Dark Photon Models for CMS

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5th Workshop on LLPs @ LHC
CERN - May 27, 2019
CMS Working Subgroup

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Disclaimer

- All plots are at Madgraph generator level
- No CMS simulation is used
- No CMS data are used or shown here
Dark Photon Coupling to Scalar Dark Matter Particles

Model 1: Scalars

\[ Z_D \text{ and/or } s_D \] could be a LLP

Coupling \( Z_D \) to \( s_D \) could be larger than \( Z_D \) to \( f \)

Note:
\( s_D \) is not taken as a self-conjugate scalar here; i.e. \( s_D \) and \( s_D^\ast \) are NOT the same particle.

Black: SM particles
Blue: DM particles
Dark Photon Coupling to Fermionic DM Particles

Model 2: Fermions

- $Z_D$ and/or $f_D$'s could be a LLP

- Coupling $Z_D$ to $f_D$ could be larger than $Z_D$ to $f$

- $f_D$ stable $\Rightarrow$ Missing $E_T$
Couplings Used in Dark Photon Model Lagrangians

Using Feynrules + MadGraph to generate events

Using MadAnalysis to analyze and plot

Scalar model

- Dark Scalar is **NOT self-conjugate**
- 1. $\bar{q}Y^\mu (g_Y^D \pm g_Y^A) q Z_{D\mu}$
- 2. $g_Y^{D\bar{s}Y}(\bar{s_D}\partial^\mu s_D - s_D\partial^\mu \bar{s_D}) Z_{D\mu}$
- 3. $g_{s\bar{s}}^D (\bar{\mu} \mu s_D$

Three distinct couplings
Couplings Used in Dark Photon Model Lagrangians

Scalar model

\[ \text{Fermionic model} \]

- Dark Scalar is **NOT self-conjugate**
  - 1. \( \bar{q} \gamma^\mu (g_V^D \pm g_A^D \gamma^5) q Z_{D\mu} \)
  - 2. \( g_{V}\gamma (\bar{s}_D \gamma^\mu s_D - s_D \gamma^\mu \bar{s}_D) Z_{D\mu} \)
  - 3. \( g_{s\lambda} \bar{\mu} \mu s_D \)

- Dark Fermions are **self-conjugate**
  - 1. \( \bar{q} \gamma^\mu (g_V^D \pm g_A^D \gamma^5) q Z_{D\mu} \)
  - 2. \( g_{A\gamma}^D \bar{f}_{D1} \gamma^\mu \gamma^5 f_{D1} Z_{D\mu} \)
  - 3. \( g_{A\gamma}^D \bar{f}_{D1} \gamma^\mu \gamma^5 f_{D2} Z_{D\mu} \)
  - 4. \( \bar{\mu} \gamma^\mu (g_V^D + g_A^D \gamma^5) \mu Z_{D\mu} \)

Four distinct couplings
## Varying the Coupling Constants

<table>
<thead>
<tr>
<th>Lagrangian</th>
<th>gV</th>
<th>gA</th>
<th>Does it work?</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\gamma^\mu(g_{\gamma}^D \pm g_{\Lambda}^D\gamma^5)q , Z_{D\mu}$</td>
<td>0.25</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>0.001</td>
<td></td>
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<tr>
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<td>0.25</td>
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<tr>
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<td>0</td>
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</tr>
<tr>
<td>$f_{D1}(g_{\gamma}^D \pm g_{\Lambda}^D\gamma^5)f_{D1} , Z_{D\mu}$</td>
<td>0</td>
<td>0.25</td>
<td>Mathematica error: Not hermitian</td>
</tr>
<tr>
<td></td>
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<td>0.25</td>
<td>Mathematica error: Not hermitian</td>
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<td>0</td>
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</tr>
<tr>
<td>$f_{D1}(g_{\gamma}^D \pm g_{\Lambda}^D\gamma^5)f_{D2} , Z_{D\mu}$</td>
<td>0</td>
<td>0.25</td>
<td>Mathematica error: Not hermitian</td>
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<tr>
<td></td>
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<tr>
<td></td>
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<td>0</td>
<td></td>
</tr>
<tr>
<td>$\mu\gamma^\mu(g_{\nu\pi}^D + g_{\Lambda\pi}^D\gamma^5)\mu , Z_{D\mu}$</td>
<td>0.25</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>0.001</td>
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</tbody>
</table>
Masses-at-a-glance

**Scalar model**

<table>
<thead>
<tr>
<th>$Z_D$(GeV)</th>
<th>$s_D$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>1000</td>
<td>2</td>
</tr>
</tbody>
</table>

**Fermionic model**

<table>
<thead>
<tr>
<th>$Z_D$(GeV)</th>
<th>$f_{D1}$ (GeV)</th>
<th>$f_{D2}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>100</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>1000</td>
<td>30</td>
<td>4</td>
</tr>
</tbody>
</table>
Samples with Dimuon Final States – All plots at generator level

Scalar Model
P_T of Leading, Subleading, 3^{rd}, and 4^{th} Muon

Scalar Model

M. Hohlmann, M. Rahmani, Dark Photon Models for CMS, LLP Workshop, CERN - May 27, 2019
η of Muons and Δη between Muons from Same Vertex
$\Delta \phi$ and $\Delta R$ between Muons from Same Vertex

Scalar Model
Samples with Dimuon Final States – All plots at generator level

Fermionic Model
Invariant Mass of Muons from Same $f_{d1}$

For the Fermionic Model, we have:

$m_{f_{d1}} - m_{f_{d2}} = 11$ GeV

$m_{f_{d1}} - m_{f_{d2}} = 26$ GeV

The graph shows the distribution of invariant masses for muon pairs with masses $< f_{d1}$, where $f_{d1}$ and $f_{d2}$ are the masses of different fermionic states.
Summary & Plans

• Developing 2 models with decays of dark photons into scalar or fermionic dark matter particles with two dimuon pairs in final state
• Complementary to models with direct dark photon decays into dimuons (see Cristiano’s and Teruki’s talks)
• Investigating different coupling types & strengths with MadGraph
• Event kinematics & topology look reasonable at generator level
• Next:
  – Simulate and reconstruct events in CMS detector (in progress)
  – Connect with CMS searches for two displaced dimuon pairs
    • Look into reinterpreting 2016 dimuon pair results for these models
    • Full Run 2 analysis
The End
Backup slides
Event Generation

**Feynrules**
- Mathematica package that allows the calculation of Feynman rules in momentum space for *any* QFT physics mode which can then be used to implement the new physics model into MadGraph, see [https://arxiv.org/pdf/1508.00564.pdf](https://arxiv.org/pdf/1508.00564.pdf)

**MadGraph**
- Computation of cross sections; generation of hard scattering events

**MadAnalysis**
- Framework for phenomenological investigations at generator level which we use for analysis and producing plots.
Lagrangian Terms in MadGraph

- $\gamma_D$ production from quarks
  - $V \pm A$ coupling: $\bar{q} \gamma^\mu (g_\nu^D \pm g_A^D \gamma^5) q Z_{D\mu}$

Using Feynrules + MadGraph to generate events

Using MadAnalysis to analyze and plot events
Lagrangian Terms in MadGraph

- $\gamma_D$ production from quarks
  - V ± A coupling: $\bar{q} \gamma^\mu (g^D_V \pm g^D_A \gamma^5) q Z_{D\mu}$

- Pure dark coupling of $\gamma_D$ to dark fermions in pair production
  - axial coupling *only*: $g^D_A f_{D1} \gamma^\mu \gamma^5 f_{D1} Z_{D\mu}$
Lagrangian Terms in MadGraph

• $\gamma_D$ production from quarks
  - V ± A coupling: $\bar{q}\gamma^\mu (g_V^D ± g_A^D \gamma^5)q Z_{D\mu}$

• Pure dark coupling of $\gamma_D$ to dark fermions in pair production
  - axial coupling only: $g_A^D \bar{f}_{D1}\gamma^\mu \gamma^5 f_{D1} Z_{D\mu}$

• Pure dark coupling of $\gamma_D$ to dark fermions in decay
  - axial coupling only: $g_A^D \bar{f}_{D1}\gamma^\mu \gamma^5 f_{D2} Z_{D\mu}$
Lagrangian Terms in MadGraph

- \( \gamma_D \) production from quarks
  - V ± A coupling: \( \bar{q}\gamma^\mu (g^D_V \pm g^D_A \gamma^5) q Z_{D\mu} \)

- Pure dark coupling of \( \gamma_D \) to dark fermions in pair production
  - axial coupling *only*: \( g^D_A f_{D1} \bar{f}_{D1} \gamma^\mu \gamma^5 f_{D2} Z_{D\mu} \)

- Pure dark coupling of \( \gamma_D \) to dark fermions in decay
  - axial coupling *only*: \( g^D_{Af} \bar{f}_{D1} \gamma^\mu \gamma^5 f_{D2} Z_{D\mu} \)

- Coupling of \( \gamma_D \) to muons
  - V ± A coupling: \( \bar{\mu}\gamma^\mu (g^D_{V\mu} + g^D_{A\mu} \gamma^5) \mu Z_{D\mu} \)
Example for a Parameter Set

- $g_V^p = 0.25$
- $g_A^p = 0$
- $g_V^{sY} = 10^{-3}$
- $g_{sl}^D = 0.25$
- $M_{ZD} = 20, 100, 1000 \text{ GeV}$
- $Width_{ZD} = 1 \text{ GeV}$
- $M_{sD} = 2 \text{ GeV}$
- $Width_{sD} = 0.00407 \text{ GeV}$
Example for a Parameter Set

Scalar model

- \( g_V^D = 0.25 \)
- \( g_A^D = 0 \)
- \( g_{VsY}^D = 10^{-3} \)
- \( g_{sl}^D = 0.25 \)

- \( M_{ZD} = 20, 100, 1000 \, GeV \)
- \( \text{Width}_{ZD} = 1 \, GeV \)
- \( M_{SD} = 2 \, GeV \)
- \( \text{Width}_{SD} = 0.00407 \, GeV \)

Fermionic model

- \( g_V^D = 0.25 \)
- \( g_A^D = 0 \)
- \( g_{AfY}^D = 10^{-3} \)
- \( g_{Aff}^D = 0.25 \)
- \( g_{vl}^D = 0.25 \)
- \( g_{AI}^D = 10^{-3} \)

- \( M_{ZD} = 40, 100, 1000 \, GeV \)
- \( \text{Width}_{ZD} = 2 \, GeV \)
- \( M_{fD1} = 30 \, GeV \)
- \( M_{fD2} = 4 \, GeV \)
- \( \text{Width}_{fD1} = 1 \, GeV \)
- \( \text{Width}_{fD2} = 1 \, GeV \)
Long-lived $s_D$ vs. Short-lived $s_D$

Samples with Dimuon Final States – All plots at generator level

Scalar Model
$P_T$ & $\phi$ of $S_D$
$\eta$ & $\Delta \eta$ of $s_D$
$\Delta \phi$ & $\Delta R$ of $S_D$
$P_T$ & $\phi$ of $\mu$
$\eta$ & $\Delta \eta$ of $\mu$s
$\Delta \varphi$ & $\Delta R$ of $\mu$s
$\eta$ & $\Delta \eta$ of $\mu$s

\begin{align*}
\Delta \Phi_{\eta, \mu} & \quad \text{[mu+ < sd, mu- < sd-]} \\
\Delta \eta & \quad \text{[\text{mu+ < sd}, \text{mu+ < sd-}]} \\
\end{align*}

- \text{et = 1cm}
- \text{et = 80m}
$\eta$ & $\Delta \eta$ of $\mu$s (different vertices)
$P_T$ of leading, sub-leading 3$^{rd}$ and 4$^{th}$ $\mu$s
Methodology – Feynrules

• A Mathematica package that allows the calculation of Feynman rules in momentum space for *any* QFT physics model.

• We provide FeynRules with the minimal information required to describe the our model, contained in the so-called model-file.

• This information is then used to calculate the set of Feynman rules associated with the Lagrangian.

• The Feynman rules calculated by the code can then be used to implement the new physics model into MadGraph.

• Implementation of our model with Feynrules is based *simplified dark Matter* model:
Methodology – MadGraph

- MadGraph is a framework that aims at providing all the elements necessary for SM and BSM phenomenology.
- Computations of cross sections, the generation of hard events.
- Processes can be simulated to LO accuracy for any user-defined Lagrangian, and the NLO accuracy in the case of QCD corrections to SM processes.
- Matrix elements at the tree- and one-loop-level can also be obtained.
- We use MadGraph to privately generate events for our models with different particle masses and life times.
Methodology – MadAnalysis

• MadAnalysis is a framework for phenomenological investigations at particle colliders.
• Based on a C++ kernel, this program allows to efficiently perform, in a straightforward and user-friendly fashion, sophisticated physics analyses of event files such as those generated a large class of Monte Carlo event generators.
• We are using MadAnalysis to analyze our and produce plots for our parton level events.
Lots more kinematics and topology plots

Samples with Dimuon Final States – All plots at generator level

Scalar
$P_T$ plots

**Left Panel:**
- **Title:** N. of $zd$ (scaled to one)
- **X-axis:** $p_T \text{ [zd]}$ (GeV/c)
- **Y-axis:** N. of $zd$
- **Legend:**
  - ZD = 20 GeV
  - ZD = 100 GeV
  - ZD = 1000 GeV

**Right Panel:**
- **Title:** N. of $sd$ (scaled to one)
- **X-axis:** $p_T \text{ [sd]}$ (GeV/c)
- **Y-axis:** N. of $sd$
- **Legend:**
  - ZD = 20 GeV
  - ZD = 100 GeV
  - ZD = 1000 GeV
$p_T$ of Muons

![Graph showing $p_T$ of muons](image)

- $ZD = 20$ GeV
- $ZD = 100$ GeV
- $ZD = 1000$ GeV
\( \varphi \) \& \( \eta \) of \( S_D \)
\[ \Delta \varphi \, \Delta \eta \text{ of the } s_D \, \bar{s}_D \]
ZD Mass

- ZD = 20 GeV
- ZD = 100 GeV
- ZD = 1000 GeV

N. of (sd, sd-) pairs (scaled to one)

$\Delta R [ sd, sd~ ]$

M. Hohlmann, M. Rahmani, Dark Photon Models for CMS, LLP Workshop, CERN - May 27, 2019
ZD Mass

- $ZD = 20$ GeV
- $ZD = 100$ GeV
- $ZD = 1000$ GeV

$N_{\text{pairs}} \left( \eta^2 > \eta^2_{\text{cut}} \right)$
ΔR [ mu+ < sd, mu+ < sd~ ]

ZD Mass

- ZD = 20 GeV
- ZD = 100 GeV
- ZD = 1000 GeV
Events (scaled to one) vs $p_T$ [GeV/c] for different $ZD$ masses: $ZD = 20$ GeV (green), $ZD = 100$ GeV (red), and $ZD = 1000$ GeV (black).
Events (scaled to one)

\[ p_T \text{ [ } \mu_4 \text{ ] (GeV/c)} \]

**ZD Mass**

- \( ZD = 20 \text{ GeV} \)
- \( ZD = 100 \text{ GeV} \)
- \( ZD = 1000 \text{ GeV} \)
Lots more kinematics and topology plots

Samples with Dimuon Final States – All plots at generator level

Fermionic
**$P_T$ Plots**

- **Left Diagram:**
  - Title: N. of zd (scaled to one)
  - $p_T$ (GeV/c) on the x-axis.
  - Logarithmic scale from $10^{-16}$ to $10^{-12}$ for $p_T$.
  - Different energies: 40 GeV, 100 GeV, 1000 GeV.

- **Right Diagram:**
  - Title: N. of fd11 (scaled to one)
  - $p_T$ (GeV/c) on the x-axis.
  - Logarithmic scale from $10^{-2}$ to $10^3$ for N. of fd11.
  - Different energies: 40 GeV, 100 GeV, 1000 GeV.
$P_T$ of Leading, Subleading, 3$^{rd}$, and 4$^{th}$ Muon

$Z_D$ masses

Fermionic Model
$\Delta \eta$ and $\Delta \phi$ between Muons from Same Vertex

Fermionic Model
$\Delta \varphi$ & $\Delta \eta$ of $f_{d1S}$
$\Delta R$ of $\mu$s

$Z_D$ masses
$P_T$ of $f_{d2}$
\( \Delta \phi & \Delta \eta \ of \ f_{d2s} \)
$P_T$ of $\mu$s
$P_T$ of $\mu^+$
Missing momentum
ZD Mass

N. of fd11 (scaled to one)

\[ \phi [\text{ fd11 }] \]

- 40 GeV
- 100 GeV
- 1000 GeV
ZD Mass

40 GeV

100 GeV

1000 GeV

N. of fd21 (scaled to one)

$\phi$ [fd21]
ZD Mass

- 40 GeV
- 100 GeV
- 1000 GeV

N. of \((fd21, fd22)\) pairs (scaled to one)

\[ \Delta R [fd21, fd22] \]
ZD Mass

- 40 GeV
- 100 GeV
- 1000 GeV

\[ \Delta \Phi_{0,\pi} \ [ \text{mu}^+ < \text{fd11}, \text{mu}^+ < \text{fd12} ] \]
ZD Mass

- 40 GeV
- 100 GeV
- 1000 GeV

\[
\Delta \eta \left[ (\mu^+ < fd_{11}) (\mu^+ < fd_{12}) \right]
\]
ZD Mass

- 40 GeV
- 100 GeV
- 1000 GeV

Events (scaled to one)

$P_T [\text{m}_4] (\text{GeV/c})$