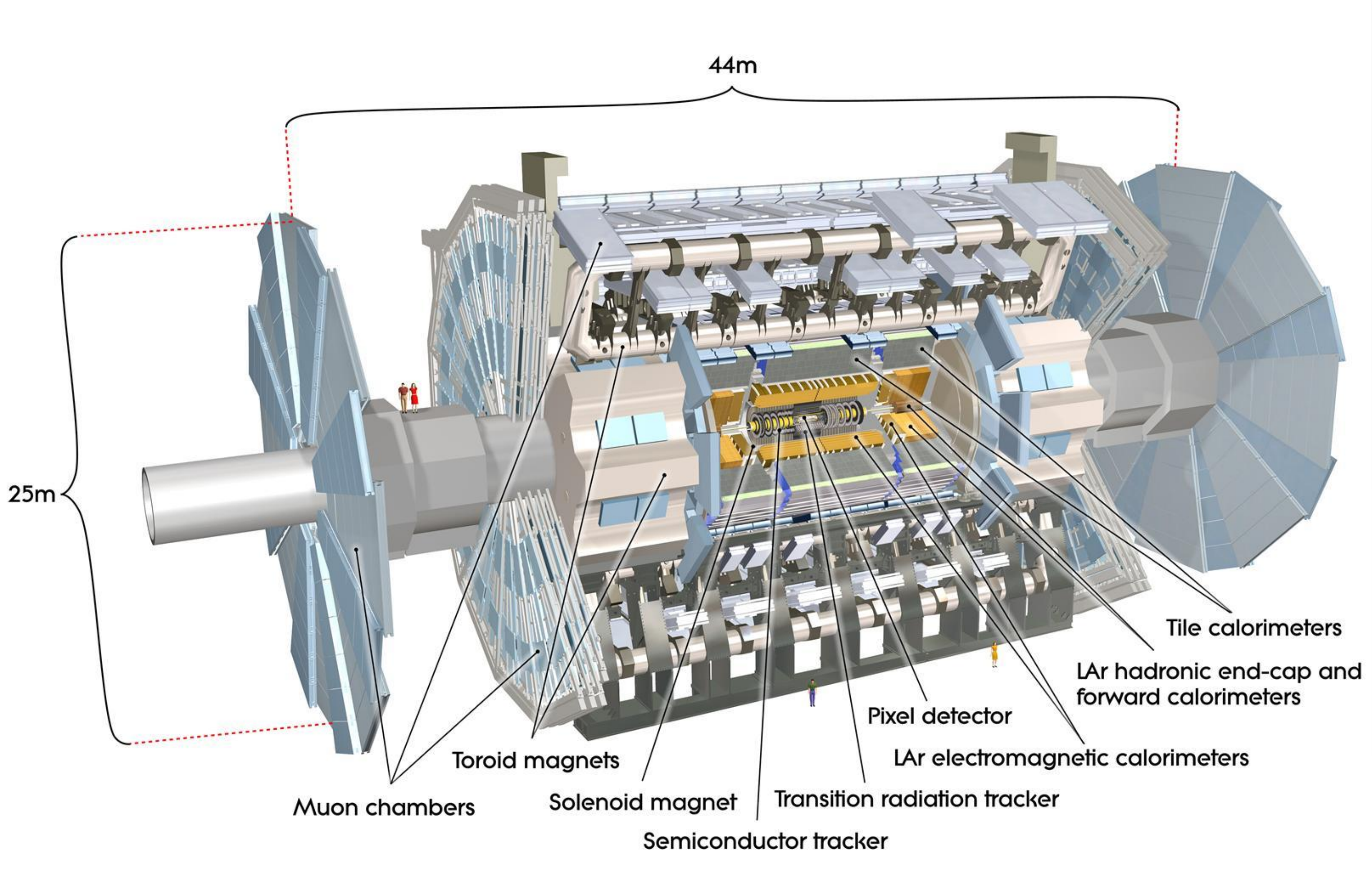
- The matter we know (Standard Model) is ~5% of the universe
- The rest is dark matter, and dark energy
- Dark matter is consistent with non baryonic, stable, and weakly interacting particles at the electroweak scale (WIMP)
- Many theories beyond the SM predict such particles, for example supersymmetry (SUSY)
- No WIMP’s observed so far
- Maybe we can make dark matter at the LHC?
- And detect it with ATLAS?



SLAC/Nicole Rager



ATLAS Experiment at the LHC

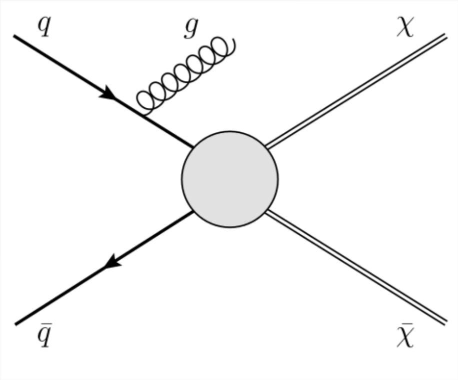


http://atlas.ch/

Searching for DM in ATLAS

- Dark matter production in pp collisions
  - Direct pair production of WIMP's: pp -> $\chi\bar{\chi}$
    - Effective field theory approach, contact interaction
    - Simplified model, for example through a vector boson mediator Z'
    - ATLAS-CMS-Theorists-DM-Forum recent agreement to use simplified models for Run 2
  - Gravitino production, in GMSB SUSY models
  - Invisible decays of the Higgs
  - Squarks/gluinos decaying to LSP
  - Other model dependent scenarios
- Dark matter signatures
  - Missing Et (MET) from DM particles escaping detection
  - Associated particles (typically ISR) – jet, bosons, heavy quarks, Higgs
  - Other complicated signatures
- This talk will focus on direct searches
  - Run 1 results at 8 TeV with ~20 fb^{-1}
  - Expectations for Run 2

Monojet + MET Search



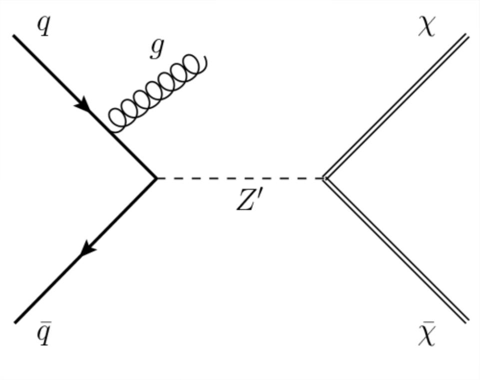


Table 2 Event selection criteria applied for the selection of monojet-like signal regions, SR1–SR9.

Selection criteria									
Preselection									
Primary vertex $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV Jet quality requirements At least one jet with $p_{\mathrm{T}} > 30$ GeV and $\lvert\eta\rvert < 4.5$ Lepton and isolated track vetoes									
Monojet-like selection									
The leading jet with $p_{\mathrm{T}} > 120$ GeV and $\lvert\eta\rvert < 2.0$ Leading jet $p_{\mathrm{T}}/E_{\mathrm{T}}^{\mathrm{miss}} > 0.5$ $\Delta\phi(\mathrm{jet}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) > 1.0$									
Signal region	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8	SR9
Minimum $E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	150	200	250	300	350	400	500	600	700

http://arxiv.org/abs/1502.01518

Monojet SM Expectations

Table 4 Data and SM background expectation in the signal region for the SR1–SR5 selections. For the SM expectations both the statistical and systematic uncertainties are included. In each signal region, the individual uncertainties for the different background processes can be correlated, and do not necessarily add in quadrature to the total background uncertainty.

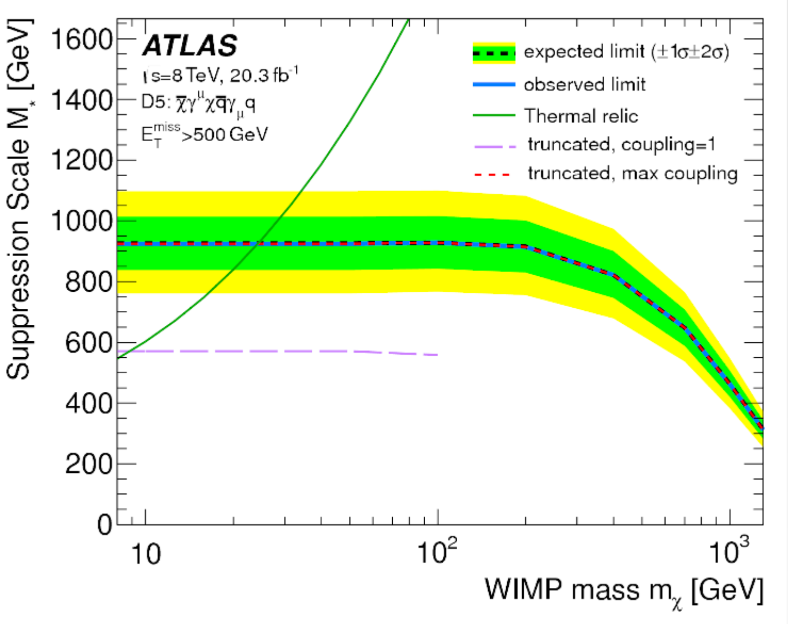
Signal Region	SR1	SR2	SR3	SR4	SR5
Observed events	364378	123228	44715	18020	7988
SM expectation	372100 ± 9900	126000 ± 2900	45300 ± 1100	18000 ± 500	8300 ± 300
$Z(\to \nu\bar{\nu})$	217800 ± 3900	80000 ± 1700	30000 ± 800	12800 ± 410	6000 ± 240
$W(\to \tau\nu)$	79300 ± 3300	24000 ± 1200	7700 ± 500	2800 ± 200	1200 ± 110
$W(\to e\nu)$	23500 ± 1700	7100 ± 560	2400 ± 200	880 ± 80	370 ± 40
$W(\to \mu\nu)$	28300 ± 1600	8200 ± 500	2500 ± 200	850 ± 80	330 ± 40
$Z/\gamma^*(\to \mu^+\mu^-)$	530 ± 220	97 ± 42	19 ± 8	7 ± 3	4 ± 2
$Z/\gamma^*(\to \tau^+\tau^-)$	780 ± 320	190 ± 80	45 ± 19	14 ± 6	5 ± 2
$t\bar{t}$, single top	6900 ± 1400	2300 ± 500	700 ± 160	200 ± 70	80 ± 40
Dibosons	8000 ± 1700	3500 ± 800	1500 ± 400	690 ± 200	350 ± 120
Multijets	6500 ± 6500	800 ± 800	200 ± 200	44 ± 44	15 ± 15

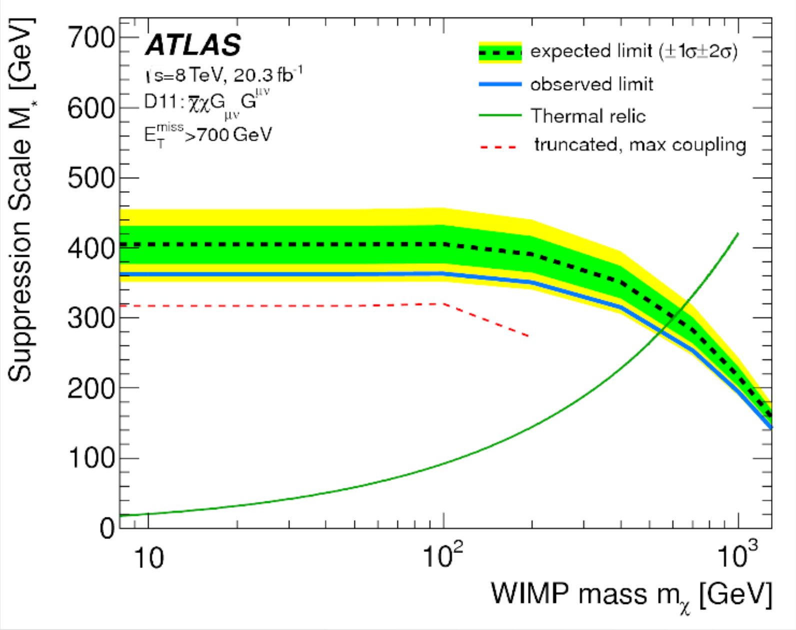
Table 5 Data and SM background expectation in the signal region for the SR6–SR9 selections. For the SM expectations both the statistical and systematic uncertainties are included. In each signal region, the individual uncertainties for the different background processes can be correlated, and do not necessarily add in quadrature to the total background uncertainty.

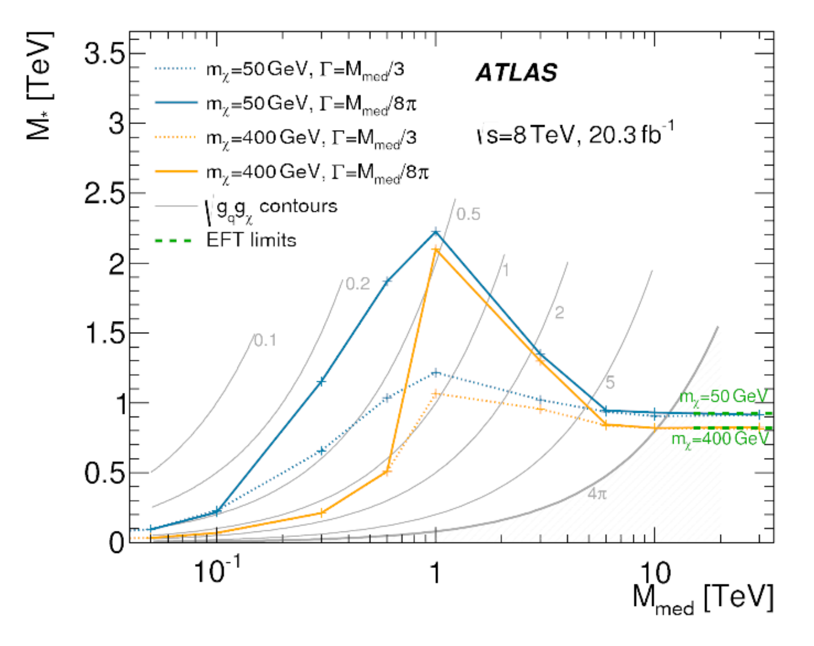
Signal Region	SR6	SR7	SR8	SR9
Observed events	3813	1028	318	126
SM expectation	4000 ± 160	1030 ± 60	310 ± 30	97 ± 14
$Z(\to \nu\bar{\nu})$	3000 ± 150	740 ± 60	240 ± 30	71 ± 13
$W(\to \tau\nu)$	540 ± 60	130 ± 20	34 ± 8	11 ± 3
$W(\to e\nu)$	170 ± 20	43 ± 7	9 ± 3	3 ± 1
$W(\to \mu\nu)$	140 ± 20	35 ± 6	10 ± 2	2 ± 1
$Z/\gamma^*(\to \mu^+\mu^-)$	3 ± 1	2 ± 1	1 ± 1	1 ± 1
$Z/\gamma^*(\to \tau^+\tau^-)$	2 ± 1	0 ± 0	0 ± 0	0 ± 0
$t\bar{t}$, single top	30 ± 20	7 ± 7	1 ± 1	0 ± 0
Dibosons	183 ± 70	65 ± 35	23 ± 16	8 ± 7
Multijets	6 ± 6	1 ± 1	0 ± 0	0 ± 0

Monojet Limits

- All measurements are consistent with SM – no evidence of DM
- Limits – 6 different EFT operators
- Most sensitive signal region (SR) is used in each case (SR7 or SR9)
- Result also interpreted in simplified model







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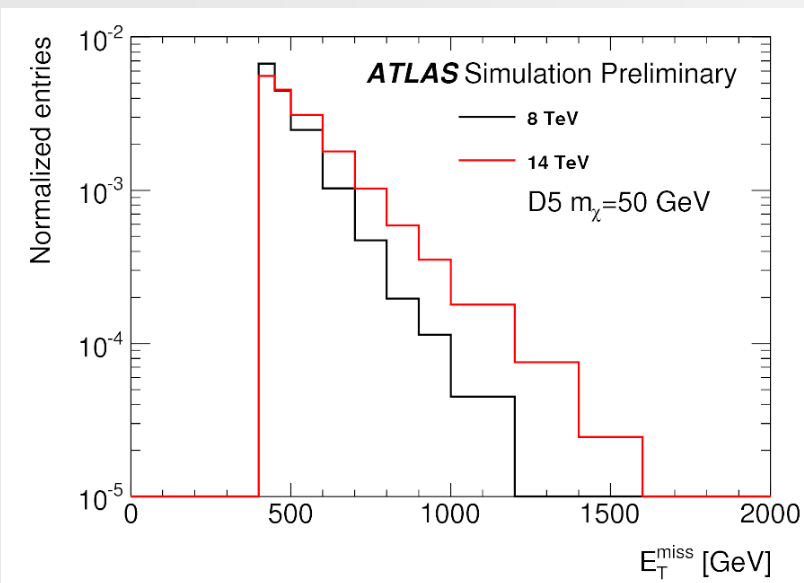
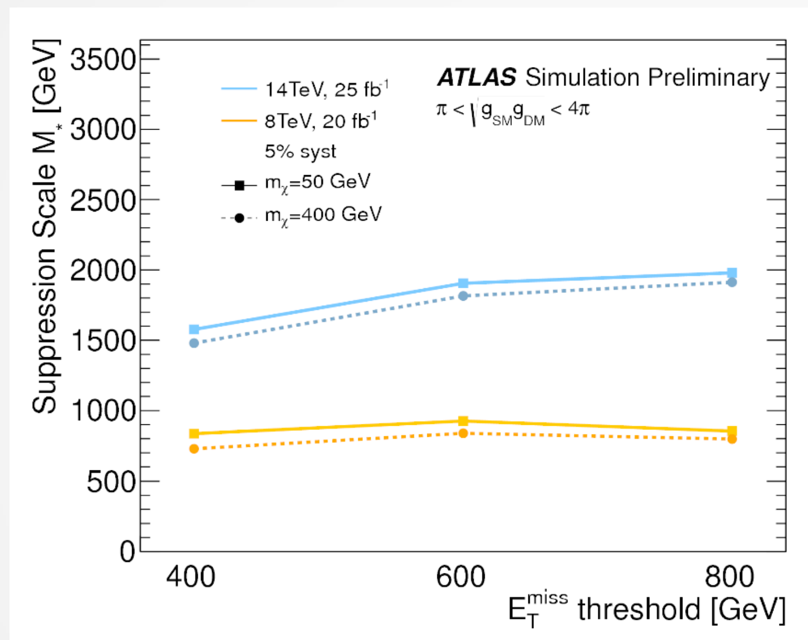
MC Monojet Studies for Run 2

	$\sqrt{s} = 8$ TeV		$\sqrt{s} = 14$ TeV
data quality	trigger primary vertex jet cleaning		primary vertex
lepton veto	muons: electrons:	$p_T > 7$ GeV, $\lvert\eta\rvert < 2.5$ $p_T > 7$ GeV, $\lvert\eta\rvert < 2.47$	emulated using the lepton selection efficiency from 8 TeV data
jet and E_T^{miss} cuts	jet definition: leading jet: $E_T^{miss} > 400, 600, 800$ GeV $\Delta\phi(\text{jet}, E_T^{miss}) > 0.5$ $N_{jet} \leq 2$	$p_T > 30$ GeV, $\lvert\eta\rvert < 4.5$ $p_T > 300$ GeV, $\lvert\eta\rvert < 2.0$	$p_T > 50$ GeV, $\lvert\eta\rvert < 3.6$ $p_T > 300$ GeV, $\lvert\eta\rvert < 2.0$ $E_T^{miss} > 400, 600, 800$ GeV $\Delta\phi(\text{jet}, E_T^{miss}) > 0.5$ $N_{jet} \leq 2$

Table 2: Event selection for the 8 TeV and 14 TeV analysis.

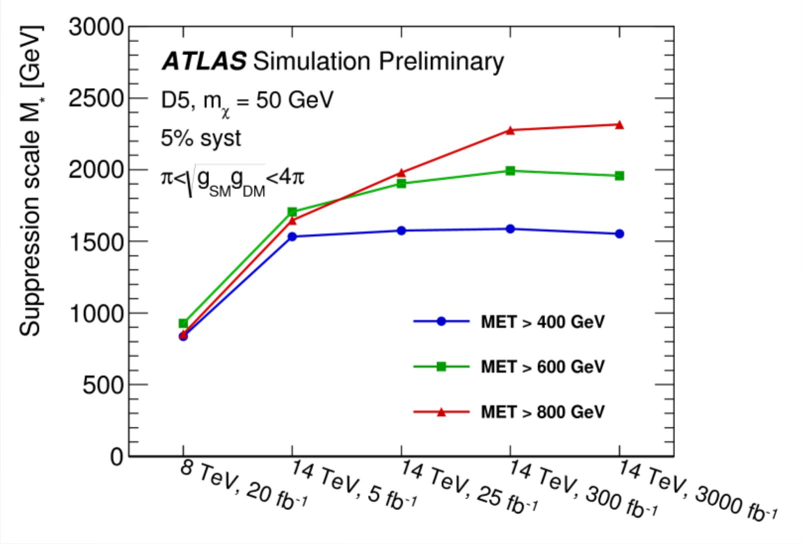




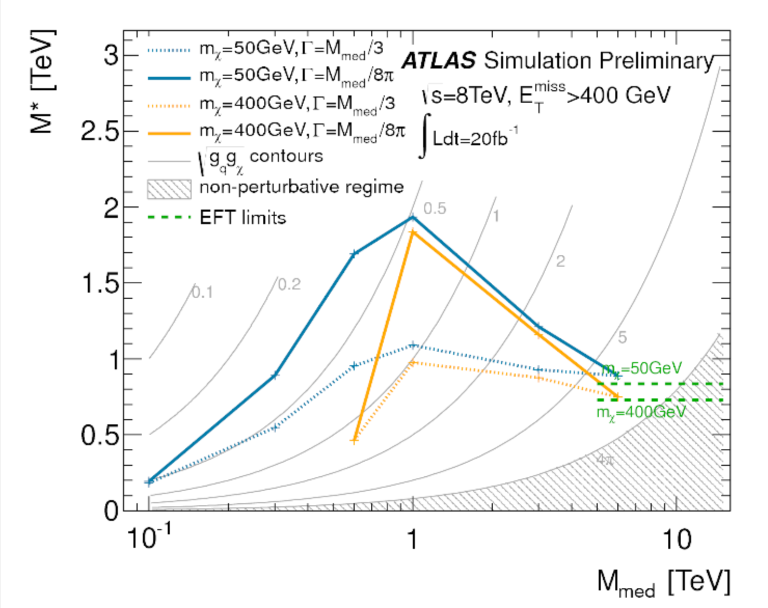
https://cds.cern.ch/record/1708859

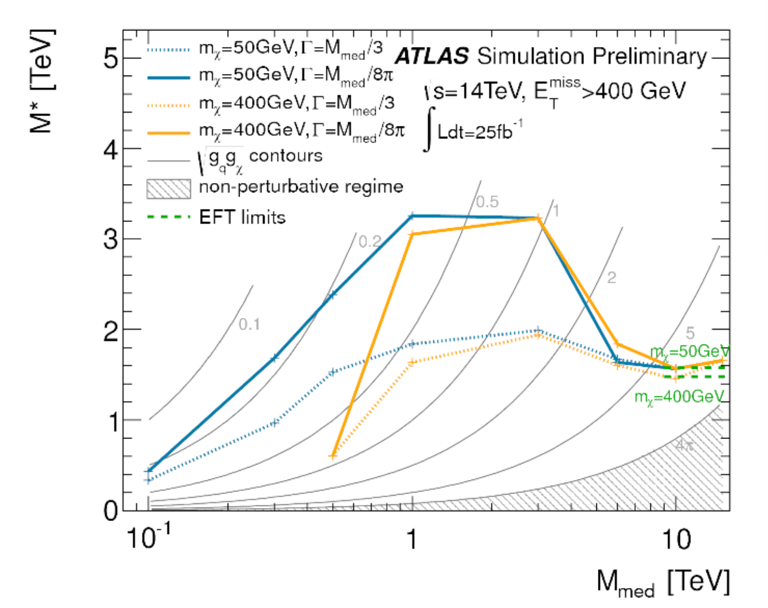
Monojet Expectations for Run 2

- EFT result assuming 100% validity for illustration
- Simplified model also studied
- Same MC based analysis for 8 TeV and 14 TeV CM energy
- Enhanced reach within one year of Run 2

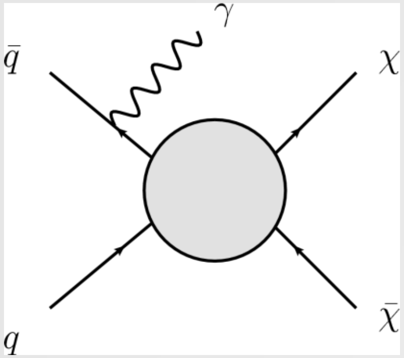


Simplified Models



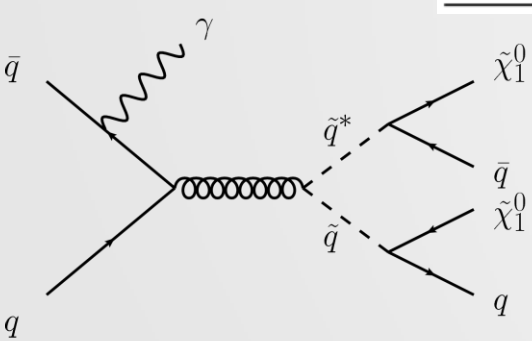


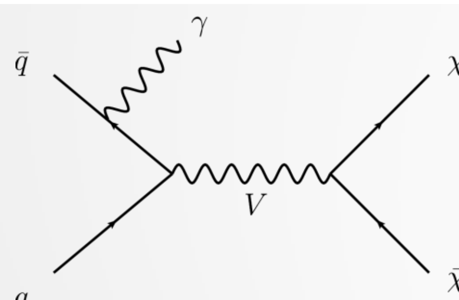
Photon + MET Production

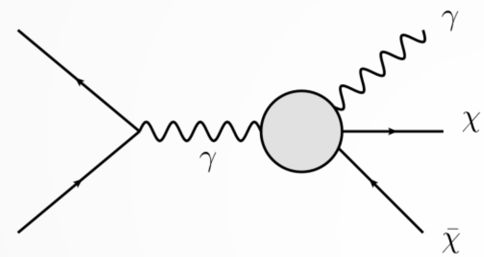


Example cutflow for
m_squark=200 GeV
m_chi0=195 GeV
10,000 events

Nominal	9989
Pre-selected:	
1. Trigger	8582
2. Good vertex	8574
3. Cleaning cuts	8213
SR Cuts:	
1. $E_{\mathrm{T}}^{\mathrm{miss}}$> 150 GeV	4131
2. At least one loose photon with p_{T}> 125 GeV($\lvert\eta\rvert < 2.37$)	2645
3. The leading photon is tight with $\lvert\eta\rvert < 1.37$	2068
4. The leading photon is isolated	1898
5. $\Delta\phi(\gamma^{\mathrm{leading}}, \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}})$ >0.4	1887
6. Jet veto: $N_{\mathrm{jet}} \leq 1$ and $\Delta\phi(\mathrm{jet}, \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$	1219
7. Lepton veto	1188







Phys. Rev. D 91, 012008 (2015)

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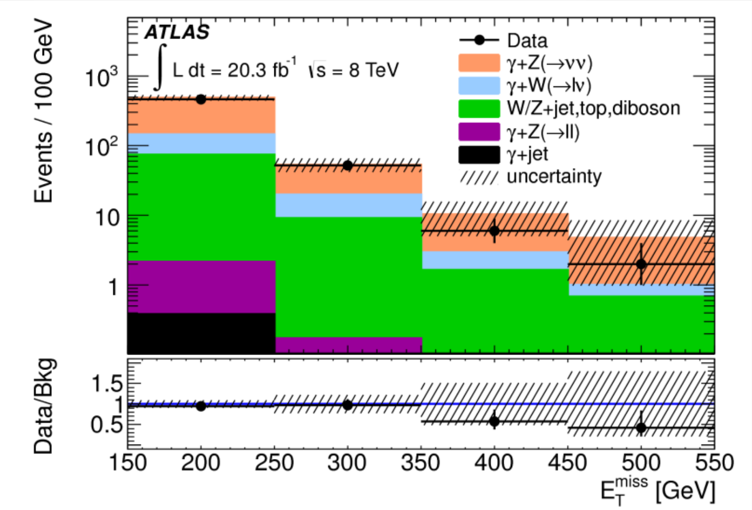
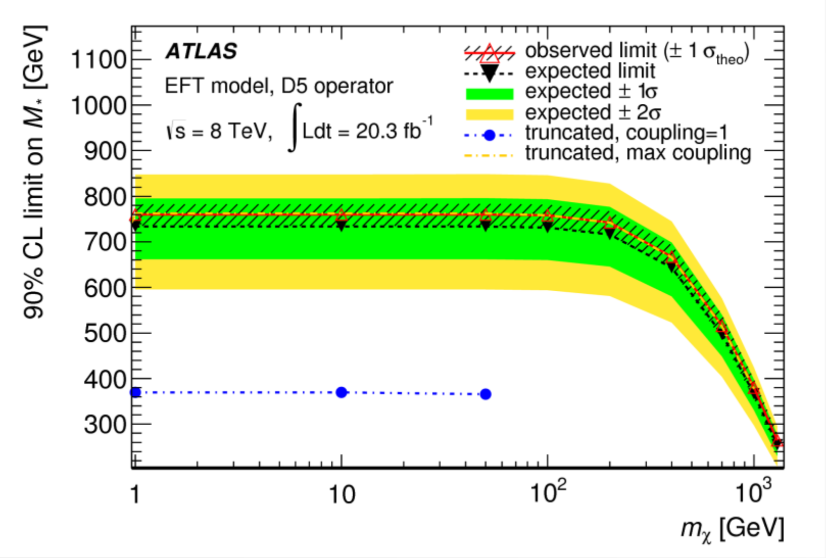
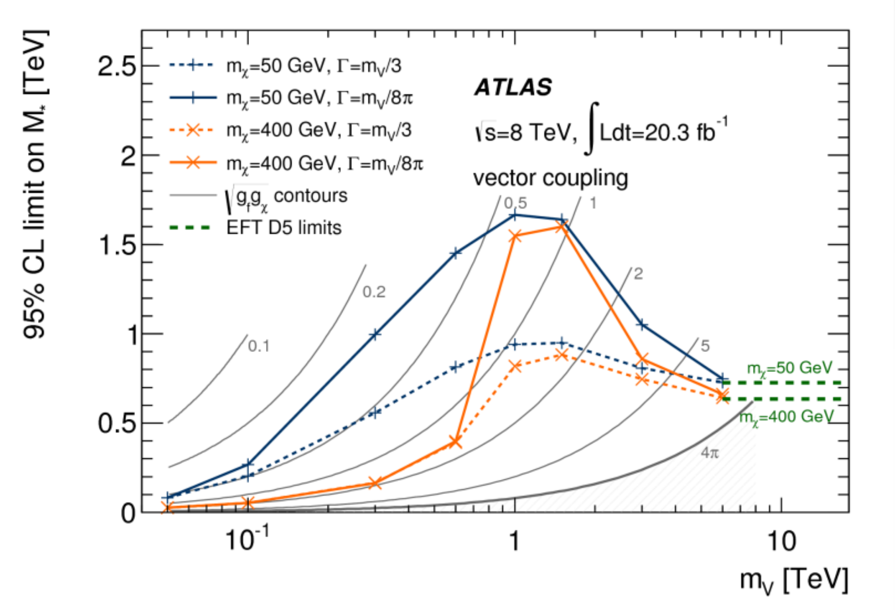
Photon + MET Results

Process	Event yield (SR)	Event yield (VR)
$Z(\to \nu\nu) + \gamma$	$389 \pm 36 \pm 10$	$153 \pm 16 \pm 10$
$W(\to \ell\nu) + \gamma$	$82.5 \pm 5.3 \pm 3.4$	$67 \pm 5 \pm 5$
$W/Z + \text{jet}, t\bar{t}, \text{diboson}$	$83 \pm 2 \pm 28$	$47 \pm 2 \pm 14$
$Z(\to \ell\ell) + \gamma$	$2.0 \pm 0.2 \pm 0.6$	$2.9 \pm 0.3 \pm 0.6$
$\gamma + \text{jet}$	$0.4^{+0.3}_{-0.4}$	$2.5^{+4.0}_{-2.5}$
Total background	$557 \pm 36 \pm 27$	$272 \pm 17 \pm 14$
Data	521	307

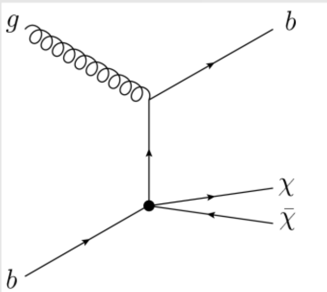


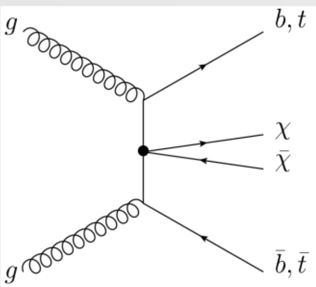
Data consistent with SM



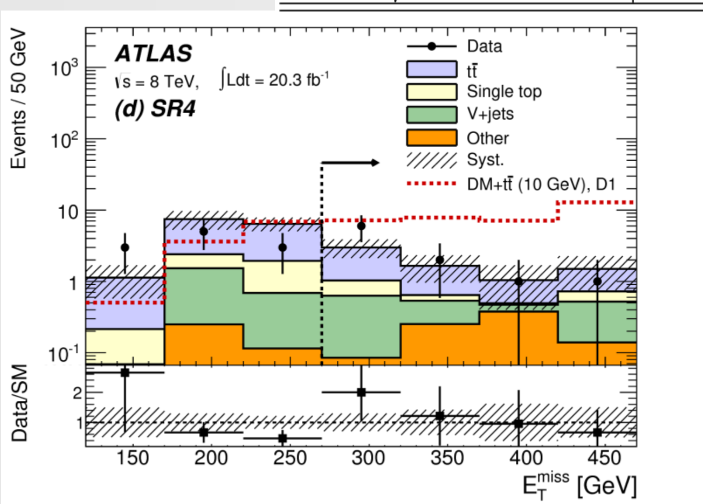


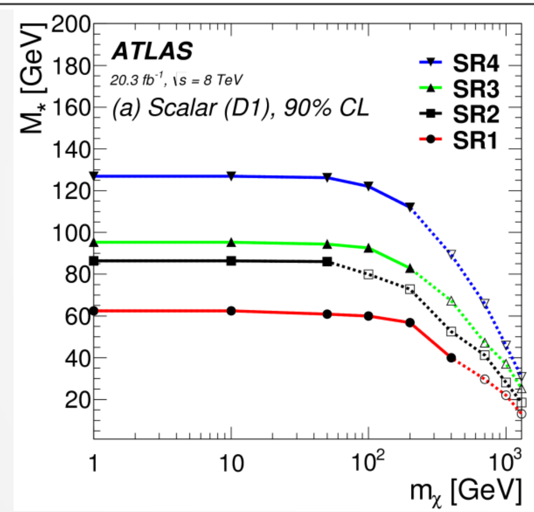
Heavy quark + MET Search





	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	$\geq$5	$\geq$4
b-jet multiplicity n_b	>0 (60% eff.)	>0 (60% eff.)	>1 (70% eff.)	>0 (70% eff.)
Lepton multiplicity n_ℓ	0	0	0	1 ℓ ($\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 $\sqrt{\mathrm{GeV}}$



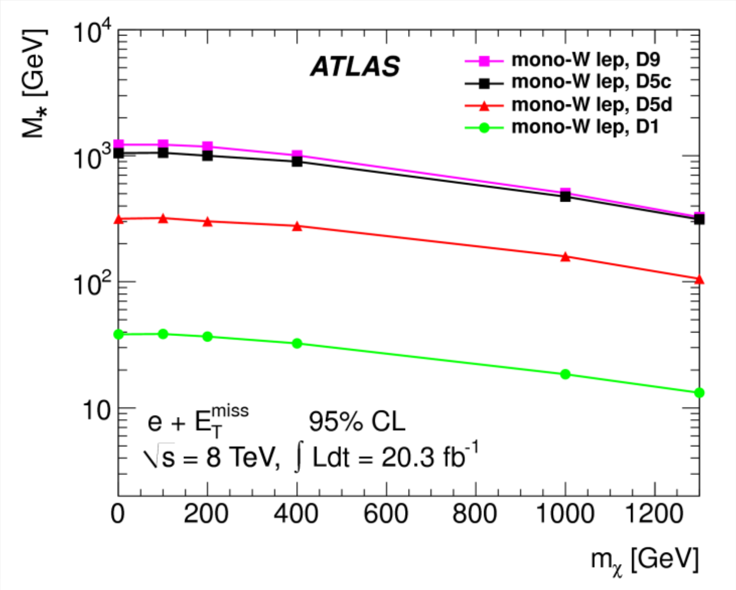


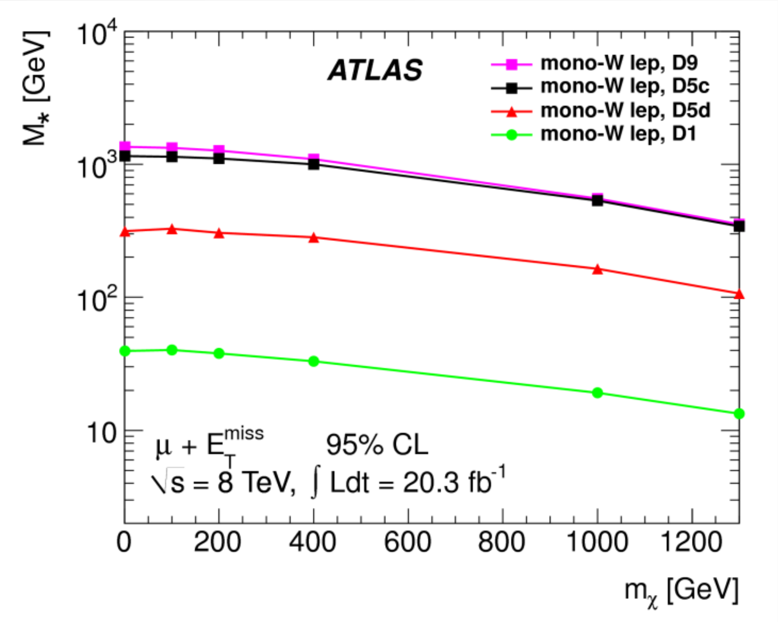
Eur. Phys. J. C (2015) 75:92

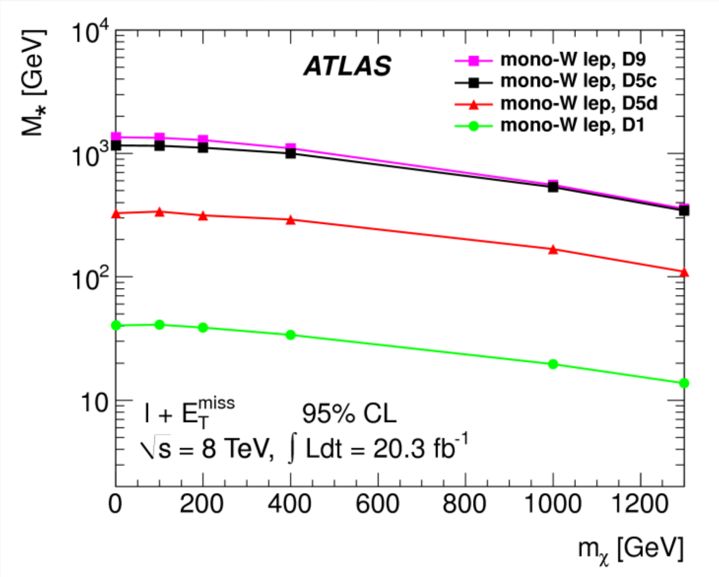
Lepton + MET Search

- W produced in association with DM pair
- Data consistent with SM
- Interpreted as limit on EFT

JHEP09(2014)037



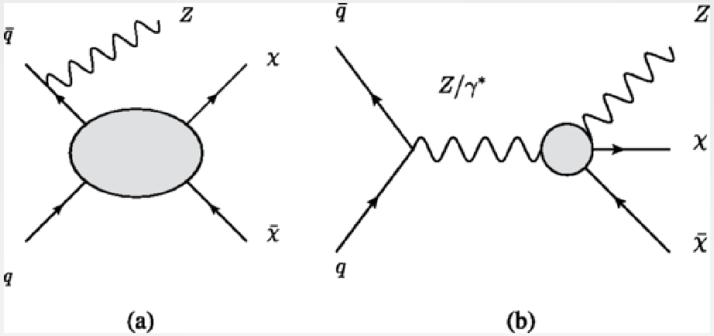


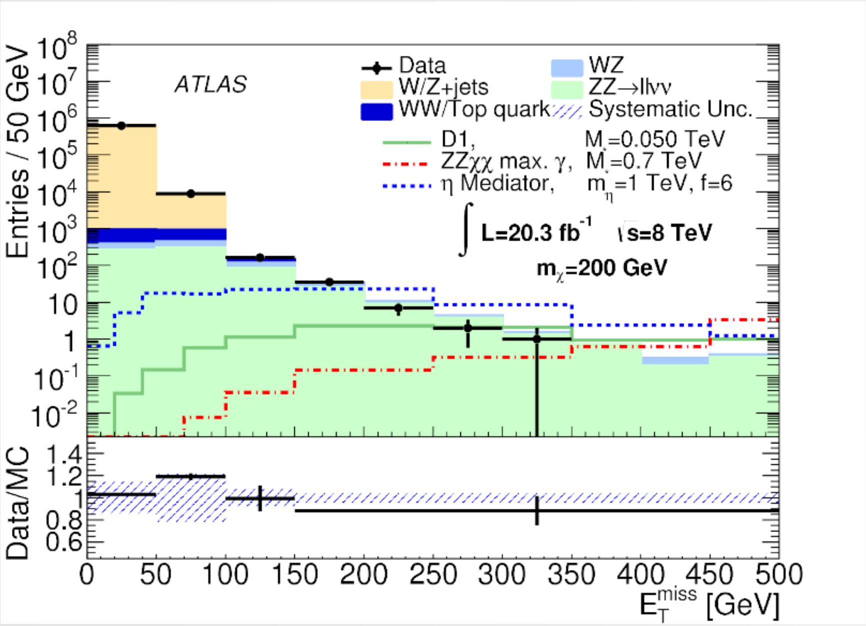


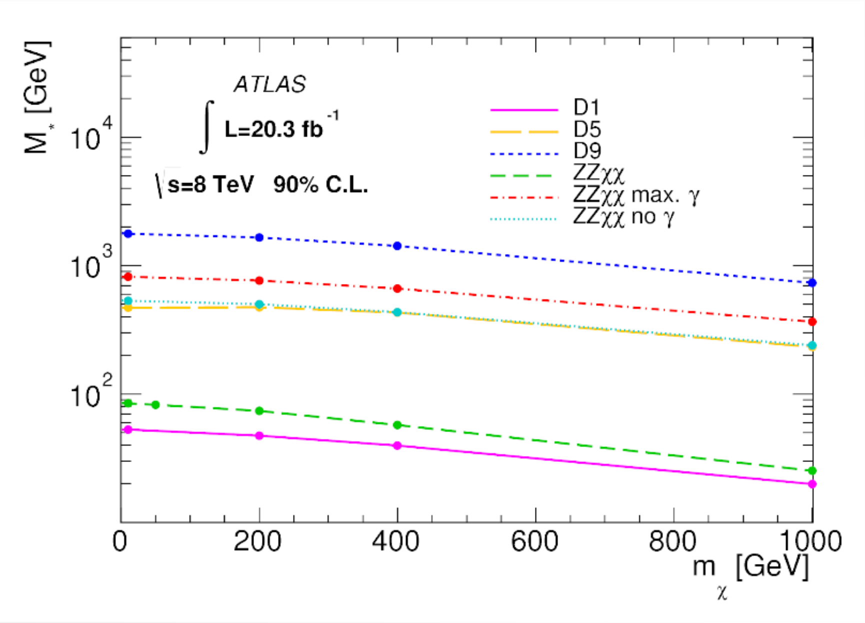
Z + MET Search

- Z->ll + MET signature
- l = electron, muon
- Consistent with SM

[Phys. Rev. D. 90, 012004 (2014)]

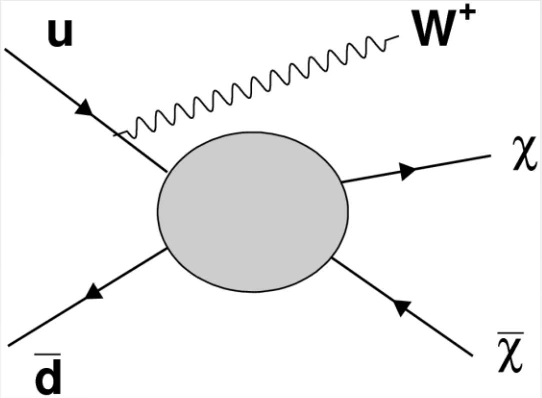




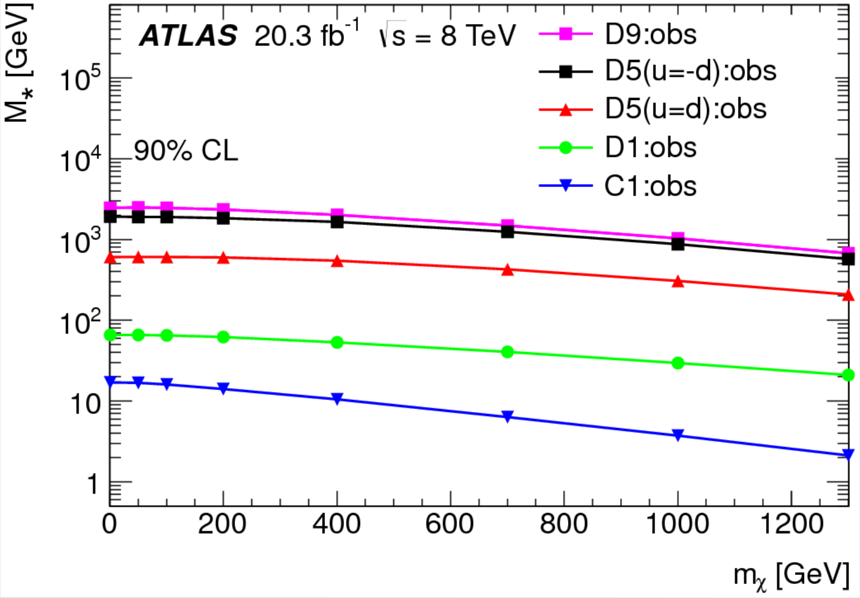


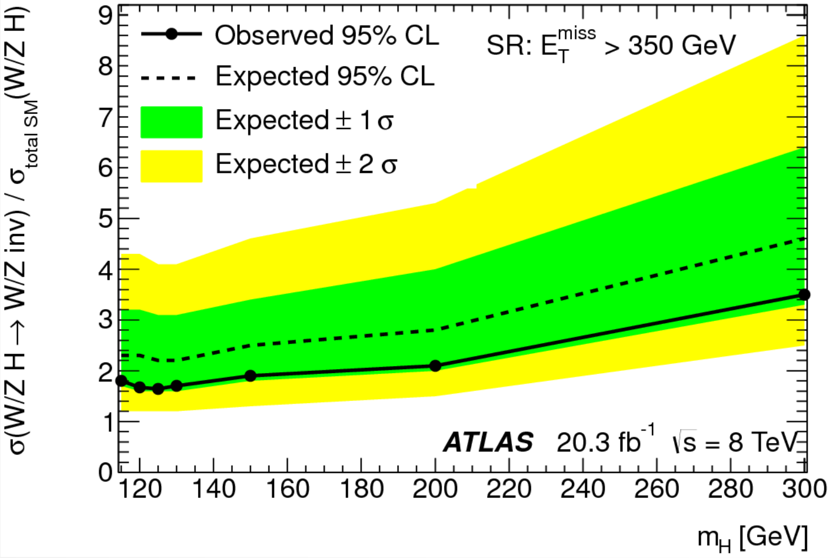
W/Z + MET Search

- DM pair produced in association with W/Z
- Hadronic decay of W/Z
- Similar to monojet
- ATLAS data consistent with SM



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

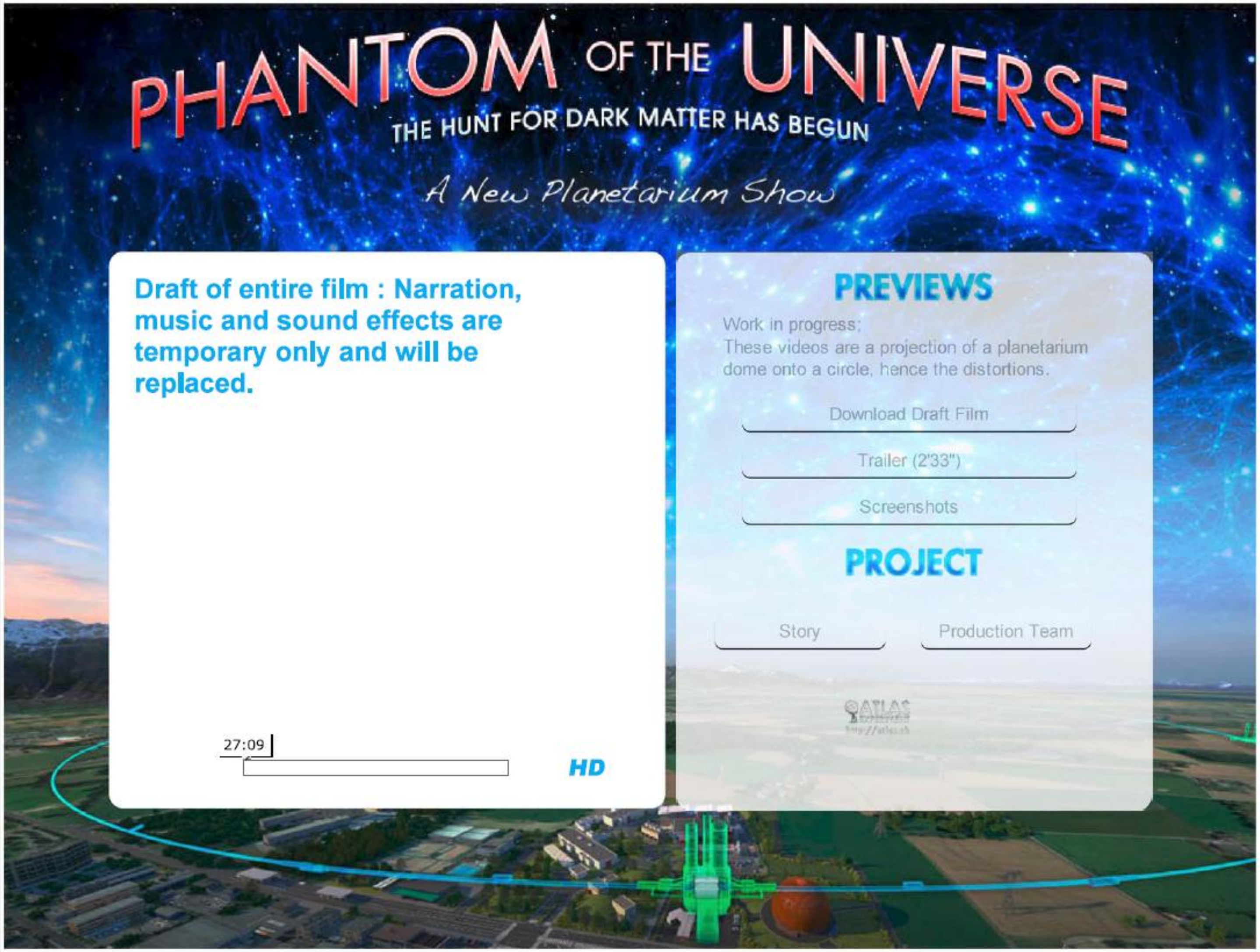




Conclusion

- Evidence for the nature of dark matter remains one of the oldest unsolved mysteries in physics
- Direct searches by the ATLAS experiment for dark matter produced in LHC pp collisions did not find any evidence during Run 1 at 8 TeV
- Other complimentary searches are also consistent with Standard Model
- Run 2 starting now at the LHC with 8 TeV -> 13 TeV CM energy can probe DM at higher scales
- In the meantime, we encourage you to look for…

Coming Soon to a Planetarium Near You



http://phantomoftheuniverse.com/

Backup Slides

EFT Operators Tested by ATLAS

Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

eg. J. Goodman et al., Phys. Rev. D 82 (2010) 116010