Search for Dark Matter Produced in Association with a Dark Higgs Boson with the ATLAS Detector

WNPPC Conference

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Dark Matter Detection

Direct detection searches:
- Dark matter scatters off particle (nucleon, photon, etc.) in detector material
  - Measure recoil energy
- Search target: galactic dark matter

Collider searches:
- Dark matter produced in high-energy collision along with detectable particle(s)
- Search target: dark matter produced by collision
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The ATLAS Detector

- General-purpose detector for studying particles produced by high-energy beam collisions at the LHC

- Used both for precision standard model measurements and to search for new physics
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- Showers initiated by quarks and gluons referred to as “jets”
- Jets reconstructed in cone of angular radius $R$
  - “small-radius” jet: $R=0.2 \rightarrow 0.4$
  - “large-radius” jet: $R=0.8 \rightarrow 1.0$

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

- Neutrinos ($\nu$) and dark matter particles ($\chi$) pass through undetected
  → Presence inferred from imbalance of momentum transverse to the beam line, a.k.a. $E_T^{\text{miss}}$

$$E_T^{\text{miss}} = - \left| \sum \vec{p}_T \right|$$
Dark Matter Production Models for Collider Searches

Effective Field Theories (EFT)
- Dark matter production mechanism unspecified

Simplified Models
- First-order description of new physics
- Bridge gap between EFT and complete models

Complete Models
- Dark matter predicted as part of a complete unified theory
  - Eg. Supersymmetry
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“Dark Higgs” Signal Model

- **χ**: Dark Matter
  - Mass fixed to 200 GeV for consistency with other LHC searches

- **Z’**: Vector boson in dark sector
  - Mass not fixed in model
  - Search region explores $m_{Z'} > 2m_\chi$, thus allowing for $Z' \rightarrow \chi\chi$ decay

- **s**: Higgs boson in dark sector (a.k.a. “dark Higgs”)
  - Mass not fixed in model
  - Search region explores $m_s < 2m_\chi$, thus forbidding $s \rightarrow \chi\chi$ decay

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Search with Dark Higgs Decay to WW

- Search for dark Higgs model in $s \rightarrow bb$ channel was completed in 2019 (ATL-PHYS-PUB-2019-032)

- $s \rightarrow bb$ decay has highest cross section for $m_s \lesssim 135$ GeV

- $s \rightarrow WW$ dominates for high-mass dark higgs

⇒ Motivates dedicated dark matter search in $s \rightarrow WW$ channel
Search in Hadronic Channel (WW → qqqq)

Completed in late 2020
- Used full ATLAS Run 2 data

**Signature in ATLAS detector:**
- Hadronic jets in calorimeter recoiling against missing transverse momentum from $\chi\chi$
- WW pair boosted due to high-mass $Z'$ mediator

Dominant standard model background:
$Z$+jets (where $Z \rightarrow \nu\nu$)
Search in Hadronic Channel (WW → qqqq)

- Constrained dark Higgs model parameters $m_s$ and $m_{Z'}$ in the appx. range:

  $160 \text{ GeV} < m_s < 240 \text{ GeV}$

  ($s \rightarrow bb$ coverage: $50 \text{ GeV} < m_s < 150 \text{ GeV}$)

Search in Semileptonic Channel ($WW \rightarrow qq\ell\nu$)

Ongoing → search began last February
- Using full ATLAS Run 2 data

Signature in ATLAS detector:
- Hadronic jets + lepton in calorimeter recoiling against $E_T^{\text{miss}}$ from $\chi\chi$
- $E_T^{\text{miss}}$ includes contributions from $\chi\chi$ and $\nu$

Semileptonic: One $W$ now decays to $\ell+\nu$
Semileptonic vs. Hadronic Channel

Pros

● 1-lepton requirement reduces some backgrounds compared with hadronic channel (eg. Z+jets)

● Ability to reconstruct hadronically-decaying $W$ boson → can select for mass window near on-shell $W$ mass (80.4 GeV)

Cons

● $\nu$ in final state:
  ○ adds additional (non-dark-matter) source of $E_T^{\text{miss}}$
  ○ prevents direct reconstruction of dark higgs candidate
  ■ Developed a minimization strategy for approximate dark higgs mass reco (see backup)
Semileptonic Channel: Transverse Mass

\[ m_T(\ell, E_T^{\text{miss}}) = \sqrt{2p_{T,\ell}E_T^{\text{miss}}(1 - \cos \theta_{\ell, E_T^{\text{miss}}})} \]

- Expectation for standard model background (for on-shell W):
  \[ m_T(\ell, E_T^{\text{miss}}) \leq m_W \]

- Dark matter in signal model adds \( E_T^{\text{miss}} \) with different \( \cos \theta_{\ell, E_T^{\text{miss}}} \) distribution

- Selecting \( m_T(\ell, E_T^{\text{miss}}) > 200 \text{ GeV} \) substantially reduces standard model backgrounds, especially W+jets

- **Interesting feature:** Remaining W+jets background is mainly events with very off-shell W mass (\( >> 80.4 \text{ GeV} \))
Semileptonic Channel: Analysis Regions

Resolved Category
- Less-boosted
- Hadronized quarks reconstructed as two resolved small-radius jets

Merged Category
- More-boosted
- Hadronized quarks reconstructed as large-radius jet
Semileptonic Channel: Analysis Regions

Resolved category: Higher stats, lower signal/background

Merged category: Lower stats, higher signal/background

No signal scaling
Summary

- Ongoing search for dark matter production with \( WW + E_{T \text{miss}} \) in final state
- Motivated and optimized with “dark Higgs” simplified model
- Exclusion limits have been set in \( WW \rightarrow qqqq \) final state
- Search in \( WW \rightarrow qq\ell\nu \) final state ongoing
Backup Slides
Definitions

Transverse Mass

- Reconstructed mass of two final-state objects in the plane transverse to the LHC beam line
- Transverse mass between lepton and $E_T^{\text{miss}}$ is defined assuming lepton and $E_T^{\text{miss}}$-producing object(s) are appx. massless:

$$m_T(\ell, E_T^{\text{miss}}) = \sqrt{2 p_T, \ell E_T^{\text{miss}} (1 - \cos \theta_{\ell, E_T^{\text{miss}}})}$$

Missing Transverse Energy ($E_T^{\text{miss}}$)

- Total momentum of undetected final-state objects in the plane transverse to the beam line
- Two-dimensional vectorial sum over all visible final-state objects in the transverse

$$\vec{E}_T^{\text{miss}} = - \sum_i \vec{p}_{x,i} + \vec{p}_{y,i}$$

LHC Run 2

- Data collected at the LHC from 2015-2018 at a proton-proton collision energy of 13 TeV
Definitions, cont.

**Pseudorapidity**

- Describes angle of particle relative to beam axis (z-axis)
- Changes $\Delta \eta$ in pseudorapidity are Lorentz invariant under boosts along the longitudinal axis

\[
\eta = -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right]
\]

- $\Delta N/\Delta \eta$ is approximately constant for $|\eta| \leq 5$
  - $N$: number of charged tracks in pileup events
Dark Matter Detection

Direct detection searches:
- Low energy (~keV)
- Low background

Collider searches:
- High energy (~TeV)
- High background
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Sudbury, ON

~2 km

SNOLAB
Search in Hadronic Channel ($WW \rightarrow qqqq$)

- Most sensitive in the “merged” regime
- None of the jets can be resolved into individual small-radius jets → all reconstructed within a single large-radius jet

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**Merged Category**
- Most boosted regime
- None of the jets can be resolved into individual small-radius jets → all reconstructed within a single large-radius jet

**Intermediate Category**
- Less-boosted regime
- Some of the jets can be resolved into individual small-radius jets
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Analytical Solution of $m_S$ in $s \rightarrow WW \rightarrow qq\ell\nu$ System

- **Idea:** Find the minimum $m_S$ consistent with observed $W_H$ and $\ell$ momenta and $W$ mass constraint $m_W = 80.4$ GeV.

1. In frame where $\ell$ travels along the $z$ axis and $W_H$ is in the $xz$ frame:

   \[
   m_S^2 = (p_{W_H} + p_\ell + p_{\nu})^2
   \]

   \[
   m_S^2 = (E_{W_H} + E_\ell + E_{\nu})^2 - (p_{W_{Hx}} + E_\nu \sin \theta_{\ell\nu} \cos \phi_{\nu})^2
   \]

   \[
   - (E_\nu \sin \theta_{\ell\nu} \sin \phi_{\nu})^2 - (E_\ell + p_{W_{Hz}} + E_\nu \cos \theta_{\ell\nu})^2
   \]

2. Determine $\phi_{\nu}$ and $\theta_{\ell\nu}$ that minimize $m_S$.
   - $\phi_{\nu} = 0$, and $\theta_{\ell\nu}$ can be solved for numerically.

3. Eliminate $E_\nu$ using $W$ mass constraint for $W \rightarrow \ell\nu$ system, then rotate back to lab frame.
The TAR Algorithm

Use excellent angular resolution of the ATLAS tracker system

\[
p_{T,\text{track,new}} = p_{T,\text{track,old}} \times \sum_{i \in j} \frac{p_{T,i}}{p_{T}}
\]
Asimov Signal Significance

Expected Asimov signal significance $Z$ used in optimizing selection cuts. Defined as:

\[
Z = \sqrt{2} \left[ \ln \left( \frac{(s + b)(b + \sigma_b^2)}{b^2 + (s + b)\sigma_b^2} \right) - \frac{b^2}{\sigma_b^2} \ln \left( 1 + \frac{\sigma_b^2 s}{b(b + \sigma_b^2)} \right) \right]
\]

$s$: expected number of signal events (based on simulation)

$b$: expected number of background events (based on simulation)

$\sigma_b$: uncertainty associated with expected number of background events
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- Showers initiated by quarks and gluons are referred to as “jets”

Jets reconstructed in cone of angular radius \( R \)

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- Muon spectrometer detects muons, which pass through the calorimeters
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