Search for Dark Matter in the Mono-Higgs Channel with the ATLAS Detector

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Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

ATLAS EXPERIMENT

Search for Dark Matter with the ATLAS Detector

- Dark Matter (DM) particles (χ) escape the detector undetected (no interaction with the detector material - like neutrinos)
- Search for DM particles by looking for:
  - a SM particle recoiling against DM
  - large imbalance of energy in the transverse plane ($E_{\mathrm{T}}^{\mathrm{miss}}$) due to DM

⇒ Typical DM search: $E_{\mathrm{T}}^{\mathrm{miss}}$ + X (X = jet/γ/W/Z/Higgs boson)

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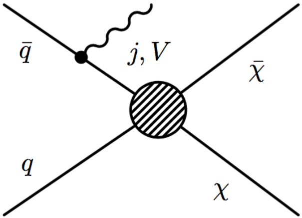

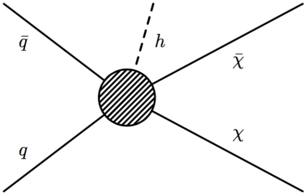

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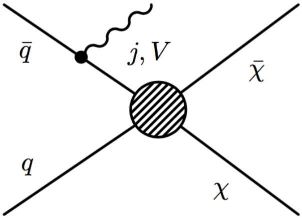
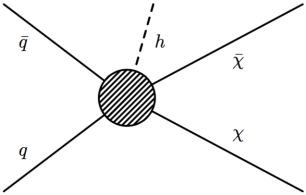


Jet or vector boson is produced via initial state radiation: mono-X

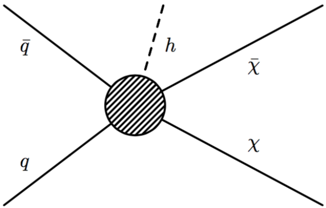


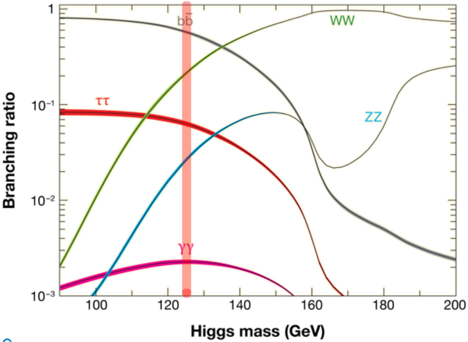
Higgs boson is directly involved in the production mechanism: mono-Higgs

The mono-Higgs channel is complementary to the mono-X channels with initial state radiation

Search for Dark Matter in the Mono-Higgs Channel

DM is produced in association with the SM Higgs boson h ($m_h = 125$ GeV)





Different Higgs decay channels can be used within the mono-Higgs channel

$\mathcal{BR}(h \to b\bar{b}) \approx 57$ %

$\sigma \times \mathcal{BR}$ ↑

- mono-Higgs ($h \to b\bar{b}$)
- mono-Higgs ($h \to \gamma\gamma$)
- mono-Higgs ($h \to ZZ^* \to 4\ell$)

Background ↓

Mono-Higgs ($b\bar{b}$) is very challenging due to high background, but high statistics is needed when looking for rare events!

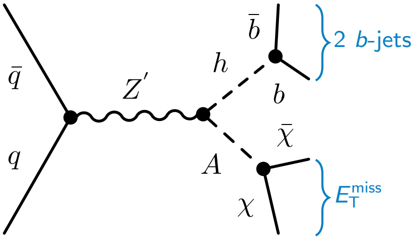
Search for DM in the Mono-Higgs ($b\bar{b}$) Channel

- Search for events with large $E_{\mathrm{T}}^{\mathrm{miss}}$ in association with the SM Higgs boson ($h \to b\bar{b}$)

$\Rightarrow$ Signatur: 2 b-tagged jets, $m_{bb} \approx 125$ GeV and large $E_{\mathrm{T}}^{\mathrm{miss}}$

Simplified signal model: Z'-2-Higgs-dublet-model (2HDM) (type-II)
(arXiv:1402.7074)

- Massive mediators:
  - Z' from additional $\mathrm{U}(1)_{Z'}$ symmetry
  - A is pseudo-scalar boson from extended Higgs sector (h, H, A, H^-, H^+)
- DM pair production, with χ a Dirac fermion



- Free model parameters: $m_A, m_{Z'}, m_\chi, \tan\beta, g_{Z'}$

$\Rightarrow$ $m_\chi = 100$ GeV, $\tan\beta = 1$, $g_{Z'} = 0.8$, $\mathcal{BR}(A \to \chi\bar{\chi}) = 100$ %

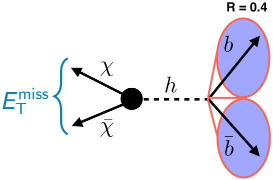
$\Rightarrow$ Scan in ($m_A, m_{Z'}$) plane ($m_A > 2 \cdot m_\chi$)

Event Topology

- Higgs boson and DM are produced back-to-back
  - Due to production mechanism: Higgs boson is boosted ($p_{\mathrm{T}}^{\mathrm{Higgs}} \approx E_{\mathrm{T}}^{\mathrm{miss}}$)

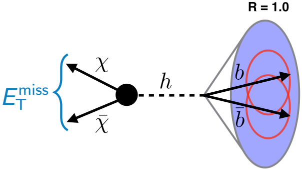
Resolved regime

$150\ \mathrm{GeV} < E_{\mathrm{T}}^{\mathrm{miss}} \leq 500\ \mathrm{GeV}$



Merged regime

$E_{\mathrm{T}}^{\mathrm{miss}} > 500\ \mathrm{GeV}$



$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

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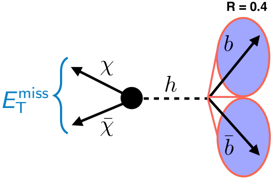

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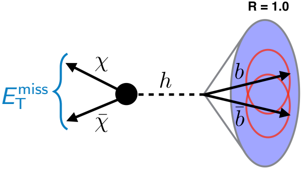

- ≥ 2 small-R calorimeter jets (anti-k_t R=0.4)

$\Rightarrow$ Used for b-jet identification

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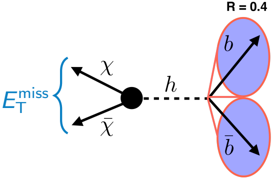

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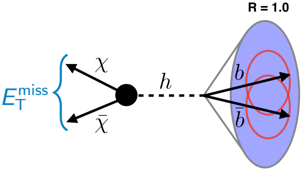

- ≥ 1 large-R calorimeter jet (anti-k_t R=1.0)
- ≥ 1 sub-jets (R=0.2) builed from tracks

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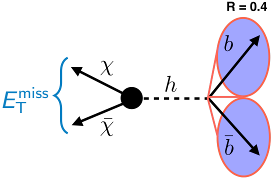

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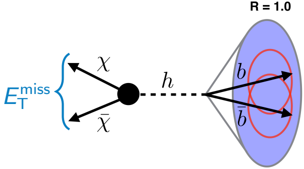


- ≥ 1 large-R calorimeter jet (anti-k_{t} R=1.0)
- ≥ 1 sub-jets (R=0.2) builed from tracks

$\Rightarrow$ Used for *b*-jet identification

Variable of interest for reconstructing the Higgs boson candidate mass:

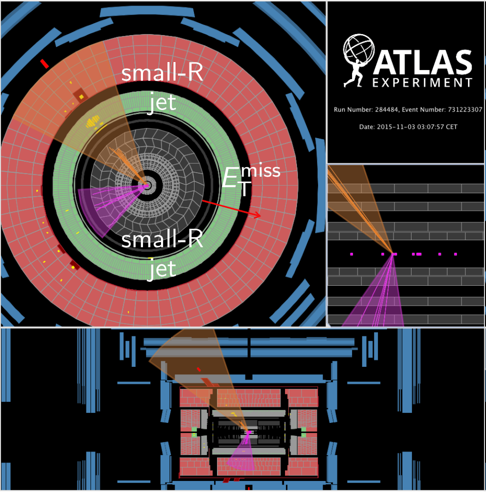
Invariante mass of the two-*b*-tagged jets with the highest p_{T}

Invariant mass of the large-R jet with the highest p_{T} and *b*-tagged sub-jets

$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

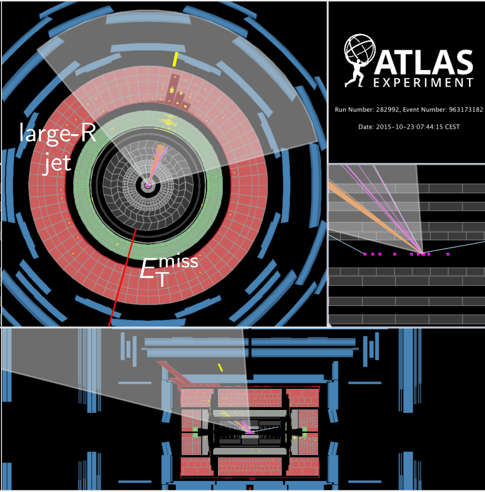
Display of Candidate Events

Resolved regime



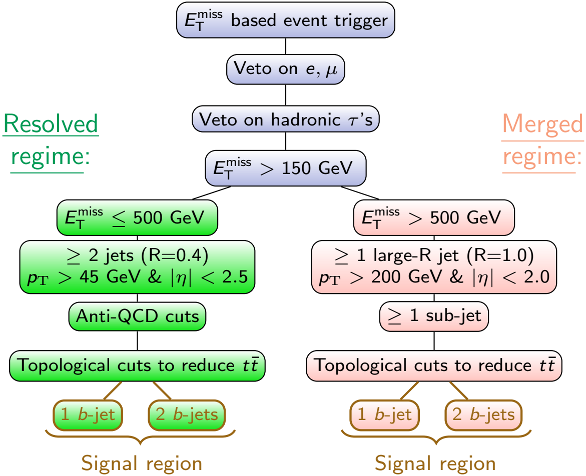
$$E_{\mathrm{T}}^{\mathrm{miss}} = 213 \text{ GeV}$$
$$m_{jj} = 120 \text{ GeV}$$

Merged regime



$$E_{\mathrm{T}}^{\mathrm{miss}} = 694 \text{ GeV}$$
$$m_{J} = 106 \text{ GeV}$$

Event Selection



NB: 1 *b*-tag region is also used
to recover some *b*-tag inefficiencies

Background Processes

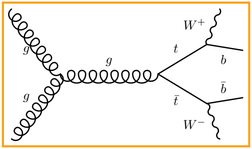
$t\bar{t}$		55 %
Z	+ jets	30 %
W	+ jets	10 %

Main backgrounds:

$t\bar{t}$, $Z(\rightarrow \nu\nu)$ + jets and $W(\rightarrow \ell\nu)$ + jets

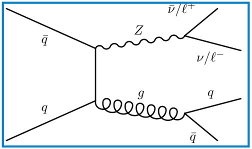
$t\bar{t}$ production:

- $E_{\mathrm{T}}^{\mathrm{miss}}$ from leptonic W decay
  (ℓ might not be reconstructed)
- $\geq 2b$-Jets



$Z(\rightarrow \nu\nu)$ + jets:

- high $E_{\mathrm{T}}^{\mathrm{miss}}$ from neutrinos
  (smaller contribution from $Z(\rightarrow \tau\tau)$)
- Jets from gluon splitting



$W(\rightarrow \ell\nu)$+Jets:

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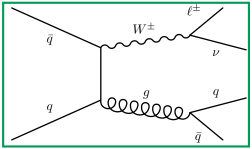
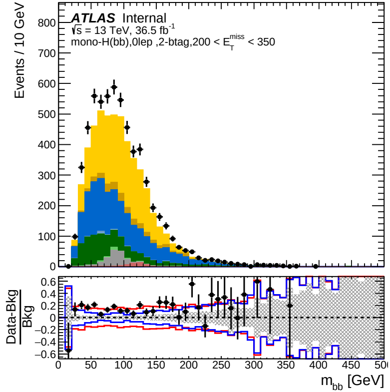


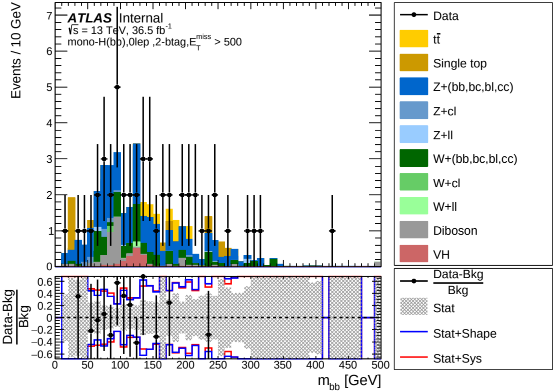
- Other backgrounds: SM Vh, diboson, single top and multijet background

Templates of the different backgrounds are build from Monte Carlo (MC) simulation

Resolved regime



Merged regime



- Main backgrounds: $t\bar{t}$, $Z(\to \nu\bar{\nu})$ + jets and $W(\to \ell\nu)$ + jets
- Data / MC agreement looks fine within uncertainties
- But can we do better?

$\Rightarrow$ Introduce control regions for the dominant background processes

Idea of a Control Region (CR)

- A background-enriched region to estimate a certain background in the SR
- Apply the same base selection in SR and CR

⇒ Similar phase space

- But SR and CR orthogonal to be statistically independent:

  E.g. 0, 1 or 2 lepton selection

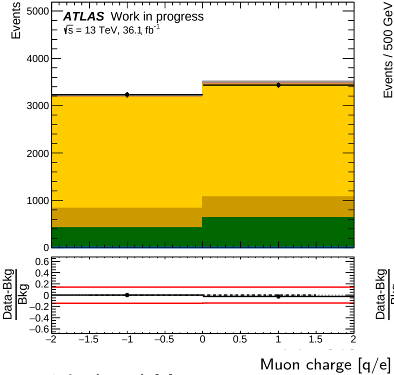
⇒ Can be modelled by separate PDFs, and thus be combined into one simultaneous fit to data

⇒ Finally extract the right background normalisation

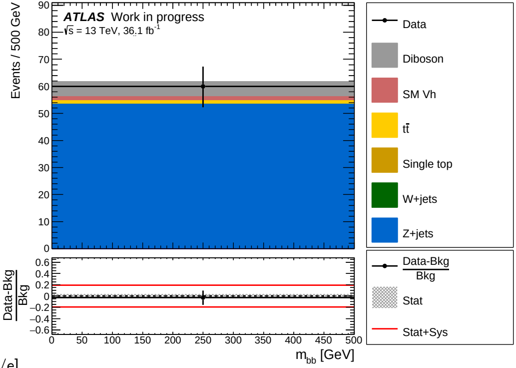
Backgrounds are estimated from Monte Carlo simulation,
with scale factors (where necessary) derived in control regions

Control Regions

1-μ CR: $t\bar{t}$ and W+Jets



2-ℓ CR: Z+Jets



- 1 isolated Myon
- 2 b-jet region: mainly $t\bar{t}$
- 1 b-jet region: $t\bar{t}$ and W + jets
- Muon charge helps to separate $t\bar{t}$ and W + jets

⇒ Two bins for the two background processes

- $\ell\ell$ ($\ell = e, \mu$) pairs from Z boson decay (kinematically similar to the $Z \to \nu\bar{\nu}$ decay)
- Mainly Z + jets, as designed

⇒ One single bin of m_{jj}/m_J for normalization only

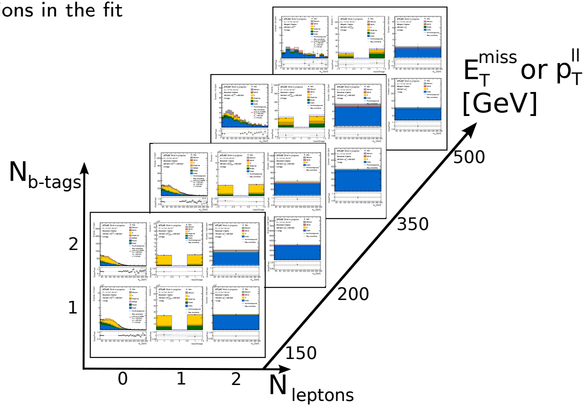
Background Estimation

- Binned profile-likelihood fit: simultaneously of all SR and CRs to data

⇒ Extract the right normalizations of the main backgrounds

- 4 bins of $E_{\mathrm{T}}^{\mathrm{miss}}$ are used to have a better signal / background ratio
- 1 / 2 b-tag region

⇒ 24 regions in the fit



- Freely floating parameters in the fit:
  - 3 normalisations: Z + jets, W + jets and $t\bar{t}$
  - signal strength μ

$E_{\mathrm{T}}^{\mathrm{miss}} = |\vec{E}_{\mathrm{T}}^{\mathrm{miss}}|$

$E_{\mathrm{T}}^{\mathrm{miss}}(1\mu - CR) = |\vec{E}_{\mathrm{T}}^{\mathrm{miss}} + \vec{\mu}|$

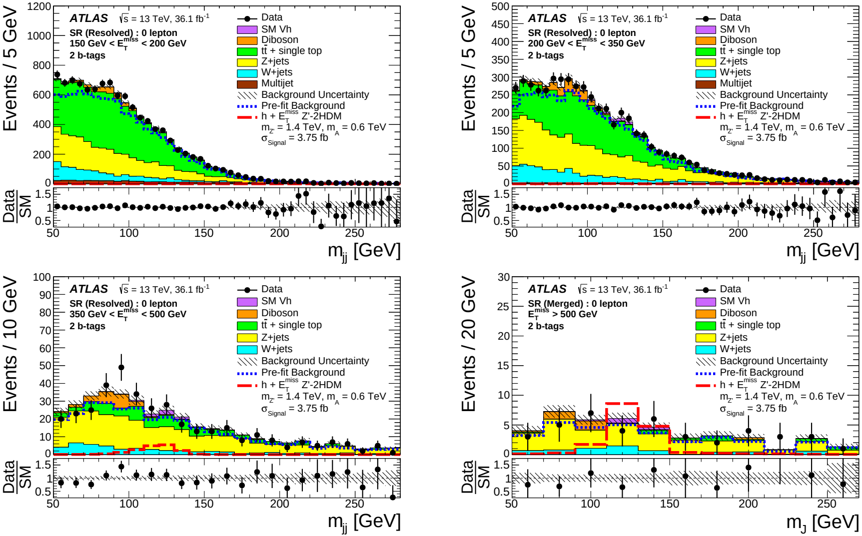
$E_{\mathrm{T}}^{\mathrm{miss}}(2\ell - CR) = |\vec{\ell}_1 + \vec{\ell}_2|$

Brand new results: 5th of July

Using 2015 + 2016 Data (36.1 fb^{-1})

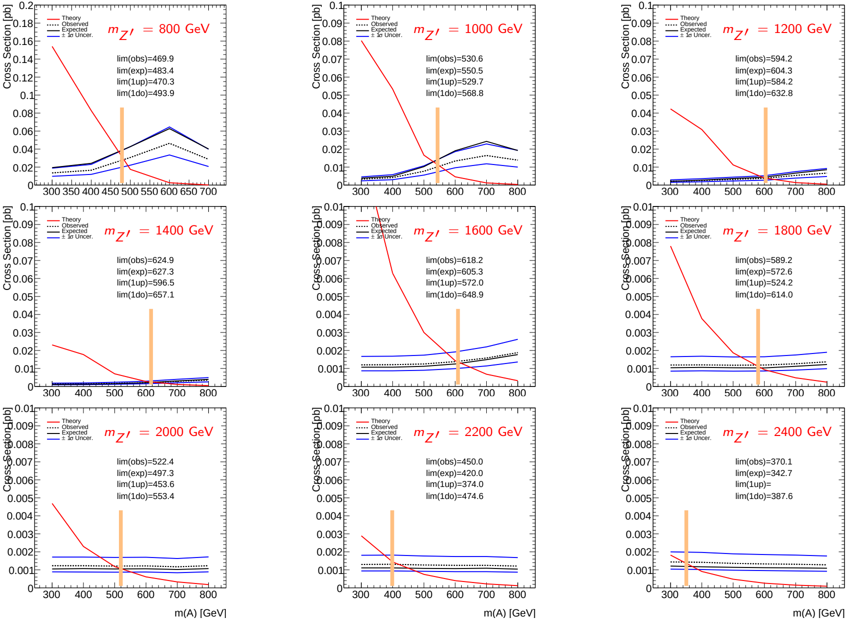
arXiv: 1707.01302, submitted to PRL

Results - 2 *b*-Tagged Jets

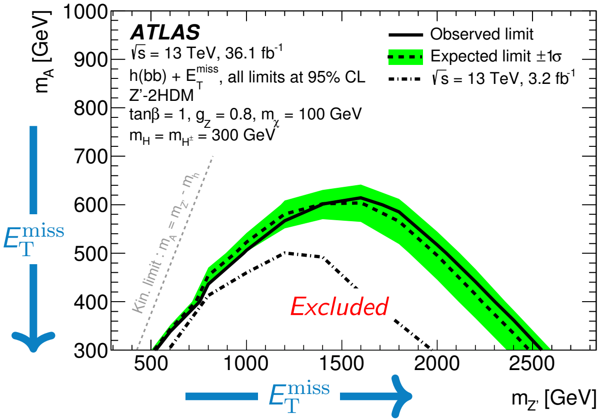


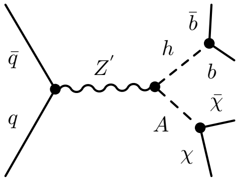
Much better data / MC agreement after the fit!
No significant deviation from the SM prediction.

Results - XS Limits - Fixed m_A Mass



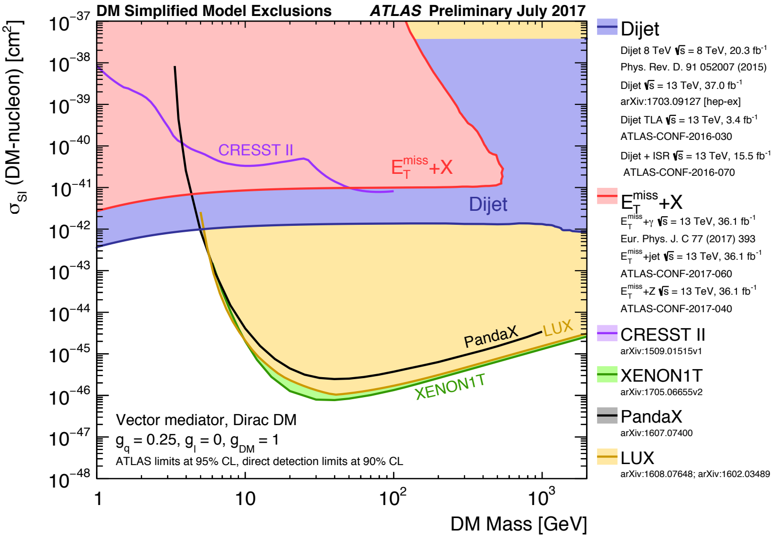
Simplified signal model: Z'-2HDM





- Cross-section limits translated into $(m_A, m_{Z'})$ plane
- Excluding m_A up to 0.6 TeV
- Excluding $m_{Z'}$ up to 2.6 TeV

Comparison to Direct Detection - Mono-X Searches in General



Summary

- After the discovery of the Higgs boson in 2012, the search for Dark Matter is one of the most important topics of the LHC physics program
- The LHC is in particular competitive in the low DM mass region and provides complementary DM results
- The mono-Higgs ($h \to b\bar{b}$) channel can directly probe the DM production mechanism
- More data will be collected this year, and hopefully the discovery of DM at the LHC is around the corner

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Thank You!

Backup

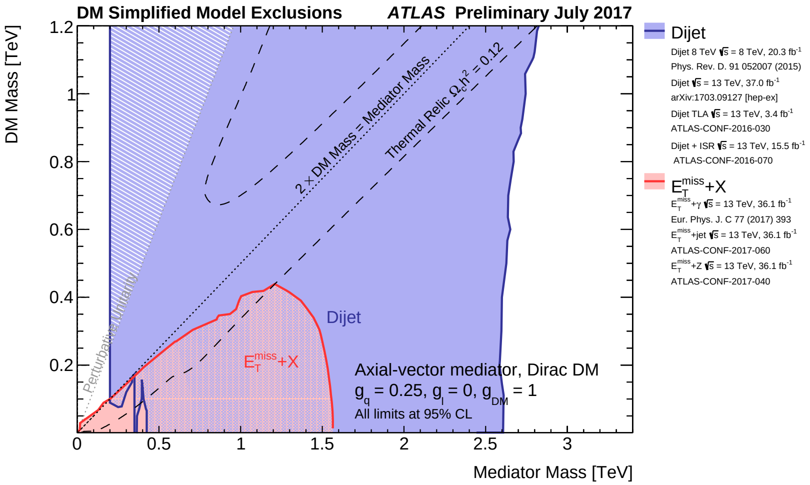
Model Independent Limits

Range in $E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$\sigma^{\mathrm{obs}}_{\mathrm{vis},h+\mathrm{DM}}$ [fb]	$\sigma^{\mathrm{exp}}_{\mathrm{vis},h+\mathrm{DM}}$ [fb]	$\mathcal{A} \times \varepsilon$ [%]
$[150, 200)$	19.1	$18.3^{+7.2}_{-5.1}$	15
$[200, 350)$	13.1	$10.5^{+4.1}_{-2.9}$	35
$[350, 500)$	2.4	$1.7^{+0.7}_{-0.5}$	40
$[500, \infty)$	1.7	$1.8^{+0.7}_{-0.5}$	55

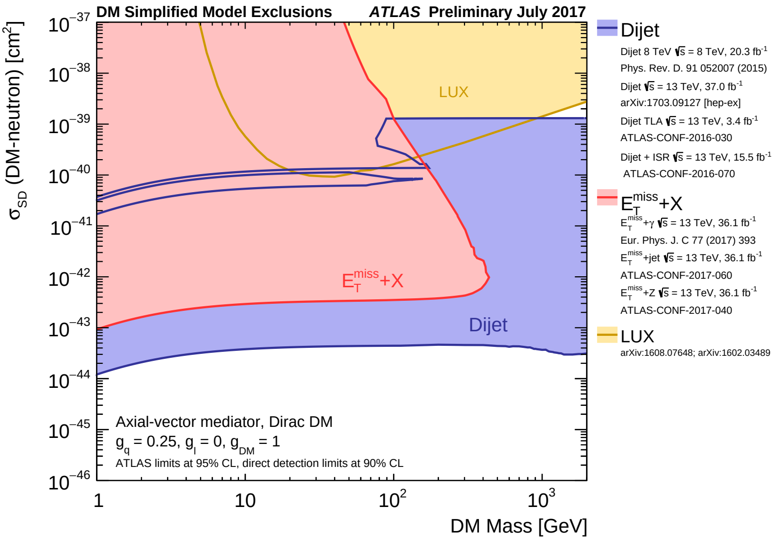
Translating Collider Limits

$$\sigma_{\mathrm{SI}} \approx 6.9 \cdot 10^{-41}\ \mathrm{cm}^2 \cdot \left(\frac{g_q g_{DM}}{0.25}\right)^2 \cdot \left(\frac{1\mathrm{TeV}}{M_{med}}\right)^4 \cdot \left(\frac{\mu_{n\chi}}{1\mathrm{GeV}}\right)^2$$

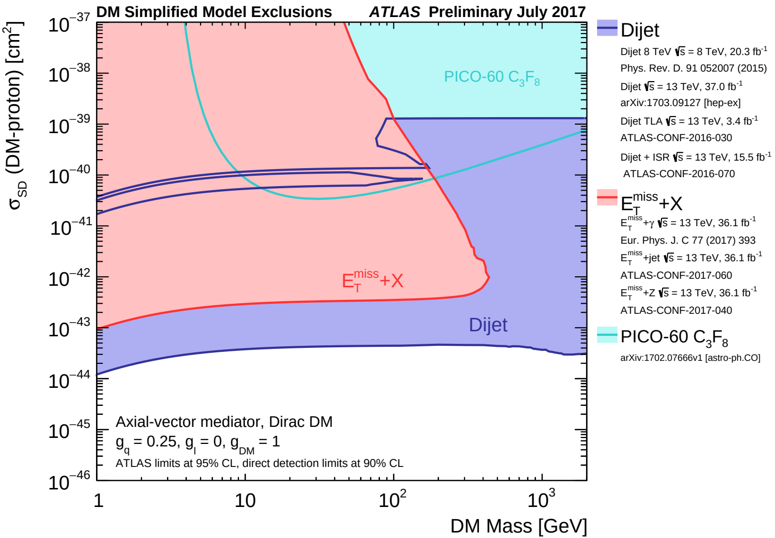
Results - Spin Dependent - Neutron



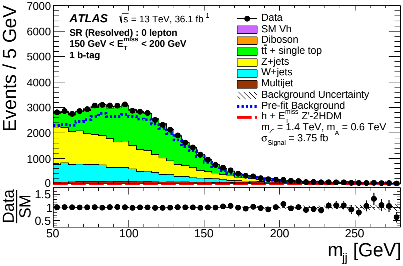
Results - Spin Dependent - Proton

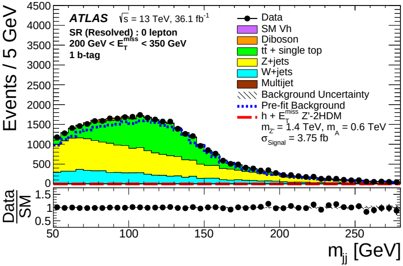


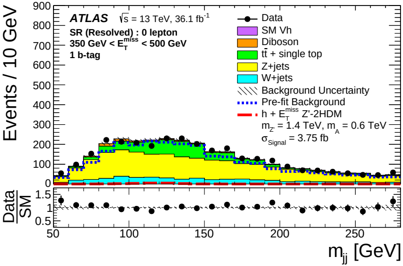
Results

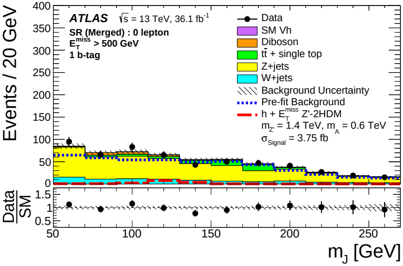

DM Simplified Model Exclusions
ATLAS Preliminary July 2017
PICO-60 C_3F_8
E_T^{miss}+X
Dijet
Axial-vector mediator, Dirac DM
$g_q = 0.25$, $g_l = 0$, $g_{DM} = 1$
ATLAS limits at 95% CL, direct detection limits at 90% CL
σ_{SD} (DM-proton) [cm^2]
DM Mass [GeV]
Dijet
Dijet 8 TeV $\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Phys. Rev. D. 91 052007 (2015)
Dijet $\sqrt{s}$ = 13 TeV, 37.0 fb^{-1}
arXiv:1703.09127 [hep-ex]
Dijet TLA $\sqrt{s}$ = 13 TeV, 3.4 fb^{-1}
ATLAS-CONF-2016-030
Dijet + ISR $\sqrt{s}$ = 13 TeV, 15.5 fb^{-1}
ATLAS-CONF-2016-070
E_T^{miss}+X
E_T^{miss}+γ $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Eur. Phys. J. C 77 (2017) 393
E_T^{miss}+jet $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS-CONF-2017-060
E_T^{miss}+Z $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS-CONF-2017-040
PICO-60 C_3F_8
arXiv:1702.07666v1 [astro-ph.CO]

Results - 1 *b*-Tagged Jets

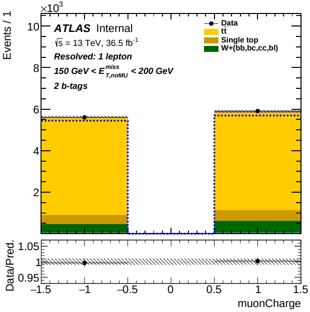


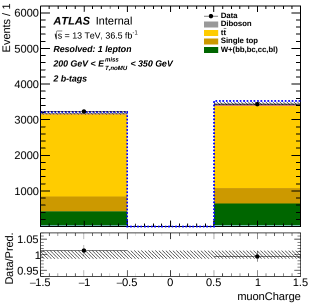


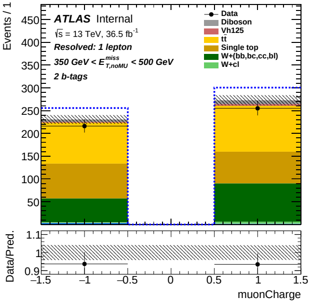


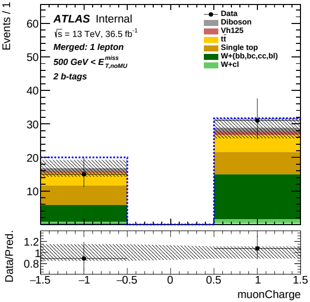


Results - CR - 2 b-Tagged Jets

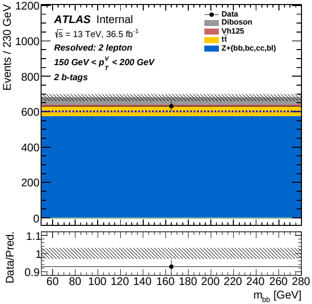


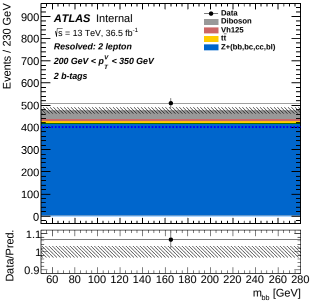


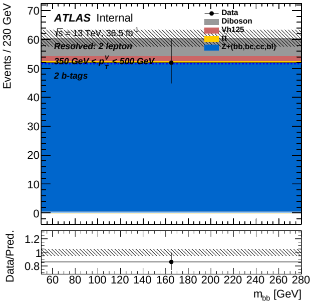


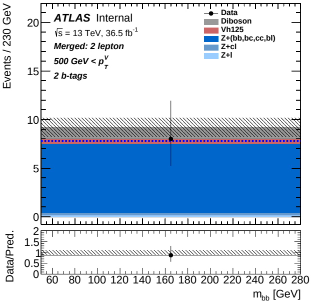


Results - CR - 2 *b*-Tagged Jets

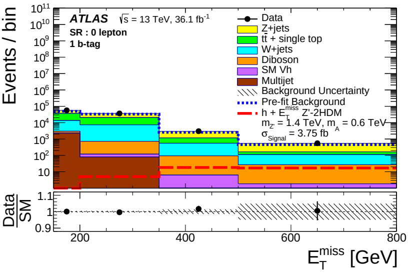


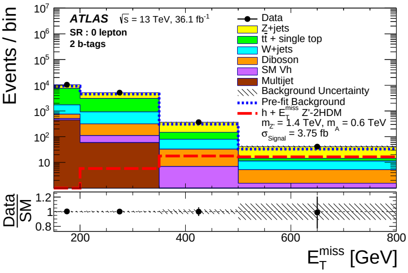




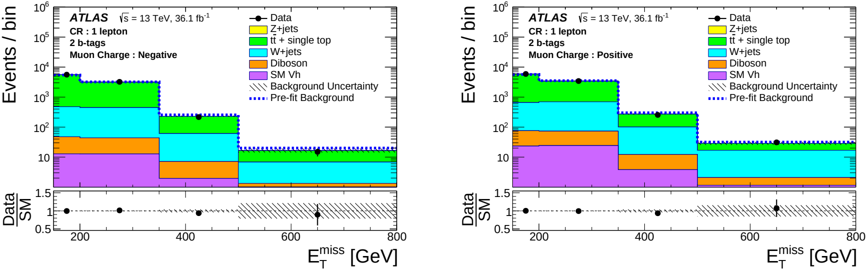


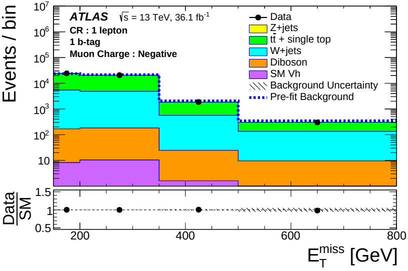
Results - SR - $E_{\mathrm{T}}^{\mathrm{miss}}$

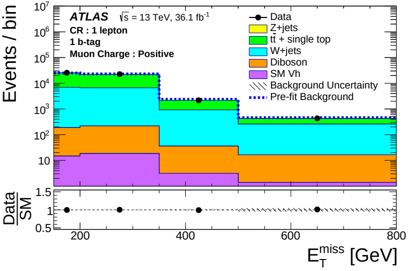




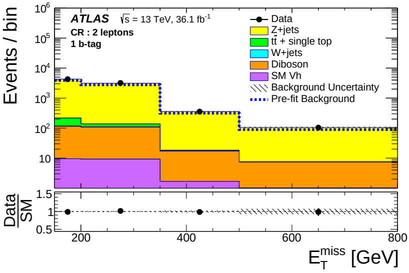
Results - 1 μ CR 2 b-Tagged Jet - $E_{\mathrm{T}}^{\mathrm{miss}}$

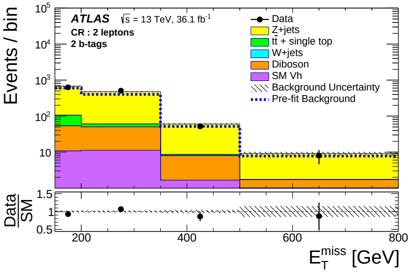



ATLAS √s = 13 TeV, 36.1 fb-1
CR : 1 lepton
1 b-tag
Muon Charge : Negative
Data
Z+jets
tt̄ + single top
W+jets
Diboson
SM Vh
Background Uncertainty
Pre-fit Background
Events / bin
Data/SM
E_T^miss [GeV]


ATLAS √s = 13 TeV, 36.1 fb-1
CR : 1 lepton
1 b-tag
Muon Charge : Positive
Data
Z+jets
tt̄ + single top
W+jets
Diboson
SM Vh
Background Uncertainty
Pre-fit Background
Events / bin
Data/SM
E_T^miss [GeV]

Results - 2 ℓ CR - E_T^{miss}





Results - SR - 2 b-Tagged Jets

Category	Range in E_T^{miss} [GeV]			
	[150, 200)	[200, 350)	[350, 500)	[500, ∞)
$t\bar{t}$+single top	5 820 ± 170	2 160 ± 76	69.2 ± 4.8	3.17 ± 0.66
W+jets	973 ± 170	605 ± 110	46.6 ± 8.7	6.1 ± 1.2
Z+jets	2 940 ± 190	2 070 ± 130	217 ± 13	27.0 ± 2.4
Diboson	247 ± 30	205 ± 25	25.8 ± 3.2	3.65 ± 0.62
SM $Vh(b\bar{b})$	56 ± 17	51 ± 18	6.9 ± 2.6	1.54 ± 0.64
Multijet	448 ± 120	59 ± 46	negligible	negligible
Total Bkg.	10 500 ± 100	5 150 ± 62	366 ± 12	41.4 ± 3.3
Data	10 514	5 160	366	41
Exp. signal	0.3	5.8	17.7	16.4

Results - SR - 1 b-Tagged Jets

Category	Range in E_T^{miss} [GeV]			
	[150, 200)	[200, 350)	[350, 500)	[500, ∞)
$t\bar{t}$+single top	23 060 ± 530	13 190 ± 310	614 ± 32	53.7 ± 5.1
W+jets	10 500 ± 1 300	6 620 ± 810	458 ± 58	84.5 ± 14
Z+jets	20 000 ± 1 300	16 200 ± 1 100	1 800 ± 120	383 ± 40
Diboson	644 ± 82	605 ± 79	87.8 ± 12	25.0 ± 3.6
SM $Vh(b\bar{b})$	40 ± 13	39 ± 14	6.3 ± 2.3	1.8 ± 0.7
Multijet	2 310 ± 240	80 ± 99	negligible	negligible
Total Bkg.	56 570 ± 240	36 710 ± 190	2 965 ± 42	548 ± 19
Data	56 611	36 584	3 015	551
Exp. signal	0.2	5.0	18.2	16.9