Searches for dark matter with the ATLAS Experiment at the LHC

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https://indico.cern.ch/event/1199102/
Literature on dark matter

I scoured titles on arXiv.org

Zwicky and Rubin

1933 ... 1962 ...

arXiv entries per year

Higgs
SUSY
SUPERSYMMETRY

DM
DARK MATTER

Dark matter papers see continued growth

Scaled up 2023 since ½ way
DM & collider theories
Wide range of ideas from effective to complete


Devi et al., Phys. Dark Univ. 9-10 (2015) 8-23

Abdallah et al., Phys. Dark Univ. 9-10 (2015) 8-23

Snowmass 2013, Ch. 4, [1401.6085]
Outline
10+ papers, so only a taste of new results

Intro
• Models, LHC, ATLAS, MET

This talk
• DM via scalars: VBF H, ZH, t\bar{t}\phi
• DM via methods: dark sector jets, single t, anomaly ML
• DM in SUSY: 2 tau, 1 e/\mu lepton + jets, 2-3 e/\mu leptons

Related ATLAS talks, posters

July 14  S. Bansal  New symmetries in the Higgs sector  : High-, low-mass scalars, H_{125} to light scalars
July 18  S. Ezzarqtouni  Combo of ATLAS DM searches  : Direct & assoc. prod., via mediator
July 11  A. Rodriguez Vera  New phenomena  : Lepto-q, vector-like q, DM via unconven. / long-lived
July 13  R. Zhang  Active Learning in DM search  : Z_{dark} to 4 leptons in preserved data w/ Panda & iDDS
July 18  A. Cheng  Unsupervised ML for anomaly  : One b-jet + one (b-jet / e / \mu)
July 20  E. Torro Pastor  Challenging & Long-lived  : Fractional charge, long-lived
July 11  E. Antipov  Strong SUSY production  : Gluino, squark - stop / sbottom, RPC / RPV w/o MET
July 20  Y. Cai  Electroweak SUSY production  : Sleptons, charginos, neutralinos

upcoming
Table of characteristics

<table>
<thead>
<tr>
<th>Property</th>
<th>Spin 0</th>
<th>Spin 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Q</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Mass m</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>Mediator is similar to</td>
<td>$H, \phi$</td>
<td>$\gamma, Z, Z'$</td>
</tr>
<tr>
<td>Lorentz structure</td>
<td>scalar 1 pseudosc. $\gamma_5$</td>
<td>vector $\gamma^\mu$ axial v. $\gamma^\mu \gamma_5$</td>
</tr>
<tr>
<td>Coupling “g”</td>
<td>$\propto$ mass</td>
<td>$\propto$ charge</td>
</tr>
<tr>
<td>Consequences</td>
<td>$m_t \gg m_u$</td>
<td>$Q_b = Q_d$</td>
</tr>
<tr>
<td>Channels in this talk</td>
<td>VBF $H, ZH, t\bar{t}H/\phi$ (p.11 - 14)</td>
<td>dark QCD, top, anomaly (p.15 - 18)</td>
</tr>
</tbody>
</table>

Lagrangian terms

- $g_q \bar{q}qA$ matter-mediator
- $g_\chi \bar{\chi}\chi A$ DM-mediator

Counting parameters

<table>
<thead>
<tr>
<th>$g_q$</th>
<th>$m_q$</th>
<th>$m_A$</th>
<th>$g_\chi$</th>
<th>$m_\chi$</th>
<th>$m_A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>known</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>-</td>
</tr>
</tbody>
</table>

Caveat emptor

2d exclusion plot necessarily assumes 2 other parameters

complementary probes
Data

• Following results use the entire 13 TeV sample (left)
• ~ 30 simultaneous collisions per crossing (right)

**Integrated luminosity**

- **ATLAS** Preliminary
- \( \sqrt{s} = 13 \text{ TeV} \)
- Delivered: 156 fb\(^{-1}\)
- Recorded: 147 fb\(^{-1}\)
- Physics: 139 fb\(^{-1}\)

**Pileup distribution**

- **ATLAS** Online, 13 TeV
- \( \int L dt = 146.9 \text{ fb}^{-1} \)
- 2015: \( \langle \mu \rangle = 13.4 \)
- 2016: \( \langle \mu \rangle = 25.1 \)
- 2017: \( \langle \mu \rangle = 37.8 \)
- 2018: \( \langle \mu \rangle = 36.1 \)
- Total: \( \langle \mu \rangle = 33.7 \)

DM production at LHC
Leaves MET ($E_T^{\text{miss}}$, Missing $E_T$) transverse to the collision axis

Direct production: $pp \rightarrow \text{DM} + \text{recoil}$

Momentum conservation
Hadronic jet, MET, lepton, photon

Perspective side view

Transverse x-y view
ATLAS experiment
Many upgrades from Run-1 to Run-2 (also for Run-3, HL-LHC)

Detector

Toroid  LAr / Tile Calorim.  Muon  Spectrometer
Solenoid  Si Trackers

Event display with photon
$Z_{ee} H, H \rightarrow \gamma \gamma_{dark}$

Transverse x-y view
$m_{ee} = 92$ GeV
$m_T = 123$ GeV

Electron 57 GeV
Photon 62 GeV
MET = 63 GeV
Electron 34 GeV

Run: 359171
Event: 2874513621
2018-08-26 19:46:03 CEST

TDAQ
Upgraded L1Calo hardware, MET trigger algorithms, etc.

Computing
Simul. 10B events / yr using 300k CPU
General feature: **MET (Missing $E_T$)**
DM escapes leaving momentum imbalance in the transverse plane

**MET distribution of $W_{ev}$**

Nice description of core + tail

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**Event display with VBF jets**

$\text{VBF} H \rightarrow \text{XX}$, veto $W, Z$

Perspective side view

$m_{jj} = 2.5$ TeV

Hadronic jet

408 GeV

Hadronic jet

301 GeV

MET = 504 GeV

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https://atlas.cern/updates/briefing/invisible-Higgs-search
Dark matter via scalars: $H_{125}$, $\phi$

Overview

- Search is challenging like precision measurement
- Assume $\sigma_{H_{125}}$ for Higgs, $\sigma$ fits allow $B_{inv} \approx O(10\%)$

Challenges

- Need recoil, no ggF $H_{125}$: use VBF, VH, $t\bar{t}H$ (left)
- Orders-of-mag. dominant QCD process: large MET, but trigger has pileup dependence (right)

ATLAS, Nature 607 (2022) 52-59

$H_{125}$ cross section

- ATLAS, J. High Energy Phys. 08 (2020) 80

**Trigger rate**

- Major pileup dependence
- Higher pile-up at the start

Search for invisible Higgs-boson decays in events with vector-boson fusion signatures using 139 fb$^{-1}$ of proton-proton data recorded by the ATLAS experiment

**Summary**

- **Background est.**
  - $Z\nu\nu$, est. w/ $Z_{ll}$ & $W_{\nu}$
  - QCD multijet CR

- **Analysis**
  - Trig. MET > 160 GeV
  - High $m_{jj}$ (binned fit)

**Results (%)**

- Errors on $\hat{\mu}$
  - stat 2.9
  - multijet 2.1

- 95% CL limits
  - $BR_{\text{inv}}$ on $H_{125}$ 14.5 (10.3)
  - Combination 10.7 (7.7)

- Higgs portal
  - scalar DM: $\sigma_{\text{WIMP}} \sim m_{\chi}^{-2} \cdot \Gamma_{\text{inv}}$
  - fermion DM: $\sigma_{\text{WIMP}} \sim \text{const} \cdot \Gamma_{\text{inv}}$

ATLAS, Phys. Lett. B 842 (2023) 137963 / HIGG-2021-05

B$_{H \to \text{inv}} < 0.093$

All limits at 90% CL
**DM pair in \( \phi, H \) decays: \( t\bar{t}\phi, t\bar{t}H \)**


Constraints on spin-0 dark matter mediators and invisible Higgs decays using ATLAS 13 TeV pp collision data with two top quarks and missing transverse momentum in the final state

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**Summary**

- Yukawa-type coupling to 3rd gen
- Lepton channels
  - \( 2\ell \) : JHEP 04 (2021) 165
  - \( 1\ell \) : JHEP 04 (2021) 174
  - \( 0\ell, \text{MET}>250 \): EPJC 80 (2020) 737, no DM
  - \( 0\ell, \text{MET}>160 \): This work
- Analysis of 0 lep, MET > 160 GeV
  - Compute \( \chi^2 \)
  - \( \cosh_{\text{max}}, \text{pseudo-top reco. var.} \)

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**Results**

- Tightest bound on spin-0
- Also \( \text{BR}_{\text{inv}} \) limit on \( H_{125} \)
  - 38% (30% exp’d)
Dark $\gamma$ in $H_{125}$ decays: $ZH$


Search for dark photons from Higgs boson decays via $ZH$ production with a photon plus missing transverse momentum signature from $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

**Summary**

- Background est.
  - $MET_{\text{fake}}$ from $Z$ w/ mismear. jet $\to \gamma$
  - Analysis
    - Transv. mass $m_T$
    - BDT bins

**Results** (%)

- Errors on $N_{SM}$ 28
  - $MET_{\text{fake}}$ shape 18
  - data stat 16
  - 95% CL limits
    - $BR_{\text{dark massless}} \gamma$ 2.3 (2.8) exp'd
    - Massive $\gamma$ interpretation
Dark matter via various methods

Overview
• Anomaly detection
• Single top + DM
• Dark QCD with varying visibility (left, right)

Dark QCD
• Vary invisible frac.
• Semi-visible jet aligns with MET

Event display with jets
Semi-visible jet aligned with MET

By C. Doglioni after discussion with K. Pedro, C. Fallon

**Summary**

- **Signal** - M**AD**G**RA**P**H** + **PYTHIA8
  - $m_{\text{dark had.}} = 10$ GeV, $m_\phi = O(1)$ TeV, vary $R_{\text{inv}} = \text{inv. frac. in jets}$
- **Analysis**
  - Bin in $p_T^{\text{bal}} v. \Delta \phi_{jj}$ (not b-to-b)
  - 2+ jets > 250, extra > 30 GeV
  - Trig + MET > 200 GeV

**Results**

- **Sample size**
  - 17k, mostly W+jet, Z+jet
- **95% CL limits**
  - Exclude $m_\phi \gtrsim 2$ TeV for $\lambda = 1$
DM produced w/ single top
ATLAS-CONF-2022-036 (2022)

Search for invisible particles produced in association with single top quarks in proton-proton collisions at $\sqrt{s} = 13$ TeV with ATLAS

Summary

• Signal models
  • Vector-like quark $T \rightarrow t \ Z_{VV}$
  • Non-resonant $\phi \rightarrow t \ X$
  • Resonant $u \rightarrow t \ V_{XX}$

• Analysis
  • Trig + MET $> 250$ GeV
  • BDT w/ xgBoost

Results

• 95% CL limits Prev.
  • $m_T < 2.2$ TeV $1.7$
  • $m_\phi < 5.0$ TeV $3.5$
  • $m_V < 2.8$ TeV $1.9$

ATLAS, JHEP 05 (2019) 041
CMS, JHEP 05 (2022) 093
DM produced via anomaly
[2307.01612] (2023) / EXOT-2022-07 subm. to PRL

Search for new phenomena in two-body invariant mass distributions using unsupervised machine learning for anomaly detection at $\sqrt{s} = 13$ TeV with the ATLAS detector

Summary

- Teach SM w/o signal model
  - Train w/ data, validate w/ MC
- Analysis
  - Lep. trig, use BumpHunter 9 $m_{j+\mu}$
  - 1.3k inputs to a.e., exclude 9 $m_{j+\mu}$
  - Cut $\log(\text{Loss})$, then look at 9 $m_{j+\mu}$
- “Loss function” ~ input-output distance
  - Peaks low for SM
  - Peaks high for BSM or appear as bump

Results

- 5 benchmark BSM
  - $tbH^+$, $H^+ \to tb$
  - $W_{KK}$, $W+$radion
  - $Z' \to E\ell$, $E \to Z\ell$
  - $W' \to WZ' \to \ell\nuq\bar{q}$
  - DM $Z' \to q\bar{q}$
- BumpHunter 2.9σ
  - $m_{j\mu} = 4.8$ TeV, 10 pb AR
Dark matter via supersymmetry

Overview

- SUSY produced → SM + LSP
- Direct vs. indirect production
  - E-weak vs. strong production
- (higgsino wino bino) = (charginos neutralinos)

Challenges

- Huge param. space, so simplify with tan β etc., but shrinking with results
- Can expand R-parity, baryon #
- R-parity conserved, violated

R-parity conserving
LSP = DM candidate

R-parity violate
No LSP, but gravitino / axino = DM

Baryon # violate

This talk
DM LSP in direct: 2 tau
ATLAS-CONF-2023-029 (2023)

Search for electroweak SUSY production in final states with two τ-leptons in \(\sqrt{s} = 13\) TeV pp collisions with the ATLAS detector

**Summary**

- **Signal**
  - Bino-like LSP with wino-like C1 / N2 (see)
  - WH+2 LSP (not shown)
  - \(\sigma_{\text{TL}} \gtrsim 2 \cdot \sigma_{\text{TR}}\)

  Fuks et al., JHEP 1401 (2014) 168

- **Background est.**
  - τ mis-id validate

- **Cuts**
  - \(m_{T2}\) to detect kinematic endpoint
  - Trig: asym. di-tau (+MET for high-mass)
  - For WH, use \(m_{\text{lep,had}} \sim m_H\)

**Results**

- Chargino excludes 1.2 TeV, indp’t WH excludes 300 GeV
- First limit on \(\tau_R\)
DM LSP in direct: 1 lepton + jets

ATLAS-CONF-2022-059 (2022)

Search for direct production of electroweakinos in final states with one lepton, jets and missing transverse momentum and in $pp$ collisions at 13 TeV with the ATLAS detector

Summary

- Background est.
  - $W + jets$ (50 - 75%)
- Analysis
  - $m_{jj}$, $m_T$, $S_{MET}$,
  - Final sample $m_{eff}$

Results

- Yield
  - $O(10)$
- Errors
  - Stats, JES
- 95% CL limits
  - $m_{\chi_{1}\pm} > 500$ GeV

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

SRHM C1N2-WZ

Events / 250 GeV

$ATL\alpha$S Preliminary

Data

- Total SM
- Diboson1l
- Diboson2l
- W+jets
- Single top
- Others

$m_{\chi_{1}\pm}$ ($p_{T\ell} + \Sigma p_{Tjet} + MET$) [GeV]

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

SRHM C1N2-WZ

Expected Limit ($\pm 1 \sigma_{\text{exp}}$)

Observed Limit ($\pm 1 \sigma_{\text{obs}}$)


Excess

2 lep + MET

Boosted bosons

This work

important orthogonal final state
DM LSP in direct: 2 SS or 3 lep.
ATLAS-CONF-2022-042 (2022)

Search for direct production of winos and higgsinos in events with two same-charge leptons or three leptons in $pp$ collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector

Summary

- Background
  - Di-boson CR
- Analysis
  - Trig. dilep or MET > 250

Results

- Error RPC
  - Stats
  - Fake / Non-Pr
- 95% CL limits
  - $m_{\tilde{w}} > 525$, WH$_{125}$
  - $m_{\tilde{w}} > 250$, WZ

Lepton GeV

handful events in the tail

WH$_{125}$ This work

WZ (This work), orthog. to Wh

lepton

OS lepton

OS lepton
This talk

- DM via scalars: VBF H, ZH, $t\bar{t}\phi$
- DM via methods: dark sector jets, single t, anomaly ML
- DM in SUSY: 2 tau, 1 e/\mu lepton + jets, 2-3 e/\mu leptons

Conclusions

- Novel approaches: simplified model, unsupervised, full model
- Like Minoans, ATLAS is always leaping to produce the best results!
Extra
Theory on theories on DM

Nice schematic

Dark matter at the LHC

Complementarity in approaches

Dark Matter

Nuclear Matter
quarks, gluons

Leptons
electrons, muons, taus, neutrinos

Photons,
W, Z, h bosons

Other dark
particles

Astrophysical
Probes

DM
DM
DM
DM

Particle
Colliders

SM
SM
SM
SM

Direct
Detection

Indirect
Detection

DM
DM
DM
DM

This talk

[1401.6085]
Regions in the (mediator-mass, DM-mass) plane excluded at 95% CL by visible and invisible searches, for leptophobic axial-vector mediator simplified models. Each shaded region represents the union of the exclusion contours of the individual analyses listed in the legend, where more than one result contributes. The exclusions are computed for a DM coupling $g_X = 1$, quark coupling $g_q = 0.25$, universal to all flavours, and no coupling to leptons. Dashed curves labelled "thermal relic" correspond to combinations of DM and mediator mass values that are consistent with a DM density of $\Omega h^2 = 0.12$ and a standard thermal history, as computed in MadDM [Phys. Dark Univ. 26 (2019) 100377, AIP Conf. Proc. 1743 (2016) 1, 060001]. Between the two curves, annihilation processes described by the simplified model deplete $\Omega h^2$ to below 0.12. A dotted line indicates the kinematic threshold where the mediator can decay on-shell into DM. Excluded regions that are in tension with the perturbative unitary considerations of [JHEP 02 (2016) 016] are indicated by shading in the upper left corner. The reinterpretation procedure for the TLA analysis follows the procedure recommended by ATLAS in Appendix A of [Phys. Rev. D 91 (2015) 052007], while the high-mass dijet and dijet+ISR analyses are reinterpreted following [Phys. Lett. B 769 (2017) 520].
Hadronic resonance search contours for 95% CL upper limits on the coupling $g_\gamma$ as a function of the resonance mass $m_{Z'}$ for the leptophilic axial-vector mediator simplified model. The expected limits from each search are indicated by dotted lines. The TLA dijet analysis has two parts, employing different datasets with different selections in the rapidity difference $y^*$ as indicated. The dijet+ISR ($\gamma$) analysis also has two parts, each using a different trigger strategy, and each further studied in inclusive and b-tagged channels. Two lines are also shown for the di-b-jet search. These are from separate analyses, one which used b-jet triggers and provides the limit at lower mass, and one which used inclusive jet triggers and provides the high mass limit. Coupling values above the solid lines are excluded, as long as the signals are narrow enough to be detected using these searches. The TLA dijet search with $|y^*| < 0.6$ is sensitive up to $\Gamma/m_{Z'} = 7\%$, the TLA dijet with $|y^*| < 0.3$ and dijet + ISR searches are sensitive up to $\Gamma/m_{Z'} = 10\%$, and the dijet and di-b-jet searches are sensitive up to $\Gamma/m_{Z'} = 15\%$. The dijet angular analysis is sensitive up to $\Gamma/m_{Z'} = 50\%$. No limitation in sensitivity arises from large width resonances in the $t\bar{t}$ resonance analysis. Benchmark width lines are indicated in the canvas. $\Gamma/m_{Z'} = 50\%$ lies beyond the canvas borders.
Abstract

The presence of a non-baryonic Dark Matter (DM) component in the Universe is inferred from the observation of its gravitational interaction. If Dark Matter interacts weakly with the Standard Model (SM) it could be produced at the LHC. The ATLAS Collaboration has developed a broad search program for DM candidates in final states with large missing transverse momentum produced in association with other SM particles (light and heavy quarks, photons, Z and H bosons, as well as additional heavy scalar particles) and searches where the Higgs boson provides a portal to Dark Matter, leading to invisible Higgs decays. The results of recent searches on 13 TeV pp data from the LHC, their interplay and interpretation will be presented.