Massless Dark-Photon Phenomenology at Colliders

based on:

S.Biswas, E.Gabrielli, M.Heikinheimo, BM, PRD 93 (2016) 093001
E.Gabrielli, M.Heikinheimo, BM, M.Raidal, PRD 90 (2014) 055032
E.Gabrielli, M.Raidal, PRD 89 (2014) 015008

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Autumn Institute - Challenges in collider physics
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Outline

- SM successful but not enough!
  importance of BSM signature-based searches at LHC
- massive and massless Dark Photons
- Hidden Sectors explaining Flavor hierarchy
  \((Y_f's\ not\ fundamental\ constants\ but\ effective\ low-energy\ couplings)\)
  and predicting massless Dark Photons
- new Higgs signatures from Dark Photons at colliders
- FCNC's mediated by Dark Photons in heavy-flavour decays

Outlook

everywhere in my slides:

Dark \leftrightarrow \text{uncharged under SM} \quad \text{Hidden} \leftrightarrow \text{“not observed”}

\begin{align*}
\text{DP} &= \text{Dark Photon} \\
\text{Df} &= \text{Dark fermion}
\end{align*}

\begin{align*}
\text{HS} &= \text{Hidden Sector}
\end{align*}
SM-Lagrangian criticalities

**SM gauge group:**
\[ \text{SU}(3)_\text{QCD} \times \text{SU}(2)_L \times \text{U}(1)_B \]

\[ \rightarrow \text{SU}(3)_\text{QCD} \times \text{U}(1)_{\text{em}} \]

**Higgs Lagrangian:**
\[
\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi^\dagger \phi) - \bar{\psi}_L \Gamma \psi_R \phi - \bar{\psi}_R \Gamma^\dagger \psi_L \phi^\dagger
\]

**masses fix all Higgs interactions**

\[
V(\phi^\dagger \phi) = -\mu^2 \phi^\dagger \phi + \frac{1}{2} \lambda (\phi^\dagger \phi)^2
\]

\[
m_H^2 = 2\mu^2 = 2\lambda v^2
\]

**Higgs sector**

\[ \rightarrow \text{Criticalities} \]

\[ \rightarrow \text{Opportunities} \]

- Naturalness
- Flavor
- Nature of EWPT
- Higgs portal
- Non-decoupling
- Extra scalars
**Higgs non-decoupling!**

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

\((m_{top} \rightarrow \infty)\)

- Non-decoupling can also apply to new heavy chiral states!
- Finite (potentially large) effects from heavy BSM states!
Mystery in Hierarchy of SM Yukawa’s

\[ \mathcal{L}_{Y_f} \sim \frac{m_f}{v} \bar{f} f H \]

$m_f$'s span many orders of magnitudes...

origin of Flavor Symmetry Breaking?
in general:

many proposed TH solutions to SM puzzles around, but ...

presently no real EXP hint on how to enlarge SM to solve its issues

make BSM searches at colliders as inclusive as possible!
Ingredients to optimize BSM searches at colliders

- highest collision cm energy and luminosity to produce heavy states with moderate production coupling

- highest ability to separate S from B, in particular in high-pT tails and m(i,j) distributions (revealing scattering exchange of new states)

- highest ability to cover stealthy kinematical configurations (mass degeneracies, soft final objects ...)

- exploiting as much as possible signature-based searches!

A most valuable activity in BSM model building is suggesting new kinds of signatures! Help pushing LHC discovery potential in a model-independent way ...
Hidden Sector models can chart the way in devising new kinds of signatures to look for!
FOCUS on Dark Photon (DP) from extra U(1)

- HS can contain light or massless gauge bosons (Dark Photons, DP) mediating long-range forces between Dark particles
- previous studies mainly involving “massive” DP
- a massive DP interacts with SM matter via “kinetic mixing” with SM hypercharge U(1)$_Y$ gauge boson:
  \[ B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \quad [U(1) \text{ gauge invariant}] \]

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 \(-\chi e Q_{el}\)
Dark Photons

in Cosmology:
- may solve the small-scale structure formation problems
- can explain the dark discs of galaxies

in Astroparticle Physics:
- may induce Sommerfeld enhancement of DM annihilation cross section
  (from PAMELA-Fermi-AMS2 positron anomaly)
- may assist DM annihilations for the required magnitude
  making asymmetric DM scenarios viable

K.M. Zurek, Phys Rept. 537 (2014)


D.N. Spergel, P.J. Steinhardt, PRL 84 (2000)

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strong astrophysical and collider bounds on massive DP (Z')
let’s turn to the massless-DP case …

if $U(1)_F$ unbroken no such constraints!

(on-shell DP can be fully decoupled from SM sector at tree level)

(Holdom, PLB 166, 1986, 196)

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

$\rightarrow$ potentially large DP couplings in the
Hidden Sector (HS) allowed!

(massless-DP Cosmology recently considered in Agrawal, Cyr-Racine, Randall, Scholtz)
arXiv:1610.04611
Explaining Yukawa hierarchy via HS and extra $U(1)_F$

- HS containing $N_f$ heavy fermions (Dark Matter ?) charged under Dark unbroken $U(1)_F$ (massless DP $\tilde{\gamma}$)
- Chiral Symmetry spontaneously broken in HS via non-perturbative effects (higher-derivative in DP field $\sim 1/\Lambda$ $\rightarrow$ Lee-Wick ghosts)

$\rightarrow$ Dark fermions ($D_f$) get $M_{D_f}$ mass depending on their $U(1)_F$ charge $q_{D_f}$:

$$M_{D_f} \sim \exp\left(-\frac{\kappa}{q_{D_f}^2 \bar{\alpha}}\right)$$

for integer-$q_{D_f}$ sequence ($q_{D_f}=1, 2, 3, 4...$) $\rightarrow$ exponential hierarchy in $M_{D_f}$

Gabrielli, Raidal, arXiv:1310.1090

Gabrielli arXiv:0712.2208
further ingredient: heavy scalar messengers $S_{L,R}$

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

Messengers
(Scalars)

Dark Sector
(Fermions+ singlet Scalar)
the scalar messengers transfer radiatively Flavor and Chiral Symm. Breaking from HS fermions to SM fermions generating Yukawa couplings at one-loop!
radiative Yukawa's follow $M_{\text{Df}}$ hierarchy !!!

- $Y_f = 0$ at tree level [due to $(H \leftrightarrow -H)$ Symmetry]
- $Y_f$'s arise radiatively
  (via loop-messenger exchange)
  with same pattern
  of exponential hierarchy of
  Dark fermion ($D_f$) masses:

$$Y_f \sim M_{D_f} \sim \exp\left(-\frac{\kappa}{q_{D_f}^2 \alpha}\right)$$

Flavor $\iff$ Non-Universal $q_{\text{Df}}$

example:
for $q_{D_e} = 4$, $q_{D_\mu} = 5$, $q_{D_\tau} = 6$

→ given $m_e$, $m_\mu$ as input \(\Rightarrow m_\tau \simeq 1.9 \, \text{GeV}\)

(and, for Dirac V's, $q_{D_{\nu_\tau}} = 3 \Rightarrow m_{\nu_\tau} \sim 5 \, \text{eV}$)
Df are lightest Dark particles, potentially contributing to Dark Matter

rich phenomenology at colliders if Df-mass scale accessible (yet to be explored…)

FOCUS ON MASSLESS-DP PHENO

shows up by a neutrino-like signature

one straightforward (nontrivial) new signature in Higgs decays…

[colored-\text{SL,R mass scale > 50 TeV}]

(vacuum stability)
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

\[ \Gamma(H \rightarrow \gamma \bar{\gamma}) \sim \frac{1}{M_{Heavy}^2} \rightarrow \frac{1}{v^2} \]

\[ BR_H(\gamma\gamma) \text{ prediction in minimal models} \]

Similar loop effects contribute to:

\[ H \rightarrow \gamma\gamma \]

\[ H \rightarrow \gamma\gamma \]

Affects \( BR_{\text{inv}} \): \( BR(H \rightarrow \gamma\gamma) \)

Solid lines correspond to:

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

\[ BR(H \rightarrow \gamma\gamma) \text{ up to 5\%} \]
resonant mono-photon signature at 8 TeV

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

\( E_{\text{miss}} \sim E_{\gamma} \sim m_{H}/2 \)

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

\( (A_1) \ 50 \text{ GeV} < p_T^\gamma < 63 \text{ GeV} \)

\( (A_2) \ 60 \text{ GeV} < p_T^\gamma < 63 \text{ GeV} \)

\[ \begin{array}{|c|c|c|}
\hline
\text{Signal} & \text{BR}_{H\rightarrow\gamma\gamma} = 1\% & \sigma (\text{fb}) \\
\hline
\gamma j & 715 & 65 \\
\gamma Z \rightarrow \gamma \nu\bar{\nu} & 157 & 27 \\
j Z \rightarrow j \nu\bar{\nu} & 63 & 11 \\
W \rightarrow e\nu & 22 & 0 \\
\hline
\text{Total background} & & 957 \\
\hline
\end{array} \]

\[ S/\sqrt{S + B} \ (\text{BR}_{H\rightarrow\gamma\gamma} = 1\%) \]

\[ S/\sqrt{S + B} \ (\text{BR}_{H\rightarrow\gamma\gamma} = 0.5\%) \]

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

model-independent measurement of \( \text{BR}_{\text{DP}} \)!
resonant mono-photon signature at 14TeV

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

\[ p_T^\gamma \]

\[ M_{T\gamma\gamma} \]

\[ \sigma \] (fb)

\[
\begin{array}{|c|c|c|}
\hline
\text{process} & \sigma \times A \ [8\text{ TeV}] & \sigma \times A \ [14\text{ TeV}] \\
\hline
H \rightarrow \gamma\gamma & 44 & 101 \\
\gamma j & 63 & 202 \\
jj \rightarrow \gamma j & 59 & 432 \\
e \rightarrow \gamma & 55 & 93 \\
W(\rightarrow \ell\nu)\gamma & 58 & 123 \\
Z(\rightarrow \nu\nu)\gamma & 102 & 174 \\
\text{total background} & 337 & 1024 \\
\hline
\end{array}
\]

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

MadGraph5_aMC@NLO + PHYTIA (bckgr)
ALPGEN + PHYTIA (H signal)

Biswa, Gabrielli, Heikinheimo, BM, arXiv:1603.01377 (PRD)
mono-photon signature in VBF at 14TeV

two extra forward jets!

reference BR$_{DP}$

\[
\sigma \text{ (fb)}
\]

<table>
<thead>
<tr>
<th>Cuts (sequential)</th>
<th>Signal</th>
<th>$\gamma + \text{jets}$</th>
<th>$\gamma + Z + \text{jets}$</th>
<th>QCD multiijet</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 + PHOTIA
ALPGEN + PHOTIA
**Discovery potential @ LHC 14 TeV**

$gg \rightarrow H \rightarrow \gamma\gamma$ vs $VV \rightarrow H \rightarrow \gamma\gamma$

<table>
<thead>
<tr>
<th>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>3σ 5σ</td>
<td>3σ 5σ</td>
<td>3σ 5σ</td>
</tr>
<tr>
<td>BR$_{\gamma\gamma}$ (VBF)</td>
<td>1.1 1.9</td>
<td>0.65 1.1</td>
<td>0.21 0.34</td>
</tr>
<tr>
<td>BR$_{\gamma\gamma}$ (ggF)</td>
<td>0.096 0.16</td>
<td>0.055 0.092</td>
<td>0.017 0.029</td>
</tr>
</tbody>
</table>

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

$(\text{VBF} \sim 10 \text{ times worse ...})$
new Higgs signatures at $e^+e^-$ colliders from stable dark photons

**in H production:**

$$e^+e^- \rightarrow H \tilde{\gamma} \rightarrow b\bar{b} \tilde{\gamma}$$

$p_{\text{Higgs}}$ balanced by a massless invisible system

Biswa, Gabrielli, Heikinheimo, BM, arXiv:1503.05836 (JHEP)

**in H decays:**

$$H \rightarrow \gamma\tilde{\gamma}$$

$$e^+e^- \rightarrow ZH \rightarrow Z \gamma\tilde{\gamma}$$ (photon + $E_{\text{miss}}$) resonant signature

Biswa, Gabrielli, Heikinheimo, BM, in progress
$e^+ e^- \rightarrow H \bar{\gamma} \rightarrow b\bar{b} \bar{\gamma}$

**Model independent analysis:**

**Effective Lagrangian parametrization**

$$\mathcal{L}_{D\Phi H} = \frac{\alpha}{\pi} \left( \frac{C_{\gamma\bar{\gamma}}}{v} \gamma^{\mu\nu} \bar{\gamma}_{\mu\nu} H + \frac{C_{Z\gamma}}{v} Z^{\mu\nu} \bar{\gamma}_{\mu\nu} H + \frac{C_{\gamma\gamma}}{v} \bar{\gamma}^{\mu\nu} \bar{\gamma}_{\mu\nu} H \right)$$

**Total $x$-section**

$$R = C_{Z\gamma}/C_{\gamma\gamma}$$

$$R_{Z\gamma}^q = \frac{R_{\tilde{u}} + R_{\tilde{d}}}{2} \approx 0.79 \quad \text{→ from a squark doublet}$$
FCC-ee (~ ILC) : \( \sqrt{S} = 240 \text{ GeV} \) with \( \int L \sim 10 \text{ ab}^{-1} \)

Basic cuts
\[
\begin{align*}
\mathbf{p}_T^b &> 20 \text{ GeV} , \quad |\eta_b| < 2.5 \\
\Delta R(bb) &> 0.4 , \quad \not{E}_T > 40 \text{ GeV} \\
\end{align*}
\]

\[
\Delta R(bb) = \sqrt{\Delta \eta^2 + \Delta \phi^2}
\]

Main backgrounds for \( b \bar{b} + \not{E}_T \)

Irreducible

\[
\begin{align*}
\nu \bar{\nu} b \bar{b} &\\
Z Z &\rightarrow \nu \bar{\nu} b \bar{b} \\
Z H &\rightarrow \nu \bar{\nu} b \bar{b} \\
WW \text{ fusion} &\rightarrow H \nu \bar{\nu}. \\
\end{align*}
\]

Reducible

\[
\nu \bar{\nu} q \bar{q} : \begin{cases}
\text{Mostly from on-shell Z pairs} \\
\text{where two light jets are misidentified with two b-jets}
\end{cases}
\]

we assume: b-tagging efficiency of 80%
fake b-jet rejection factor 1/100
$e^+ e^- \rightarrow H \gamma \rightarrow b\bar{b} \gamma$

Significance for $L=10^{ab-1}$

$5\sigma$

$2\sigma$

Normalized BRs vs $C_{\gamma\gamma}/C_{Z\gamma}$

$5\sigma$ values of $C_{\gamma\gamma}$ and $C_{Z\gamma}$ in the natural range of predictions for the $U(1)_F$ Flavor model

$$\text{signif.} = \frac{S}{\sqrt{S + B}}$$
\[ e^+ e^- \rightarrow ZH \rightarrow \mu^+ \mu^- \gamma\bar{\gamma} \]

\[ m_{\gamma} = 0 \]

\[ M_{\text{miss}} \]

**simulation:**

PYTHIA for signal and MadGraph+PYTHIA for backgrounds

ISR/FSR effects described by PYTHIA

Finite detector resolutions for photon and muons according to ILD detector specifications in [arXiv:1605.00100]
\[ \sqrt{S} = 240 \text{ GeV} \quad \int L \sim 10 \text{ ab}^{-1} \]

leptonic and hadronic Z show comparable potential:

5\sigma sensitivity for \( \text{BR}_{\text{DP}} \sim \text{a few } 10^{-4} \) !!!

\[ e^+ e^- \rightarrow ZH \rightarrow qq \gamma \bar{\gamma} \]
FCNC’s mediated by Dark Photons

\[ t \rightarrow q \bar{\gamma} \]

\[ b \rightarrow s \bar{\gamma} \]

\[ \ell \rightarrow \ell' \bar{\gamma} \]

Gabrielli, BM, Raidal, Venturini
arXiv:1607.05928 (PRD)

\[ \mathcal{L}_{\text{eff}} = \sum_{q=U,D} \sum_{i,j=1}^{3} \left( \frac{1}{2(\Lambda_{q}^{L})_{i,j}} \left[ \bar{q}_{R}^{j}(x)\sigma_{\mu\nu}F_{\mu\nu}(x)q_{L}^{i}(x) \right] + \frac{1}{2(\Lambda_{q}^{R})_{i,j}} \left[ \bar{q}_{L}^{j}(x)\sigma_{\mu\nu}\bar{F}_{\mu\nu}(x)q_{R}^{i}(x) \right] \right) \]

\[ \bar{F}_{\mu\nu} = \text{dark photon field strength} \]

- **DP coupled to SM fermions by FC magnetic-dipole operators**

- **suppressed by scales \( \Lambda_{L,R} \) proportional to typical messenger mass scale**

- **Decay width**

\[ \Gamma(q^{i} \rightarrow q^{j}\bar{\gamma}) = \frac{m_{q_{i}}^{3}}{16\pi^{3}} \left( \frac{1}{(\Lambda_{q}^{L})_{i,j}^{2}} + \frac{1}{(\Lambda_{q}^{R})_{i,j}^{2}} \right) \]
connection with FCNC's mediated by photons

\[ t \rightarrow (c, u) \overline{\gamma} \]

\[ t \rightarrow q \overline{\gamma} \text{ versus } t \rightarrow q \gamma \]

new heavy states in loops contribute with same flavor matrix (but different U(1) charges) to FCNC decays into photon and dark photon

\[ \overline{\gamma}, \gamma \]

same for \[ b \rightarrow s \overline{\gamma} \]

versus \[ b \rightarrow s \gamma \]

LHC (present bounds):

\[
\begin{align*}
\text{BR}^{\text{exp}}(t \rightarrow u \gamma) &< 1.3 \times 10^{-4} \\
\text{BR}^{\text{exp}}(t \rightarrow c \gamma) &< 1.7 \times 10^{-3}
\end{align*}
\]

but ... imposing vacuum-stability and dark-matter bounds gives \[ \text{BR}(t \rightarrow q \overline{\gamma}) < 10^{-4} \]
further upper bounds from $f \to f' \gamma$ constraints

$$\text{BR}^{\exp}(\bar{B} \to X_S \gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$$

$$\text{BR}^{(b \to s \gamma)}(b \to s \gamma) < 8.5 \times 10^{-3} \left( \frac{\bar{\alpha}}{0.1} \right)$$

$$\text{BR}(\tau^- \to e^- \gamma) < 3.3 \times 10^{-8}$$

$$\text{BR}(\tau^- \to \mu^- \gamma) < 4.4 \times 10^{-8}$$

$$\text{BR}^{(\tau \to \mu \gamma)}(\tau \to \mu \gamma) < 5.9 \times 10^{-6} \left( \frac{\bar{\alpha}}{0.1} \right)$$

$$\text{BR}^{(\tau \to e \gamma)}(\tau \to e \gamma) < 1.1 \times 10^{-5} \left( \frac{\bar{\alpha}}{0.1} \right)$$
Large and possibly measurable BR's are allowed in most cases

- \( \text{BR}(\bar{t} \to q \bar{\gamma}) \sim 10^{-10} - 10^{-7} \)
- \( \text{BR}(c \to u \bar{\gamma}) \sim 10^{-8} - 10^{-4} \)
- \( \text{BR}(\tau \to l \bar{\gamma}) \sim 10^{-10} - 10^{-6} \)
- \( \text{BR}(\mu \to e \bar{\gamma}) \sim 10^{-10} - 10^{-6} \)

depending on various parameters and on flavor universality structure of messenger sector
new class of (very distinctive) FCNC signatures at ee colliders

\[ f \rightarrow f' \bar{\gamma} \]

for light fermions: \[ E_{\text{miss}} \sim E_{f'} \sim E_f/2 \]

Sensitivity is likely just limited by statistics!

at FCC-ee

10^6 top pairs \( \rightarrow \) \( \text{BR}_{\text{top}} \sim 10^{-5} \)
10^{11} b pairs \( \rightarrow \) \( \text{BR}_{b} \sim 10^{-10} \)
10^{10} tau pairs \( \rightarrow \) \( \text{BR}_{\tau} \sim 10^{-9} \)

in top decays:

"top" + (mono-j + \( E_{\text{miss}} \)) resonant at \( m_{\text{top}} \)

At \( tt \) threshold: \( \sim \) large monochr. \( E_{\text{miss}} \)

\[ E_{\text{miss}} \sim E_q \sim m_{\text{top}}/2 \]

Biswa, Gabrielli, BM, in progress
at LHC new FCNC signatures in BOTH top decay AND top production

in top decay:

```
\begin{align*}
g \rightarrow t \bar{t} \rightarrow \text{stop-like, for massless } x^0
\end{align*}
```

“top” + (mono-j + $E_T^{\text{miss}}$) resonant at $m_{\text{top}}$

in top production:

```
\begin{align*}
\text{cg} \rightarrow t \bar{\gamma}
\end{align*}
```

“top” plus massless invisible system


no constraint on $M_{\text{inv}}$
Hidden Sectors fruitful (and theoretically-consistent) way to parametrise our ignorance about what is missing in SM

useful also for devising new kinds of exp. signatures to boost LHC potential for BSM discovery

massless Dark Photon theoretically appealing (evading most of present experimental bounds on massive DP !)

Higgs boson can be the SM portal to DP's : new effective vertices involving DP can appear from HS explaining Flavor Hierarchy (or possibly other BSM ...)

new class of FCNC signatures from top, b, c, tau, mu decays into a massless dark photon

very distinctive \( \rightarrow \) bounds expected to be mostly limited by statistics !

rich phenomenological implications @ LHC and ee colliders

potential implications for astroparticle/cosmology yet to work out !