Dark Matter searches with ATLAS

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on behalf of the
ATLAS collaboration

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Deep Inelastic Scattering
and Related Subjects
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The WIMP Hypothesis

- Astrophysics / cosmology: Most of the matter content of the universe is transparent.
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- **Appealing scenario:**
  Weakly Interacting Massive Particle(s)
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- **Direct and indirect searches:** confirmation of or pressure onto the WIMP hypothesis in the next few years
The WIMP Hypothesis

▶ Astrophysics / cosmology:
Most of the matter content of the universe is transparent.

▶ Appealing scenario:
Weakly Interacting Massive Particle(s)

▶ Direct and indirect searches:
confirmation of or pressure onto the WIMP hypothesis in the next few years

▶ How does ATLAS contribute to the search for Dark Matter?
Outline

- Collider approach to Dark Matter
- Dark Matter signatures and searches
- Combinations of Dark Matter searches
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Collider approach to Dark Matter

General Strategies

- Direct detection: nuclear recoil from elastic scattering
Collider approach to Dark Matter

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- **Direct detection**: nuclear recoil from elastic scattering
- **Indirect detection**: dark matter annihilation
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- **Collider searches**: associated production of dark matter and SM particles

\[ \text{SM} \xrightarrow{\chi} \text{SM} \]

Comparison of search strategies:
- **Direct**
- **Indirect**
- **Collider**

Typical mass range:
- \(10 \text{ GeV} < m_\chi < 1 \text{ TeV}\)
- \(m_\chi \approx 1 \text{ TeV}\)

Observables beyond:
- \(m_\chi \sigma_{\chi N \rightarrow \chi N}\)
- \(m_\chi \sigma_{\chi \chi \rightarrow NN}\)

Model dependence
- DM on Earth
- DM in space
- Particle physics
Collider approach to Dark Matter
General Strategies

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Comparison of search strategies:

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<th>Collider - LHC</th>
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<td>$10 \text{ GeV} &lt; m_\chi &lt; 1 \text{ TeV}$</td>
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Collider approach to Dark Matter
Interpretation of collider Dark Matter searches

- Recent years: growing interest in DM frameworks which are not necessarily connected to SUSY - simplified models as a generic approach
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- Simplified signal models

- e.g. a single mediator $\Phi$ (scalar or vector-coupling, parity +1 or -1)
- Assumption: decoupling of further, heavier particles at LHC energies
- Prediction of different signatures

- Dark matter + SM particle $X$
- SM resonances
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- Dark Matter candidates from Supersymmetry with R-parity conservation (UV-complete models), covered in tomorrow's WG3 sessions

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Dark Matter Searches with ATLAS
Collider approach to Dark Matter
ATLAS Run 2 Dataset

- Large dataset collected by ATLAS in Run 2 (2015-2018):
  \[ \sqrt{s_{pp}} = 13 \text{ TeV} \]
  \[ \int L dt = 139 \text{ fb}^{-1} \]

- Analysis of this dataset ongoing; up to 80 fb\(^{-1}\) used for the results presented in the following

- \(E_T^{\text{miss}}\) Trigger used for most Dark Matter searches, fully efficient for \(E_T^{\text{miss}} \gtrsim 200 \text{ GeV}\)
Outline

- Collider approach to Dark Matter
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Outline

▶ Collider approach to Dark Matter

▶ \textit{Dark Matter signatures and searches: }$E_T^{\text{miss}}$ +
  ▶ Jet
  ▶ $H(bb)$
  ▶ $W/Z(qq)$
  ▶ $Z(\ell\ell)$
  ▶ “VBF”

▶ Combinations of Dark Matter searches
Dark Matter Signatures: Monojet

- $E_T^{\text{miss}} > 250$ GeV + up to 4 jets $\Rightarrow$ sensitivity to several new phenomena
- Signal region (no leptons) + $W(e\nu)$, $W(\mu\nu)$, $Z(\mu\mu)$ and top-quark control regions

- High precision theoretical predictions of $W/Z$ $p_T$ distributions (NLO EWK) $\Rightarrow$ accurate modelling of the $E_T^{\text{miss}}$ distribution in the signal region
- Combined fit of signal and control regions

JHEP 01 (2018) 126
Dark Matter Signatures: Monojet
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Interpretation wrt. various signal models. Here: Dark Matter pair production via an axial-vector mediator.
Dark Matter Signatures: Mono-Higgs(bb)

- Associated production of Dark Matter and a Higgs boson $\Rightarrow$ no “ISR model”, probing dark matter interactions more directly

- Aiming for $h \rightarrow bb$ decays (largest branching ratio)
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- 2 topologies, depending on the Higgs boson momentum
  
  ▶ Resolved: Pair of separated jets
Dark Matter Signatures: Mono-Higgs(bb)

- Associated production of Dark Matter and a Higgs boson $\Rightarrow$ no “ISR model”, probing dark matter interactions more directly

- Aiming for $h \rightarrow bb$ decays (largest branching ratio)

- 2 topologies, depending on the Higgs boson momentum
  - Resolved: Pair of separated jets
  - Boosted: Single large-Radius jet

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High energy signature

Low energy signature
Boosted topology: using large-R jet substructure with two $b$-tagged track jets

For large $p^h$: track jets close to each other $\Rightarrow$ Fixed-Radius (FR) track jets merge

Hence **decrease the track jet radius as $p_T^{\text{track jet}}$ increases** $\Rightarrow$ Variable-Radius (VR) track jets
Dark Matter Signatures: Mono-Higgs(bb)

Run 2 data from 2015 - 2017:
\[ \int L dt = 80 \text{ fb}^{-1} \]

Discriminating variables:
di-jet or large-R jet mass, \( E_T^{\text{miss}} \)

Interpret results in terms of mass limits on new mediators

Compared to predecessor analysis:
improvement in particular due to the use of Variable-Radius track jets
  Relevant also for other searches for new phenomena with ATLAS
Dark Matter Signatures: $W/Z(qq) + E_T^{\text{miss}}$

- Different interpretations, including $H \rightarrow \text{inv. decays}$
- Considering both resolved and boosted $W/Z \rightarrow qq$ - decays
- $E_T^{\text{miss}}$ for different $b$-tag multiplicities as discriminating variable variable

ATLAS
$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
SR: merged topology
0 leptons, 0 $b$-tags, HP
$Z + \text{jets}$
$W + \text{jets}$
$+ \text{single top}$
$\text{Diboson}$
$\text{Multijet}$

Background Uncertainty
Pre-fit Background
$H \rightarrow \text{inv. decays}$ ($B_{\text{inv}} = 100\%$)
$H \rightarrow \text{inv. decays}$
$m_Z = 600$ GeV, $m_H = 1$ GeV

Data/SM

Mono-$W/Z(qq)$: Vector, Dirac

$g_{SM} = 0.25, g_{DM} = 1.0$

Relic density

ATLAS
$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
Mono-$W/Z(qq)$: Vector, Dirac
$g_{SM} = 0.25, g_{DM} = 1.0$

Observed 95% CL
Expected 95% CL
($\pm 1\sigma$ and $\pm 2\sigma$)

$m_{Z'}$ [GeV]

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Dark Matter Searches with ATLAS

PLB 776 (2017) 318

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Dark Matter Signatures: $Z(\ell\ell) + E_T^{\text{miss}}$

- Different interpretations, including $H \to \text{inv. decays}$

- Single lepton triggers $\Rightarrow$ sensitivity to signals with lower $E_T^{\text{miss}}$

- $E_T^{\text{miss}}$ in $ee$ and $\mu\mu$ signal regions as discriminating variable
Dark Matter Signatures: VBF+$E_T^{\text{miss}}$

- Events with 2 jets with a rapidity difference $|\Delta \eta_{jj}| > 4.8$ and $E_T^{\text{miss}} > 180 \text{ GeV}$ ⇒ distinct signature ("Vector Boson Fusion")

- Background constraints derived from $W$+jets and $Z$+jets control regions

- Max. Likelihood Fit using three bins of $m_{\text{dijet}}$ starting at 1 TeV

- Resulting observed (expected) limit:
  $$\mathcal{B}(H\to\text{inv.}) < 0.37 \ (0.28^{+0.11}_{-0.08})$$
  (without constraints from Higgs boson observations)

arxiv 1809.06682, subm. to PLB
Dark Matter Signatures: More Searches

More Mono-X signatures

- Further Dark Matter production modes and alternative Standard Model decays
  - Mono-Photon
  - Mono-\(H(\gamma\gamma)\)
  - Mono-Top-Quark
  - Dark Matter + heavy flavour pair production

New Resonances

- Complementary constraints within the simplified model context
- Dedicated ATLAS talk by Johannes Erdmann tomorrow
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  - Spin-1 mediators
  - $H \rightarrow$ invisible decays
Combinations of Dark Matter searches
Vector Mediators

▶ Summary of exclusion limits of dark matter and resonance searches, both hadronically and leptonically

▶ Complementarity: large exclusion range achieved via combination

▶ Similar results for axial-vector mediators

1903.01400, subm. to JHEP
Combinations of Dark Matter searches
Vector Mediators, comparison with direct searches

Vector mediator, Dirac DM
\( g_q = 0.1, g_l = 0.01, g_\chi = 1 \)

All limits at 95% CL
Combinations of Dark Matter searches
Vector Mediators, comparison with direct searches

For the... Rev. Lett. 116, 161302 (2016)
LUX: higher sensitivity of the
... 1903.01400, subm. to JHEP

(Vector mediator, Dirac DM)

$g = 0.1, g = 0.01, g = 1$

$\chi = 0.01, g = 1$

$\chi = 1$

$m_{\chi} [\text{TeV}]$

$m_{\chi} [\text{TeV}]$

$E_T \gamma + X$

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Combinations of Dark Matter searches
Vector Mediators, comparison with direct searches

For the model parameters chosen here: higher sensitivity of the $E_T^{\text{miss}} + \text{jet}$ search compared to direct searches at low values of $m_{\chi}$ (where the $\chi$-nucleon elastic scattering cross-section is small)
Combinations of Dark Matter searches
Higgs-boson decays to weakly interacting particles

- Statistical combination of
  - 3 channels
  - Run 1 and Run 2 data up to 2016

- Resulting observed (expected) limit:
  \[ \mathcal{B}(H \rightarrow \text{inv.}) < 0.26(0.17^{+0.07}_{-0.05}) \]

(without constraints from Higgs boson observations)

ATLAS-CONF-2018-054
Summary

- Analysed Run 2 data with up to $\int L dt = 80 \, fb^{-1}$
- Numerous final states covered
- Interpretation in view of simplified models

Conclusions

1. Complementarity of direct, indirect and collider Dark Matter searches
2. Complementarity of different final states
3. Analysis improvements due to both increased statistics and new analysis techniques, both to come with the analysis of the full Run 2 dataset
**Z(νν)/Z(ℓℓ) ratio measurement**

- Differential measurements of
  
  \[ R^{\text{miss}} = \frac{\sigma_{\text{fid}}(Z\rightarrow\nu\nu+\text{jets})}{\sigma_{\text{fid}}(Z\rightarrow\ell\ell+\text{jets})} \]

- Two regions with different unfoldings
  - \( \geq 1 \) jet: \( E_T^{\text{miss}} \)
  - VBF: \( E_T^{\text{miss}} \), dijet mass, dijet \( \Delta \phi \)

- Allowing to constrain many (future) jets + \( E_T^{\text{miss}} \) BSM models

ATLAS

\( \sqrt{s} = 13 \text{ TeV}, 3.2 \, \text{fb}^{-1} \)

\[ m_A \text{ [GeV]} \]

\[ m_\chi \text{ [GeV]} \]

Axial-vector mediator
Dirac fermion DM

\( g_q = 0.25, g_{\ell} = 1 \)

\[ R_{\text{miss}} = \frac{\sigma_{\text{fid}}(p_T^{\text{miss}} + \text{jets})}{\sigma_{\text{fid}}(\ell + \text{jets})} \]

Exp. limit 95% CL (Perturbativity limit
Relic density
Exp. PRD94 (2016) 032005
Obs. PRD94 (2016) 032005

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Photon+$E_T^{\text{miss}}$

- $E_T^\gamma$ and $E_T^{\text{miss}} > 150$ GeV + up to one jet
  - Photon trigger allows for lower $E_T^{\text{miss}}$ values compared to the mono-jet analysis
  - Again, combined fit of signal and control regions using $E_T^{\text{miss}}$

![Graph showing ATLAS results with m:\gamma vs m_{\chi}\bar{\chi} for signal and background regions.](image-url)
Mono-\(h(\gamma\gamma)\)

- Circumvent \(E_T^{\text{miss}}\) trigger threshold of the Mono-\(h(bb)\) analysis: \(h \rightarrow \gamma\gamma\)
- \(\mathcal{BR}(h \rightarrow \gamma\gamma) < \mathcal{BR}(h \rightarrow bb)\), but better \(m_h\) resolution
- \(Z' + 2HDM\) limits, also referring to the spin-indep. DM-Nucleon cross-section
Single top + $E_T^{\text{miss}}$

- Resonant and non-resonant top + dark matter production (+ Vector-like $T$-quark search with $T \to tZ$ decays)
- Several reducible backgrounds (SM top), negligible irreducible background: FCNCs
- Two approaches: leptonic top decays and boosted hadronic top decays
Heavy Flavour Quarks + $E_T^{\text{miss}}$

- Several models with new scalar particles mediating between SM and DM particles
- Avoid constraints from flavour physics ⇒ Yukawa couplings set proportional to fermion masses
- Five signal regions sensitive to different BSM scenarios + several control regions for background normalisation
- Limits on new particle masses + model independent limits on detector level cross-sections
2HDM + Pseudoscalar Model

- Careful extension of the SM avoiding numerous constraints, UV complete
- Dark matter: fermion, SM gauge group singlet
- Many relevant production modes; notably including resonant production $H \rightarrow aZ$ and $A \rightarrow ah$
Combinations of Dark Matter searches

- UV-complete model, avoiding constraints from direct searches

- Rich phenomenology with several important final states

- Proposed in JHEP05 2017 138, i.e. in the middle of Run 2 ⇒ desire for reinterpretation
  - Rerunning analyses, in case of Mono-H(bb) semi-automatically - see this ATLAS contribution at last week’s LHC reinterpretation workshop

- Ability to perform reinterpretations becoming more important
Mono-Higgs(bb)
Improvement due to VR track jets

**Expected upper limit on $\mu$ (95% CL)**

**ATLAS** Preliminary
$\sqrt{s} = 13$ TeV, 79.8 fb$^{-1}$

$h(bb) + E_T^{miss}$: $Z'$+2HDM simplified model
$tan \beta = 1$, $g_Z = 0.8$, $m_\chi = 100$ GeV, $m_A = 500$ GeV

VR track jets 2b
(±1σ and ±2σ)

FR track jets 2b
(scaled)