Searches for dark matter at CMS

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Gravitational Evidence for Dark Matter

Simulations on NCSA by A. Kravtsov (U.Chicago) and A. Klypin (NMSU); visualization by A. Kravtsov
Dark Matter Candidate: Gross Features

**Dark**
- Electrically neutral
  - Limits on charge and electric/magnetic dipole moment

**Collisionless**
- Limits on $\sigma_{xx}/m_x$

**Classical**
- Confined in kpc scale $\rightarrow$ de Broglie wavelength
  - $m > 10^{-22}$ eV (boson)
  - $m > 25$ eV (spin $\frac{1}{2}$ fermion)

**Fluid**
- Stability of bound systems $\rightarrow$ $m < 10^3 M_{\text{Sun}} \sim 10^{70}$ eV

**Stable (or long-lived)**
- Should not have decayed by now
Dark Matter: Hunter’s Guide

Direct detection
- Scattering between DM particle and nuclei \(\rightarrow\) recoil detection

Indirect detection
- Annihilation of DM pairs \(\rightarrow\) effects on particle distribution

Production at colliders
- Complementary to direct and indirect detection
- Rich phenomenology
Status of Direct Detection of Dark Matter

Results for spin-independent (SI) interaction only – but see later for spin-dependent (SD)
Modelling the Dark Matter Production

Direct production of DM pair
- At LHC energies: explicit mediator

Signature
- DM leaves no signal in the detector → transverse momentum imbalance ($p_T^{\text{miss}}$)
- Back-to-back DM pair is invisible → trigger on recoiling SM particles → “mono-X” search.

But also...
- Cascade decays (like SUSY)
- Searches with long-lived particles
- Limits on pure mediator production
The LHCC Dark Matter Working Group

Guidelines and recommendations for benchmark models

LHC x Direct and Indirect Detection

DM limits from mediator searches

Model evolution:
  spin-0, t-channel
Large Hadron Collider

LHC: most powerful particle collider in operation

- Four large experiments: ATLAS, CMS, ALICE, LHCb
- Delivered $\sim 150/fb$ of pp collisions at $\sqrt{s} = 13$ TeV to ATLAS and CMS in Run
- Also used for HI studies
Compact Muon Solenoid
LHC @ 13 TeV – A Harsh Environment

CMS Average Pileup (pp, $\sqrt{s}=13$ TeV)

- Run II: $\langle \mu \rangle = 34$
- 2018: $\langle \mu \rangle = 37$
- 2017: $\langle \mu \rangle = 38$
- 2016: $\langle \mu \rangle = 27$
- 2015: $\langle \mu \rangle = 13$

$\sigma_{\text{pp}}^{\text{pp}}(13\text{TeV}) = 80.0\text{mb}$
Searching for DM at Collider Experiments

$p_T^{\text{miss}}$ signature

Standard trigger:
- $p_T^{\text{miss}}, H_T^{\text{miss}} > 120 \text{ GeV}; H_T > 60 \text{ GeV}$
- No muons in the computation

- Control regions

![Efficiency Graph](http://cds.cern.ch/record/2631527)

![PFMet (µ subtracted) Graph](http://cds.cern.ch/record/2631527)
Missing $p_T$ Reconstruction

Extensive cleaning needed for sensible $p_T^{\text{miss}}$ distribution

Dominated by $Z(\nu\nu)$ + jets at higher values

Pileup per particle identification

- Smaller pileup dependence
$M_T$ with regular PF $p_T^{\text{miss}}$

$M_T$ with PUPPI PF $p_T^{\text{miss}}$
EXO-16-048: DM + jet (1)

Baseline DM search analysis

- **Standard trigger (no HT threshold)**
- **Monojet selection**
  - $p_T^{miss} > 250$ GeV
  - AK4 jet, $p_T > 100$ GeV, $|\eta| < 2.4$
  - Mono-V category
    - AK8 jet, $p_T > 250$ GeV, $|\eta| < 2.4$
    - $\tau_2/\tau_1 < 0.6$
    - $m_{jet}$ in [65, 105] GeV range
- **Vetos**
  - $p_T^{miss}$ close to jet
  - B-tagged jets
  - Isolated leptons and photons
- **Surviving SM backgrounds**
  - $Z (\nu\bar{\nu}), W(l\nu) +$ jets
    - Lost lepton in the W case
- **Control regions:**
  - 1 & 2 ele/mu single photon
EXO-16-048: DM + jet (2)

Low $p_T^{\text{miss}}$
- Systematically limited
- Lots of effort to model V+jets background
- Challenge increases with pileup

High $p_T^{\text{miss}}$
- Statistically limited
- Improve slowly with luminosity

Precise predictions needed for both regimes!
- NLO QCD + EWK: https://arxiv.org/abs/1705.04664
EXO-16-048: DM + jet (3)

Interpretation in different planes

- $m_{DM} \times m_{med}$, fixed couplings
- $g_q \times m_{med}$, fixed $m_{med}/m_{DM}$ ratio
- $\sigma \times m_{DM}$, fixed coupling
  - Cast to $\sigma$(DM-nucleon) or $<\sigma v>$
Collider search probes low-mass DM and pseudoscalar/axial mediators.
Dark Matter with ...

### Photon

![Photon](image1.png)

- **Events / GeV**
  - Data / Bkg.
  - 3.2 - 10
  - 1 - 10
  - 1 - 10
  - 1 - 10
  - 1 - 10

### Z (ll)

![Z (ll)](image2.png)

- **Events / GeV**
  - Data / Bkg.
  - 0.5 - 1
  - 0.5 - 1
  - 0.5 - 1
  - 0.5 - 1

### Top and ttbar

![Top and ttbar](image3.png)

- **Events**
  - Data / Bkg.
  - 0.5 - 1
  - 0.5 - 1
  - 0.5 - 1

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**CMS**

- **35.9 fb⁻¹ (13 TeV)**
- **Dark Matter with ...**
- **Photon**
- **Z (ll)**
- **Top and ttbar**

**Vector, Dirac, g_q = 0.25, g_{DM} = 1**

- Observed \( \mu_{\text{exp}} = 1 \)
- Theoretical uncertainty
- Median expected \( \mu_{\text{exp}} = 1 \)
- 68% expected
- \( \Omega_{\chi} h^2 \geq 0.12 \)

**Scalar, Dirac, g_q = g_{DM} = 1, m = 1 \text{ GeV}**

- Expected 95% CL
- Expected ± 1 s.d.
- Expected ± 2 s.d.
- Observed 95% CL

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**Theoretical uncertainty**

- **68% expected**
- **95% CL expected**

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**Expected 95% CL**

- **Observed 95% CL**

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**CMS**

- **Observed 95% CL**
- **Median expected 95% CL (t+DM, tt+DM)**
- **68% CL expected**
- **95% CL expected**
Dark Matter Summary Plots
Dark Matter + Higgs Boson (1)

All different H decay channels
- $b\bar{b}b\bar{b}$, with AK8 and CA15 jets
- $\gamma\gamma$, in bins of $p_T^{\text{miss}}$
- $\tau\tau$, with both 1 and 2 $\tau_h$
- WW and ZZ
  - WW in $e\mu\nu$ channel only
  - ZZ in 4e, 4$\mu$ and 2$e2\mu$ channels
Interpretations in terms of different benchmark models

- Z' + 2HDM: Z' + pseudoscalar A + Dirac DM
- Baryonic Z': Z' + baryonic Higgs h_B (mixes with H)

Competitiveness with DD: m_{DM} in [1, 5] GeV range
Dark Matter and Nonprompt Jets (1)

Long-lived particle decaying to DM + q/g
- Signature: displaced, nonprompt jet + $p_T^{\text{miss}}$
- Measure delay with ECAL timing
- Backgrounds are purely instrumental

**Baseline jet selection**
- $|\eta| < 1.48$
- $p_T > 30\text{ GeV}$

**Signal jet selection**
- $E_{\text{ECAL}} > 20\text{ GeV}$
- $N_{\text{cell}}^{\text{ECAL}} > 25$
- HEF > 0.2 and $E_{\text{HCAL}} > 50\text{ GeV}$
- $t_{\text{jet}}^{\text{RMS}} / t_{\text{jet}} < 0.4$ and $t_{\text{jet}}^{\text{RMS}} < 2.5\text{ ns}$
- $\text{PV fraction}_{\text{track}} < 0.08$
- $E_{\text{ECAL}} / E_{\text{HCAL}} < 0.8$
- $t_{\text{jet}} > 3\text{ ns}$

**Event level selection**
- At least one signal jet
- $p_T^{\text{miss}} > 300\text{ GeV}$
- Quality filters
  - $\max(\Delta \phi_{\text{DT}}) < \pi/2$
  - $\max(\Delta \phi_{\text{RPC}}) < \pi/2$

Avoid noise and APD hits
Avoid prompt jets and jets satellite bunches
Avoid beam halo

- barrel has better timing

Full Run 2
Dark Matter and Nonprompt jets (2)

Interpretation in terms of GMSB model (gluino + gravitino only)

- Efficiency up to 35% for 2.4 TeV gluino, $1 < c\tau_0 < 10$ m
Missing $p_T + Z(\ell\ell) \gamma$

Benchmark model with massless $\gamma_D$
- New U(1) symmetry
- Dark photon $X$ photon mixing
- Could be recast in terms of dark matter model

Main background is WZ
- Control regions: $e\mu$, WZ and ZZ

Event selection
- $p_T^{miss} > 110$ GeV
- $p_T^{\ell\ell} > 60$ GeV
- $p_T{\gamma} > 25$ GeV
- $m_{\ell\ell\gamma} > 100$ GeV
  - Reject resonant $Z\gamma$
- $m_T < 350$ GeV
  - Reject WW background

Dark Matter and Leptoquarks

Benchmark model with LQ pair production
- Coannihilation paradigm – Naker at al. (2015)
- $LQ \rightarrow c(s) + \mu$, $LQ \rightarrow DM + X$

Search in $m_{\mu j}$ distribution
- $p_T (\text{jet}), p_T^{\text{miss}} > 100$ GeV
- $p_T (\mu) > 60$ GeV
- $m_T > 500$ GeV
- Veto $b$-jets, $e$, $\tau_h$
- Main backgrounds: inclusive W and ttbar production

Dependency on $B(\text{LQ} \rightarrow c(s) + \mu)$

Conclusions...

The quest for dark matter is one of the next goals of the LHC
- Complementarity between collider and direct and indirect detection

The LHC DM WG: guidelines and recommendations
- Benchmark models
- LHC results together with other experiments
- Comparison with visible mediator searches

CMS is well underway on its analysis of the Run 2 data
- Different channels considered
- Techniques under continuous refinement
- Reinterpretations and new ideas
LHC Run 3 will bring ~ additional 150/fb.

HL-LHC in the horizon...
  - ... with all the challenges of PU 200.

Direct detection experiments reaching the neutrino floor soon.

Exciting times ahead!
Thank You!