Search for Dark Matter in X+MET signatures at the LHC

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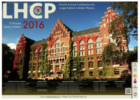
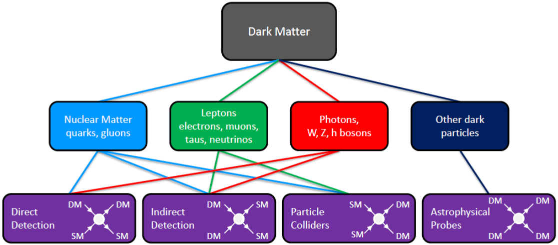


Thursday 16th June 2016

Collider Searches for Dark Matter

Though the presence of Dark Matter is well established, its particle content is an open question.

- Dark Matter - needed to explain:



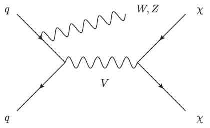
(from 1305.1605)

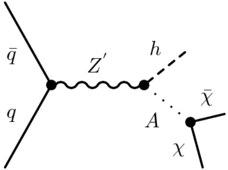
- WIMP dark matter is one attractive option.
  - Produced in early universe, now in thermal relic density.
  - Interaction with quarks via heavy mediator pair-production.
  - Search for signatures of Dark Matter at the LHC through tagging ISR, or searching for mediator production.

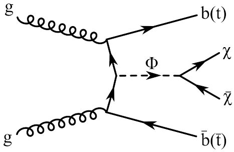
Introduction to X+MET DM searches

- Any WIMP DM produced at collider experiments will interact weakly and pass invisibly through the detector.
- Inferred through ‘Missing E_T’ (E_T^{miss}) when event does not balance in plane transverse to beam.

- Consequently, collider searches focus on events with production of a SM particle(s) (X) with large E_T^{miss}: X+MET
- Initial state radiation (photons, jet, vector bosons) can also be used to tag DM pair production.
- Lepton vetoes can be used to reduce backgrounds containing genuine sources of E_T^{miss}.





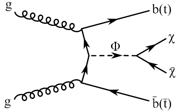


LHC Searches for WIMP Dark Matter

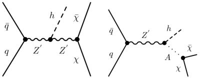
EFTs and simplified models [arXiv:1507.00966] [arXiv:1506.03116] [arxiv:1603.04156]

- Assume dark matter has very small couplings to the SM.
- Use information from astrophysics, detection experiments to focus search.
- Need a model for comparisons with astrophysics.
- The LHC can investigate and characterise the interaction between DM and SM.
- For Run-2, focus on simplified models, with mediator.

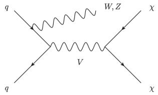
Assocated production:
Scalar/Pseudo-scalar model



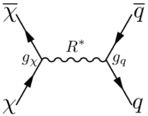
Higgs signatures



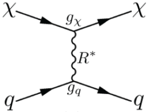
Vector model



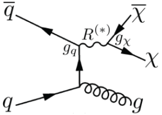
indirect detection



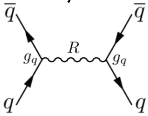
direct detection



mono-jets

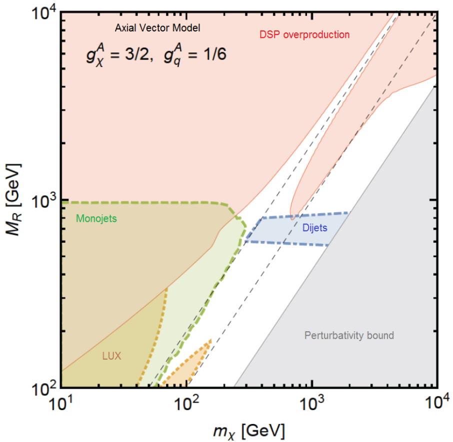


di-jets



Dark Matter at LHC

- Simplified models provide a solution to the question of Effective Field Theory (EFT) validity.
- Parameters: mediator mass, couplings to SM and DM, width, DM mass.
- Mediator also a discovery target - strength of LHC searches.
- Explore the complementarity of different channels.



(from 1503.05916)

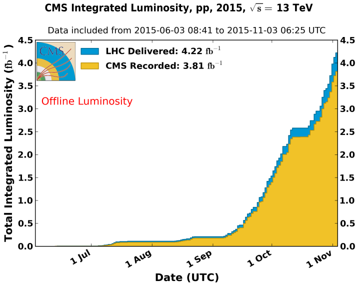
- Can also be investigated by EFT, with interactions between the WIMPs and SM particles.
- Caveat: momentum transfer must be below the EFT interaction

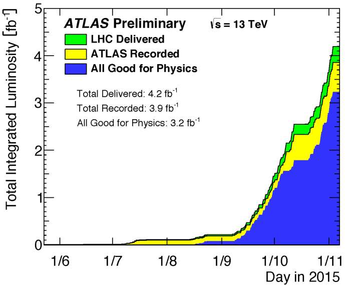
Outline

- LHC searches for Dark Matter in X+MET channels
  - (Mono-)jet plus E_T^{miss}
  - $\gamma/W/Z$ & E_T^{miss}
  - Dijet searches
  - Heavy quarks & E_T^{miss}
  - Higgs plus E_T^{miss}
- Conclusions & Outlook

More details tomorrow:

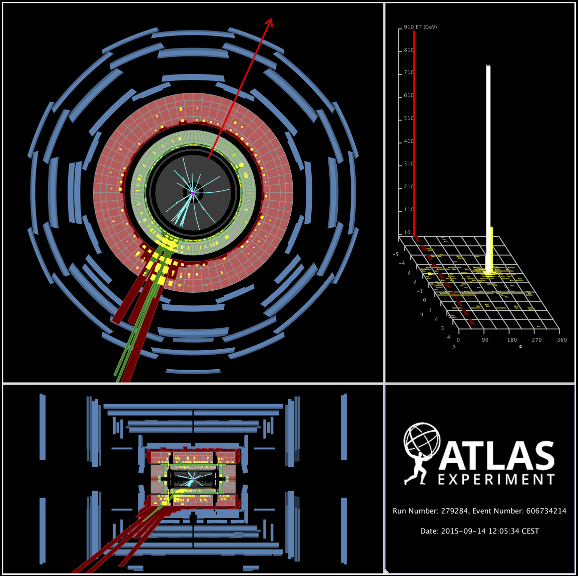
Ruth Pottgen & Bo Jayatilaka





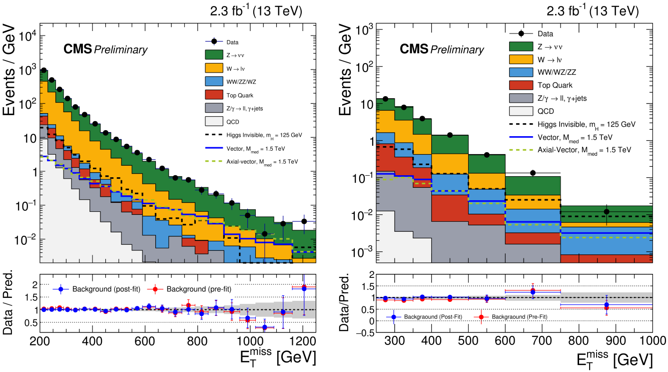
The highest E^{T}_{miss} monojet event in the 2015 ATLAS data

jet $p_T = 973$ GeV
$E^{T}_{\text{miss}} = 954$ GeV



Look for an excess of events with:

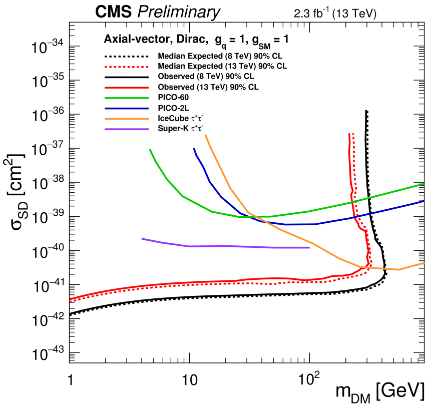
- $E_T^{miss} > 200$ GeV, $R = 0.8$ jet with $p_T > 250$ GeV
- Separate mono-V from monojet with $E_T^{miss} > 250$ and boson-tagging: ($65 < m_j < 105$, N-subjettiness: $\tau_2/\tau_1 < 0.6$).
  - The post-fit signal regions for monojet (L) and mono-V (R):



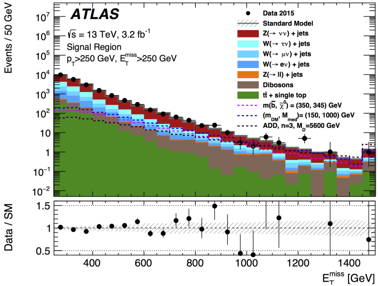
Mono-jet (2) (incl. V→qq) [CMS-PAS-EXO-16-013]

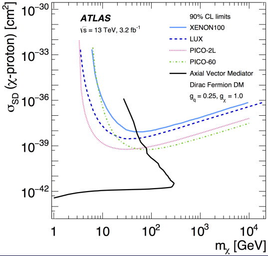
- Z/W+jets backgrounds estimated with ten CRs: 1-/2-e/μ,γ+jets
- Orthogonal by SR lepton/photon vetoes.
- Model SM E_T^{miss}shape in SR.
- $g_q = 1, g_{SM} = 1$:

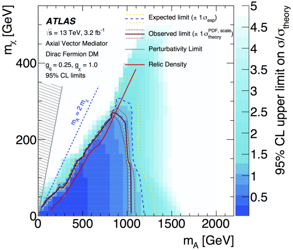
Vector/axial-vector mediators $<$ 1.3 TeV excluded.



- Look for events with a jet, $p_T > 250$ GeV, $E_T^{miss} > 250$ GeV, separated from any jet with $p_T > 30$ GeV.
- Lepton veto.
- W/Z+jets estimated with simultaneous fit in (1e,1-/2-μ) control regions.

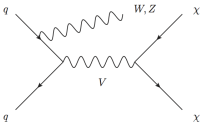


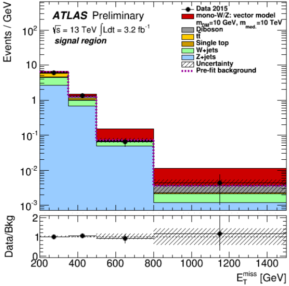


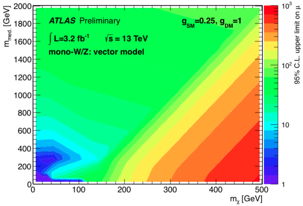


- Non-collision and multijet rates from data.
- m_χ excluded up to 250 GeV for $g_q = 0.25$.

Mono-W/Z Search [ATLAS-CONF-2015-080]



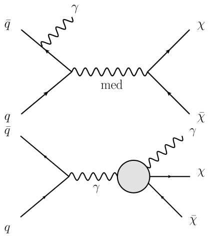




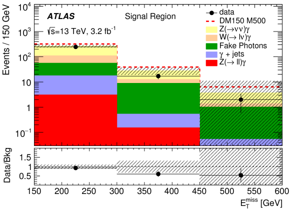
- Tag ISR boson.
- Look for a boosted boson recoiling against DM particles.
- Search for an R=1.0 jet and E_T^{miss}(>250 GeV), tagging bosons using jet mass and D_2 (dominant uncertainty $\sim$ 10 %).
- Main backgrounds: W+jets, Z+jets and $t\bar{t}$.
- Vector-mediated simplified model - already probing low m_χ with 2015 data!

Boson + E_T^{miss} DM searches

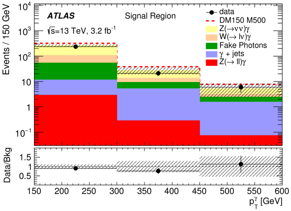
Mono-photon search (I) [arxiv:1604.01306]



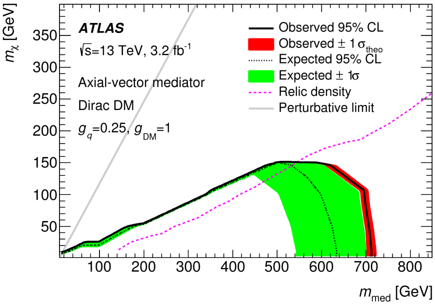
Signal region: $E_T^{\rm miss}$

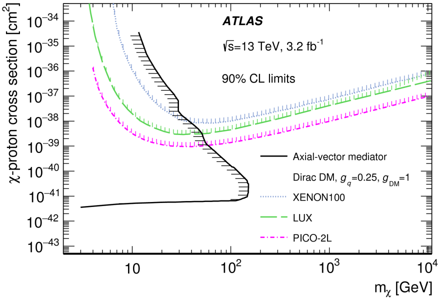


Photon p_T



- Look for high $p_T (> 150$ GeV) photon, opposite E_T^{miss}.
- Use 1-/2-μ, 2-el, and lower E_T^{miss} γ-jet CRs to estimate backgrounds (Z($\nu\nu$)+γ, W/Z+γ, γ+jets). Lepton veto.
- Dominant uncertainties: statistics (9%), e$\rightarrow\gamma$ fake factor (6%)



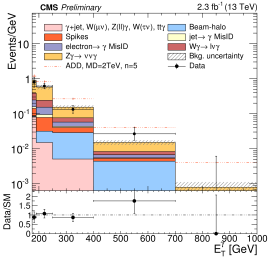


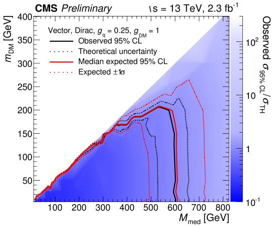
- Interpretation via Axial-vector model.
- For large g_{DM}, rule out a large range of mediator masses with $m_\chi < 150$ GeV.
- Limits on the EFT: $\gamma\gamma\chi\chi$
- Stringent DM cross-section limits at low masses.

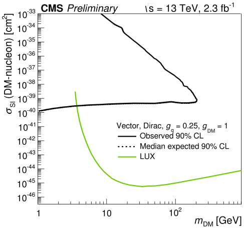
Boson + E_T^{miss} Dark Matter Searches

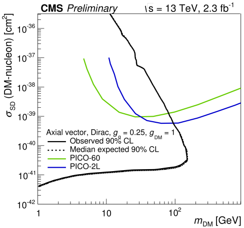
mono-photon search CMS-PAS-EXO-16-014

- Isolated γ, $p_T > 175$ GeV,$|\eta| < 1.44$
- $E_T^{miss} > 170$ GeV.
- $Z/W + \gamma$ from MC and CR, data-driven estimate of e/jets mis-identified as γ.
- Limits set on vector/axial-vector mediator scenarios.





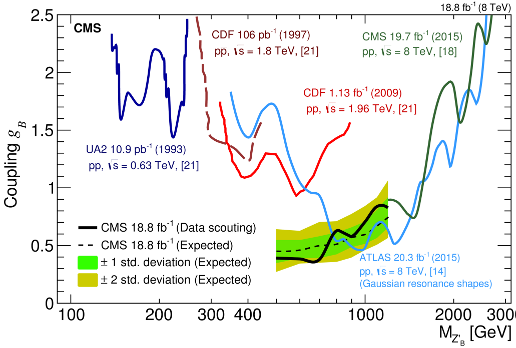




Jet Dark Matter Searches

Looking for DM mediators with jets - challenges [arXiv:1604.08907] [arXiv:1512.01530]

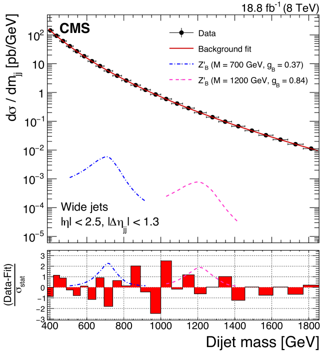
- High-mass searches provide constraints for massive mediators.
- Weaker constraints at lower masses, due to the large prescales on triggers.
- Need alternative approaches to access mediators below $\sim$ 1 TeV.
- Complementary strategies...



Jet Dark Matter Searches

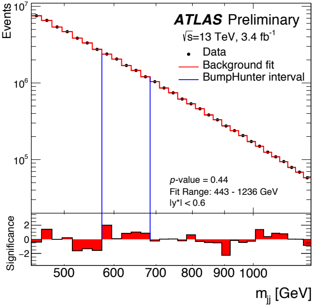
Trigger Level Analysis [arXiv:1604.08907] [ATLAS-CONF-2016-030]

- Write out trigger jets for all events with $H_T > 250$ GeV, (jet $p_T > 40$ GeV).
- Considerable improvement on sensitivity at lower masses.



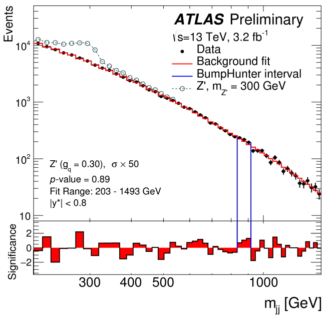
Record trigger jets in events with an L1 trigger jet $E_T > 75$ GeV:

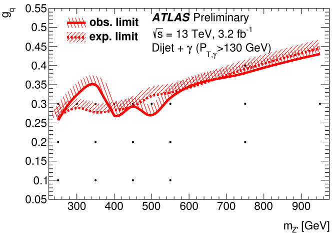
- $p_T > 185$ GeV, $|y^*| < 0.6$
- Use reduced y^* cut (< 0.3) to access lowest masses.



Search for resonances decaying to a jet pair in association with a photon from ISR.

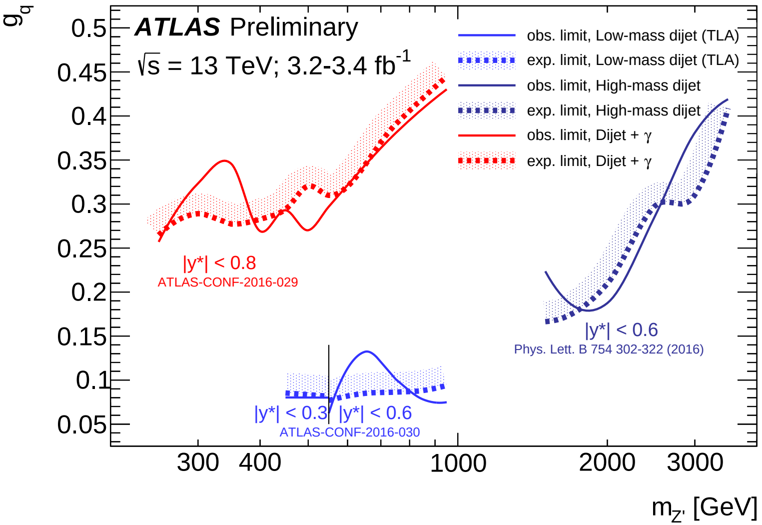
- Use a lower p_T ISR photon to access lower resonance masses.
- Trigger on the event with the photon, and construct dijet m_{jj}, down to 200 GeV.
  - γ, $p_T > 130$ GeV, and 2+ jets ($p_T > 25$ GeV).
  - Photon separated from closest jet by $\Delta R > 0.85$.
  - $y_{jj} = |y_{j1} - y_{j2}|/2 < 0.8$
- Background fit with functional form, as for dijet analysis.
- Exclude masses down to 250 GeV ($g_{SM} > 0.26$).



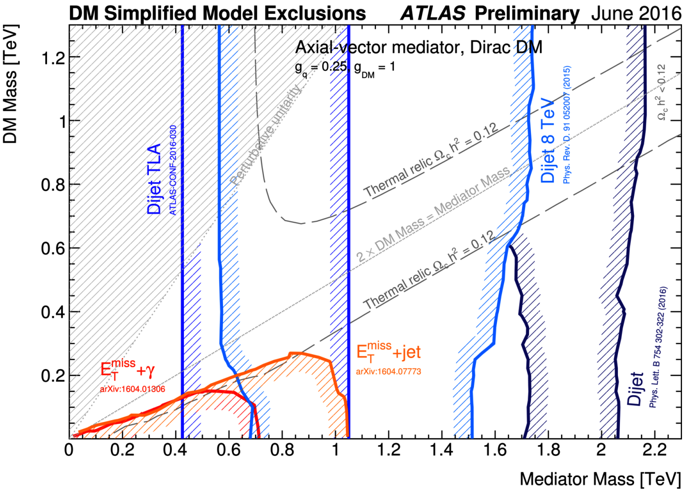


Low mass summary (with 13 TeV high-mass)

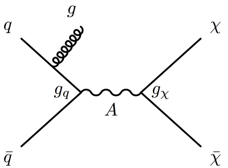
[ATLAS-CONF-2016-029 & ATLAS-CONF-2016-030] & [arxiv:1512.01530]



Mono-jet and Dijet Complementarity



- Relative exclusion power depends on the relative model couplings, g_q and $g_{DM} = g_\chi$.

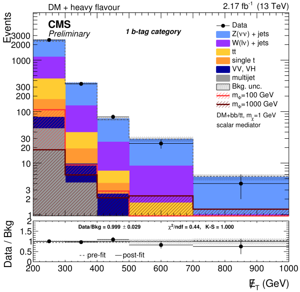


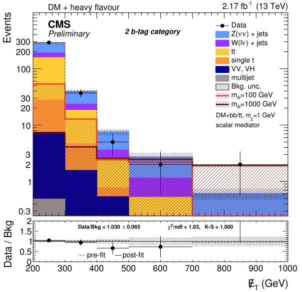
Heavy flavour DM searches

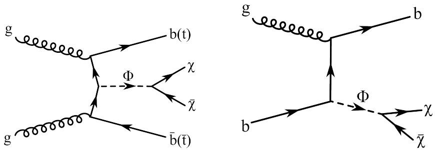
mono-b searches

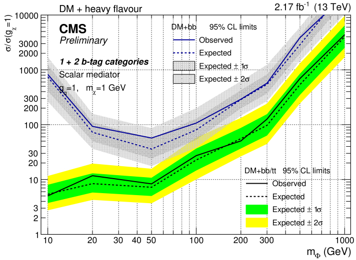
CMS-PAS-B2G-15-007

- Search for DM in association with one or more b/t-quarks.
- Important for (pseudo-)scalar mediators.







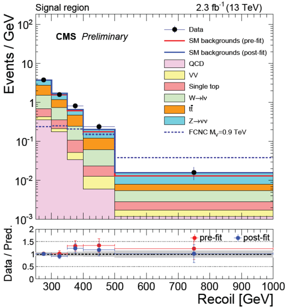


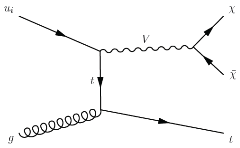
- E_T^{miss}> 200 GeV, lepton veto, require 1(2) b-tagged jets with $p_T > 50$ GeV.

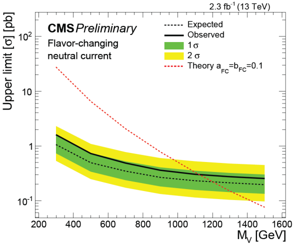
Heavy Flavour Dark Matter Searches

mono-top searches CMS-PAS-EXO-16-017

- Hadronic top decay in association with E_T^{miss}.
- Select b-tagged large-R jet with $110 < m < 210$ GeV, τ_3/τ_2, with $E_T^{miss} > 250$ GeV.
- Veto extra b-tags or charged leptons.
- E_T^{miss} search, using 1/2-e/μ,γ+jet regions.

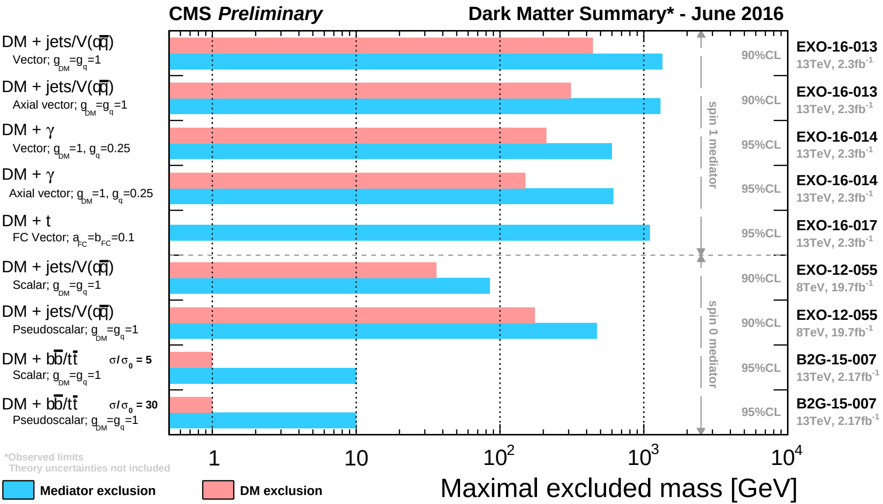






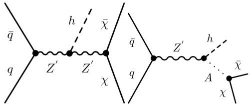
For $a_{FC} = b_{FC} = 0.1$, mass exclusion $M_V = 300 - 1100$ GeV.

DM Mediator Mass Summary

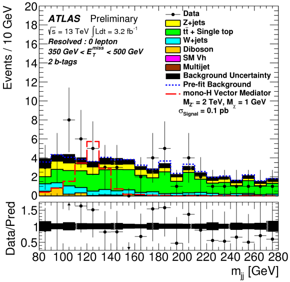


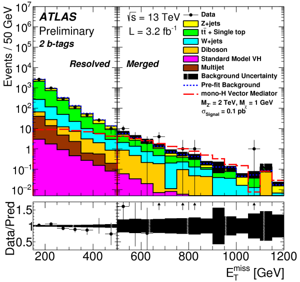
Searches in Higgs channels

mono-Higgs searches - bb channel ATLAS-CONF-2016-019

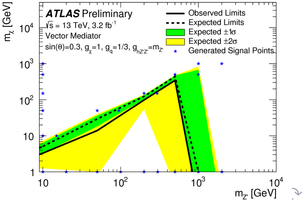


- Higgs could couple to dark sector too.
- Boosted and 3 resolved channels (E_T^{miss}), 2 b-tags.



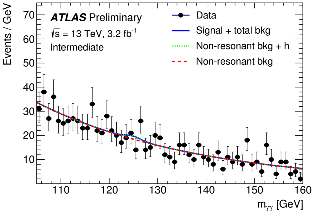


- Main backgrounds: W/Z+jets, $t\bar{t}$ - estimated from 1-/2-lepton control regions.
- Z' vector model. $g_{DM} = 1, g_q = 1/3$.
  - $m_{Z'} < 900$ GeV is excluded.
  - Constraints on 2HDM, $m_A < 500$ GeV

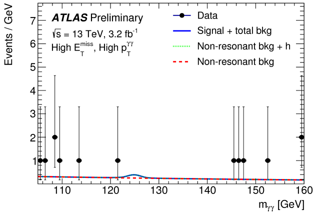


- Look for H boson recoiling against DM.
- 4 signal regions.

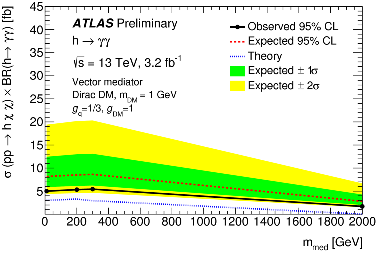
$50 < E_T^{miss} < 100$ GeV, $p_T^{jets+\gamma} > 40$ GeV



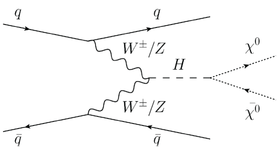
$E_T^{miss} > 100$ GeV, $p_T^{\gamma\gamma} > 100$ GeV

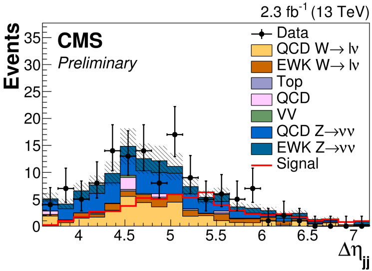


- Signal and background are estimated with functional fit to $m_{\gamma\gamma}$ distribution.
  - Statistical error dominates.
  - Vector simplified model
  - Heavy scalar interpretation.

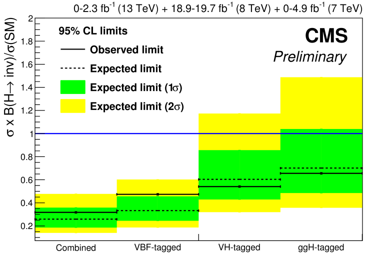


 CMS-PAS-HIG-16-009



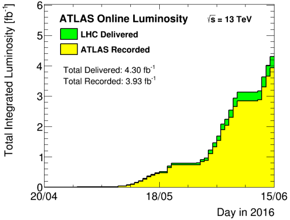


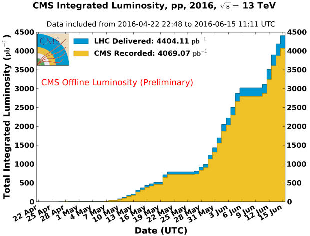
- Look for VBF Higgs decay to invisibles.
- Signal and background yields from fits to control regions
  - Z($\mu\mu$), W($e\nu$,$\mu\nu$,$\tau\nu$), multijet.
- Limit on invisible BF is 69% from 2015 data, improving to 32% with Run-1 combination.



Conclusions and Outlook

- The LHC machine and experiments performed very well during the start of LHC Run-2 in 2015.
- Wide range of DM channels being probed with 2015 data.
- Important part of the LHC programme, with new techniques and methodologies.
- Simplified models provide framework for comparison of other channels, direct and indirect detection experiments.
  - Common set of benchmark models.

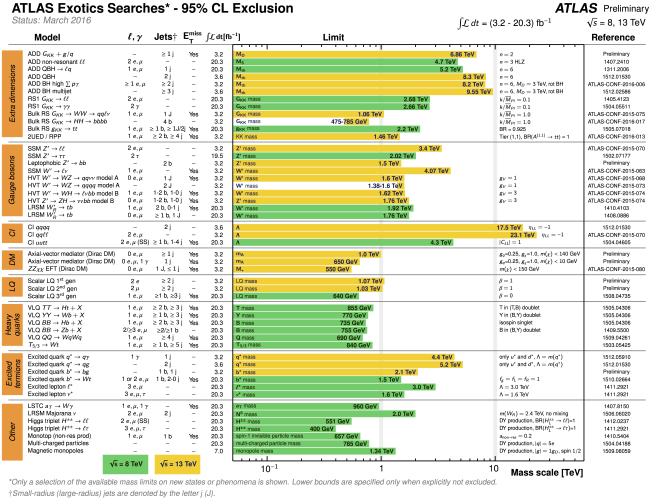




- 2016 data will bring greater sensitivity - Many more results with 13 TeV data coming soon!
- Great complementarity with non-LHC experiments

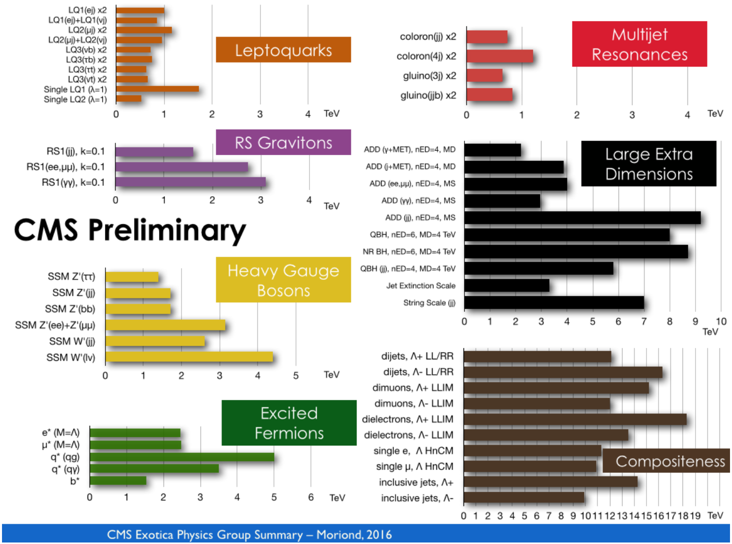
BACKUP SLIDES

Summary of ATLAS Exotics Results



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

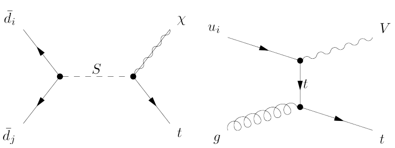
Summary of CMS Exotics Results

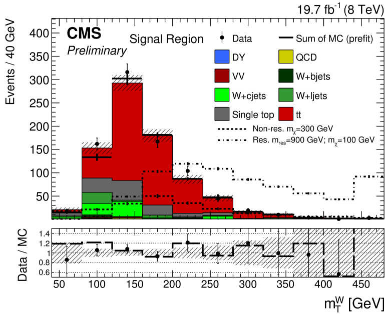


http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/index.html

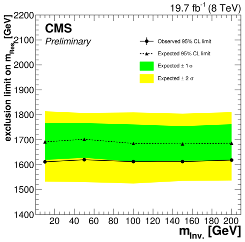
Heavy Flavour Dark Matter Searches

mono-top searches CMS-PAS-B2G-15-001





- Leptonic top quark decay in association with E_T^{miss}.

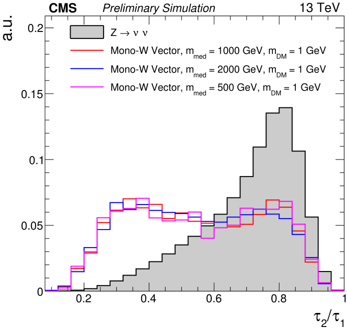


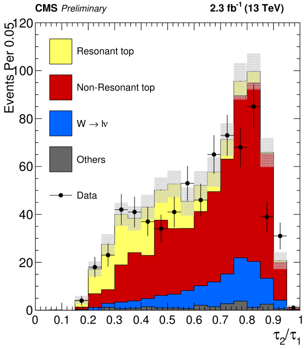
- Isolated muon, $p_T^W > 50$ GeV, 1 b-tagged jet ($p_T > 70$ GeV), $E_T^{miss} > 100$ GeV.
- Look for broadening of M_T^W.
- Model W+jets, $t\bar{t}$ fit in control regions.
- For $a = 0.1$, scalar masses below 1610 GeV excluded.

Jet Dark Matter Searches

Mono-jet (inc. V→qq) [CMS-PAS-EXO-16-013]

E_T^{miss} Range (GeV)	$Z(\nu\nu)$+jets	$W(\ell\nu)$+jets	$Z(\ell\ell)$+jets	γ+jets	Top	Diboson	QCD	Total (Pre-fit)	Total (Post-fit)	Data
250 – 300	354 ± 17	244 ± 14	3.2 ± 1.0	3.5 ± 1.8	33 ± 9	41 ± 9	0.63 ± 0.69	744 ± 38	680 ± 21	666
300 – 350	239 ± 15	133 ± 9	2.5 ± 0.9	2.9 ± 1.2	12 ± 4	26 ± 6	0.17 ± 0.15	450 ± 21	416 ± 15	393
350 – 400	115 ± 8	52 ± 4	1.0 ± 0.5	1.5 ± 1.0	6.6 ± 2.1	12 ± 3	0.12 ± 0.10	210 ± 10	189 ± 9	196
400 – 500	94 ± 74	32 ± 3	0.23 ± 0.19	0.4 ± 0.3	2.8 ± 1.0	8.9 ± 2.2	0.03 ± 0.02	155 ± 7	138 ± 8	141
500 – 600	29 ± 3	8.2 ± 1.1	0.03 ± 0.04	0.5 ± 0.3	0.5 ± 0.2	3.8 ± 1.1	0 ± 0	45 ± 2	42 ± 4	41
600 – 750	11 ± 2	2.9 ± 0.5	0.01 ± 0.01	0.23 ± 0.12	0.24 ± 0.25	1.6 ± 0.6	0 ± 0	15 ± 1	16 ± 2	20
> 750	2.8 ± 0.8	0.4 ± 0.1	0.01 ± 0.00	0.01 ± 0.01	0.18 ± 0.07	0.92 ± 0.41	0 ± 0	5.4 ± 0.6	4.3 ± 0.9	3





Jet Dark Matter Searches

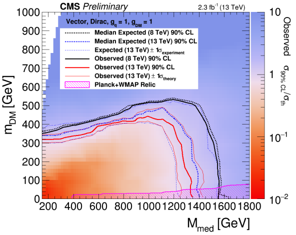
Mono-jet (inc. V→qq) (1) [CMS-PAS-EXO-16-013]

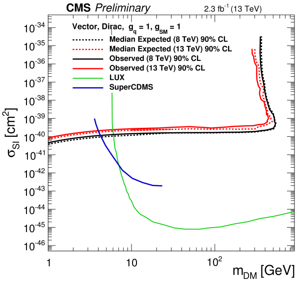
E_T^{miss} Range (GeV)	$Z(\nu\nu)$+jets	$W(\ell\nu)$+jets	$Z(\ell\ell)$+jets	γ+jets	Top	Diboson	QCD	Total (Pre-fit)	Total (Post-fit)	Data
$200-230$	14919 ± 221	11976 ± 196	207 ± 13	230 ± 14	564 ± 55	251 ± 41	508 ± 171	27761 ± 1464	28654 ± 171	28601
$230-260$	7974 ± 116	5776 ± 101	92.9 ± 5.7	101 ± 6	267 ± 26	157 ± 26	308 ± 104	14114 ± 757	14675 ± 97	14756
$260-290$	4467 ± 70	2867 ± 50	37.9 ± 2.3	63.7 ± 3.9	116 ± 11	77.3 ± 12.7	38.3 ± 21.0	7193 ± 351	7666 ± 68	7770
$290-320$	2518 ± 46	1520 ± 34	18.4 ± 1.1	29.6 ± 1.8	56.7 ± 5.6	42.9 ± 7.1	29.8 ± 10.5	4083 ± 204	4215 ± 48	4195
$320-350$	1496 ± 35	818 ± 20	10.0 ± 0.6	19.7 ± 1.2	33.6 ± 3.3	25.4 ± 4.2	9.0 ± 5.4	2385 ± 118	2407 ± 37	2364
$350-390$	1204 ± 31	555 ± 15	3.9 ± 0.2	12.7 ± 0.8	24.5 ± 2.4	22.1 ± 3.6	6.0 ± 3.5	1817 ± 87	1826 ± 32	1875
$390-430$	684 ± 20	275 ± 9	2.1 ± 0.1	8.3 ± 0.5	9.8 ± 1.0	13.9 ± 2.3	3.0 ± 1.6	978 ± 45	998 ± 23	1006
$430-470$	382 ± 14	155 ± 6	0.96 ± 0.06	4.9 ± 0.3	9.4 ± 0.9	6.6 ± 1.1	1.0 ± 0.8	589 ± 30	574 ± 17	543
$470-510$	248 ± 11	87.3 ± 3.8	0.47 ± 0.03	3.7 ± 0.2	0.22 ± 0.02	5.1 ± 0.8	0.65 ± 0.44	337 ± 15	344 ± 12	349
$510-550$	160 ± 8	52.2 ± 2.7	0.23 ± 0.01	2.0 ± 0.1	2.7 ± 0.3	2.2 ± 0.4	0.28 ± 0.19	211 ± 9	219 ± 9	216
$550-590$	99.5 ± 6.0	29.2 ± 1.9	0.12 ± 0.01	1.8 ± 0.1	0.94 ± 0.09	2.0 ± 0.3	0.19 ± 0.14	134 ± 6	134 ± 7	142
$590-640$	77.3 ± 4.9	18.9 ± 1.4	0.09 ± 0.01	0.46 ± 0.03	< 0.13	1.7 ± 0.3	0.11 ± 0.08	100 ± 4	98.5 ± 5.8	111
$640-690$	44.8 ± 3.5	11.2 ± 0.9	0.017 ± 0.001	0.19 ± 0.01	< 0.13	1.5 ± 0.2	0.06 ± 0.05	59.6 ± 2.6	58.0 ± 4.1	61
$690-740$	27.8 ± 2.5	6.1 ± 0.6	0.013 ± 0.0008	0.57 ± 0.04	< 0.13	0.69 ± 0.11	0.02 ± 0.02	36.6 ± 1.5	35.2 ± 2.9	32
$740-790$	21.8 ± 2.3	5.3 ± 0.6	< 0.005	0.28 ± 0.02	0.23 ± 0.02	0.11 ± 0.02	0.02 ± 0.02	23.8 ± 1.0	27.7 ± 2.7	28
$790-840$	13.5 ± 1.9	2.8 ± 0.4	< 0.005	0.18 ± 0.01	0.27 ± 0.03	0.010 ± 0.001	0.008 ± 0.007	15.3 ± 0.7	16.8 ± 2.2	14
$840-900$	9.5 ± 1.4	2.0 ± 0.3	< 0.005	0.28 ± 0.02	< 0.13	0.25 ± 0.04	< 0.008	12.2 ± 0.6	12.0 ± 1.6	13
$900-960$	5.4 ± 1.0	1.1 ± 0.2	< 0.005	< 0.08	< 0.13	0.37 ± 0.06	< 0.008	7.6 ± 0.3	6.9 ± 1.2	7
$960-1020$	3.3 ± 0.8	0.77 ± 0.21	< 0.005	0.12 ± 0.01	< 0.13	0.23 ± 0.04	< 0.008	5.2 ± 0.3	4.5 ± 1.0	3
$1020-1160$	2.5 ± 0.8	0.52 ± 0.16	< 0.005	< 0.08	< 0.13	0.16 ± 0.03	< 0.008	3.6 ± 0.2	3.2 ± 0.9	1
$1160-1250$	1.7 ± 0.6	0.3 ± 0.11	< 0.005	< 0.08	< 0.13	0.16 ± 0.03	< 0.008	2.3 ± 0.1	2.2 ± 0.7	2
> 1250	1.4 ± 0.5	0.19 ± 0.08	< 0.005	< 0.08	< 0.13	0.06 ± 0.01	< 0.008	1.6 ± 0.1	1.6 ± 0.6	3

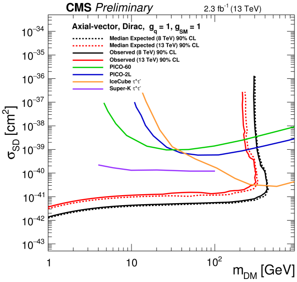
Jet Dark Matter Searches

Mono-jet (inc. V→qq) (2)

[CMS-PAS-EXO-16-013]







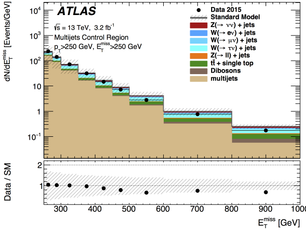
Jet Dark Matter Searches

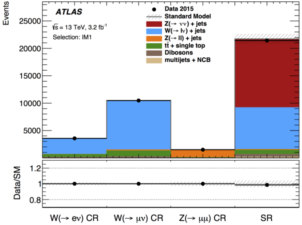
Mono-jet (3) [arXiv:1604.07773]

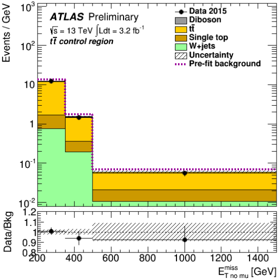
Selection criteria							
Primary vertex							
$E_T^{miss} > 250$ GeV							
Leading jet with $p_T > 250$ GeV and $\|\eta\| < 2.4$							
At most four jets with $p_T > 30$ GeV and $\|\eta\| < 2.8$							
$\Delta\phi(\text{jet}, \vec{p}_T^{miss}) > 0.4$							
Jet quality requirements							
No identified muons with $p_T > 10$ GeV or electrons with $p_T > 20$ GeV							
Inclusive signal region	IM1	IM2	IM3	IM4	IM5	IM6	IM7
E_T^{miss} (GeV)	> 250	> 300	> 350	> 400	> 500	> 600	> 700
Exclusive signal region	EM1	EM2	EM3	EM4	EM5	EM6	
E_T^{miss} (GeV)	[250–300]	[300–350]	[350–400]	[400–500]	[500–600]	[600–700]	

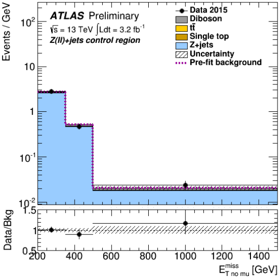
Signal Region	IM1	EM3	EM5	IM7
Observed events (3.2 fb^{-1})	21447	2939	747	185
SM prediction	21730 ± 940	3210 ± 170	686 ± 50	167 ± 20
$W(\to e\nu)$	1710 ± 170	228 ± 26	37 ± 7	7 ± 2
$W(\to \mu\nu)$	1950 ± 170	263 ± 28	44 ± 8	11 ± 2
$W(\to \tau\nu)$	3980 ± 310	551 ± 47	101 ± 15	19 ± 4
$Z/\gamma^*(\to e^+e^-)$	0.01 ± 0.01	–	–	–
$Z/\gamma^*(\to \mu^+\mu^-)$	76 ± 30	9 ± 5	5 ± 2	2 ± 1
$Z/\gamma^*(\to \tau^+\tau^-)$	48 ± 7	5 ± 1	0.9 ± 0.2	0.2 ± 0.1
$Z(\to \nu\bar{\nu})$	12520 ± 700	1940 ± 130	443 ± 42	109 ± 18
$t\bar{t}$, single top	780 ± 240	108 ± 32	19 ± 7	3 ± 1
Dibosons	506 ± 48	82 ± 8	36 ± 5	15 ± 2
Multijets	51 ± 50	6 ± 6	1 ± 1	0.4 ± 0.4
Non-collision background	110 ± 110	19 ± 19	–	–

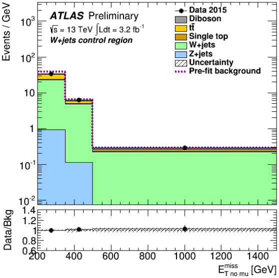
Signal Region	IM1	IM2	IM3	IM4	IM5	IM6	IM7
Observed events (3.2 fb^{-1})	21447	11975	6433	3494	1170	423	185
SM prediction	21730 ± 940	12340 ± 570	6570 ± 340	3390 ± 200	1125 ± 77	441 ± 39	167 ± 20
Signal Region	EM1	EM2	EM3	EM4	EM5	EM6	
Observed events (3.2 fb^{-1})	9472	5542	2939	2324	747	238	
SM prediction	9400 ± 410	5770 ± 260	3210 ± 170	2260 ± 140	686 ± 50	271 ± 28	

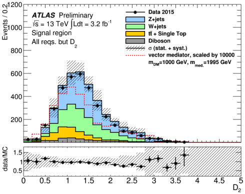












Process	events
Z+jets	519 ± 31
W+jets	326 ± 22
$t\bar{t}$ and single-top	217 ± 18
Diboson	88 ± 12
Total Background	1150 ± 30
Data	1143

Boson + E_T^{miss} DM searches

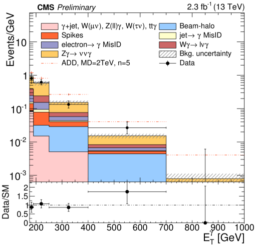
Mono-photon search (I)

[arxiv:1604.01306]

	SR	1muCR	2muCR	2eleCR	PhJetCR
Observed events	264	145	29	20	214
Fitted Background	295±34	145±12	27±4	23±3	214±15
$Z(\to \nu\nu)\gamma$	171±29	0.15±0.03	0.00±0.00	0.00±0.00	8.6±1.4
$W(\to \ell\nu)\gamma$	58±9	119±17	0.14±0.04	0.11±0.03	22±4
$Z(\to \ell\ell)\gamma$	3.3±0.6	7.9±1.3	26±4	20±3	1.2±0.2
γ + jets	15±4	0.7±0.5	0.00±0.00	0.03±0.03	166±17
Fake photons from electrons	22±18	1.7±1.5	0.05±0.05	0.00±0.00	5.8±5.1
Fake photons from jets	26±12	16±11	1.1±0.8	2.5±1.3	9.9±3.1
Pre-fit background	249±29	105±14	23±2	19±2	209±50

Total background	295
Total background uncertainty	11%
Electron fake rate	5.8%
PDF uncertainties	2.8%
Jet fake rate	2.4%
Muons reconstruction/isolation efficiency	1.5%
Electrons reconstruction/identification/isolation efficiency	1.3%
Jet energy resolution [62]	1.2%
Photon energy scale	0.6%
E_T^{miss} soft term scale and resolution	0.4%
Photon energy resolution	0.2%
Jet energy scale [50]	0.1%

Process	Estimate
$Z(\to \nu\bar{\nu}) + \gamma$	41.7 ± 5.9
$W(\to \ell\nu) + \gamma$	10.6 ± 1.5
$W \to e\nu$	7.3 ± 0.7
jet $\to \gamma$ fakes	1.7 ± 0.6
Beam halo	5.9 ± 4.7
Spikes	5.6 ± 2.2
ttγ	1.5 ± 0.1
$W\mu\nu$	0.9 ± 0.7
$Z(\ell\ell)\gamma$	0.5 ± 0.04
$\gamma + jet$	0.01 ± 0.01
Total background	76.0 ± 8.1
Data	77

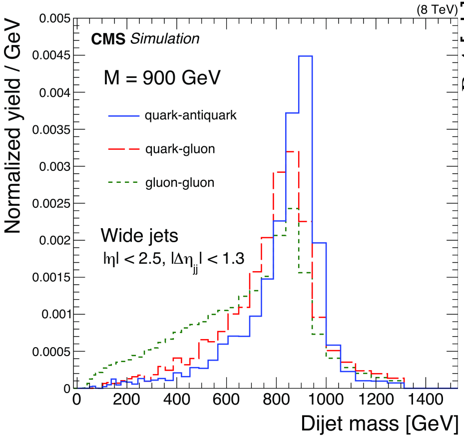


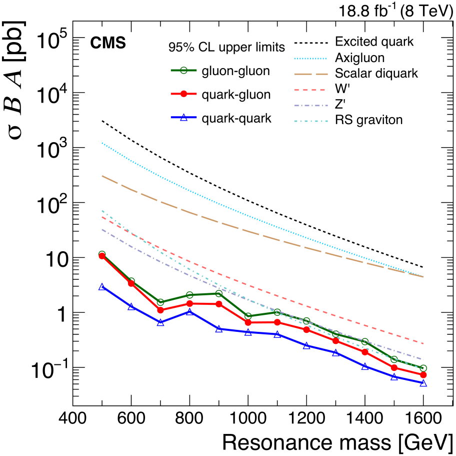
Sources	$Z(\nu\bar{\nu}) + \gamma$	Wγ	Jets faking γ	Electron faking γ	jet+γ	Beam Halo	Spikes	Other bkgs
Luminosity	2.7%	2.7%	-	-	2.7%	-	-	2.7%
PDF and Scale	5.4%	8.9%	-	-	-	-	-	-
EWK corrections	11%	7%	-	-	-	-	-	-
Jets faking γ	-	-	35%	-	-	-	-	-
Elecron faking γ	-	-	-	8%	-	-	-	-
Jet+γ	-	-	-	-	100%	-	-	-
Jet, $\not{E}_T$, γ energy scale	3.2%	4.2%	-	-	3%	-	-	3%
Scale Factors	6%	6%	-	-	6%	-	-	6%
BeamHalo	-	-	-	-	-	79%	-	-
Spikes	-	-	-	-	-	-	39%	-

Jet Dark Matter Searches

Trigger Level Analysis

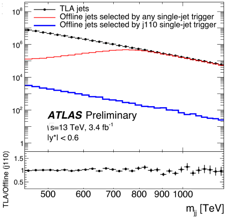
[arXiv:1604.08907]

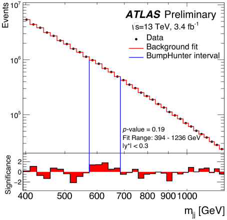


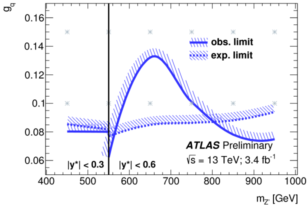


Jet Dark Matter Searches

Trigger Level Analysis [ATLAS-CONF-2016-030]

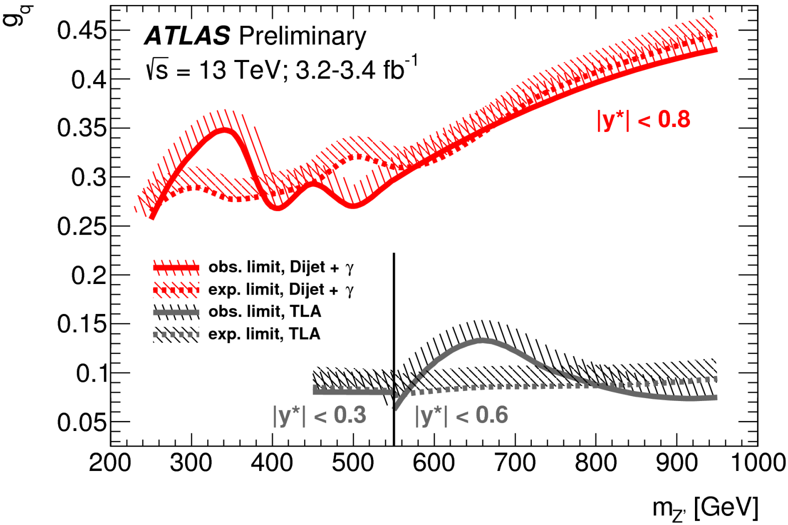






Low mass summary

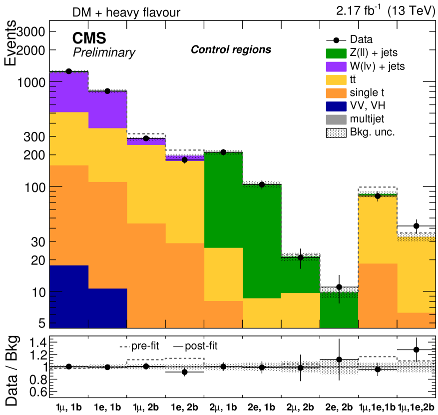
[ATLAS-CONF-2016-029 & ATLAS-CONF-2016-030]



Heavy flavour DM searches

mono-b searches

CMS-PAS-B2G-15-007



	process	2ℓ	1ℓ	$1\mu, 1e$	SR1	SR2
MET resolution	all	1%	1%	< 1%	1%	1%
MET scale	all	< 1%	< 1%	< 1%	< 1%	< 1%
JES	VV, ST, multijet	1%	1%	2%	< 1%	1%
b-tagging	all	7%	9%	7%	8%	11%
lepton trigger, id, iso	all	4%	3%	3%	3%	3%
trigger	all		< 1%		< 1%	
pile-up	all	2%	1%	1%	1%	< 1%
Fact. scale	all	4%	3%	4%	4%	4%
Ren. scale	all	7%	6%	12%	5%	6%
EWK corr.	V+jets	4%	2%	< 1%	5%	3%
PDF	all	1%	1%	1%	1%	1%
luminosity	VV, ST, multijet			2.7%		
Other bkg cross section	VV, ST			15%		
Multijet cross section	multijet			50%		

Searches in Higgs channels

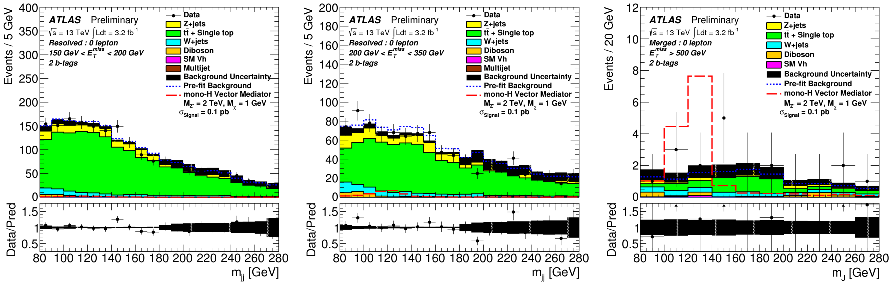
mono-Higgs searches - bb channel

ATLAS-CONF-2016-019

Region	Signal Region	Z+jets Control Region	W+jets and $t\bar{t}$ Control Region
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single Lepton
N(lepton)	0 μ and e	Exactly 1 μ	Exactly 2 μ or e
Merged	$E_{\mathrm{T}}^{\mathrm{miss}}$ ¿500 GeV	$p_T(\mu, E_{\mathrm{T}}^{\mathrm{miss}})$¿500 GeV	$p_T(\ell, \ell)$¿500 GeV
	$p_{\mathrm{T}}^{\mathrm{miss}}$¿30 GeV	$p_T(\mu, p_{\mathrm{T}}^{\mathrm{miss}})$¿30 GeV	–
	N(large-R jets)$\geq$1		
	Division by track jet b-tags		
	Final discriminant = Large-R jet mass		
Resolved	$E_{\mathrm{T}}^{\mathrm{miss}}$ =[150,500] GeV	$p_T(\mu, E_{\mathrm{T}}^{\mathrm{miss}})$=[150,500] GeV	$p_T(\ell, \ell)$=[150,500] GeV
	$p_{\mathrm{T}}^{\mathrm{miss}}$¿30 GeV	$p_T(\mu, p_{\mathrm{T}}^{\mathrm{miss}})$¿30 GeV	–
	$\min\left(\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets}\right)\right) > 20^\circ$		–
	$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right)$		–
	N(central small-R jets)$\geq$2		
	$p_T(j^1_{h_r}) \geq$45 GeV or $p_T(j^2_{h_r}) \geq$45 GeV		
	$\Delta\phi\left(j^1_{h_r}, j^2_{h_r}\right) < 140^\circ$		
	H_T(2jets)¿120 GeV or H_T(3jets)¿150 GeV		
	$\Delta\phi\left(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, h_r\right) > 120^\circ$		
	–	–	$E_{\mathrm{T}}^{\mathrm{miss}} / \Sigma p_T(\mathrm{jets}, \mathrm{leptons})$ ¡ 3.5
	Division by small-R calorimeter jet b-tags		
	Final discriminant = Dijet mass		

Searches in Higgs channels

mono-Higgs searches - bb channel ATLAS-CONF-2016-019

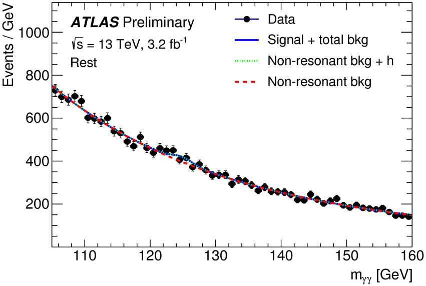


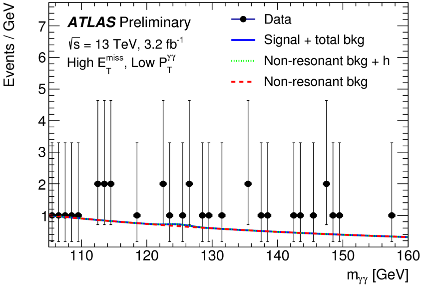
E_T^{miss} (GeV)	Resolved			Merged
	150–200	200–350	350–500	>500
$Z + jets$	259 ± 27	171 ± 13	14.6 ± 1.2	3.80 ± 0.44
$W + jets$	95 ± 28	70 ± 22	7.5 ± 2.4	2.48 ± 0.71
$t\bar{t}$ & Single top	1444 ± 44	656 ± 25	30.8 ± 1.4	4.83 ± 0.88
Multijet	21 ± 10	11 ± 5	0.58 ± 0.27	–
Diboson	17.8 ± 1.6	18.7± 1.0	2.53 ± 0.22	1.20 ± 0.12
$SMVh$	2.8 ± 1.3	2.8 ± 1.4	0.46 ± 0.23	0.15 ± 0.08
Tot. Bkg.	1840 ± 33	930 ± 20	56.5 ± 2.1	12.5 ± 1.3
Data	1830	942	56	20
Exp. Signal	80 ± 8	245 ± 18	161 ± 12	149 ± 34

Searches in Higgs channels

mono-Higgs searches to diphotons

ATLAS-CONF-2016-011





Category	E_T^{miss} [GeV]	p_T^{hard} [GeV]	$p_T^{\gamma\gamma}$ [GeV]
High E_T^{miss}, high $p_T^{\gamma\gamma}$	> 100	-	> 100
High E_T^{miss}, low $p_T^{\gamma\gamma}$	> 100	-	≤ 100
Intermediate E_T^{miss}	> 50 and ≤ 100	> 40	-
Rest	-	-	> 15

Process	Generators used	PDF set (ME, PS)	Tune
ggF, $h \to \gamma\gamma$	Powheg [15] + Pythia 8.186	CT10 [16], CTEQ6L1 [17]	AZNLO [18]
VBF, $h \to \gamma\gamma$	Powheg + Pythia 8.186	CT10, CTEQ6L1	AZNLO
Wh, $h \to \gamma\gamma$	Pythia 8.186	NNPDF2.3LO	A14
Zh, $h \to \gamma\gamma$	Pythia 8.186	NNPDF2.3LO	A14
$t\bar{t}h$, $h \to \gamma\gamma$	Pythia 8.186	NNPDF2.3LO	A14
$b\bar{b}h$, $h \to \gamma\gamma$	Pythia 8.186	NNPDF2.3LO	A14

Searches in Higgs channels

mono-Higgs searches to diphotons

ATLAS-CONF-2016-011

Category	Intermediate	High E_T^{miss}, High $p_T^{\gamma\gamma}$	High E_T^{miss}, Low $p_T^{\gamma\gamma}$	Rest
Data	111	0	6	2477
Heavy scalar, $m_H = 275\ GeV$, $m_\chi = 60\ GeV$				
Yields	16.2 ± 2.3	3.41 ± 0.45	3.83 ± 0.58	26.5 ± 3.6
Selection Eff(%)	11.0 ± 1.6	2.31 ± 0.31	2.59 ± 0.39	17.9 ± 2.4
Z'_B model, $m_{Z'} = 10\ GeV$, $m_\chi = 1\ GeV$				
Yields	1.54 ± 0.21	1.56 ± 0.20	0.21 ± 0.03	1.03 ± 0.14
Selection Eff(%)	15.8 ± 2.1	16.0 ± 2.1	2.19 ± 0.33	10.6 ± 1.4
Backgrounds				
SM Higgs boson	5.2 ± 1.6	0.51 ± 0.09	0.23 ± 0.19	98 ± 16
Non-resonant	110.7 ± 3.7	1.51 ± 0.43	3.95 ± 0.70	2372 ± 17

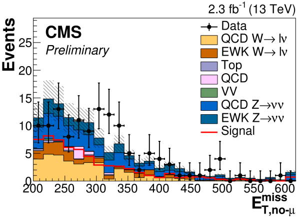
Source	Maximum uncertainty (%)
Experimental	
Luminosity	5
Trigger efficiency	0.4
Vertex selection	3.6 (Intermediate), 20 (High E_T^{miss})
Photon identification efficiency	2.8
Photon energy scale	1
Photon energy resolution	2
Photon isolation efficiency	4
E_T^{miss} reconstruction	1 (Rest), 20 (Intermediate and High E_T^{miss})
Pile-up reweighting	4.5
Theoretical	
QCD scale uncertainty of ggH p_T spectrum	10 - 20
Modelling of ggH E_T^{miss} spectrum	25
PDF	9
MPI	1 (Intermediate), 50 (High E_T^{miss})
BR($h \to \gamma\gamma$)	4.9

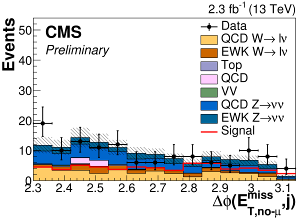
Searches in Higgs channels

Invisible decays of a Higgs boson

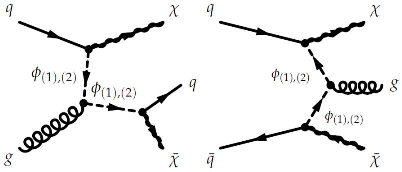
CMS-PAS-HIG-16-009

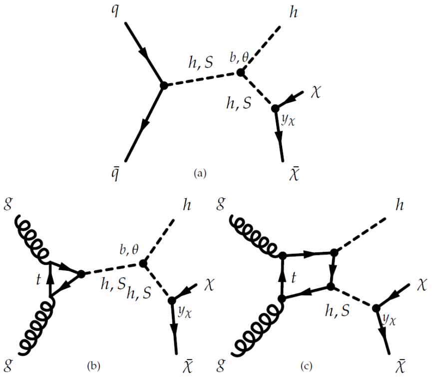
Process	Control Regions $e\nu$	$\mu\nu$	$\tau\nu$	$\mu\mu$	QCD	Signal Region
QCD $Z \to \mu\mu$	–	–	–	3.7 ± 1.1	–	–
EWK $Z \to \mu\mu$	–	–	–	2.1 ± 0.7	–	–
QCD $Z \to \nu\nu$	–	–	–	–	–	40 ± 12
EWK $Z \to \nu\nu$	–	–	–	–	–	22 ± 6
QCD $W \to \mu\nu$	–	53 ± 6	0.38 ± 0.16	–	42 ± 5	13 ± 2
EWK $W \to \mu\nu$	–	27 ± 3	–	–	5.9 ± 0.9	4.4 ± 0.8
QCD $W \to e\nu$	16 ± 2	–	0.2 ± 0.3	–	37 ± 4	9.5 ± 1.5
EWK $W \to e\nu$	7.8 ± 1.3	–	0.24 ± 0.14	–	7.7 ± 1.1	5.5 ± 1.0
QCD $W \to \tau\nu$	0.05 ± 0.05	–	11 ± 2	–	70 ± 10	13 ± 2
EWK $W \to \tau\nu$	–	–	5.2 ± 1.2	–	25 ± 4	5.6 ± 1.3
Top-quark	1.4 ± 0.2	6.8 ± 0.9	7.1 ± 1.0	0.22 ± 0.06	80 ± 10	2.3 ± 0.4
QCD multijet	–	5 ± 2	0.4 ± 0.2	–	1200 ± 100	3 ± 20
Dibosons	0.4 ± 0.4	0.8 ± 0.4	–	0.02 ± 0.02	1.9 ± 0.6	0.7 ± 0.3
Total Bkg	26 ± 3	92 ± 9	25 ± 3	6.1 ± 1.3	1500 ± 100	120 ± 27
Data	29	89	24	7	1461	126
Signal ($m_H = 125$ GeV)						
VBF	–	–	–	–	–	53.6 ± 4.9
ggH	–	–	–	–	–	5.4 ± 3.6





More mediators!





- Further benchmarks? Guide:
  - New experimental signature?
  - Does the kinematics change between models (points)?
  - t-channel exchanges (above)
  - Higgs Portal - scalar coupling to DM and h
- Active topic of LHC DM WG!

http://lpcc.web.cern.ch/lpcc/index.php?page=dm_wg