Dark matter searches at ATLAS

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On behalf of ATLAS collaboration
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Dark Matter

• One of the BSM we are certain of
  – 24% of matter-energy content of the universe

• One possible candidate: Weakly Interacting Massive Particle (WIMP)
  – Naturally account for the amount of dark matter we observe in the Universe
  – Occurs in many models of physics beyond the SM
  – We can use particle physics experimental techniques to search for it.
Strategy of Dark Matter Search

- Indirect detection and direct detection
  - Look for DM annihilation and DM-nucleus scattering
  - Assumption of dark matter profile, density etc
  - Kinematic limitations

- Collider search
  - Produce dark matter directly
  - Independent of astrophysical experiments
  - Sensitive to light dark matter particles

\[ \text{WIMP-Nucleon cross section} \]
Collider Mono-X Searches

- **Mono-X** (jet, photon, Z, W, etc)
  - $E_T^{\text{miss}} + \text{SM}$: Invisible WIMPs balanced with associated SM particle

- **Effective field theory (EFT)** (Phys. Rev. D 82 116010, 2010):
  - Broad coverage of models by integrating out the details
  - Free parameters: mass scale $M^*$ and dark matter mass $m_\chi$
  - Various operators:
    - Coupling with quarks or gluons:
      - $D5$ (vector), $D9$ (tensor), $D11$ (gluon), etc
    - Coupling with boson $VV\chi\chi$ vertex
  - Validity concerns (to be discussed)

- **Simplified model**: UltraViolet-complete
  - Keep the information of intermediate state
  - $s$-channel or $t$-channel
  - Parameters: Mediator mass $M_{\text{med}}$, width $\Gamma$, couplings
    \[
    \sqrt{g_{SM}g_{DM}} \in [0, 4\pi] \quad M_{\text{med}} = \sqrt{g_{SM}g_{DM}} M^*
    \]
Mono-jet (8 TeV 10.5 fb⁻¹)

- Central leading jet
- 0 or 1 extra jet(s)
- Veto electrons and muons
- SR1, 2, 3, 4: ¹E_Tmiss, p_Tjet¹
  - > 120, 220, 350, 500 GeV

Main backgrounds
- Z(νν)+jets
- W(ℓν)+jets: missed leptons, τ_{had}

Good agreement between data and SM backgrounds

In EFT framework, set limits at 90% CL on M* as a function of m_χ:
- D5: M* > ~800 GeV for low m_χ
- Assuming full EFT validity

\[ \text{Suppression scale } M^* \text{ as a function of } m_\chi \]

\[ \int \text{Ldt} = 10.5 \, \text{fb}^{-1} \]

\[ \sqrt{s} = 8 \, \text{TeV} \]

\[ \text{Data / BG} \]

\[ \text{Observed limit (Theory)} \]

\[ \text{Effective theory not valid} \]

\[ \text{Expected limit (± 1 ± 2σ_{exp})} \]

\[ \text{ATLAS Preliminary} \]

\[ \text{ATLAS-CONF-2012-147} \]

Ning Zhou 2014-07-04
EFT validity

• EFT being a valid approximation to UV-complete models requires
  – momentum transfer $Q_{tr} < M_{med}$

• Not all the events generated from EFT are valid.
  – cut off those invalid events

• As a consequence, $M^*$ limits decrease.
  – Strongly depending on the couplings

• For D5, $m_\chi = 50$ GeV, usage of EFT is fully valid when
  \[ \pi \leq \sqrt{g_{SM} g_{DM}} < 4\pi \]

• Details depend on the UV-complete theories
  – Use UV-complete model to address this validity issue
  – Simplified models, SUSY, etc

\[ M_{med} = \sqrt{g_{SM} g_{DM}} M^* \]
\[ \sqrt{g_{SM} g_{DM}} \in [0, 4\pi) \]

More details in S. Schramm’s poster “Searching for dark matter in the monojet channel with ATLAS”
Mono-W/Z(qq) (8 TeV 20.3 fb⁻¹)

- Reconstruct W/Z with central large-R jet
  
  \[ p_T > 250 \text{ GeV}, \ m_{\text{jet}} \in [50, 120] \text{GeV} \]
- 0 or 1 extra small-R jet, veto lepton/γ
- SR1 and SR2: \( E_T^{\text{miss}} > 350, 500 \text{ GeV} \)

Sensitive to the sign of DM couplings to up and down quarks

- \( C(u) = -C(d) \): constructive interference
- \( C(u) = C(d) \): destructive interference

Improve the collider constraints on WIMP-nucleon cross section at low \( m_\chi \) by one order of magnitude

- EFT: \( M^* > \sim 2 \text{ TeV} \) for D5 constructive mode
Mono-W ($\ell \nu$) (8 TeV 20.3 fb$^{-1}$)

- One isolated lepton:
  - Electron: $p_T, E_T^{\text{miss}} > 125$ GeV
  - Muon: $p_T, E_T^{\text{miss}} > 45$ GeV

- Cut on transverse mass $m_T(\ell, E_T^{\text{miss}})$ to suppress the dominant background $W(\ell \nu)$

- Good agreement between data and SM backgrounds

- In EFT, $M^*$ limit as a function of $m_\chi$ is calculated assuming full validity of EFT model.
  - $M^* > \sim 1$ TeV for D5 constructive

**ATLAS-CONF-2014-017**
Mono-Z ($\ell \ell$) (8 TeV 20.3 fb$^{-1}$)

- Two oppositely charged $e^+e^-$ and $\mu^+\mu^-$ with $m_{\ell \ell} [76, 106]$ GeV
- $\Delta\phi(p_T^\ell \ell, E_T^{\text{miss}}) > 2.5$, $|\eta^{\ell \ell}| < 2.5$ and $|p_T^\ell \ell - E_T^{\text{miss}}| / p_T^\ell \ell < 0.5$
- Veto on third lepton and jet
- SR1-SR4: $E_T^{\text{miss}} > 150, 250, 350, 450$ GeV

Main background:
- $Z(\ell \ell)Z(\nu\nu)$
- $Z(\ell \ell)W(\ell\nu)$
- From MC, with theoretical error of 35%

Good agreement between data and backgrounds

arXiv:1404.0051 (accepted by PRD)
Mono-Z ($\ell\ell$) (8 TeV 20.3 fb$^{-1}$)

For EFT with DM couplings to quarks, not as sensitive as other mono-X channels

- D5: $M^* > \sim 500$ GeV for low $m_\chi$

Unique sensitivity to DM couplings to Z boson: $ZZ\chi\chi$ and $\gamma^*Z\chi\chi$

Simplified model: t-channel with a scalar colored mediator $\eta$ (similar to squark)

Derive upper limits on the coupling constant as a function of $m_\chi$ and $m_\eta$

Degenerate region (uncovered)

Larger relic abundance

95% C.L. on coupling $f$

$\int L = 20.3$ fb$^{-1}$ $\sqrt{s} = 8$ TeV

$\chi$ and $\eta$

$\eta$

$\gamma$

$Z$

$\chi$

$\chi$

$\eta$

$\eta$

$\gamma$

$Z$

M [GeV]

$\int L = 20.3$ fb$^{-1}$ $\sqrt{s} = 8$ TeV

$\chi$ and $\eta$

$\eta$

$\gamma$

$Z$

$\chi$

$\chi$

$\eta$

$\eta$

$\gamma$

$Z$

M [GeV]
Z+H(inv) (7 and 8 TeV 24.8 fb⁻¹)

- Higgs-portal dark matter model: Higgs as mediator between DM and SM
- Search for Higgs invisible decay in Z(\ell\ell)+E_T^{miss}
  - $E_T^{miss} > 90$ GeV, $\Delta\phi(E_T^{miss}, p_T^{miss}) < 0.2$
  - This channel has the highest sensitivity to this model
- Derive limits on DM-nucleon scattering cross section.
  - Vector, scalar, fermion DM particles
  - Sensitive to DM with $m_\chi < m_H/2$

PRL 112, 201802 (2014)
Mono-photon (7 TeV 4.6 fb⁻¹)

- Good photon, \( E_T > 150 \) GeV
- 0 or 1 additional jet
- Veto on electron and muon
- SR: \( E_T^{\text{miss}} > 150 \) GeV

Main backgrounds: \( Z(\nu\bar{\nu})+\gamma \) and \( W(\ell\nu)+\gamma \)

Good agreement between data and SM backgrounds

Set limits within EFT framework:
- D5 \( M^* > \sim 600 \) GeV for low \( m_\chi \)

Result with 8 TeV 20.3 fb⁻¹ is on the way.
Mono-jet prospects (14 TeV)

- Various milestones of 14 TeV data-taking:
  - 25 fb\(^{-1}\) (1st year), 300 fb\(^{-1}\) (end of Run-II), 3000 fb\(^{-1}\) (HL-LHC)

- Event selection:
  - Central jet \(p_T > 300\) GeV
  - 0 or 1 additional jet
  - Veto electrons and muons
  - \(E_T^{\text{miss}} > 400, 600, 800\) GeV

- Background from pure MC simulation

- Uncertainties
  - Two flat systematics
    - 5%, reasonable in early Run-II
    - 1%, ultimate goal for HL-LHC
  - Statistics varies with luminosity
Mono-jet prospects (14 TeV)

- EFT model:
  - 5σ discovery potential: $M^* \sim 1.7$ TeV with 300 fb$^{-1}$
  - Exclusion limits: can be improved by a factor of $\sim 2$ with 25 fb$^{-1}$
    - D5: $M^* > 1.5$ TeV for low $m_\chi$
- Simplified model: s-channel with a vector mediator $Z'$
  - EFT and simplified model limits meet at high $M_{\text{med}}$
  - Result from EFT is conservative for $M_{\text{med}}$ above 1 TeV, optimistic below that
Summary

• LHC may be able to produce dark matter and detect it.
• We’ve performed various signature-based mono-X searches for it.
• From ATLAS Run-I intensive dark matter searches (including SUSY dark matter candidates), we have not discovered a dark matter candidate yet.
• Let’s continue with LHC Run-II data!
The ATLAS detector

- One of the two general-purpose experiments at LHC

Inner detector: track $|\eta|<2.5$

Electromagnetic calorimeter: $\gamma$ and $e$ $|\eta|<2.37$ and $2.47$

Hadronic calorimeter: jet $|\eta|<4.5$

Muon spectrometer: $\mu$ $|\eta|<2.4$

Day in 2012

Total Integrated Luminosity

- Preliminary ATLAS
- LHC Delivered
- ATLAS Recorded
- Good for Physics

Total Delivered: 22.8 fb$^{-1}$
Total Recorded: 21.3 fb$^{-1}$
Good for Physics: 20.3 fb$^{-1}$

2014-07-04 Ning Zhou
Mono-jet (7 TeV 4.7 fb⁻¹)

- Complementary information for astrophysical experiments
  - Assume full validity of EFT approach
  - WIMP-nucleon scattering cross section for direct detection experiments
- Sensitive to light dark matter mass
- WIMP annihilation for indirect detection experiments

**ATLAS**

$\sqrt{s} = 7$ TeV, 4.7 fb⁻¹, 90%CL

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<tr>
<th>Cross Section [cm²]</th>
<th>WIMP mass $m_\chi$ [GeV]</th>
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<td>$10^{-29}$</td>
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<tr>
<td>$10^{-28}$</td>
<td>10</td>
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<tr>
<td>$10^{-27}$</td>
<td>100</td>
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<tr>
<td>$10^{-26}$</td>
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**ATLAS**

$\sqrt{s} = 7$ TeV, 4.7 fb⁻¹, 95%CL

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<th>Annihilation Rate [cm³/s]</th>
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