Searching for massless Dark Photons at the LHC via Higgs production

based on:
S.Biswas, E.Gabrielli, M.Heikinheimo, BM, PRD 93 (2016) 093001
E.Gabrielli, M.Heikinheimo, BM, M.Raidal, PRD 90 (2014) 055032
a few facts

- expected exp hints of fashionable theory solutions to SM puzzles are being late in showing up

- more and more crucial to look at signature-based BSM searches at the LHC → boosts LHC discovery potential in a model-independent way

- Hidden/Dark (SM-uncharged) Sectors can provide new signatures not covered by present searches
Outline (Dark Photon $\rightarrow$ DP)

- Hidden Sectors with unbroken extra U(1)
  possibly solving Yukawa hierarchy + Dark Matter
  $\rightarrow$ predict massless DP's

- Higgs decays into massless DP's

- new Higgs signatures from DP's at colliders

- $gg$ vs VBF at the LHC

- Outlook
Dark Photons (DP) from extra U(1)’s

- Hidden Sectors can contain light or massless gauge bosons mediating long-range forces between Dark particles
- DP’s may have a relevant role in Cosmology and Astrophysics
- previous pheno studies mainly involving “massive” DP
- a massive DP interacts with SM matter via “kinetic mixing” with SM hypercharge U(1)_Y gauge boson:

\[ B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \quad [\text{U(1) gauge invariant}] \]

4D interaction between field-strengths of two different U(1) allowed →

\[ \mathcal{L}_{\text{mix}} = \chi B_{\mu\nu} C^{\mu\nu} \]

→ a massive DP couples to SM particles with strength \(-\chi e Q_{el}\)

→ quite a few exp bounds on that by now!
the massless Dark Photon case

if $U(1)_F$ unbroken no such constraints!
(on-shell DP's can be fully decoupled from SM sector at tree level)

massless DP's then interact with SM sector only through higher-dimensional (→ suppressed by $1/M^{D-4}$) interactions via messenger (if any) exchange!

→ potentially large DP couplings $\tilde{\alpha}$ in the Hidden Sector (HS) allowed!

if produced in collisions:
→ stable + noninteracting
→ neutrino-like signature

(massless-DP Cosmology recently considered in Agrawal, Cyr-Racine, Randall, Scholtz, arXiv:1610.04611)

(Holdom, PLB 166, 1986, 196)
Explaining Yukawa hierarchy via HS and extra $U(1)_F$

- Hidden Sectors (HS) possibly explaining Flavor hierarchy + Dark Matter
- Yukawa's are not fundamental constants but effective low-energy couplings
  -$\rightarrow$ scalar messengers transfer radiatively Flavor and Chiral Symm. Breaking from HS fermions to SM fermions giving Yukawa couplings at one-loop
- predict extra unbroken $U(1)_F \rightarrow$ massless DP's
- for integer-$q_{\text{(dark fermions)}}$ sequence:
  $M_{D_f} \sim \exp(-\frac{\kappa}{q_{D_f}^2 \bar{\alpha}})$
  -$\rightarrow$ exponential hierarchy in $M_{\text{(Dark fermions)}}$
  -$\rightarrow$ exponential hierarchy in radiative $\gamma_{\text{(SM fermions)}}$
- Dark fermions as dark-matter candidates

Gabrielli, Raidal, arXiv:1310.1090
Higgs non-decoupling in SM!

\[ A_{gg \rightarrow H} \sim \frac{Y_{top}}{m_{top}} \rightarrow \frac{1}{\nu} \]

(m_{top} \rightarrow \infty)

non-decoupling can also apply to new heavy chiral states!

finite (potentially large) effects even from heavy BSM states!
Higgs as a “source” of Dark Photons

$H \rightarrow \gamma \bar{\gamma}$

mono-photon resonant signature

massless (invisible) Dark Photon

(mediating long-range $U(1)_F$ force between Dark particles)

heavy scalar messengers (squark/slepton-like) connecting SM to HS

$\Gamma(H \rightarrow \gamma \bar{\gamma}) \sim \frac{1}{M^2_{Heavy}} \rightarrow \frac{1}{v^2}$


Dobrescu, hep-ph/0411004 (PRL)
\[ BR_H(\gamma\gamma) \] prediction in minimal models

![Graph showing BR(\gamma) as a function of \bar{\alpha}]

**similar loop effects contribute to:**

\[ H \rightarrow \gamma\gamma \]

\[ H \rightarrow \gamma\gamma \]

**affects \( BR_{\text{inv}} \):**

(assuming NP does not affect \( H \rightarrow gg, WW \)…)

**solid lines corresponds to:**

\[ \frac{BR_{\gamma\gamma}^{\text{SM}}}{2} \leq BR_{\gamma\gamma} \leq 2 \cdot BR_{\gamma\gamma}^{\text{SM}} \]

\[ BR(H \rightarrow \gamma\gamma) \]

up to 5%!
new Higgs signature at colliders
resonant mono-photon signature at 8 TeV

\[ gg \rightarrow H \rightarrow \bar{\gamma}\gamma \]

\[ E_{\text{miss}} \sim E_\gamma \sim m_H/2 \]

\[ M_T = \sqrt{2p_T^\gamma E_T(1 - \cos \Delta\phi)} \]

<table>
<thead>
<tr>
<th>( \sigma ) (fb)</th>
<th>( \sigma \times A_1 )</th>
<th>( \sigma \times A_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( BR_{H \rightarrow \bar{\gamma}\bar{\gamma}} = 1% )</td>
<td>65</td>
<td>34</td>
</tr>
<tr>
<td>( \gamma j )</td>
<td>715</td>
<td>65</td>
</tr>
<tr>
<td>( \gamma Z \rightarrow \gamma \nu \bar{\nu} )</td>
<td>157</td>
<td>27</td>
</tr>
<tr>
<td>( j Z \rightarrow j \nu \bar{\nu} )</td>
<td>63</td>
<td>11</td>
</tr>
<tr>
<td>( W \rightarrow e\nu )</td>
<td>22</td>
<td>0</td>
</tr>
<tr>
<td>Total background</td>
<td>957</td>
<td>103</td>
</tr>
</tbody>
</table>

\[ S/\sqrt{S + B} \ (BR_{H \rightarrow \bar{\gamma}\bar{\gamma}} = 1\%) \]

\[ S/\sqrt{S + B} \ (BR_{H \rightarrow \bar{\gamma}\bar{\gamma}} = 0.5\%) \]

\[ (8\text{TeV}/20\text{fb}^{-1}) \]

model-independent measurement of \( BR_{DP} \)!

Barbara Mele
EPS-HEP, Venice, 6 July 2017
resonant mono-photon signature at 14TeV

\[ gg \rightarrow H \rightarrow \gamma\gamma \]

- **\( p_T^\gamma \)**  
  
- **\( M_T^{\gamma\gamma} \)**

### TABLE I: Cross section times acceptance \( A \) (in fb) for the gluon-fusion signal and backgrounds at 8 and 14 TeV, assuming \( \text{BR}_{\gamma\gamma} = 1\% \), with the selection \( p_T^\gamma > 50 \text{ GeV}, |\eta^\gamma| < 1.44, \not{E}_T > 50 \text{ GeV}, \) and 100 GeV < \( M_T^{\gamma\gamma} < 130 \text{ GeV} \).

<table>
<thead>
<tr>
<th>Process</th>
<th>( \sigma \times A ) [8 TeV]</th>
<th>( \sigma \times A ) [14 TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow \gamma\gamma ) (BR(\gamma\gamma = 1% ))</td>
<td>44</td>
<td>101</td>
</tr>
<tr>
<td>( \gamma j )</td>
<td>63</td>
<td>202</td>
</tr>
<tr>
<td>( jj \rightarrow \gamma j )</td>
<td>59</td>
<td>432</td>
</tr>
<tr>
<td>( e \rightarrow \gamma )</td>
<td>55</td>
<td>93</td>
</tr>
<tr>
<td>( W(\rightarrow \ell\nu)\gamma )</td>
<td>58</td>
<td>123</td>
</tr>
<tr>
<td>( Z(\rightarrow \nu\nu)\gamma )</td>
<td>102</td>
<td>174</td>
</tr>
<tr>
<td>total background</td>
<td>337</td>
<td>1024</td>
</tr>
</tbody>
</table>

**MadGraph5_aMC@NLO + PYTHIA (bckgr)**  
**ALPGEN + PYTHIA (H signal)**

\( \gamma j \) bckgr modeled on data at 8 TeV  

Biswa, Gabrielli, Heikinheiro, BM,  
arXiv:1603.01377 (PRD)
\( gg \) fusion vs VBF

- \( p\gamma T > 30 \text{ GeV} \)
- \( |\eta\gamma| < 2.5 \)
- \( \text{EMiss,T} > 30\text{GeV} \)
- \( p\bar{\jmath} > 20 \text{ GeV and } |\eta\jmath| < 5.0 \)
- \( \eta\jmath_1 \times \eta\jmath_2 < 0 \text{ and } |\eta\jmath_1 - \eta\jmath_2| > 4.0 \)
- \( 100 \text{ GeV} < M_T < 130 \text{ GeV} \)
- \( \Delta\phi(\jmath_i, \text{EMiss,T}) > 1.5 \)
**mono-photon signature in VBF at 14TeV**

\[ VV \rightarrow H \rightarrow \gamma\gamma + \text{two extra forward jets}! \]

**reference BR\(_{\text{DP}}\)**

\[ \text{BR}_\gamma\gamma = 1\%. \]

### \( \sigma \) (fb)

<table>
<thead>
<tr>
<th>Cuts (sequential)</th>
<th>Signal</th>
<th>( \gamma + \text{jets} )</th>
<th>( \gamma + Z + \text{jets} )</th>
<th>QCD multijet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic cuts</td>
<td>17.7</td>
<td>266636</td>
<td>1211</td>
<td>72219</td>
</tr>
<tr>
<td>Rapidity cuts</td>
<td>8.8</td>
<td>8130</td>
<td>38.1</td>
<td>33022</td>
</tr>
<tr>
<td>( M^T_\gamma\gamma ) cuts</td>
<td>5.0</td>
<td>574</td>
<td>6.5</td>
<td>3236</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cuts (individual)</th>
<th>Signal</th>
<th>( \gamma + \text{jets} )</th>
<th>( \gamma + Z + \text{jets} )</th>
<th>multijet</th>
<th>L=300 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y^* &lt; 1.0 )</td>
<td>2.67</td>
<td>84.2</td>
<td>1.84</td>
<td>758</td>
<td>1.6 ( \sigma )</td>
</tr>
<tr>
<td>( \Delta \phi(j_i, E_T) ) &gt;1.5</td>
<td>1.82</td>
<td>6.9</td>
<td>2.16</td>
<td>37</td>
<td>4.6 ( \sigma )</td>
</tr>
<tr>
<td>both cuts</td>
<td>1.21</td>
<td>1.2</td>
<td>0.67</td>
<td>19</td>
<td>4.5 ( \sigma )</td>
</tr>
</tbody>
</table>

**MadGraph5_aMC@NLO + PYTHIA**

**ALPGEN + PYTHIA**

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Biswa, Gabrielli, Heikinheimo, BM, arXiv:1603.01377 (PRD)
model-independent bounds @ LHC 14 TeV

\[ gg \rightarrow H \rightarrow \gamma\gamma \quad \text{vs} \quad VV \rightarrow H \rightarrow \gamma\gamma \]

<table>
<thead>
<tr>
<th>( \text{BR}_{\gamma\gamma} ) (%)</th>
<th>L= 100 fb(^{-1})</th>
<th>L=300 fb(^{-1})</th>
<th>L=3 ab(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance</td>
<td>2(\sigma) 5(\sigma)</td>
<td>2(\sigma) 5(\sigma)</td>
<td>2(\sigma) 5(\sigma)</td>
</tr>
<tr>
<td>( \text{BR}_{\gamma\gamma} (\text{VBF}) )</td>
<td>0.76 1.9</td>
<td>0.43 1.1</td>
<td>0.14 0.34</td>
</tr>
<tr>
<td>( \text{BR}_{\gamma\gamma} (ggF) )</td>
<td>0.064 0.16</td>
<td>0.037 0.092</td>
<td>0.012 0.029</td>
</tr>
</tbody>
</table>

gg fusion sensitive down to \( \text{BR}_{\text{DP}} \sim 10^{-4}-10^{-3} \)

(VBF \sim 10 \text{ times worse ...})
Outlook

* massless DP’s theoretically appealing
  (evading most of present exp bounds on massive DP’s !)

* Higgs boson as the SM portal to DP’s
  * new effective vertices for DP’s from Hidden Sectors explaining
    Flavor Hierarchy + Dark Matter

* rich phenomenological implications @ LHC (and ee colliders)

* new class of FCNC signatures from top, b, c, s, tau, mu
  decays into a massless DP
  * very distinctive → bounds expected to be limited just by statistics !

* implications for astro-part/cosmology (mostly yet to work out !)


Gabrielli, BM, Raidal, Venturini, arXiv:1607.05928 (PRD)
Fabbrichesi, Gabrielli, BM, arXiv:1705.03470 (PRL)
Dobrescu, hep-ph/0411004 (PRL)