Search for dark matter production at ATLAS and CMS

Alexander Grohsjean

on behalf of the ATLAS and CMS Collaborations

La Thuile 2018
XXXII Les Rencontres de Physique de la Vallée d'Aoste
The Dark Matter puzzle

University of Siegen: Rotation curve of the M83 galaxy.

- Observed
- Luminous matter

Distance vs. Velocity graph showing the discrepancy in galaxy rotation curves.

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The Dark Matter puzzle

University of Siegen: Rotation curve of the M83 galaxy.

observed

luminous matter

distance

velocity

NASA: Nine year microwave sky from Planck

Composition of the Universe from Planck (2015)

Ordinary Matter 5%
Dark Matter 27%
Dark Energy 68%
The LHC - A modern Prometheus?

Heinrich Füger, Prometheus brings fire to mankind
Dark Matter searches in a nutshell

indirect searches

direct searches

collider searches

comprehensive DM research program at LHC
geometry allows distinguishing various particles
DM particles in CMS

- Silicon Tracker
- Electromagnetic Calorimeter
- Hadron Calorimeter
- Superconducting Solenoid
- Iron return yoke interspersed with Muon chambers

Key:
- Muon
- Electron
- Charged Hadron (e.g. Pion)

… but not DM
Phenomenology of DM

by Tim Tait (simplified)

Less complete

Dark Matter Effective Field Theories
contact interaction between DM and SM

“Sketches of models”

Simplified Dark Matter Models

Complete Dark Matter Models

More complete

Minimal Supersymmetric Standard Model

Universal Extra Dimensions

Higgs Portal

Z’ boson

Dark Photon

Little Higgs

simplified models to guide analysis strategy
Simplified DM models

✧ idea:
  - restrict to relevant aspects aiming at maximal experimental coverage

✧ ingredients beyond SM:
  - mediator
  - DM particle

✧ free parameters:
  - masses, spins, coupling structure and strength

✧ recasting results in full models:
  - caveats may apply
  - parameter scans manageable

well established since 2015 for LHC searches
Overview of LHC DM searches

- EPJC 78 (2018) 18
- EPJC 77 (2017) 845
- PRD 97 (2018) 032009


- EPJC 77 (2017) 393
- JHEP 10 (2017) 073

- EPJC 78 (2018) 18
- arXiv:1801.08427

- PLB 763 (2016) 251
- arXiv:1712.02345

- PLB 776 (2017) 318
- arXiv:1711.00431

- arXiv:1712.02345

- wide spectrum of topologies
The classic channel: mono-jet

- hard QCD ISR jet recoils against DM $\rightarrow$ large cross section

- explore missing transverse momentum as sensitive observable:
  reaching down to 250 GeV (trigger thresholds)

- key requirements
  - central jet with high momentum above 100 GeV
  - lepton, photon and b jet veto in signal region
  - suppression of large jet mis-measurements: $\Delta \varphi \ (\text{jet}_{i=1..4}, \text{MET}) > 0.5$
The classic channel: mono-jet

- major backgrounds from $Z \rightarrow v\bar{v}$ (60%) and $W \rightarrow l\nu$ (30%)

  constrained from global fit to $p_T^{\text{miss}}$ in signal (SR) and control regions (CR)
The classic channel: mono-jet

- major backgrounds from $Z \rightarrow vv$ (60%) and $W \rightarrow lv$ (30%)

constrained from global fit to $p_T^{\text{miss}}$ in signal (SR) and control regions (CR)

- take hadronic recoil as proxy for $p_T^{\text{miss}}$ in CR
- bin-by-bin transfer factors linking yields in SR and CR
- 20%-40% reduced systematics
  - $p_T$-dependent NLO QCD K-factors from MG5_aMC@NLO
  - electroweak corrections from theory calculation (arXiv:1705.04664)
The classic channel: mono-jet

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excellent background modeling
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no significant deviation from SM background
Extension to hadronic V

- DM recoils against hadronically decaying Z or W
  - large Lorentz-boost:
    decay products merge in single fat jet

- particularly interesting: Higgs-strahlung with scalar mediator
  - ISR Z/W production always smaller than mono-jet

- Z/W/t\bar{t} background scale estimated from CR

- main uncertainty from modeling fat jet
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main uncertainty from modeling fat jet

no excess over SM background
**Mono-photon search**

- $p_T^\gamma > 150$ GeV
- up to 1 jet
- $\mu/e$ veto
- $E_T^{\text{miss}} > 150$ GeV

- **DM recoils against a photon from QED ISR**
  - clean signal, but $\alpha_{\text{QED}} < \alpha_{\text{QCD}}$

- **major backgrounds** $(Z\rightarrow\nu\nu)+\gamma$ (55%) and $(W\rightarrow l\nu)+\gamma$ (15%) from $(Z\rightarrow ll)+\gamma$ and $(W\rightarrow \mu\nu)+\gamma$ CR where $E_T^{\text{miss}}$ includes corresponding charged lepton

- **difficult (but subdominant) instrumental backgrounds**
  - jets/electrons faking photons estimated from data

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Good match of data to background-only prediction
Mono-($Z \rightarrow ll$) searches

- DM recoils against a $Z$ boson from electroweak ISR

- Dilepton trigger give access to low missing momentum
  \[ p_T^{ll} > 100 \text{ GeV} \]
  \[ \Delta \Phi > 2.6 \text{ rad} \]
  \[ | p_T^{\text{miss}} - p_T^{ll} | / p_T^{ll} < 0.4 \]

- Very clean backgrounds of mainly ZZ (60%) and WZ (25%) from 4 resp. 3 lepton CR

- Non-resonant background (e.g. $t\bar{t}$, tW, WW) from electron-muon enriched data sample

No excess over SM background

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Heavy quark pair associated DM production

- favored if couplings Yukawa-like
  - high sensitivity to (pseudo)scalar mediators
- optimize selection according to different experimental signatures
- dominant backgrounds of $\bar{t}t$, $\bar{t}t+Z$ and $Z+jets$
  constrained from several CR

$$\bar{b}b : \cos \theta^*_{\bar{b}b} = \tanh (\Delta \eta_{\bar{b}b} / 2)$$

$$tt \text{ (all-had)} : m_j$$

$$tt \text{ (dilepton)} : \xi = m_{T2}^{ll} + 0.2 E_T^{\text{miss}}$$

no significant deviation from SM background
presented analysis found data compatible with background-only expectation

use results to set limits on simplified models
  - resonant enhancement when mediator produced on-shell (s-channel)
  - limits suppressed when going off-shell
  - cross section (sensitivity) drops at high mediator mass

limits depend on assumptions
  - mediator type
  - coupling strength
  - ...

use simplified models to interpret DM searches
Strongest limits on (axial)vector mediators

- **mono-jet channel** most sensitive
  - exclude mediator masses up to \(\sim 1.8\) TeV and DM masses up to \(\sim 700/500\) GeV
  - similar sensitivity for ATLAS and CMS

- need much more luminosity to improve results

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**CMS**

*Vector med, Dirac DM, \(g_q = 0.25, g_{DM} = 1\)*

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*Median expected 95% CL*

*\(\pm 1\sigma_{\text{experiment}}\)*

*Observed 95% CL*

*Observed \(\pm \text{theory unc.}\)*

**\(\Omega_c x h^2 \approx 0.12\)**

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arXiv:1712.02345

35.9 fb\(^{-1}\) (13 TeV)
Strongest limits on (pseudo)scalar mediators

- heavy flavor searches allow excluding scalar mediator masses up to \( \sim 120 \text{ GeV} \)
  - can reach increased sensitivity by combining all \( tt \) final states

- mono-jet searches most sensitive to pseudoscalar mediators
  - exclude masses up to \( \sim 400 \text{ GeV} \)

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[Graphs and data showing exclusion limits for scalar and pseudoscalar mediators, with arrows pointing to exclusion regions.]

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arXiv:1712.02345

35.9 fb\(^{-1}\) (13 TeV)

[Graph showing observed and expected exclusion regions for different mediator masses and coupling values.]
Visible mediator searches

- dark matter searches can be constrained by visible mediator decays
  - probe region where mediator cannot decay to DM

- search for a bump in dijet or dilepton invariant mass spectrum
  - coupling choices determine interplay between DM and resonance searches
  - for e.g. $g_q=0.25$ and $g_l=0$ mediator masses down to $\sim 50$ GeV

(CMS, JHEP 01 (2018) 097) and up to 2.5 TeV can be excluded
- simplified models allow unambiguous comparison in the WIMP-DM cross section versus DM mass plane

- advantage:
  - visualizes the complementarity of collider and other DM searches

- disadvantage:
  - comparison model-dependent
  - oversimplification can lead to misinterpretation

use simplified models to compare different results
Translation to direct-detection plane

- nice complementarity between LHC and direct detection experiments
  - LHC searches more sensitive to low DM masses

arXiv:1712.02345

SI: vector

arXiv:1710.11412

SI: scalar
Translation to direct-detection plane

- nice complementarity between LHC and direct detection experiments
  - LHC searches more sensitive to low DM masses
  - axialvector couplings
Extensions of simplified models: mono-top

- DM recoils against a single top quark
  - flavor-changing simplified model or
  - colored, charged scalar
- explore hadronically decaying boosted top quarks
  - CA15 jet w.
  - $p_T > 250$ GeV
  - $100 < m_j / \text{GeV} < 210$
  - $p_T^{\text{miss}} > 250$ GeV

- BDT discriminating fat jets from top vs quark/gluon initiated
- extract signal strength from fit to $p_T^{\text{miss}}$ in 2 BDT bins
Extensions of simplified models: mono-top

CMS arXiv:1801.08427

$g_u' = 0.25, g_d' = 1$ [FCNC]

- Median expected 95% CL
- Exp. $\pm 1\sigma$ experiment
- Obs. $\pm 1\sigma_{\text{theory}}$

Observed $\sigma_{\text{95% CL}}/\sigma_{\text{theory}}$

$\sigma_{\text{95% CL}}(pp \to \phi \to \psi)$

Resonant scalar production
- $a_u = b_u = 0.1$
- $a_d = b_d = 0.2$
- $m_\psi = 100$ GeV

$36 \text{ fb}^{-1}$ (13 TeV)

no excess over SM expectation observed
Extended scalar models: $H \rightarrow \gamma\gamma / H \rightarrow b\bar{b}$ searches

- DM recoils against a Higgs boson
  
- need to boost production cross section with dedicated models (eg. $Z'$-2HDM)
  - Higgs initial state radiation tiny

- $H(\rightarrow \gamma\gamma)$:
  - excellent mass resolution (<2%)
  - use $p_T^{\text{miss}}$ inside Higgs mass window
Extended scalar models: $H \rightarrow \gamma\gamma / H \rightarrow b\bar{b}$ searches

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- $H(\rightarrow \gamma\gamma)$:
  - excellent mass resolution ($<2\%$)
  - use $p_T^{\text{miss}}$ inside Higgs mass window

- $H(\rightarrow b\bar{b})$:
  - largest branching fraction ($\sim 60\%$) but poor mass resolution ($\sim 10\%$)
  - explore resolved $m_{bb}$/merged $m_j$ in 4 different $p_T^{\text{miss}}$ bins
Extended scalar models: $H \rightarrow \gamma\gamma/H \rightarrow b\bar{b}$ searches

- DM recoils against a Higgs boson
- need to boost production cross section with dedicated models (e.g., $Z'$-2HDM)
  - Higgs initial state radiation tiny

- $H(\rightarrow \gamma\gamma)$:
  - excellent mass resolution (<2%)
  - use $p_T^{\text{miss}}$ inside Higgs mass window

- $H(\rightarrow b\bar{b})$:
  - largest branching fraction (~60%) but poor mass resolution (~10%)
  - explore resolved $m_{bb}/$merged $m_j$ in 4 different $p_T^{\text{miss}}$ bins

exclude $Z'$ up to ~2.5 TeV for pseudoscalar of 300 GeV
manifold DM program at ATLAS and CMS
  • missing transverse momentum signatures and visible mediator searches
  • completed by rich SUSY research program providing natural DM candidate in a UV complete theory
  • complementarity to direct and indirect searches

LHC Run-II going full speed
  • factor 3 more collisions to analyze during LHC Run-II

many developments, e.g.
  • more realism/complexity in scalar sector (extra scalar with H mixing)
  • include scenarios with longlived particles
The LHC - A modern Prometheus?

Heinrich Füger, Prometheus brings fire to mankind