Searches for dark matter in ATLAS

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Astrophysical evidence for the existence of dark matter

- First observed by Fritz Zwicky → velocity dispersions of galaxies in the Coma cluster (idea neglected for 40 years!)
- Precisely measured by Vera Rubin → velocity of gas near Andromeda
  - Estimated factor of 10 more dark mass than visible mass
- Planck revealed an almost perfect universe
- Dark matter web connecting galaxies
Whereabouts?

...trying to connect the dots...
Looking for Dark Matter

Dark matter is consistent with non baryonic, stable, and weakly interacting particles at the electroweak scale (WIMP)

- WIMP miracle: matches observed relic density for mass and coupling at ~ EW scale \( \rightarrow \) LHC!
- Many theories beyond the SM predict such particles
- Complementary dark matter experiments (good news!)

**Indirect detection:** DM-DM annihilation process

**Direct detection:** recoil from DM-nucleus scattering

**At the LHC:**

- No DM interaction with the detector \( \rightarrow \) missing \( E_T \)
- Initial state radiation to detect it (jets, photons, W, …)
- Searches for high-mass di-jet resonances
The ATLAS Experiment

- ATLAS is a multipurpose experiment designed to achieve the highest possible flexibility in different sectors of the high energy physics.

Key ingredients for DM searches:

- Great MET performance
- Well understood jet calibration
Dark Matter with Mono-X and Di-X

- Invisible dark matter escapes the detector
  - Tag events using recoiling objects
  - Measure missing transverse momentum

- Dark matter mediator searches in di-jets events
  - Production rates for BSM signals decaying to di-jets can be large
  - Anomalous di-jet production at high masses
  - Significant amount of jets produced at large $\theta^*$

**Approaches:**
- Effective Field Theories (EFT) [arXiv:1008.1783] – valid for $\Delta p \ll m_{\text{med}}$ (easily breaks @ LHC)
- Simplified models (main interpretation framework for Run 2) [arXiv: 1507.00966, 1603.04156]
  - Spin-1 and spin-0 mediators
  - Free parameters: $m_\chi$, $m_{\text{med}}$, couplings (suppression scale $M^* = \frac{m_{\text{med}}}{\sqrt{(g_q g_\chi)}}$)

See previous talk from M. Park
Very Intense Searches in ATLAS...

Illustration by Sandbox Studio, Chicago with Corinne Mucha
Dark Matter with Mono-photon (1)

Looking for a high $p_T$ photon(s) + MET

- Very high sensitive channel when $X$ comes from ISR
- Define 5 different SRs with different $E_T^{\text{miss}}$ requirements
- Background (events containing true $\gamma$ or objects misidentified as $\gamma$)
  - Dominated by $Z \rightarrow (\nu\nu)\gamma$ (+ $W(\rightarrow l\nu)\gamma$ and $Z(\rightarrow ll)\gamma$)
  - Normalisation factors extracted from a simultaneous fit in bkg-enriched CRs
  - Fake $\gamma$ (estimated from data, contribute 1.3-5 % uncertainty on bkg)

Results interpreted in terms of simplified model

Measure complementary to direct search

arXiv:1704.03848
Dark Matter with Mono-photon (2)

Looking for a high $p_T$ photon(s) + MET

- $\gamma\gamma\ XX$ contact interaction unique measurement in this channel
- Define 5 different SRs with different $E_T^{\text{miss}}$ requirements
- Background (events containing true $\gamma$ or objects misidentified as $\gamma$)
  - Dominated by $Z \rightarrow (\nu\nu) \gamma$ (+ $W(\rightarrow l\nu)\gamma$ and $Z(\rightarrow ll)\gamma$)
  - Normalisation factors extracted from a simultaneous fit in bkg-enriched CRs
  - Fake $\gamma$ (estimated from data, contribute 1.3-5 % uncertainty on bkg)

- Excluded model values of $M_*$ up to $\sim 790$ GeV

Results interpreted in terms of EFT

Effect of truncation for two representative values of EFT coupling $g^*$

EFT is not always valid!
Looking for a high $p_T$ jet(s) + MET

- Very high sensitive channel
  - $E_T^{\text{miss}} > 250$ GeV
  - Leading jet $p_T > 250$ GeV and $|\eta| < 2.4$
  - At most four jets with $p_T > 30$ GeV and $|\eta| < 2.8$
  - $\Delta\phi(\text{jet}, E_T^{\text{miss}}) > 0.4$ (reduce multijet bkg)
  - Leptons veto

- Main background uncertainties:
  - $W$+jets and $Z(\rightarrow \nu\nu)$ + jets background
  - Jet/MET reconstruction, energy scale and resolution

\[ \text{assumng simplified model with an axial-vector mediator in the s-channel and specific coupling values} \]

\[ \text{spin-dependent } \chi-\text{proton elastic scattering cross section} \]
Dark Matter with Mono-V

Looking for $W/Z$ jet(s) + MET

- Based on boson-tagged high $p_T$ large-R jet
  - $E_T^{\text{miss}} > 250$ GeV
  - One large-R jet with $p_T > 200$ GeV and $|\eta| < 2.0$
  - Mass jet and $D_2$ (jet shape variable) consistent with $W/Z$ decay
  - $p_T^{\text{miss}} > 30$ GeV (suppress multijets and $tt$ bkg)
  - $\Delta\phi(\text{jet},E_T^{\text{miss}}) > 0.6$ and $\Delta\phi(E_T^{\text{miss}},p_T^{\text{miss}}) < \pi/2$
  - Leptons veto

- Background from $Z \rightarrow \nu\nu +$ jets, $W/Z+$jet bkg, $tt$

![ATLAS plot](image)

Limit on mass scale $M^*$ in EFT model

Limit on signal strength for vector-mediated simplified model

2015 data

arXiv: 1608.02372
New Phenomena (and Dark Matter) with Di-jets

Looking for resonances in $m_{jj}$ spectrum

- Completely data-driven
- Performed a functional fit with a new sliding window technique
- Define $y^* = (y_1 - y_2)/2$ (between the two leading jets)
- $|y^*| < 0.6$ selection optimised for model independent search, to constrain $q^*$, QBH, $W'$, $Z'$ models (reduces QCD bkg)
- Leading jet $p_T > 440$ GeV and $m_{jj} > 1.1$ TeV

New folding with transfer-matrix: limits on generic Gaussian with a truth-level width
Dark Matter Model Exclusions

**Di-jet searches at low masses**
- **Di-jet + ISR searches**
  - Triggering on events with $\gamma$/jet as ISR
- **Trigger Level Analysis**
  - (lower jet $p_T$, huge stat, but more complicated fit)
- **Coupling values above the solid curves are excluded**

**Di-jet and Jet+X are filling the gaps in the phase space**

- Regions in DM mass-mediator plane excluded by ATLAS DM searches for one possible interaction between SM and DM
- Small fluctuations in the contour are a product of the di-jet reinterpretation scheme
Other Dark Matter Searches

Looking for $tt(bb) + \text{MET}$

- In many models the interaction strength between the DM and the quarks is proportional to the quark masses
  - Better sensitivity since coupling to heavy quarks is stronger
  - ATLAS-CONF-2016-077, ATLAS-CONF-2016-050, ATLAS-CONF-2016-076

Looking for $H + \text{MET}$

- For $m_{\text{DM}} > m_H/2$ mono-Higgs is relevant
- Higgs ISR is Yukawa-suppressed $\Rightarrow$ direct probe of SM-DM coupling structure
- Decay channel $\Rightarrow H \rightarrow bb$ (most sensitive – large BR)
  - ATLAS-CONF-2017-028, ATLAS-CONF-2017-024
- Decay channel $\Rightarrow H \rightarrow \gamma\gamma$ (8 TeV - Phys. Rev. Lett. 115, 131801, 2015)

Looking for displaced lepton jets

- Lepton jets are produced away from IP
- Topology: one or two LJs + leptons/jets/MET
- ATLAS-CONF-2016-042

See Yuan-Tang Chou poster
See Daniela Salvatore poster
Summary and Conclusions

- Searches for dark matter at colliders are complementary to other dark matter searches
- ATLAS is a great tool to look for dark matter
- Many complementary searches
  - No evident excesses up to now
  - Interpretation with EFT, but also some simplified models
- Room for improvements

✓ **Experimental techniques:** jet performance, flavour tagging, fitting procedure, …

✓ **Theory:** improve the control of the theoretical uncertainties, higher-order prediction for background, …

New searches @ 13 TeV are in preparation…stay tuned!
BACKUP
Dark Matter with Higgs-to-invisible

Looking for 2 jets + large MET

- 8 TeV search
- Invisible decays of Higgs boson produced via VBF process
- If $m_{DM} < m_H/2$ the measure $BR(Higgs \rightarrow invisible)$ is kinematically allowed
- Results are interpreted in the Higgs-portal DM model → limit on BR converted into upper bounds on $\chi$-nucleon scattering cross section

particularly sensitive to low $\chi$ mass
## Signal selection

| Event cleaning | Quality and Primary vertex |
|----------------|-----------------------------|
| Leading photon | $E_T^\gamma > 150 GeV$, $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$, tight, isolated, $|z| < 0.25$ m, $\Delta \phi(\gamma, E_T^{miss}) > 0.4$ |
| $E_T^{miss} / \sqrt{\sum E_T^j}$ | $> 8.5$ GeV$^{1/2}$ |
| Jets | 0 or 1 with $p_T > 30 GeV$, $|\eta| < 4.5$ and $\Delta \phi$(jets, $E_T^{miss}) > 0.4$ |
| Lepton | veto on $e$ and $\mu$ |

| $E_T^{miss}$ [GeV] | SRI1 | SRI2 | SRI3 | SRE1 | SRE2 |
|-------------------|------|------|------|------|------|
| $> 150$           | 2400 | 729  | 236  | 1671 | 493  |
| $> 225$           |      |      |      |      |      |
| $> 300$           |      |      |      |      |      |
| 150–225           |      |      |      |      |      |
| 225–300           |      |      |      |      |      |

**Background estimation**

- Normalisation factors for the $W$, $Z$ and $\gamma$ +jets backgrounds are obtained via a profile likelihood fit
- Two different configurations are used for the fit:
  - **Background-only inclusive fit**, which determines the normalisations for $W$, $Z$ and $\gamma$ +jets backgrounds for each inclusive SR independently and the
  - **Background-only multiple-bin fit**, which determines the normalisations for the three exclusive SRs simultaneously
Background-only multiple-bin fit

$\gamma + \text{jets}$ normalisation factor fixed in the common control region at low $E_T^{\text{miss}}$ (PhJetCR), while $W\gamma$ and $Z\gamma$ normalisation factors are fitted in each $E_T^{\text{miss}}$ range separately.

Figure 2: Distribution of $E_T^{\text{miss}}$ in data and for the expected total background in the CRs: 1muCR (top left), 2muCR (top right), 2eleCR (bottom left) and PhJetCR (bottom right). In 1muCR and 2muCR, the muons are treated as non-interacting particles in the $E_T^{\text{miss}}$ reconstruction; the electrons are handled similarly in 2eleCR. The total background expectation is normalised using the scale factors $k'$ derived from the multiple-bin fit. For 1muCR, 2muCR and 2eleCR, overflows are included in the third bin. The error bars are statistical, and the dashed band includes statistical and systematic uncertainties determined by the multiple-bin fit. The lower panel shows the ratio of data to expected background event yields.
PDF, scale and tune each induce systematic uncertainties of up to about 5% in the acceptance (and cross section) in the simplified DM models.
Dark Matter with Mono-photon

Vector mediator limits
Dark Matter with Mono-jets

TABLE I. Event selection criteria applied, as described in Sec. V.

| Selection criteria                                                                 |
|-----------------------------------------------------------------------------------|
| Primary vertex                                                                     |
| $E_T^{\text{miss}} > 250$ GeV                                                    |
| Leading jet with $p_T > 250$ GeV and $|\eta| < 2.4$                                |
| At most four jets with $p_T > 30$ GeV and $|\eta| < 2.8$                          |
| $\Delta \phi(\text{jet}, \vec{p}_T^{\text{miss}}) > 0.4$                        |
| Jet quality requirements                                                           |
| No identified muons with $p_T > 10$ GeV or electrons with $p_T > 20$ GeV         |

| Inclusive signal region   | IM1 | IM2 | IM3 | IM4 | IM5 | IM6 | IM7 |
|---------------------------|-----|-----|-----|-----|-----|-----|-----|
| $E_T^{\text{miss}}$ (GeV) |     |     |     |     |     |     |     |
|                            | > 250| > 300| > 350| > 400| > 500| > 600| > 700|

| Exclusive signal region    | EM1 | EM2 | EM3 | EM4 | EM5 | EM6 |
|----------------------------|-----|-----|-----|-----|-----|-----|
| $E_T^{\text{miss}}$ (GeV)  |     |     |     |     |     |     |
|                            | [250–300]| [300–350]| [350–400]| [400–500]| [500–600]| [600–700]|
Dark Matter with Mono-jets

For IM1 monojetlike kinematic selection
Dark Matter with Mono-jets

For IM1 monojetlike kinematic selection

Phys. Rev. D 94, 032005
FIG. 6. Exclusion region at 95% C.L. as a function of squark mass and the squark-neutralino mass difference for (left) the decay channel $\tilde{b}_1 \rightarrow b + \tilde{\chi}_1^0$ and (right) $\tilde{q} \rightarrow q + \tilde{\chi}_1^0$ ($q = u, d, c, s$). The dotted lines around the observed limit indicate the range of observed limits corresponding to $\pm 1\sigma$ variations of the NLO SUSY cross-section predictions. The shaded area around the expected limit indicates the expected $\pm 1\sigma$ ranges of limits in the absence of a signal.
Fig. 2. Pane (a) Distribution of $m_{\text{jet}}$ in the data and for the predicted background in the top-quark control region. Pane (b) Distribution of jet substructure variable $D_2$ in the data and for the predicted background in events satisfying all signal region requirements other than those on $D_2$. Also shown is the distribution for the simplified model with a vector-boson mediator, scaled by a factor of $10^{4}$ for given values of $m_X$ and $m_{\text{med}}$, the mediator mass. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 3. The $E_{\text{miss}}^{\tau}$ distribution of the events in the control regions after the profile-likelihood fit to the data under the background-only hypothesis. Pane (a) shows the $\bar{t}t$ control region, pane (b) shows the $Z +$ jets control region, and pane (c) shows the $W +$ jets control region. The total background prediction before the fit is shown as a dashed line. The inset at the bottom of each plot shows the ratio of the data to the total post-fit background. The hatched bands represent the total uncertainty in the background. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Dark Matter with Di-jets

\[ |y^*| < 1.2 \]

**ATLAS**
\[ \sqrt{s} = 13 \text{ TeV}, 37.0 \text{ fb}^{-1} \]

- Data
- Background fit
- BumpHunter interval

- \( W^*(\sin(\phi_x) = 0), m_{W^*} = 2.8 \text{ TeV} \)
- \( W^*(\sin(\phi_x) = 0), m_{W^*} = 3.8 \text{ TeV} \)

\( W^*(\sin(\phi_x) = 0), \sigma \times 100 \)

- \( p\text{-value} = 0.83 \)
- Fit Range: 1.7 - 8.1 TeV
- \[ |y^*| < 1.2 \]
Dark Matter with Di-jets

- Differences between the rapidities of two jets are invariant under Lorentz boosts along the z-axis, hence the following function of the rapidity difference $y^*$

$$\chi = e^{2y^*} \sim \frac{1 + \cos \theta^*}{1 - \cos \theta^*}.$$ 

is the same in the detector frame as in the partonic center-of-mass frame

- Data with $m_{jj} < 2.5$ TeV are discarded to remove trigger inefficiencies

- dataset is analysed by fitting to it a Pythia MC sample acting as an SM template
Upper limits obtained from the dijet invariant mass ($m_{jj}$) distribution on cross-section times acceptance times branching ratio to two jets for the models used in the analysis.