Dark matter searches at ATLAS and CMS

Kate Pachal
Duke University
Dark matter at colliders
Dark matter at colliders

Indirect detection

IceCube, Super-K, …
Dark matter at colliders

Indirect detection: IceCube, Super-K, …

Direct detection: LUX, XENON, …
Dark matter at colliders

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IceCube, Super-K, …

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Colliders
ATLAS & CMS
Dark matter at colliders

Colliders are a key part of this picture!

These searches complement direct and indirect detection

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Today, we discuss DM searches at ATLAS and CMS

Direct detection: LUX, XENON, …
What could dark matter *really* look like at the LHC?

- Depends on assumptions!
  - At low energies, you don’t really need a clearer picture. *Effective field theory* treats this as a 4-point interaction
  - EFTs are valid when the **momentum transfer is small** compared to fundamental processes - e.g. direct and indirect detection experiments
  - At the LHC, not valid: high energies require a **more complete picture**
  - What should it be? **Many different models** available, with different levels of completeness/simplification and different dominant signatures
  - In this talk, we’ll discuss DM in a few different models, *highlighting analyses* that best constrain each
Less complete

Dipole Interactions

Dark Matter Effective Field Theories

“Sketches of models”

More complete

Minimal Supersymmetric Standard Model

Universal Extra Dimensions

Simplified Dark Matter Models

Dark Photon

Z’ boson

“Squarks”

Complete Dark Matter Models

Higgs Portal

Little Higgs

Contact Interactions

No longer done at LHC
No longer done at LHC

We’ll discuss several of these!
No longer done at LHC

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Beyond today’s scope
Mono-X signatures

- Key final state is $M_{ET}$ plus a visible object
Mono-X signatures

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  - **Visible object** (eg. jet) gives momentum to measure and trigger on

Very model-independent!

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Mono-X signatures

- Key final state is $M_{\text{ET}}$ plus a visible object
  - **Visible object** (eg. jet) gives momentum to measure and trigger on
  - Missing energy, $M_{\text{ET}}$, is observed momentum imbalance due to invisible particles
- Very **model-independent**!
  - No matter what DM-SM interaction, you can get this signature
  - Once we assume a model, though, other signatures are powerful too
- Today we will go **beyond the mono-jet signature** to showcase recent ATLAS and CMS results in the areas of their unique strengths
S-channel Z’ model and the mediator search

• Consider simplified S-channel model: one massive mediator, one dark matter particle, two allowed vertices

• X can be vector, axial-vector, scalar, or pseudoscalar

• Let’s pick vector/axial-vector for its higher cross sections

• Mono-X is important here, of course!

• BUT we also gain a visible channel: we have coupling to $qq$ at minimum, and possibly more fermions too

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Two key signatures:

- [Diagram 1](#)
- [Diagram 2](#)
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Note: only two new couplings in this model

Values selected strongly affect limits

Two key signatures:

Resonance
Dijet resonances

- Simplest mediator search: if $qq \rightarrow Z'$ produces the mediator, it can decay back to quarks
- QCD jet invariant mass spectrum will fall smoothly, while signals will appear as peaks
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Standard approach uses fitted functional form to parameterise backgrounds
Dijet resonances

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Standard approach uses fitted functional form to parameterise backgrounds

New method scales data at high dijet $\Delta \eta$ to predict central $\Delta \eta$

Good agreement between methods
Dijet resonances

- Simplest mediator search: if \( qq \rightarrow Z' \) produces the mediator, it can decay back to quarks
- QCD jet invariant mass spectrum will fall smoothly, while signals will appear as peaks

Ratio-based estimate much more stable when peaks are wide: limits extend to width-to-mass ratio of 50%!
Leptophilic Z’ mediators

If mediator can **couple to leptons**, get a clean, powerful decay channel with lower background than for dijets

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**Figure 1:** Diagram 1

**Figure 2:** Diagram 2
Leptophilic Z’ mediators

If mediator can **couple to leptons**, get a clean, powerful decay channel with lower background than for dijets

---

**ATLAS**

\[
\sqrt{s} = 13 \text{ TeV}, \; 139 \; \text{fb}^{-1}
\]

Lepton triggers have lower thresholds, so lower masses available.
Leptophilic Z’ mediators

If mediator can **couple to leptons**, get a clean, powerful decay channel with lower background than for dijets

Lepton triggers have lower thresholds, so lower masses available

Resolution better in ee channel: track resolution degrades with $p_T$ while calorimeter resolution improves
Top quark resonances

- Hadronically decaying tops reconstructed as large-radius jets. Identify them using substructure information and high jet mass

- Constituent tracks identify b-hadron decays inside large-R jets. 2 signal regions (1b and 2b) ensure good total signal efficiency

Smooth fit to invariant mass spectrum of top-tagged jets

ATLAS EXOT-2018-48
Top quark resonances

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- Constituent tracks identify b-hadron decays inside large-R jets. 2 signal regions (1b and 2b) ensure good total signal efficiency

Statistical combination of SR 1b and SR 2b
Low-mass mediator searches

- Challenging to search for low mass mediators because decay products don’t have enough momentum to pass triggers

- Two main methods to overcome this: triggering on an associated object or performing analysis at the “trigger level”
Low-mass mediator searches

- Challenging to search for low mass mediators because decay products don’t have *enough momentum* to pass triggers.
- Two main methods to overcome this: triggering on an *associated object* or performing analysis at the “*trigger level*”

**Triggering on ISR**

![Diagram of ISR process](image)

Hard radiation produces jet passing trigger
Low-mass mediator searches

- Challenging to search for low mass mediators because decay products don’t have \textbf{enough momentum} to pass triggers.

- Two main methods to overcome this: triggering on an \textbf{associated object} or performing analysis at the “\textbf{trigger level}”.

**Triggering on ISR**

Decay products of boosted $Z'$ are collimated into one large radius jet.

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### Triggering on ISR

Decay products of boosted Z’ are collimated into one large radius jet

Use **substructure** variables to reject QCD; select two-prong-like topology

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**Triggering on ISR**

Decay products of boosted $Z'$ are collimated into one large radius jet

- Use **substructure** variables to reject QCD; select two-prong-like topology

- Estimate background with events failing large-R jet selections

Hard radiation produces jet passing trigger

![Diagram of decay products and jet passing trigger](image)
Initial state radiation of a W or Z

- Large mass range simultaneously accessible by considering W/Z radiation and **triggering on a lepton**
- Fit dijet invariant mass spectrum with functional form

![Graph of dijet invariant mass spectrum](image)

- ATLAS
  - $\sqrt{s}=13$ TeV, 139 fb$^{-1}$
  - Fit dijet invariant mass spectrum with functional form

**Legend**
- **Z'W (DM) model**
- **Observed 95% CL**
- **Expected 95% CL**

**Significance**
- **Fit to combined e/\mu channels**
- **Lower probability of radiating W/Z → lower limit**

**Equations**

\[
\sigma \times B = 10^{-2}
\]

**Observations**
- $g_q=0.25$, $g_l=0$, $g_{DM} = 1$
**Light mediators at the trigger level**

**Trigger level** strategy: instead of saving a lot of data for a small number of events, save very minimal data for a large number of events.

\[ Z' \rightarrow qq \]

- Use \( H_T \) (scalar momentum sum) trigger and save calorimeter jet info only
  - Rate limited only by **level 1 trigger**
  - Require three jets to get sufficiently high \( H_T \)
  - Fit invariant mass of two hardest jets and search for excesses
Light mediators at the trigger level

**Trigger level** strategy: instead of saving a lot of data for a small number of events, save very minimal data for a large number of events.

- Standard triggers access lower masses for leptons than jets
- But for very low mass resonances, still limiting
- **First ever trigger-level muons!** Save only 4-momentum, isolation, track quality information at very high rates

10x - 100x gain below 45 GeV thanks to trigger level analysis
Di-boson resonances

- In some models, can allow a $Z'$ to couple to $W$ and $Z$ bosons. Depending on other couplings, can produce via:

- This search is in 0, 1, 2 lepton final states
- $V \to qq$: can be high mass large-radius jet or two standard jets
- Search invariant mass or transverse mass of $X$ for resonance peaks
Invisible decays of the Higgs

- **Higgs portal DM:** new dark matter particle couples to the Standard Model **only via the Higgs**

- Assuming we understand total Higgs production cross section, how **much room** is there for BSM decays?

  - Combination of observed Higgs decays now sets upper limit on remaining branching fraction $B(h_{125}) \rightarrow \text{BSM} \text{ at } \sim 30\%$.

  - Could this include “invisible” decays to dark matter?

- **Very challenging searches!** Goal number is upper limit on possible $H \rightarrow \text{invisible}$ branching ratio.

  - For comparison, SM predicts $H \rightarrow \text{invisible} \text{ BR} \sim 0.1\%$
VBF Higgs to dark matter

High VBF production rate for Higgs; topology with forward jets helps reject V+jets backgrounds. Other challenging backgrounds from e.g. VBF $Z(\nu\nu)$.
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QCD dijet back-to-back in φ, these jets not necessarily: require forward jets at small Δφ
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Trigger on M_{ET}

QCD dijet back-to-back in φ, these jets not necessarily: require forward jets at small Δφ

Fitting multiple CRs constrains W and Z backgrounds

ATLAS-CONF-2020-008
VBF Higgs to dark matter

High VBF production rate for Higgs; topology with forward jets helps reject V+jets backgrounds. Other challenging backgrounds from e.g. VBF Z(νν).

ATLAS Preliminary

Post-fit

Events / Bin

Data

Uncertainty

W strong

W EWK

Z strong

Z EWK

e-fakes

Other

Multijet

\( H(B_{\text{inv}} = 0.13) \)

Data-driven estimate of multijet bkg

ATLAS-CONF-2020-008
VBF Higgs to dark matter

High VBF production rate for Higgs; topology with forward jets helps reject V+jets backgrounds. Other challenging backgrounds from e.g. VBF $Z(\nu\nu)$.

Fitting multiple CRs constrains W and Z backgrounds

Data-driven estimate of multijet bkg

Result: upper limit on $B(h125)\rightarrow\chi\chi$ of 13% ! (obs and exp)

ATLAS-CONF-2020-008
Comparison to direct detection limits

\[ B_{\text{inv}} < 0.11 \]
All limits at 90\% CL

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

Higgs Portal
Other experiments
Scalar WIMP
DarkSide-50
Majorana WIMP
LUX
PandaX-II
Xenon1T

Use an EFT framework to translate results into limits on WIMP-nucleon cross section
Comparison to direct detection limits

\[ B_{\text{inv}} < 0.11 \]

All limits at 90\% CL

\[ \sqrt{s} = 13 \text{ TeV}, \ 139 \text{ fb}^{-1} \]

**ATLAS** Preliminary

Different relationships between \( \Gamma_{\text{DM}} \) and \( \sigma_{\text{SI}} \) for scalar and fermion DM

- Higgs Portal
- Other experiments
  - Scalar WIMP
  - Majorana WIMP
  - DarkSide-50
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\( 1 \text{ TeV} \)

\( 10 \text{ GeV} \)
Comparison to direct detection limits

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All limits at 90% CL

\[ \sqrt{s} = 13 \text{ TeV, 139 fb}^{-1} \]

ATLAS Preliminary

Higgs Portal

Other experiments

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\[ \sigma_{\text{WIMP-nucleon}} [\text{cm}^2] \]
2HDMa and its dominant signatures

- Now instead, consider **two-Higgs doublet model** plus a pseudo-scalar.

- Like Z’ simplified model, we search in $M_{\text{ET}}+X$ or look for visible mediator decays, but couplings prioritise **third generation** and signatures with vector bosons and Higgs:

![Diagrams](image-url)
2HDMa and its dominant signatures

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![Diagram 23](image1)

![Diagram 24](image2)

![Diagram 25](image3)

![Diagram 26](image4)

Monojet

Heavy flavour resonances
2HDMa and its dominant signatures

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**Monojet**

**tt/bb+MET**

**or all visible**

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**Monojet**

$tt/bb+MET$ or all visible

**Heavy flavour resonances**

**Mono-Z/h**
Heavy flavour + MET

- Looking for DM in two tops and high missing momentum final state
- Selecting one-lepton decay balances high stats with suppression of QCD; at least two b-tags keeps top-like events
- Dominant background: ttZ with $Z \rightarrow \nu \nu$: constrain with a ttZ(\ell\ell) control region

**Figure 23:** Diagram 23

**Figure 24:** Diagram 24

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**ATLAS** Preliminary

- Data
- Total SM
- DM
- $t\bar{t}$ 2L
- W+jets
- Single top
- ttZ

Events vs. $\Delta \phi(\vec{p}_T^{\text{miss}}, \ell)$ [rad]

- $m(\phi, \chi) = 20.1$ GeV
- $m(a, \chi) = 20.1$ GeV

Multi-bin fit here

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**ATLAS** Preliminary

- Observed 95% CL
- Expected 95% CL
- Expected ±1 $\sigma$
- Expected ±2 $\sigma$
- Theory unc. on $\sigma(g=1.0)$

Pseudoscalar
$t\bar{t}a$, $a \rightarrow \chi \chi$

$g = 1.0$, $m_\chi = 1$ GeV

95% CL limit on $\sigma_{\text{obs}}(g=1)$ vs. $m_a$ [GeV]

10$^1$ to 10$^2$ range

Excluded

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Preliminary

ATLAS-CONF-2020-003

13 TeV, 139 fb$^{-1}$
Mono-V/Higgs

- Mono-Z/h has special sensitivity in 2HDM+X models
- CMS combination of Higgs to bb, γγ, ττ, WW, and ZZ interpreted in 2HDM+Z’:

![Diagrams](image.png)
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h(WW) BDT trained on momenta, transverse masses, angular variables
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  ZZ uses $M_{\text{ET}}$ distribution
Mono-V/Higgs

- Mono-Z/h has special sensitivity in 2HDM+X models
- CMS combination of Higgs to bb, γγ, ττ, WW, and ZZ interpretated in 2HDM+Z’:

Z'-2HDM, Dirac DM
m_A = 300 GeV
m_h = 100 GeV
g'_Z = 0.8, g_h = 1, tanβ = 1
m_A = m_h

h(WW) BDT trained on momenta, transverse masses, angular variables

ZZ uses M_{ET} distribution
Visible a decays

Looking for very light a (below 4 GeV): such high boost that it is reconstructed as one small-radius jet

Train on two-pronged nature of jet substructure to learn resonance mass
Visible $a$ decays

Looking for very light $a$ (below 4 GeV): such high boost that it is reconstructed as one small-radius jet

Train on two-pronged nature of jet substructure to learn resonance mass

Use learned mass, substructure variables to train selection NN

ATLAS
\(\sqrt{s}=13\) TeV, 139 fb\(^{-1}\)
\(\alpha(H)=\sigma_{\text{EW}}(H)\times 100\)
\(B(H\rightarrow Z\ell)=100\%\)

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Higgs mass window defines signal region
SUSY as a dark matter generator

• Remember that supersymmetry can be a dark matter model too:

\[ p \xrightarrow{\tilde{t}} W b \]
\[ p \xrightarrow{\tilde{t}} \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \tilde{\chi}_1^0 \]
\[ b \xrightarrow{W} \tilde{\chi}_1^0 \]

For details of our SUSY (dark matter) search program, see talk from A. Kalogeropoulos.
SUSY as a dark matter generator

- Remember that supersymmetry can be a dark matter model too:

R-parity conservation requires even number of SUSY particles in each interaction
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Therefore lightest SUSY particle must be stable → dark matter candidate!
SUSY as a dark matter generator

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R-parity conservation requires even number of SUSY particles in each interaction

Therefore lightest SUSY particle must be stable → dark matter candidate!

• Quality of DM candidate still depends on other assumptions

• Lots of parameter choices give too high relic density, be careful!

• For details of our SUSY (dark matter) search program, see talk from A. Kalogeropoulos
How are all these results related?

- Benefit of picking a few simplified models is we get a framework to put these all on the same page

- This gives context for where our search program is strongest or weakest

Example: dijet-like resonance searches
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Example: dijet-like resonance searches

ATLAS Preliminary \( \sqrt{s} = 13 \text{ TeV}, 3.6-139 \text{ fb}^{-1} \) May 2020

95% CL upper limits

- Observed
- Expected

Boosted dijet + ISR
- 36.1 fb

Boosted di-b-jet + ISR
- 80.5 fb
  - ATLAS-CONF-2018-052

Resolved dijet + ISR
- 79.8 & 76.6 fb

Resolved di-b-jet + ISR
- 79.8 & 76.6 fb

Dijet TLA
- 3.6 & 20.7 fb

Di-b-jet
- 24.3 & 159 fb
  - JHEP 03 (2020) 145

Dijet
- 139 fb
  - JHEP 03 (2020) 145

Dijet angular
- 37.0 fb

\( t \bar{t} \) resonance
- 36.1 fb

Axial-vector mediator
Dirac DM
\( m_{\chi} = 10 \text{ TeV}, g_{\chi} = 1.0 \)

Example:
\( g_{Y} = 0.07 \)

ATLAS EXOT public plots
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Example: dijet-like resonance searches
Z’ mediator models

CMS Preliminary

LHCP 2020

Exclusion at 95% CL

- Observed
- Expected

Boosted dijet (77 fb⁻¹)
[arXiv:1909.04114]

Dijet w/ btag (19.7 fb⁻¹)
[arXiv:1802.06149]

Dijet w/ ISR j (18.3 fb⁻¹)
[arXiv:1911.03761]

Dijet (35.9-137 fb⁻¹)
[arXiv:1806.00843]
[arXiv:1911.03947]

DM + j/V(qq) (35.9 fb⁻¹)
[arXiv:1712.02345]

DM + γ (35.9 fb⁻¹)
[arXiv:1810.00196]

DM + Z(ℓℓ) (35.9 fb⁻¹)
[arXiv:1711.00431]

Vector mediator
Dirac DM
$g_{\text{Dirac}} = 1.0$
$g_{q} = 0.25$
$g_{l} = 0$

New!

$M_{\text{Med}} = 2 \times m_{\text{DM}}$

$\Omega_{c} h^{2} \geq 0.12$
Z’ mediator models

Vector mediator
Dirac DM
$g_{DM} = 1.0$
$g_q = 0.25$
$g_l = 0$

CMS Preliminary

LHCP 2020

New!

$M_{Med} = 2 \times m_{DM}$

$\Omega_c h^2 \geq 0.12$

Exclusion at 95% CL

- **Observed**
- **Expected**

- **Boosted dijet** (77 fb$^{-1}$)
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- **DM + Z(ll)** (35.9 fb$^{-1}$)
  - [arXiv:1711.00431]
Z’ mediator models

CMS Preliminary

LHCP 2020

Vector mediator
Dirac DM
$g_{DM} = 1.0$
$g_{q} = 0.1$
$g_{l} = 0.01$

Exclusion at 95% CL
Observed
Expected

Dilepton (137 fb$^{-1}$)
[EXO-19-019]

Dijet (35.9-137 fb$^{-1}$)
[arXiv:1806.00843]
[arXiv:1911.03947]

Boosted dijet (77 fb$^{-1}$)
[arXiv:1909.04114]

Couplings make a huge difference!

CMS EXO public plots
With the non-collider world

- Important to contextualise collider limits alongside direct and indirect detection results
- Results are very model dependent! Here, showing comparisons to **direct detection**:
  - Axial-vector mediators have **spin-dependent** interactions, vector mediators have **spin-independent** interactions. Different sets of limits for each (also note coupling choices!):

![Plots: CombinedSummaryPlotsEXOTICS](CombinedSummaryPlotsEXOTICS)

How comparisons are made: [arXiv:1603.04156](https://arxiv.org/abs/1603.04156)

Great talk from Fady Bishara
Conclusions

• Explored the **wide range of analyses** which can constrain dark matter at the LHC, and showed the unique contributions of each

  • Higgs to invisible searches, resonance searches, and $M_{ET}$-based signatures are all **key contributors** to the DM search program

• More full Run 2 results are **in progress now** - stay tuned for exciting updates!

• DM possibilities are **super diverse**: broader dark sector searches, SUSY searches, and long-lived particle searches can all be handles on dark matter

For more, see these talks:

Dark matter in ATLAS, J. Burr
Dark matter in CMS, V. Sharma
Higgs to invisible searches, D. Schaefer

Dark sectors in ATLAS and CMS, M. Queitsch-Maitland
Heavy resonances in ATLAS and CMS, O. Gonzalez
EXO Experimental overview, I. Ochoa
Backup
2HDM+a details

- Additional Higgs doublet leads to five Higgs-like particles: SM-like \( h, H \), CP-odd pseudo-scalar \( A \), two charged Higgs \( H^+, H^- \). Extend with extra DM mediator (here, a pseudo scalar \( a \)). \( A \) and \( a \) can mix; dark matter \( \chi \) couples to \( a \).

- Relevant parameters of model: Higgs particle masses (6, with 1 fixed given that \( m_h \) should be 125 GeV), dark matter mass, quartic couplings between \( a \) and scalar doublets (3), coupling between \( a \) and DM (1), EW VEV (1), ratio of VEVs of the Higgs doublets, called \( \tan(\beta) \) (1), mixing angle of CP-even eigenstates \( \alpha \) (1), mixing angle of CP-odd eigenstates \( \theta \) (1). Total: 14.

- Therefore much more complicated to summarise/scan!
2HDM+a details

- In ATLAS summary effort, chose:
  - Type II 2HDM with $v$ and $h$ fixed by Standard Model higgs
  - Coupling of $a$ to scalar doublets large enough to ensure Higgs potential stability, and all equal
    - $m_A = m_H = m_{H^+}$
  - Coupling of $a$ to $\chi = 1$
  - Thus parameters left to vary in scan are: $m_a, m_A, m_X, \tan(\beta), \sin(\theta)$
  - Scenarios tested taken from recommendations from LHC DM WG
2HDM+a summary plots

Light DM

$\sin(\theta) = 0.35$

allows H to be heavy but keep quartic couplings reasonable

Three parameters left:

$\tan(\beta)$, $m_a$, $m_A$

Fix one and scan the other two

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

Limits at 95% CL

- Observed
- Expected

$E_T^{\text{miss}} + Z(\text{ll})$

PLB 776 (2017) 318

$E_T^{\text{miss}} + h(b\bar{b})$

PRL 119 (2017) 181804

$E_T^{\text{miss}} + h(\gamma\gamma)$

PRD 96 (2017) 112004

$E_T^{\text{miss}} + Z(q\bar{q})$

JHEP 10 (2018) 180

$h(\text{inv})$ $\sqrt{s} = 7,8$ TeV; 4.7, 20.3 fb$^{-1}$

JHEP 11 (2015) 206,
2HDM+a summary plots

Light DM

\[ \sin(\theta) = 0.35 \]

allows H to be heavy but keep quartic couplings reasonable

Three parameters left:
\[ \tan(\beta), \ m_a, \ m_A \]

Fix one and scan the other two

**ATLAS**

\[ \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \]

Limits at 95% CL
- Observed
- Expected

2HDM+a, Dirac DM

\[ m_\chi = 10 \text{ GeV, } g = 1 \]
\[ m_A = m_H = m_{H^\pm} = 600 \text{ GeV} \]
\[ \sin \theta = 0.35 \]

\[ \Gamma/m_a > 20\% \]

\[ m_a \text{ [GeV]} \]
Comparing Z’ collider limits to direct detection

- Spin-independent interactions: assume $\sigma_{SIproton} = \sigma_{SIneutron}$ and simply set one DM-nucleon interaction cross section limit. For spin-independent interactions, need to be set separately on proton and neutron.

- Calculate SI and SD cross sections for S-channel simplified models and we find:

$$\sigma_{SI} = \frac{f^2(g_q)g_{DM}^2\mu_{nX}^2}{\pi M_{med}^4}$$

$$\sigma_{SD} = \frac{3f^2(g_q)g_{DM}^2\mu_{nX}^2}{\pi M_{med}^4}$$

Vector: $f(g_q) = 3g_q$

Axial-vector: $f(g_q) = 0.32g_q$

$$\mu_{nX} = m_n m_{DM} / (m_n + m_{DM})$$

And combine information to translate from Mmed to $\sigma$.
Other direct detection ATLAS plots

Different couplings
Other direct detection ATLAS plots

Proton versus neutron