

Search for Dark Photons @ colliders

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based on:

arXiv:1607.05928	EG, B.Mele, M. Raidal, E. Venturini
PRD 93 (2016) 093001	S.Biswas, EG, M.Heikinheimo, B.Mele
JHEP 1506 (2015) 102	S.Biswas, EG, M.Heikinheimo, B.Mele
PRD 90 (2014) 055032	EG, M.Heikinheimo, B.Mele, M.Raidal
PRD 89 (2014) 015008	EG, M.Raidal

Dark Photons

- Dark Sector, responsible of Dark Matter, might possess rich internal structure and its own interactions
- could also contain light or massless gauge bosons (Dark Photons) mediating long distance interactions among dark particles.
- Dark photons so far introduced ad hoc to improve astrophysical and cosmological models (solving the small scale formation problems, explaining the dark disc of galaxies J.Fan, A.Katz, L.Randall, M.Reece, PRL 110 (2013))
- Recently, a massless Dark photon has been predicted by a new Flavor model aiming to provide a natural solution to the Flavor Hierarchy problem EG, M. Raidal, PRD 89 (2014)

Mystery in Hierarchy of SM Yukawa's

$$\mathcal{L}_{Y_f} \sim \frac{m_f}{v} \bar{f} f H \quad \mathbf{m_f's} \text{ span many orders of magnitudes...}$$

- maybe Y_f are not fundamental couplings (like gauge couplings)
→ allowed by present exp. sensitivity on Higgs measurements
- recent proposal: Y_f are low energy effective couplings
- providing a *natural* solution to the Flavor hierarchy problem

$m_f = \Lambda_{\text{eff}} \exp \left[-\frac{\gamma}{Q_f^2} \right],$ U(1) charges $Q_f = 1, 2, \dots$
- predicting stable massive Dark Fermions with unbroken $U(1)_F$ interactions → massless Dark Photon
- an intriguing dark matter scenario not yet analyzed

The Dark Sector (DS) origin of Flavor

Main paradigm: Y_f effective couplings radiatively generated **requires:**

EG, M. Raidal, PRD 89 (2014)

■ Y_f are vanishing at the tree-level → enforced by some symmetry S

■ **Dark Sector**
containing all source of
Chiral & Flavor
symmetry breaking

Dark-Fermions +
 $U(1)_F$ Dark-Photon

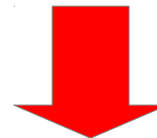
→ No tree-level
couplings
with SM fields
unbroken $U(1)_F$

■ **Messenger Sector**
universal mass sector

+

scalar fields

→ coupled to both
SM and DS fields



→ After SSB of S symmetry

SM → Higgs Yukawa's radiatively generated at 1-loop

$$Y_f \sim \frac{M_{Ff}}{\Lambda_{\text{eff}}}$$

→ Dark Fermions (DF) masses

→ 1-loop effective scale

Radiative Yukawa couplings follow M_{Df} hierarchy

EG, M. Raidal, PRD 89 (2014)

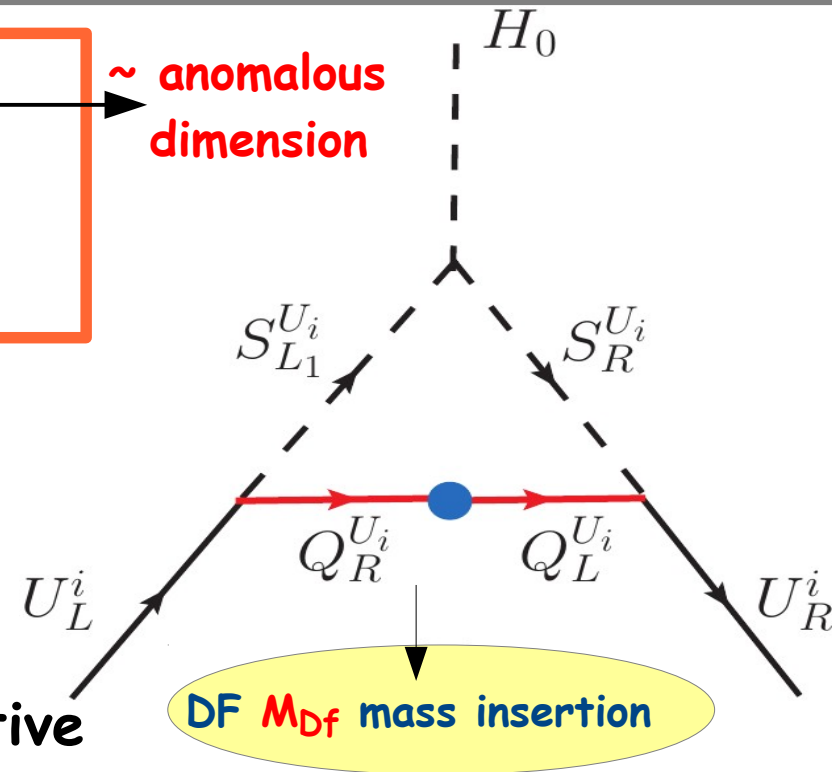
$$Y_f \sim M_{Df} \sim \exp\left(-\frac{\kappa}{q_{Df}^2 \bar{\alpha}}\right)$$

$U(1)_F$ DF charges $\rightarrow q_{Df}^2 \bar{\alpha}$

$\sim$ anomalous dimension

Flavor $\leftrightarrow$ Non-Universal q_{Df}

- ◆ Exponential spread requires a new $U(1)_F$
- ◆ DFs get Dirac masses by a non-perturbative mechanism (NJL) requiring a Lee-Wick term in $U(1)_F$ sector.



(EG, PRD 87 (2008))

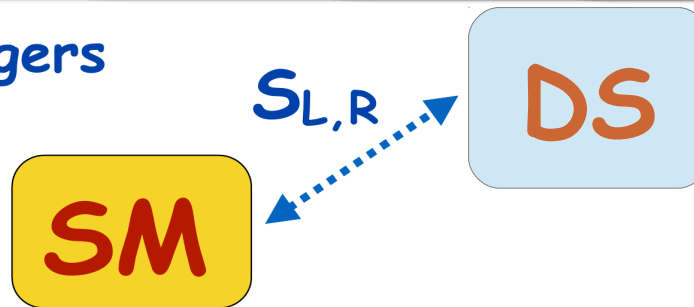
- ◆ Massless Dark Photon in the spectrum !
- ◆ Global $SU(N_F)$ Flavor symmetry broken by non-universality of DF charges

excellent matching with observed SM spectrum for q_{Df} integers...tau mass predicted within a few %

- **Dark Fermions** all stable [due to conservation of $U(1)_F$ charges]
- **DM candidates having long-range interactions** → dark photon
- **Good matching of SM spectrum** → universal messenger masses
- **DF mass spectrum is an almost rescaled SM-fermion spectrum**

■ heavy scalar messengers $S_{L,R}$

► heavy scalar messengers
(squark/slepton-like)
connecting **SM** states
with **DS** states



- **DM stability requires colored messengers to be heavy**
messenger mass in the quark sector > 50 TeV

- **EW messengers could be lighter < 1 TeV**

**Messengers
(Scalars)**

**Dark Sector
(Fermions+Scalar)**

Fields	Spin	$SU(2)_L$	$U(1)_Y$	$SU(3)_c$	$U(1)_F$
$\hat{S}_L^{D_i}$	0	1/2	1/3	3	$-q_{D_i}$
$\hat{S}_L^{U_i}$	0	1/2	1/3	3	$-q_{U_i}$
$S_R^{D_i}$	0	0	-2/3	3	$-q_{D_i}$
$S_R^{U_i}$	0	0	4/3	3	$-q_{U_i}$
Q^{D_i}	1/2	0	0	0	q_{D_i}
Q^{U_i}	1/2	0	0	0	q_{U_i}
S_0	0	0	0	0	0

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■ rich phenomenology at colliders [exploration just started]

■ in the meantime:

one straightforward new signature in Higgs decays
involving Dark Photon couplings to Higgs boson:

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

■ not yet analyzed by CMS and ATLAS collaborations (only
exp. analyses with a continuous massive system for the missing energy performed)

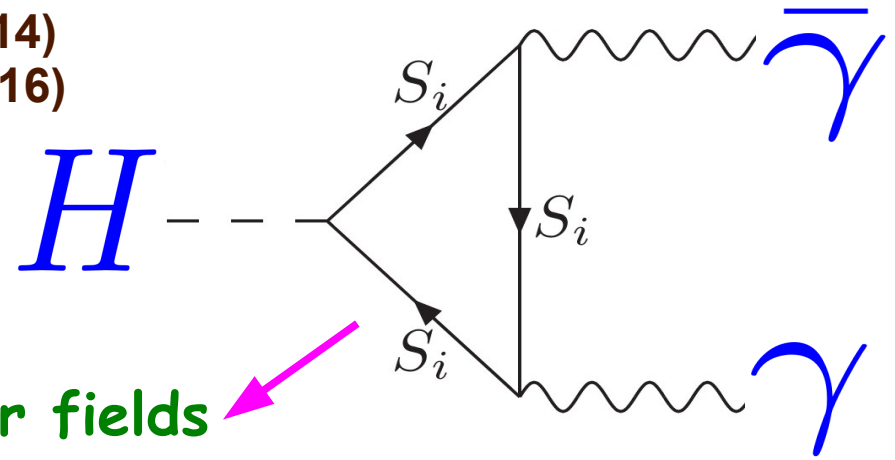
■ although inspired by this scenario, the following
analysis and results are fully model independent

Monophoton Exotic Higgs Signature @ LHC

EG, Heikinheimo, Mele, Raidal, PRD 90 (2014)

Biswas, EG, Heikinheimo, Mele PRD 93 (2016)

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



Messenger fields

- Effective coupling has same structure as $H \rightarrow \gamma \gamma$

$$\mathcal{L}_{\text{eff}}^H = \frac{\sqrt{\alpha \bar{\alpha}}}{\Lambda_{\gamma \bar{\gamma}}} \left[H \bar{F}_{\mu\nu} F_{\mu\nu} \right] \longrightarrow \text{model independent parametrization}$$

- Non-decoupling effect $\rightarrow \Lambda_{\gamma \bar{\gamma}}$ proportional to the Higgs VEV !!!

- DP coupling $\bar{\alpha}$ could be large (allowed if DP is massless)
astrophysical/cosmological constraints of massive DP do not hold

- potentially large rates expected in this scenario !

- $\text{BR}(H \rightarrow \gamma \bar{\gamma}) \sim 5\%$ consistently with all LHC constraints

Model independent analysis of $H \rightarrow \gamma\bar{\gamma}$ at LHC

■ We consider both **gluon-gluon** and **VBF** Higgs productions

gg production $pp \rightarrow H \rightarrow \gamma\bar{\gamma}$ gives rise to the signal

$$pp \rightarrow \gamma + \cancel{E}_T$$

VBF production $pp \rightarrow H jj \rightarrow jj \gamma\bar{\gamma}$ gives rise to the signal

$$pp \rightarrow \gamma + \cancel{E}_T + jj$$

with 2 jets mainly
forward/backward

● In the Lab frame useful to define M_T as the transverse invariant mass of the $\gamma + \cancel{E}_T$ system

$$M_T = \sqrt{2p_T^\gamma \cancel{E}_T (1 - \cos \Delta\phi)}$$

$\Delta\phi$ is the azimuthal distance between the **transverse** photon momentum and the **missing transverse momentum** $\cancel{E}_T$

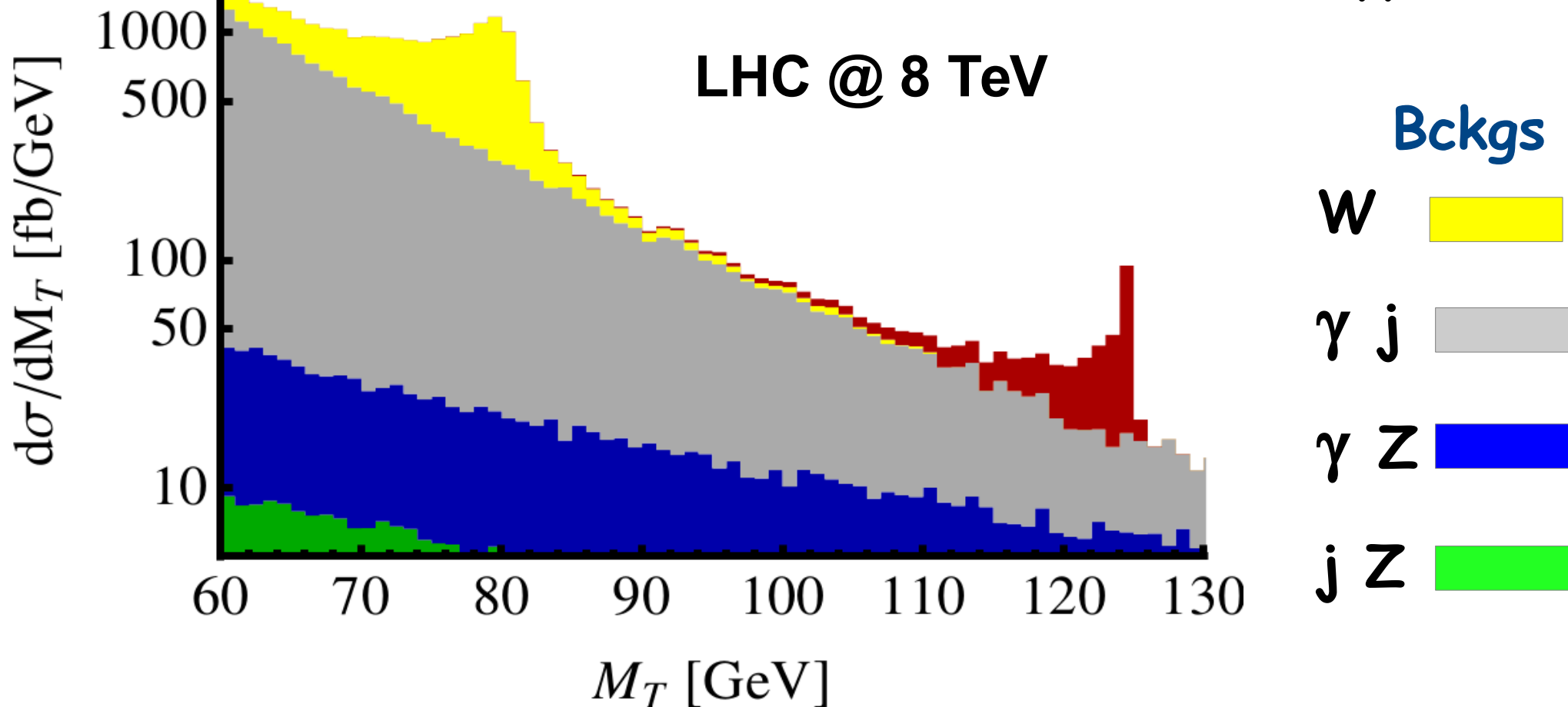
M_T distribution [fb/GeV]

- signal corresponds to $BR(H \rightarrow \gamma\bar{\gamma}) = 5\%$

Signal

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

EG, Heikinheimo, Mele, Raidal PRD 90 (2014)



- M_T distribution peaked at original M_H mass

- P_{T^γ} distribution exhibits similar structure at $M_H/2$

Event selection for $\gamma + \cancel{E}_T$

signal $pp \rightarrow H \rightarrow \gamma\bar{\gamma}$ @ 14 TeV

- one isolated ($\Delta R > 0.4$) photon with $p_T^\gamma > 50$ GeV, and $|\eta^\gamma| < 1.44$;
- missing transverse momentum satisfying $\cancel{E}_T > 50$ GeV
- transverse mass in the range $100 \text{ GeV} < M_{\gamma\bar{\gamma}}^T < 130 \text{ GeV}$
- no isolated leptons.

Significance vs BR in gg and VBF mechanisms

Biswas, EG, Heikinheimo, Mele, PRD 93 (2016)

BR $_{\gamma\bar{\gamma}}$ (%)	L=100 fb $^{-1}$		L=300 fb $^{-1}$		L=3 ab $^{-1}$	
Significance	3 σ	5 σ	3 σ	5 σ	3 σ	5 σ
BR $_{\gamma\bar{\gamma}}$ (VBF)	1.1	1.9	0.65	1.1	0.21	0.34
BR $_{\gamma\bar{\gamma}}$ (ggF)	0.096	0.16	0.055	0.092	0.017	0.029

TABLE IV: Reach in BR $_{\gamma\bar{\gamma}}$ (in percentage) for a 3 σ exclusion or a 5 σ discovery at the 14 TeV LHC, in the VBF and gluon-fusion channels, for different integrated luminosities L.

Large discovery potential @ LHC 14 TeV

by gluon-gluon fusion up to BR $\sim 10^{-4}$ - 10^{-3}

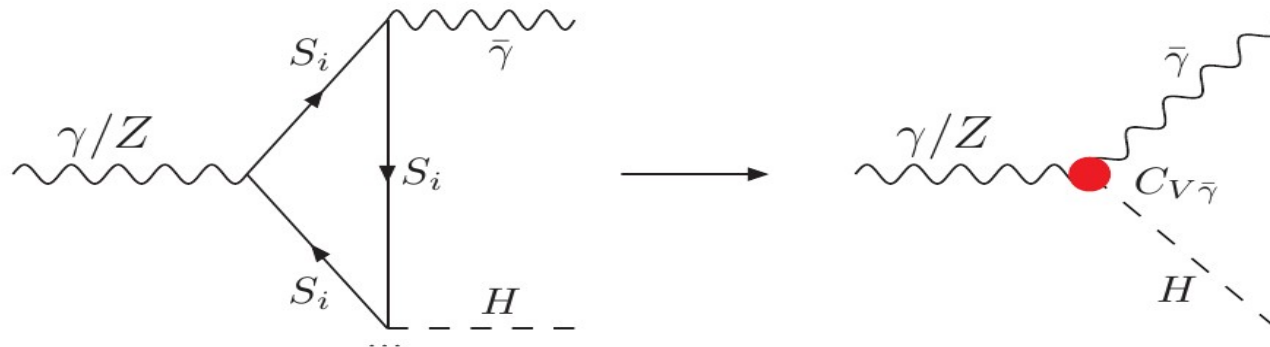
Implications of $H\bar{\gamma}$ and $H\bar{z}\bar{\gamma}$ at e^+e^- colliders

Higgs production in association to a Dark Photon @ e^+e^-

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

Biswas, EG, Heikeinheimo, Mele
JHEP 1506 (2015) 102

- we look at Higgs decay in $H \rightarrow b\bar{b}$ (best channel in e^+e^- colliders)
- dark photon undetected: signature consists of $b\bar{b}$ + missing energy



- Effective field theory approach adopted (valid for heavy messengers)
- Model independent analysis

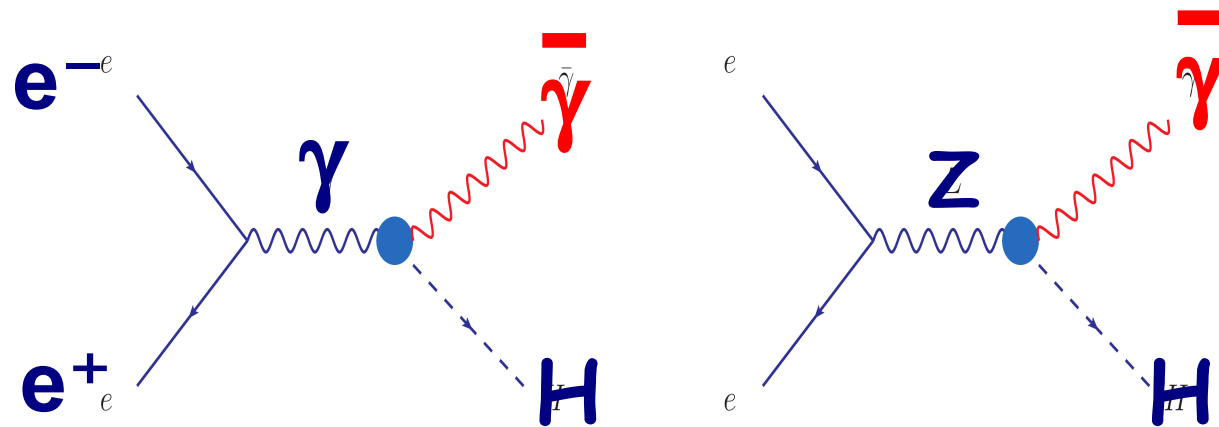
$$e^+e^- \rightarrow H\bar{\gamma} \rightarrow b\bar{b}\bar{\gamma}$$

Model independent analysis:

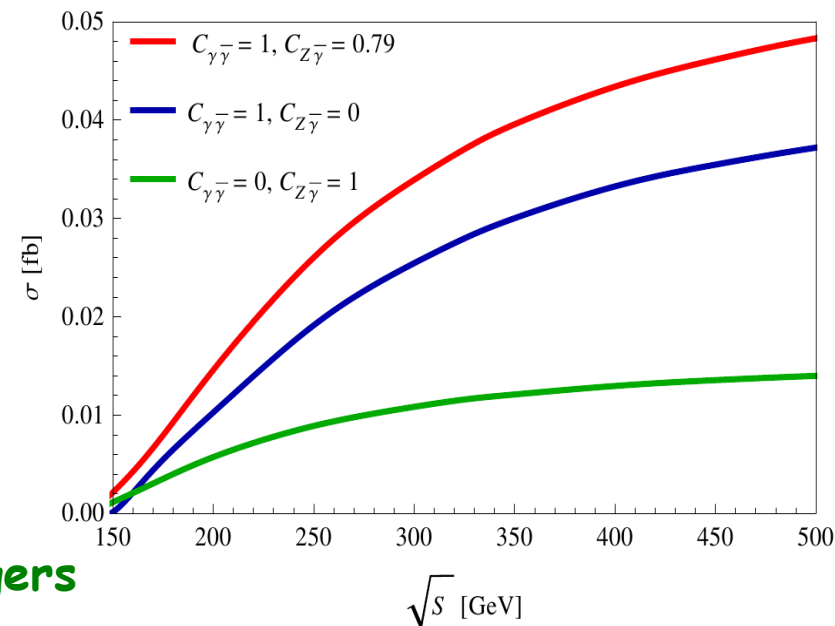
Effective Lagrangian parametrization

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

DP field strength



Total x-section



assuming mass degeneracy in Left and Right messengers

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

$$R_{Z\gamma}^{\tilde{q}} = \frac{R_{Z\gamma}^{\tilde{u}} + R_{Z\gamma}^{\tilde{d}}}{2} \approx 0.79 \rightarrow \text{from a squark doublet}$$

Signal $b\bar{b} + \cancel{E}$ $\rightarrow$ transverse missing energy

Basic cuts $\left\{ \begin{array}{l} p_T^b > 20 \text{ GeV} , \quad |\eta_b| < 2.5 \\ \Delta R(bb) > 0.4 , \quad \cancel{E} > 40 \text{ GeV} \end{array} \right.$

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

Main backgrounds for $b\bar{b} + \cancel{E}$

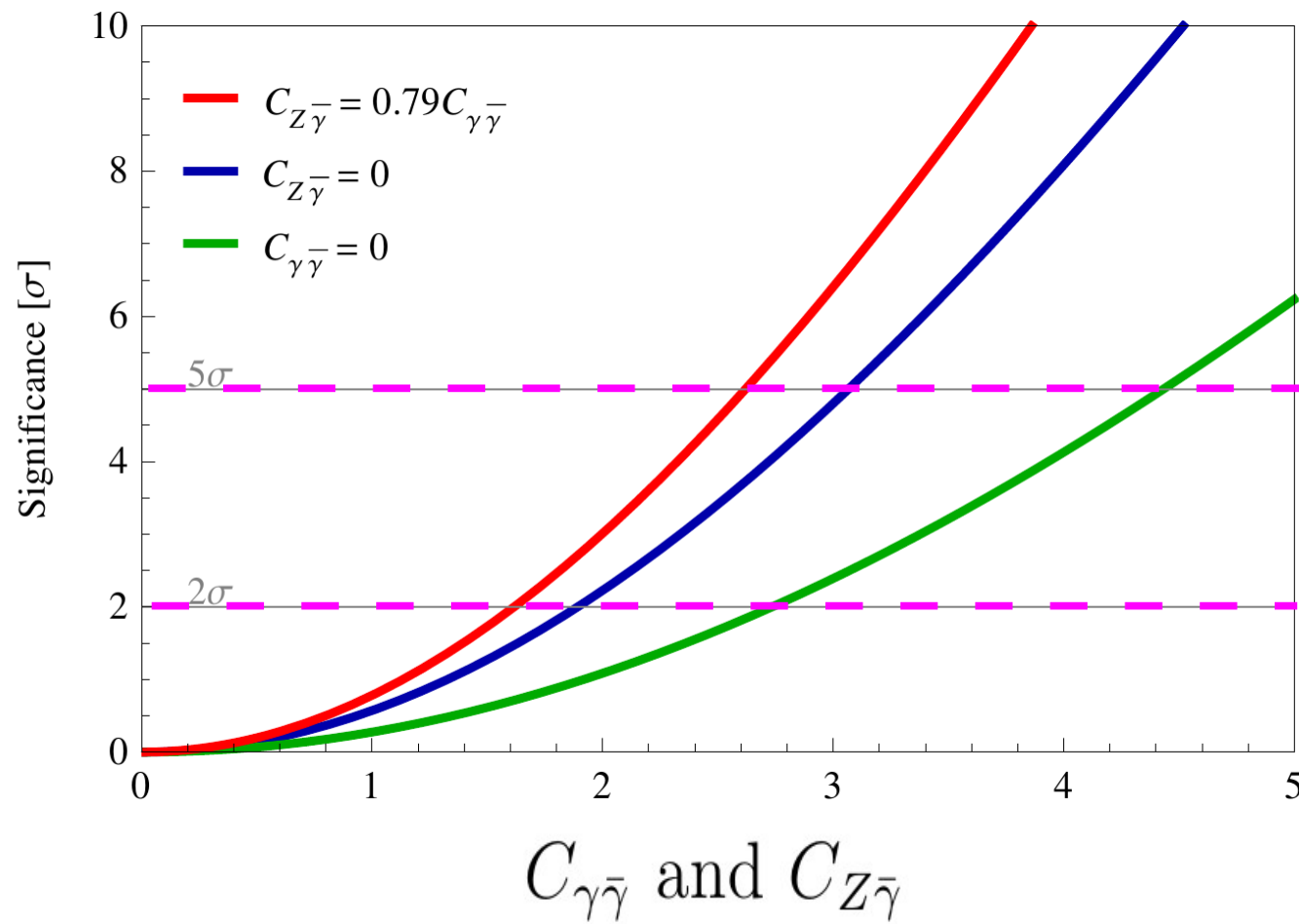
Irreducible

$$\nu\bar{\nu}b\bar{b} \left\{ \begin{array}{l} ZZ \rightarrow \nu\bar{\nu}b\bar{b} \\ ZH \rightarrow \nu\bar{\nu}b\bar{b} \\ WW \text{ fusion} \rightarrow H\nu\bar{\nu} \end{array} \right.$$

Reducible

$\nu\bar{\nu}q\bar{q}$: Mostly from on-shell Z pairs where two light jets are misidentified with two b-jets

we assume: b-tagging efficiency of 80%
fake b-jet rejection factor 1/100



$$\text{signif.} = S / \sqrt{S + B}$$

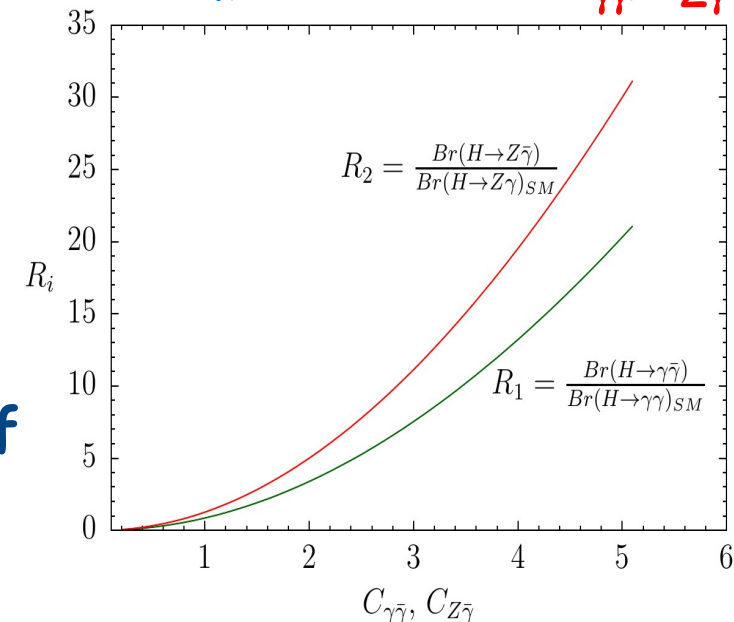
5 σ values of $C_{\gamma\bar{\gamma}}$ and $C_{Z\bar{\gamma}}$ in the natural range of predictions for the U(1)_F Flavor model

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

5 σ

2 σ

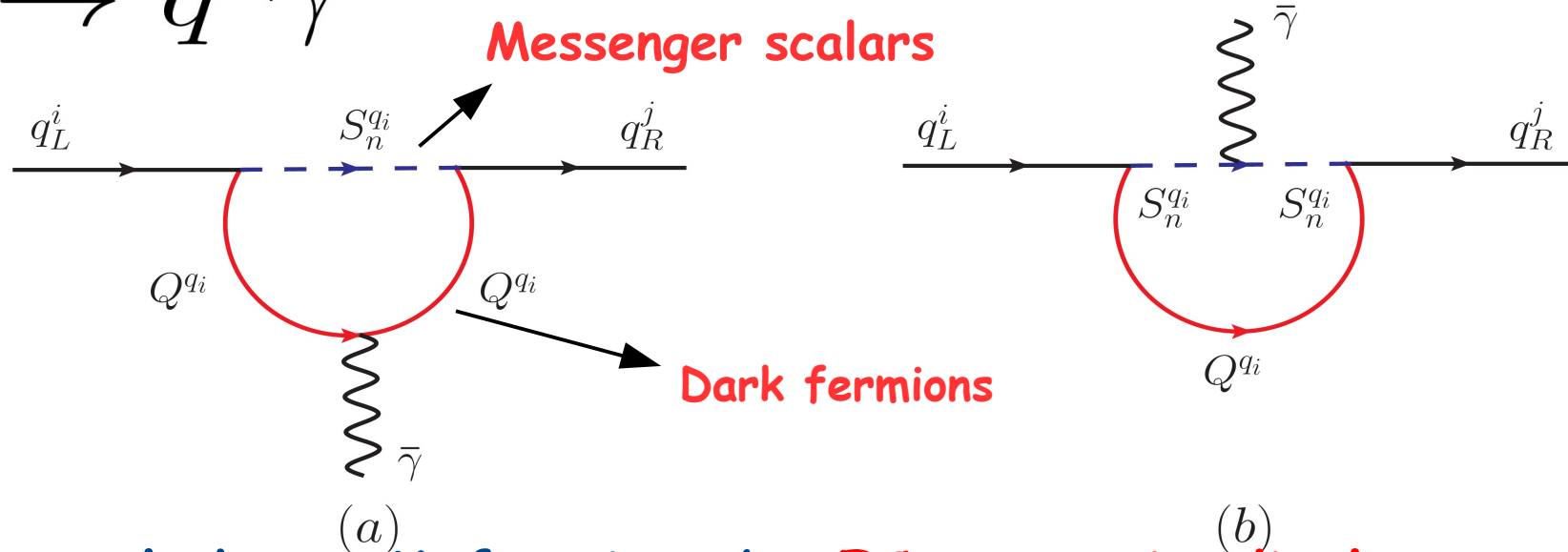
Normalized BRs vs $C_{\gamma\bar{\gamma}}/C_{Z\bar{\gamma}}$



FCNC decays of SM fermions into a Dark Photon

EG, Mele, Raidal, Venturini, arXiv: 1607.05928

$$q^i \rightarrow q^j \bar{\gamma}$$



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

$$\mathcal{L}_{\text{eff}} = \sum_{q=U,D} \sum_{i,j=1}^3 \left(\frac{1}{2(\Lambda_L^q)_{ij}} \left[\bar{q}_R^j(x) \sigma_{\mu\nu} \bar{F}^{\mu\nu}(x) q_L^i(x) \right] + \frac{1}{2(\Lambda_R^q)_{ij}} \left[\bar{q}_L^j(x) \sigma_{\mu\nu} \bar{F}^{\mu\nu}(x) q_R^i(x) \right] \right)$$

$\bar{F}_{\mu\nu}$ = dark photon field strength

■ suppressed by scales $\Lambda_{L,R}$ proportional to typical messenger mass scale

■ Decay width

$$\Gamma(q^i \rightarrow q^j \bar{\gamma}) = \frac{m_{q_i}^3}{16\pi^3} \left(\frac{1}{(\Lambda_L^q)_{ij}^2} + \frac{1}{(\Lambda_R^q)_{ij}^2} \right)$$

FCNC decays of SM fermions into a Dark Photon

EG, Mele, Raidal, Venturini, arXiv: 1607.05928

- DP coupled to SM fermions by FC magnetic-dipole operators (suppressed by typical messenger mass scale)
- Eight new kind of FCNC signatures predicted !

$$\begin{array}{l} \text{Quark sector} \left\{ \begin{array}{l} t \rightarrow c \bar{\gamma} \quad , \quad u \bar{\gamma} \\ b \rightarrow s \bar{\gamma} \quad , \quad d \bar{\gamma} \\ c \rightarrow u \bar{\gamma} \end{array} \right. \end{array} \quad \begin{array}{l} \text{Leptonic sector} \left\{ \begin{array}{l} \tau \rightarrow \mu \bar{\gamma} \quad , \quad e \bar{\gamma} \\ \mu \rightarrow e \bar{\gamma} \end{array} \right. \end{array}$$

final fermion balanced by a massless invisible (ν -like) system

- Large and possibly measurable BRs are allowed, up to
 - $\text{BR}(b \rightarrow q \bar{\gamma}) \sim 10^{-4} - 10^{-3}$
 - $\text{BR}(c \rightarrow u \bar{\gamma}) \sim 10^{-8} - 10^{-4}$
 - $\text{BR}(\tau \rightarrow l \bar{\gamma}) \sim 10^{-10} - 10^{-6}$
 - $\text{BR}(t \rightarrow q \bar{\gamma}) \sim 10^{-10} - 10^{-7}$
 - $\text{BR}(\mu \rightarrow e \bar{\gamma}) \sim 10^{-10} - 10^{-6}$

depending on various parameters and on flavor universality structure of messenger sector

Outlook

- **Dark sector** might have long distance interactions mediated by an **unbroken $U(1)_F$** → massless Dark Photon, as predicted by a recent proposal to naturally explain the Yukawa hierarchy by exponen. spread
- large couplings of Dark Photon in the hidden sector potentially allowed, due to vanishing tree-level couplings with SM fields (if DP is massless)
- **Higgs boson** can be the SM portal to Dark Photons:
new effective vertices can appear: $H-Z-\bar{\gamma}$ and $H-\gamma-\bar{\gamma}$
- Rich phenomenological implications @ **LHC** and linear colliders
 - search for $H \rightarrow \gamma \bar{\gamma}$, and $H \rightarrow Z \bar{\gamma}$ (large rates allowed and expected)
 - new production mechanisms $e^+e^- \rightarrow H(\rightarrow b\bar{b}) + \bar{\gamma}$
 - new FCNC processes: $t \rightarrow c \bar{\gamma}$, $b \rightarrow s \bar{\gamma}$, $c \rightarrow u \bar{\gamma}$, $\tau \rightarrow e \bar{\gamma}$, $\mu \rightarrow e \bar{\gamma}$
- **potential implications for astroparticle/cosmology yet to work out !**