Recent Results on Dark Sectors in CMS

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Introduction

Dark Sectors at CMS:

This talk focuses largely on 2 classes of models:

1) Hidden Valley (Dark QCD)
   Portal particle which connects SM to a higher scale BSM sector
   BSM Sector can have it’s own internal structure (often coined “Dark QCD”)
   Is seen by decays back into SM particles (can be displaced)

2) Dark Matter in final states with unbalanced $p_T$ and standard objects
   Closer to traditional dark matter searches with look for missing momentum
   Here we can have various dark matter production mechanisms
   1. 2 Higgs Doublet Models (2HDM)
   2. Dark Higgs
   Searches look for missing momentum $p_T^{\text{miss}}$ and traditional objects

First dedicated searches for:

1. Neutral long-lived particles in the Muon system (2402.01898)
2. Emerging Jets (2403.01556)
3. Soft Unclustered Energy Patterns (SUEPs) (2403.05311)
4. Dark Matter in DarkHiggs (WW+MET) (2310.12229)
5. Dark Matter produced in association with bottom quarks (2894114)
### Dark Showers

#### Decays in Muon System:
1) Covers decays far away from IP (meters)
2) Excellent background suppression from shielding material
3) Muon system acts as a sampling calorimeter
4) Large cluster of hits (>100 hits)

#### Emerging Jets:
1) Less than ~500 mm
2) Fully data driven estimate of background
3) Both Model-agnostic and GNN tagger for EMJ
4) Small background in sensitive GNN bins

#### SUEPs:
1) Fully prompt decay to SM
2) Novel Data driven estimate of large QCD Background
3) Recluster tracks with wide jets
4) Unique signature due to the sphericity and large number of tracks (>100)

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**Long-Lived**

Muon System

**Prompt**

Calorimeters+Tracker

Tracker

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Event selection:
Trigger on MET (~1% efficiency). MET (≥ 200 GeV)
DBSCAN cluster of hits (>50 hits) in the muon system with no jets or tracks (Cluster efficiency (>80%))
Split events into 3 mutually exclusive categories.
1. double clusters,
2. single Cathode Strip Chambers (CSC) cluster
3. single Drift Tube (DT) cluster
Use data-driven ABCD method (Δφ(p_T^{miss},cluster),N_{hits}) for background estimation: N_{hits} as main discriminator
No excess above SM background observed

We interpret the search result in 9 different decay modes with
- hadronic shower \((bb, dd, K^+ K^-, K^0 K^0, \pi^+ \pi^-)\)
- EM shower \((\pi^0 \pi^0, \gamma \gamma, e^+ e^-)\)
- or both \((\tau^+ \tau^-)\)

Achieve first sensitivity to sub-GeV mass LLPs at \(\text{BR}(H \rightarrow ss) = 10^{-3}\) level

Achieve first sensitivity to dark shower model produced from Higgs decay at \(\text{BR}(H \rightarrow ss) = 10^{-3}\) level

**Observed Limits**

**Twin higgs model (dd decay)**

**Twin higgs model (mixed decay)**

**Dark shower model (gluon portal)**

\([x_{10}, x_{1A}] = (2.5, 1)\)

2402.01898

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Emerging Jets

Jet-tagging:
1) Model-agnostic EMJ tagging:
   * Unflavored: leverage track displacement within jet
   * Flavor-aligned: leverage track multiplicity within jet

2) GNN EMJ tagging:
   2 ParticleNet models trained separately on unflavored and flavor-aligned scenarios

Data Driven Background Estimation:
Estimate # of bkg. events pass into SR using CR events and mistag rates from signal-free region

B-jet discriminator to calculate mistag on bs separately and b-jet fraction

Primary signature:
- High $H_T$
- 4 high $p_T$ jets (2 EMJ, 2 SM jets)
Emerging Jets

No excess observed

Limits set on 2 scenarios for both Model-agnostic and GNN.

**Unflavored down model:**
Dark quarks couple to down quarks ONLY
All $\pi_{\text{dark}}$ in event have same $c\tau$

**Flavored-aligned down model:**
Dark quarks couple to down-type quarks ONLY ($d, s, b$)
$\pi_{\text{dark}}$ lifetime differ based on dark pion composition
SUEPs

Soft unclustered energy pattern (SUEP):

prompt, high multiplicity, isotropic, low $p_T$ tracks final state

Analysis Strategy:

1) $HT > 1200$ GeV (SUEP recoil off ISR), Lepton Veto
2) Tracks cluster in wide “Jets” with $\Delta R=1.5$, $p_T>150$ GeV
3) SUEP Candidate as highest number of constituents
4) Boost into the SUEP candidate frame to calculate Sphericity

Large QCD background:

1) Fully data driven: Extended ABCD (9 regions)
2) # constituents and Sphericity of SUEP Candidate
3) Shape corrected with data driven systematics
4) Good agreement in Validation and Signal Regions

\[
SR_{Bin i} \approx F_{Bin i} \frac{H^2 F D^2 B^2}{G C A E^4} + O(\Delta^4)
\]
SUEPs

No excess observed in data:

- 4-dimensional parameter space $T$, $m_S$, $m_\phi$, $m_A$
- Discriminating variable we fit on is the # constituents, scales like $N \sim m_S/m_\phi \sim m_S/T$

Limits on the cross-section are made and exclusion limits set for each scalar mass

More SUEP-like scenarios (bottom left) are covered

Sensitive across the mass range
Dark Higgs:
2 mediators (Z’, s)
χ as Dark Matter Candidate
here: s → WW → 2l2ν/lvqq

Strategy:
Look for large MET
Reconstruct s through W decays
Data-driven estimate for fakes

2 Higgs Doublet Model (2HDM):
Higgs Doublet (H, H±, A)
Additional pseudoscalar a
A/a → χχ
χ as Dark Matter Candidate

Strategy:
Look for large MET
Events with b-tagged jets
Lepton Vetoes
DarkHiggs:
2l2v: 3 SR unrolled 2D plots
Distributions split by $\Delta R \in [0, 1.0, 1.5, 2.5]$
Binned in $m_{ll}$ and $m_T$

Top, NonPrompt, DY and WW:
Data driven NonPrompt
Rest estimated via MC through CRs.
DarkHiggs:

\( l\nu 2q \): BDT discriminator

2016 split from 2017/2018

13 optimized kinematic inputs

(mostly sensitive to MET vs visible particles boost)

Top, W+Jets, and NonPrompt:

Data driven NonPrompt

Rest estimated via MC through CRs.

Different binning from \( S/\sqrt{S+B} \)

Small local deficit: 1.8\( \sigma \) in final bin
Limits set $m_{Z'}$ and $m_s$ for various masses of $\chi$
Sensitivity for $m_s$ drops off for $m_s > 2m_\chi$
2HDM analysis:
1) MET > 250 GeV
2) Single Lepton veto (inverted for CRs)
3) b-tagging with loose ID

Combine Muon/Electron channels.
simultaneous binned profile likelihood fit on:

1b ($p_T^{miss}$):

- **SR1**: At least 2 jets
- **Z(\(\PZ\)) CR**: OSSF leptons, 70 < $M_{\ell\ell}$ < 110, Recoil > 250 GeV
- **W(\(\PZ\)) CR**: Single lepton, $p_T^{miss}$ >100, $M_T$ < 160, Recoil > 250 GeV

2b ($\cos\theta^*$):

- **SR2**: At least 2 jets
- **Z(\(\PZ\)) CR**: OSSF leptons, 70 < $M_{\ell\ell}$ < 110, Recoil > 250 GeV
- **tt(\(\PZ\)) CR**: Single lepton, $M_T$ < 160, Recoil > 250 GeV
No excess observed. Limits set on $m_a$ and the ratio of the vevs of the two Higgs doublets, $\tan \beta$.

$2\text{HDM} + a$

$bb + p_T^{\text{miss}}$

$m_A = 600 \text{ GeV}$

$m_\chi = 1 \text{ GeV}$

$\sin \theta = 0.7$

$2\text{HDM} + a$

$bb + p_T^{\text{miss}}$

$m_A = 600 \text{ GeV}$

$m_\chi = 1 \text{ GeV}$

$\tan \beta = 35$
Summary

CMS continues to probe dark sector models with traditional objects:
1) Dark Higgs → MET and Ws
2) 2HDM → MET with b-tagged jets

CMS has also grown a program looking for nontraditional objects (lifetimes):
3) SUEPs → Wide jets with large number of soft particles (prompt)
4) Emerging Jets → Jets with track displacement (cτ~100s mm)
5) Showers in the muon system → No associated tracks/muons (cτ~meters)
Dark Sector
Muon Cluster Efficiency

High cluster reconstruction efficiency throughout the detector

CMS Simulation Preliminary
**Muon Cluster**

- **N_{hits} > 130**
  - Main discriminator against background

- **$\Delta \phi(\vec{p}_T^{\text{miss}}, \text{cluster}) < 0.75$**
  - Provides additional discrimination, and provides a variable that’s independent of $N_{hits}$ for the ABCD method
  - For signal, MET and cluster are aligned because the LLP $p_T$ is responsible for the MET
• $\Delta R(\text{track, jet})$, as particles in EJs tend to have a wider angular separation than in the SM jets because of the heaviness of the dark mesons.

• $\ln(p_T^{\text{track}}/\text{1 GeV})$, $\ln(p_T^{\text{track}}/\sum_i p_T^i)$, as the combination of the dark shower and the decay of the mesons back to the SM sector causes the $p_T$ of tracks to be smaller on average for EJs than for SM jets.

• $T(d_{xy})$, $T(d_z)$. The transformation function $T(x)$ is applied to the track displacement variables, to reduce the range of values input to the GNN while preserving the variables’ sign and continuity. It is defined as:

$$T(x) = \text{sign}(x) \ln \left( \frac{x}{1 \text{ cm}} \right) + 1.$$
Mistag rate scale factor (SF)

Use events in CR with mistag rates ($\epsilon$) from FR to estimate # SM events in SR:

$$N_{SR} = \sum_{\text{evt} \in \text{CR}, j \in \text{jets}} SF_{N_{\text{EMJ}} \geq 2}(\epsilon_j)$$

$$N_{SR} \sim \sum_{\text{evt} \in \text{CR}} \frac{1}{2} \sum_{j \notin \text{tagged}} \epsilon(f_j, p_{T,j})$$

CR = JetHT trigger, $N_{\text{EMJ}}^{\text{tagged}} = 1$
SR = JetHT trigger, $N_{\text{EMJ}}^{\text{tagged}} \geq 2$
FR = $\gamma$-triggered
Soft Unclustered Energy Pattern (SUEP):

**SUEP Model:**
1. Rich phenomenology from Hidden Valley models
2. dark QCD scenario with a Heavy Spin-0 state (S)
3. Strongly coupled (large ‘tHooft coupling)
4. light pseudoscalar meson($\phi$)
   - **promptly** decays back into SM particles

**SUEP Signature:**
With large ‘tHooft coupling, dark QCD is no longer predominantly soft and co-linear, but leads to large angle, high $p_T$ radiation

1. High multiplicity of low $p_T$ tracks
2. Spherically-symmetric, soft spray of particles at the bottom of the hidden valley spectrum. (“soft bomb”)
3. case for a “Higgs-bomb” with $m_S=125$ GeV

https://arxiv.org/abs/1612.00850
Parameter variations:
$m_\phi$ and $T$ should be varied in addition to $m_S$

- Be careful to stay in a SUEP regime
- Restrict $T/m_\phi$ to $[\frac{1}{4}-4]$
- Thermal approximation breaks (Green)
- Higgs decay to a few resonances (Orange and Green)

Plan to vary $m_\phi$ and $T/m_\phi$:
Low $m_\phi$ constrained by $m_A$

$m_\phi$ : $[1, 2m_A, 2, 3, 4]$
$T/m_\phi$ : $[0.25, 0.5, 1, 2, 4]$

https://arxiv.org/pdf/2107.12379
Z+Jets and W+Jets (tt) have the largest contribution in the 1b (2b) SR
Linking SR and CR through rateParam will all the systematics taken as nuisance parameters
One rateParam for each bin and for each region
A simultaneous binned profile likelihood fit is performed in Signal and Control Region