

The Dark side of Flavor

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collaborations: D. Barducci, S. Biswas, M. Fabbrichesi, M. Heikineimo, L. Marzola, B. Mele, M. Raidal, E. Venturini

based on:

PRD 89 (2014) 015008	EG, M.Raidal
PRD 95 (2017) 035005	EG, M.Raidal, L.Marzola
arXiv:1806.05678	D. Barducci, M. Fabbrichesi, EG
PRL 119 (2017) 031801	M. Fabbrichesi, EG, B.Mele
PRL 119 (2017) 031801	M. Fabbrichesi, EG, B.Mele
PRD 96 (2017) 055012	S.Biswas, EG, M.Heikinheimo, B.Mele
PRD 94 (2016) 115013	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

model building

phenomenology

Outline

- Theoretical framework
 - Yukawa couplings as effective couplings
 - generated by a Dark Sector
 - solution to the Flavor hierarchy problem
- Phenomenological implications
- New Signatures (dark photons, dark-fermions)
- Conclusions

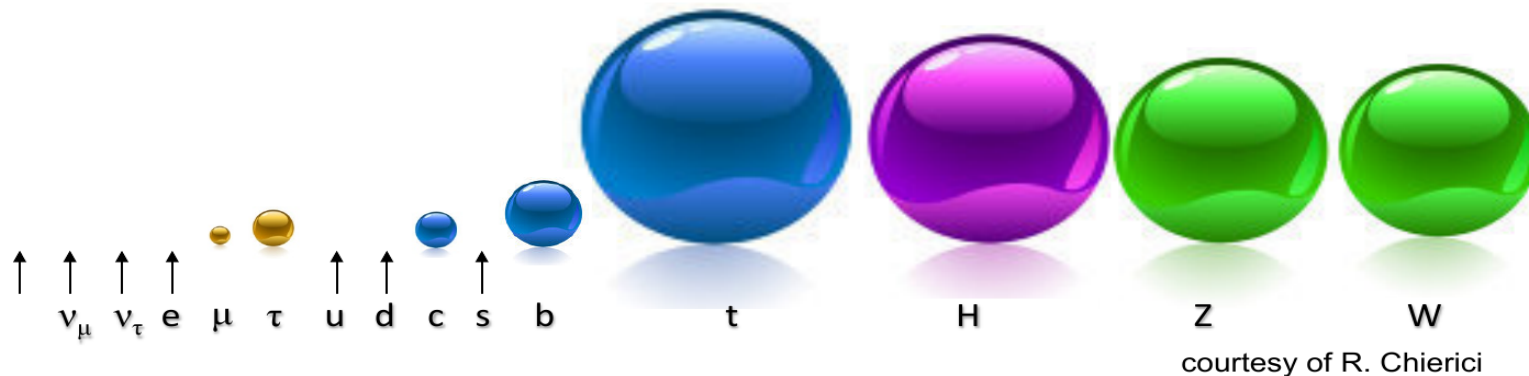
Flavor Hierarchy Problem

- SM fermion mass sector contains too many free parameters
- reflected in the structure of Yukawa couplings (**Ys**)

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...



- Fermion masses spanning from 6 orders of magnitude for charged fermions, up to 12 if we include (Dirac) neutrino masses

Flavor Hierarchy Problem

- Large hierarchy in SM fermion masses suggest Yukawa's arise as low energy effective couplings
- easier to justify the large hierarchy
- First attempt → Froggatt-Nielsen mechanism
- require ad-hoc high-dim operators → origin unknown
- A new proposal: effective Yukawa couplings generated by a renormalizable theory → require a Dark Sector

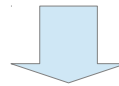
Theoretical Framework

EG, Raidal, PRD 89 (2014)
E. Ma, PRL 112 (2014)

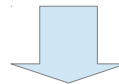
■ Main paradigm: 4-dim Yukawa operators (Y_s)
forbidden by some symmetry Σ

■ Yukawa operators $\rightarrow$ arise at low energy as effective Y_s
from operators of dim-5 after SSB of $\Sigma \rightarrow$ via a vev $\langle 0|S|0\rangle$

▶ assume existence of a Dark sector $\rightarrow$ Dark Fermions (DF)
neutral under SM gauge interactions



▶ generate Dark-Chiral Symmetry Breaking non-perturbatively
so that DF mass hierarchies arise



▶ transfer DF mass hierarchy to SM dim-5 operators using a
universal messenger sector (via renormalizable interactions)

Lowest dimension operators (dim 5) $\Rightarrow (\bar{\psi}_L^f H_L \psi_R^f) S + h.c.$

$\downarrow$
SM scalar singlet

SSB $\langle S \rangle$ vev $\Rightarrow$

$$Y_f \sim \frac{M_f}{\Lambda_{\text{eff}}}$$

$M_f \rightarrow$ Dark Fermion(f) Mass
 $\Lambda_{\text{eff}} \rightarrow$ ~ universal effective scale for universal messengers

Dual Correspondence

■ SM fermion mass $\longleftrightarrow$ Dark fermion mass
 (almost rescaled SM spectrum)

$\rightarrow$ shift the mass hierarchy problem to the DF sector

■ non-perturbative dynamics in Dark sector responsible for generating M_f hierarchy (see next slides)

Yukawa hierarchy

EG, Raidal, PRD 89 (2014)

- Require an **unbroken U(1)** gauge symmetry in the dark sector
- Exponentially spread Yukawas $\rightarrow$ hierarchy related to Dark U(1) charges

Flavor hierarchy problem solved !

- **Lee-Wick scaling law (weak coupling)**

EG, Raidal, PRD 89 (2014)

$$Y_f \sim M_f \sim \exp \left\{ -\frac{\gamma}{\alpha q_f^2} \right\}$$

$\alpha \rightarrow$ **U(1) fine-structure const.**

$q_f \rightarrow$ **U(1) quantum charges**

$\gamma \sim$ anomalous dimension

- **Miransky scaling law (strong coupling)**

EG, Marzola, Raidal, PRD 95 (2015)

$$Y_f \sim M_f \sim e^{-\frac{\pi^2}{3|q_f|\sqrt{\alpha}}}$$

$$(\alpha \gg \alpha_c = \frac{\pi}{3})$$

■ Predicted spectrum for charges O(1), including neutrino masses !

Lee-Wick scaling law

$$\bar{\alpha}(\Lambda)^{-1} \simeq \frac{3}{2\pi} \frac{q_{Q_i}^2}{1 - q_{Q_i}^2} \log \frac{m_t}{m_i}$$

inputs $q_{U_3} = 1$ $q_{D_3} = 0.9$ → using m_t and m_b predicts $\bar{\alpha}(\Lambda) = 0.14$

quark	mass	m_t	m_b	m_c	m_s	m_d	m_u
U(1)	charges	1	0.9	0.88	0.82	0.77	0.76
lepton	mass	m_τ	m_μ	m_e	m_{ν_3}	m_{ν_2}	m_{ν_1}
U(1)	charges	1	0.92	0.81	0.65	0.59	0.55

above charges for neutrinos correspond to benchmark masses

$$m_{\nu_1} = 10^{-6}\text{eV}, \quad m_{\nu_2} = 10^{-3}\text{eV}, \quad m_{\nu_3} = 1\text{eV}$$

No need for seesaw mechanism → neutrino masses are Dirac type

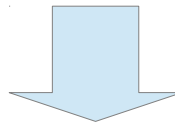
■ analogous results for Miransky scaling law (strong coupling predicted)

$$\alpha > \alpha_c \text{ for } q_{U_3} = 1 \quad \Rightarrow \quad |q_{D_3}| < 0.45$$

New particles spectrum

Scalar messengers (heavy)
SM quantum #'s as squarks and sleptons

Dark Fermions (light) → stable
guaranteed by unbroken Dark U(1) gauge



DM candidates

Multi DM scenario with long distance interactions

SOME TECHNICAL ASPECTS...

Dark-Fermions mass hierarchy

- Large hierarchy of Yukawa's suggests some non-perturbative, mechanism for dark-fermion masses M_f
- Possible realization: via Nambu & Jona-Lasinio (NJL) mechanism

Y. Nambu and G. Jona-Lasinio, Phys. Rev. 124 (1961) 246; 122 (1961) 345

- ▶ dynamical mass "m" arises as a non-trivial solution of the self-consistent mass gap equation

$$m = \Sigma(\hat{p}, m)|_{\hat{p}=m}$$

self-energy

A horizontal line with a red 'x' in the middle is followed by an equals sign, which is followed by a horizontal line with a solid black circle in the middle. An arrow points from the text 'self-energy' to the black circle.

- ▶ perturbative solution $m=0$ always there
- ▶ true ground state corresponds to non-trivial solution $m \neq 0$.

NJL Model

cut-off factor

- assume a chiral invariant 4-fermion interaction

$$G(\bar{\psi}\Gamma_i\psi)^2 \quad \Rightarrow \quad 1 = -\frac{iG}{2\pi^4} \int \frac{d^4p}{p^2 + m^2 - i\varepsilon} F(p, \Lambda)$$

- non-perturbative $m \neq 0$ solution** corresponding to the true vacuum (lowest energy), is a superposition of pair-states

$$\frac{2\pi^2}{G\Lambda^2} = 1 - \frac{m^2}{\Lambda^2} \log \left(\frac{\Lambda^2}{m^2} + 1 \right)$$

non-trivial solution m exists (raising from zero) only if

$$G > G_{\text{crit}} = \frac{2\pi^2}{\Lambda^2}$$

If cut-off is associated to a massive (Λ) particle exchange : $G \sim g^2/\Lambda^2$

Criticality $G > G_{\text{crit}} \Rightarrow g > \sqrt{2}\pi$ **strong coupling !**

Lee-Wick mechanism for ChSB

a toy model: massless fermions charged under U(1) gauge +
Lee-Wick term in the gauge sector

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{\Lambda^2} (\partial^\alpha F_{\alpha\mu}) (\partial^\beta F_\beta^\mu) + i\bar{\psi}\gamma_\mu D^\mu\psi$$

Lee-Wick, PRD 2 (1970) 1033;
NPB 9 (1969) 209.

$$D_\mu = \partial_\mu + igA_\mu$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

spin-1 ghost in the spectrum with mass $\sim \Lambda$.

if ghost decay $\rightarrow$ Perturbative unitarity can be recovered using a special prescription in
integrating loop energies Lee-Wick, (1970).

ChSB induced by U(1) Lee-Wick term

fermion mass generated non-perturbatively

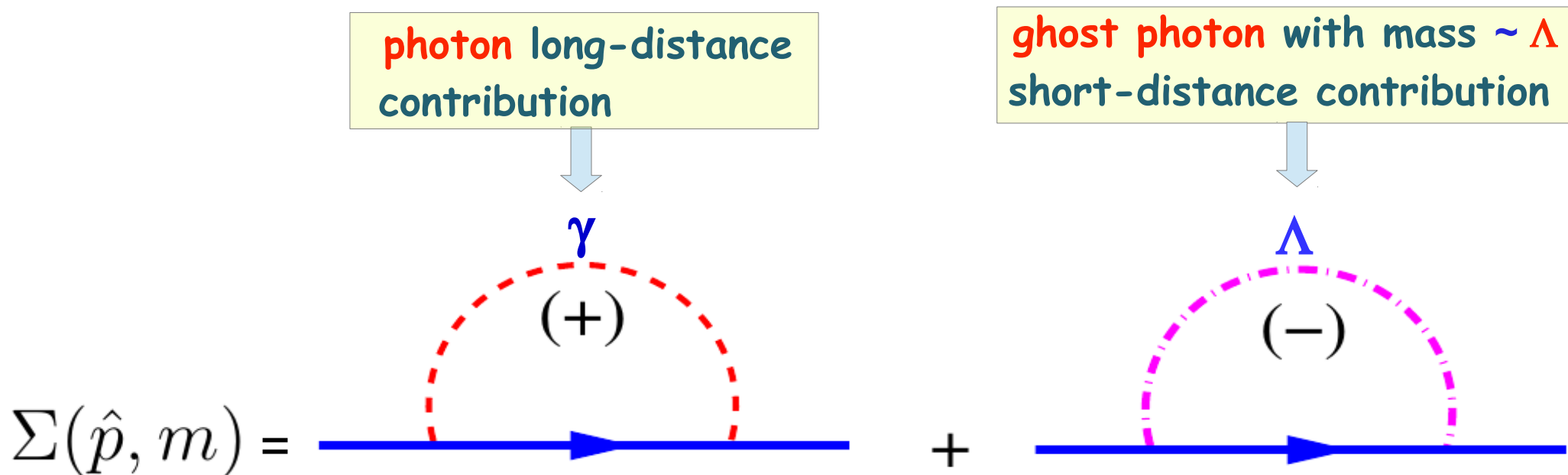
EG, PRD 77 (2008) 055020

Non-trivial solution obtained using the NJL approach

- following the steps of NJL mechanism → look at the non-trivial solution

$$m = \Sigma(\hat{p}, m)|_{\hat{p}=m}$$

- **SE finite** (due to the Lee-Wick ghost) **and gauge invariant**



- **potential at small distances** $V(r) \sim -\frac{1}{r} \left(1 - e^{-Kr}\right) \rightarrow -K + \frac{1}{2}K^2r$

- **at low energy $\ll \Lambda$** , Lee-Wick term induces a local 4-fermion interaction (chiral invariant) similar to the 4-fermion interaction of NJL

Dynamical fermion mass hierarchy

- **N fermions** coupled to **U(1) + Lee-Wick term**

EG, PRD 77 (2008)

EG, Raidal, PRD 89 (2014)

mass-gap solution

$$M_{Q_i} = \Lambda \exp \left\{ -\frac{2\pi}{3 \bar{\alpha}(\Lambda) q_i^2} + \frac{1}{4} \right\}$$

valid for weak coupling regime $\alpha < 1$

$\Lambda \rightarrow$ Lee-Wick ghost mass

- **non-universal U(1) charges $\rightarrow$ exponential mass spread**



- **scaling law could be tested non-perturbatively on the Lattice**

alternative U(1) mechanism

Miransky-Tanabashi-Yamawaki
Mod. Phys. Lett A4 (1984) 1043

- based on Miransky scaling (no ghost)
- solution of mass gap equation for U(1) @ strong coupling
- requires criticality ($\alpha > \alpha_c = \pi/3$)

$$m_\psi \approx 4\Lambda_c e^{-\frac{\pi\alpha_c}{\sqrt{\alpha - \alpha_c}}}$$

- Λ_c energy scale where U(1) becomes strong
- with N fermions at large $\alpha \gg \alpha_c$, fermion masses M_f expected to scale as

$$M_f \rightarrow 4\Lambda_c e^{-\frac{\pi^2}{3|q_f|\sqrt{\alpha}}}$$

embed this idea into effective Yukawa $\rightarrow$

Dark Fermions $\leftrightarrow$ SM fermions
messenger scalar fields

$Y_f = 0 \rightarrow$ enforced by LR gauge symmetry

■ $g_L = g_R = g$

$$SU(2)_L \times SU(2)_R \times U(1)_Y$$

EG, Marzola, Raidal,
PRD 95 (2015)



H_L



H_R

only $SU(2)$ Higgs doublets

- dim-4 Yukawa operator forbidden
- NO Higgs bi-doublets (to avoid dim-4 Yukawa operators)
- lowest dim (gauge-invariant) operator (dim-5)
(require new interactions beyond SM fields)

$$\frac{1}{\Lambda_{\text{eff}}} \left(\bar{\psi}_L^f H_L \right) \left(H_R^\dagger \psi_R^f \right) + h.c.$$

- Yukawa's generated after SSB of $SU(2)_R$
- Strong CP problem automatically solved !

Renormalizable interactions to generate Yukawa →

(fixed by chirality and gauge invariance)

New Interactions to generate Yukawa

charged under $U(1)_F$

Dark fermions

$SU(2)_L$ -doublet messenger fields

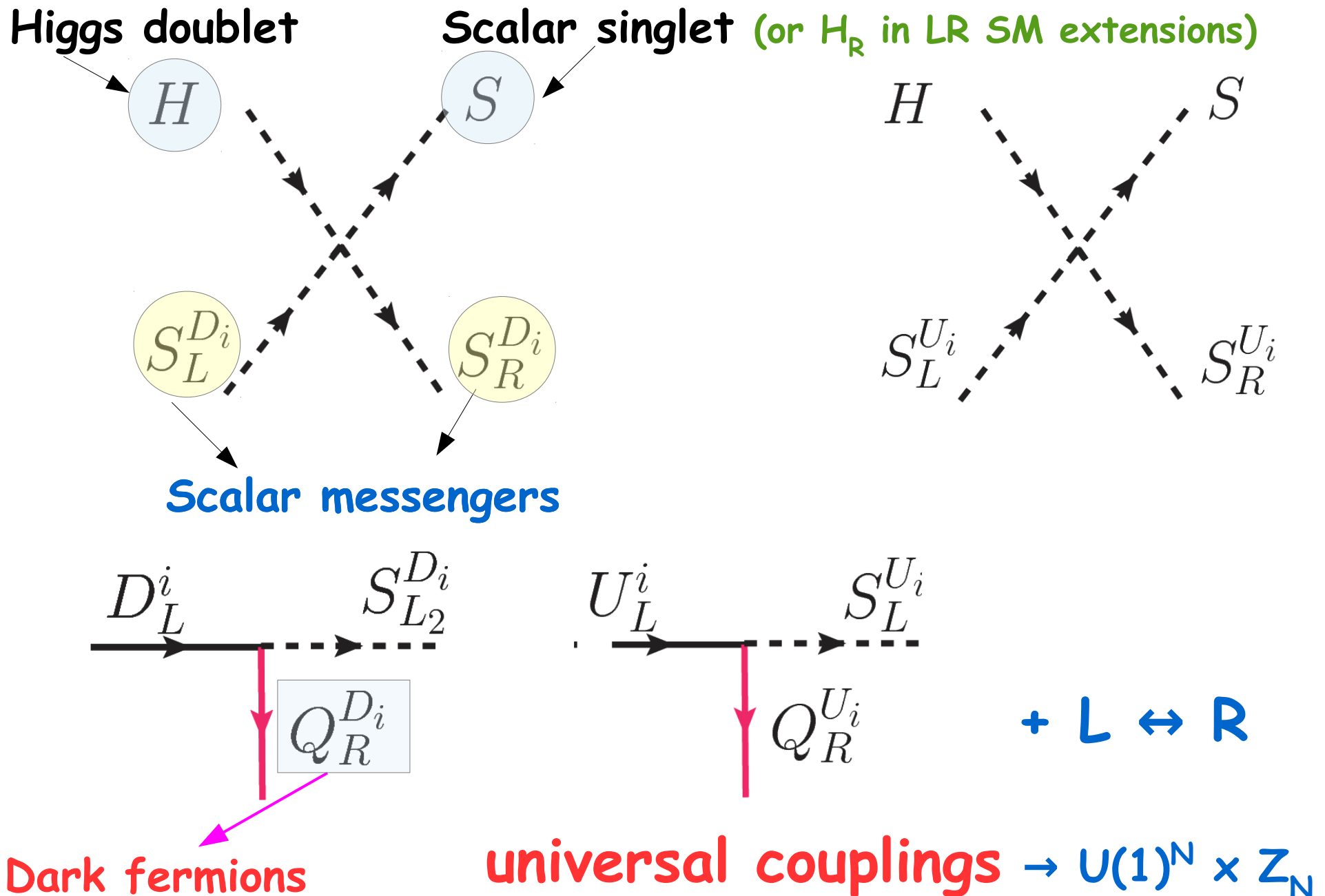
$$\begin{aligned}
 \mathcal{L}_{MS}^I = & g_L \left(\sum_{i=1}^N [\bar{q}_L^i Q_R^{U_i}] \hat{S}_L^{U_i} + \sum_{i=1}^N [\bar{q}_L^i Q_R^{D_i}] \hat{S}_L^{D_i} \right) \\
 & + g_R \left(\sum_{i=1}^N [\bar{q}_R^i Q_L^{U_i}] \hat{S}_R^{U_i} + \sum_{i=1}^N [\bar{q}_R^i Q_L^{D_i}] \hat{S}_R^{D_i} \right) \\
 & + \lambda \sum_{i=1}^N \left(\tilde{H}_L^\dagger \hat{S}_L^{U_i} \hat{S}_R^{U_i\dagger} \tilde{H}_R + H_L^\dagger \hat{S}_L^{D_i} \hat{S}_R^{D_i\dagger} H_R \right) + h.c.,
 \end{aligned}$$

$\downarrow$
 4-scalar coupling of Higgses to fermions

(LR symmetry $\rightarrow g_L = g_R$)

$SU(N) \rightarrow U(1)^N \times Z_N$ symmetry

Minimal set of new interactions



Higgs Yukawa's radiatively generated at 1-loop

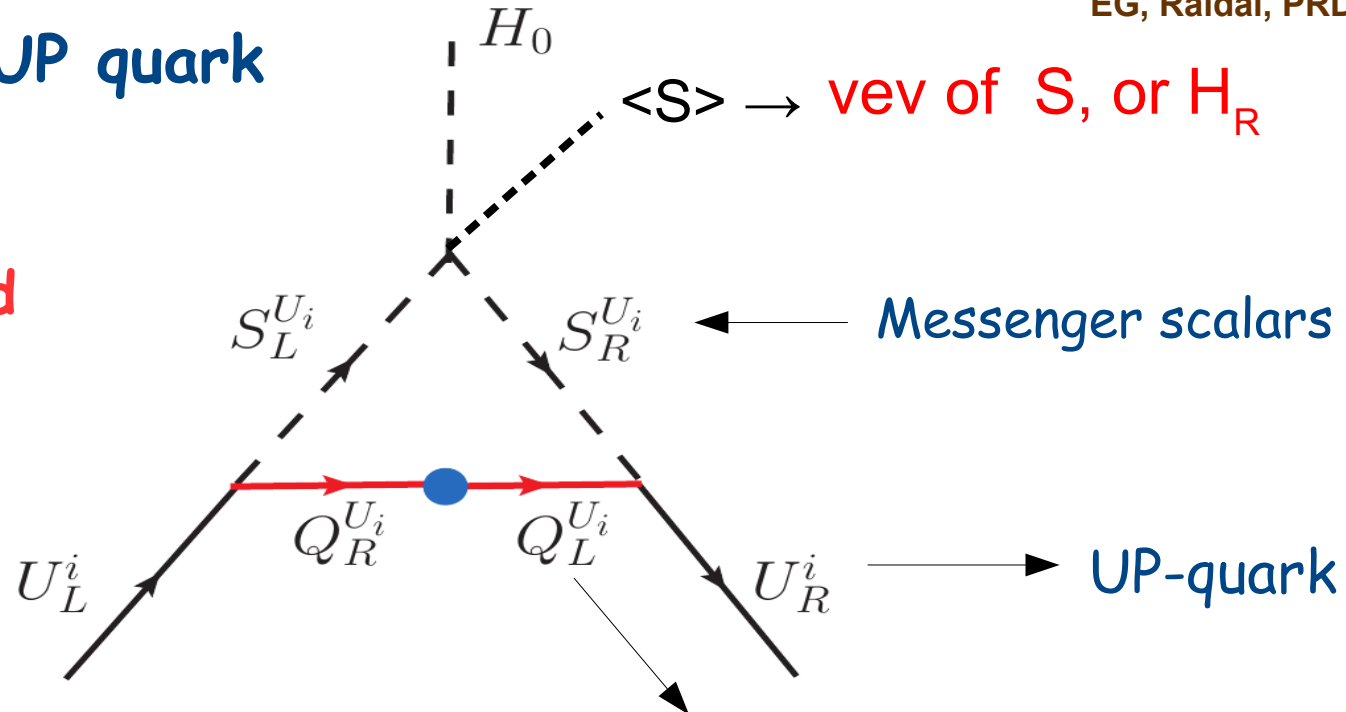
Via higher order dim. operators $\rightarrow \bar{U}_L U_R H S$ finite at any order

EG, Raidal, PRD 89 (2014)

Yukawa coupling UP quark

H_0 = Higgs field

$U(1)_F$ charge flows
only inside loop



Q = Dark-Fermions
(SM gauge singlets)

● $\rightarrow M_f$ = mass of Dark-fermion f

$$Y_f \sim \frac{M_f}{\Lambda_{\text{eff}}}$$



Yukawas follow M_f hierarchy !

Messenger mass matrix

Due to $SU(2)_L$ breaking

$$M_S^2 = \begin{pmatrix} m_L^2 & \Delta \\ \Delta & m_R^2 \end{pmatrix}$$

$$\Delta = \frac{1}{2} \lambda v_R v_L$$

Assume flavor universal structure

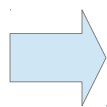
Eigenvalues $\rightarrow m_{\pm}^2 = \frac{1}{2} \left(m_L^2 + m_R^2 \pm [(m_L^2 + m_R^2)^2 + 4\Delta]^2 \right)^{1/2}$

LR symmetry requires $\rightarrow m_L^2 = m_R^2 \equiv \bar{m}^2$

$$m_{\pm}^2 = \bar{m}^2 (1 \pm \xi)$$

mixing parameter $\xi = \frac{\Delta}{\bar{m}^2}$

to avoid tachions
and color-charge breaking minima



$$0 < \xi < 1$$

Yukawa coupling

- prediction at 1-loop (in LR symmetric scheme, exact in ξ)

$$Y_f = \left(\frac{\lambda g_L g_R}{16\pi^2} \right) \left(\frac{\xi M_{Q_f} \sqrt{2}}{v_L} \right) f_1(x_f, \xi)$$

vev $\langle H_R \rangle$ reabsorbed in mixing ξ

$$x_f = M_{Q_f}^2 / \bar{m}^2$$

- After EWSB

$$M_{Q_f} = m_f \left(\frac{16\pi^2}{g_L g_R} \right) \frac{1}{\xi f_1(x_i, \xi)}$$

Dark-fermion mass $\gg$ SM fermion mass

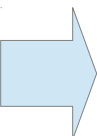
$f_1(x, \xi)$ loop function of order $O(1)$

➡ Dark fermion spectrum $\sim$ rescaled SM spectrum

Phenomenological constraints

- avoid existence of charged stable particle (DM constraints)
- due to the Flavor universality of messenger mass sector
 - ▶ lightest messenger state required to be heavier than the heaviest DF (associated to the top-quark)

$$m_- \geq M_{Q_t}$$


$$\bar{m} \geq m_t \left(\frac{16\pi^2}{g_L g_R} \right) F(\xi)$$

implying lower bounds on v_R

$$v_R \geq \frac{2m_t^2}{\lambda v_L} \left(\frac{16\pi^2}{g_L g_R} \right)^2 \xi F(\xi)^2$$

Summary of model's features

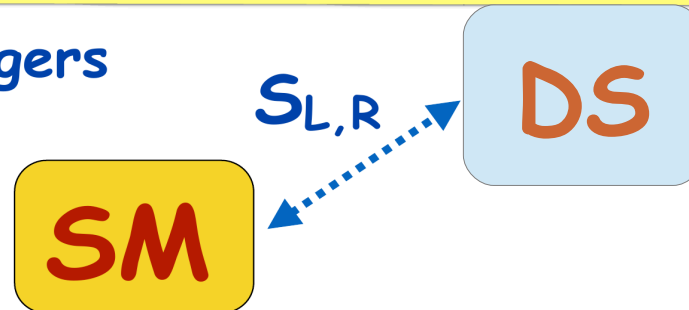
stable Dark fermions

[due to exact $U(1)$ -dark gauge symmetry]

- ▶ having long-range interactions mediated by a massless dark photon
- ▶ Dark Matter candidates (rescaled spectrum of SM fermions)

heavy scalar messengers $S_{L,R}$

▶ heavy scalar messengers (squark/slepton-like)



▶ avoiding stability requires colored messengers to be heavy $\gg$ TeV scale

Messengers (Scalars)

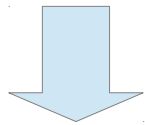
Dark Sector (Fermions+Scalar)

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

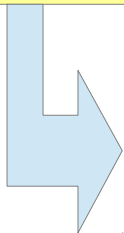
▶ EW messengers could be lighter, below TeV scale

- Dynamics responsible of dark-fermion masses predicts an unbroken $U(1)$

A main phenomenological implication



a massless dark-photon in the spectrum



neutrino-like signature in a collider experiment

Massless Dark Photons

■ different from massive Dark photons scenarios

(massive DP can have tree-level coupling to SM fields via $U(1) \times U(1)_{EM}$ kin. Mixing)

■ Kin. mixing can be rotated away on-shell massless DP can be fully decoupled from SM sector at tree-level

B. Holdom, *Phys Lett.* 166 B (1986) 196

- ▶ DP interact with SM fields only via high-dimensional operators suppressed by $1/M^{D-4}$
- ▶ present bounds on massive DP do not apply
(tree-level couplings with SM fields assumed)
- ▶ large couplings in Dark sector potentially allowed !

Massless Dark Photon signatures

■ DP discovery channel in Higgs boson physics:

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

→ non-decoupling

EG, Heikinheimo, Mele, Raidal, PRD 90 (2014)
Biswas, EG, Heikinheimo, Mele PRD 93 (2016)

+ no results by CMS and ATLAS yet

processes suppressed by UV scale → decoupling

■ 9 new FCNC processes

$$f \rightarrow f' \bar{\gamma}$$

$$f = t, b, c, s, \tau, \mu$$

EG, Mele, Raidal, Venturini, PRD 94 (2016)

■ DP discovery channel in Kaon physics

$$K^+ \rightarrow \pi^+ \pi^0 \bar{\gamma}$$

EG, Mele, Fabbrichesi, PRL 119 (2017)

■ New Z boson decay

$$Z \rightarrow \gamma \bar{\gamma}$$

(evading Landau-Yang Th.)

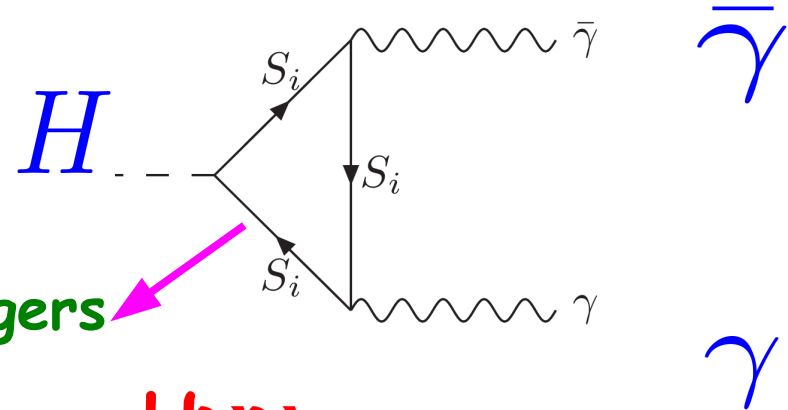
EG, Mele, Fabbrichesi, PRL 120 (2018)

Monophoton Exotic Higgs Signature

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

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

scalar messengers



- effective coupling has same structure as $H\gamma\gamma$

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

model indep. parametrization

$$\Lambda_{\gamma \bar{\gamma}} = \frac{6\pi v}{R} \frac{1 - \xi^2}{\xi^2}$$

R = product of U(1) charges

DP field strength

- non-decoupling effect $\rightarrow \Lambda_{\gamma \bar{\gamma}}$ proportional to Higgs vev !

- DP coupling $\bar{\alpha}$ could be large (allowed if DP is massless)

- potentially large rates expected !

- contribute also to $H \rightarrow \gamma\gamma$ and gg (from Higgs production $\rightarrow \xi < 0.88$)

BR predictions in a simplified model (1 messenger) for $H \rightarrow \gamma \bar{\gamma}$

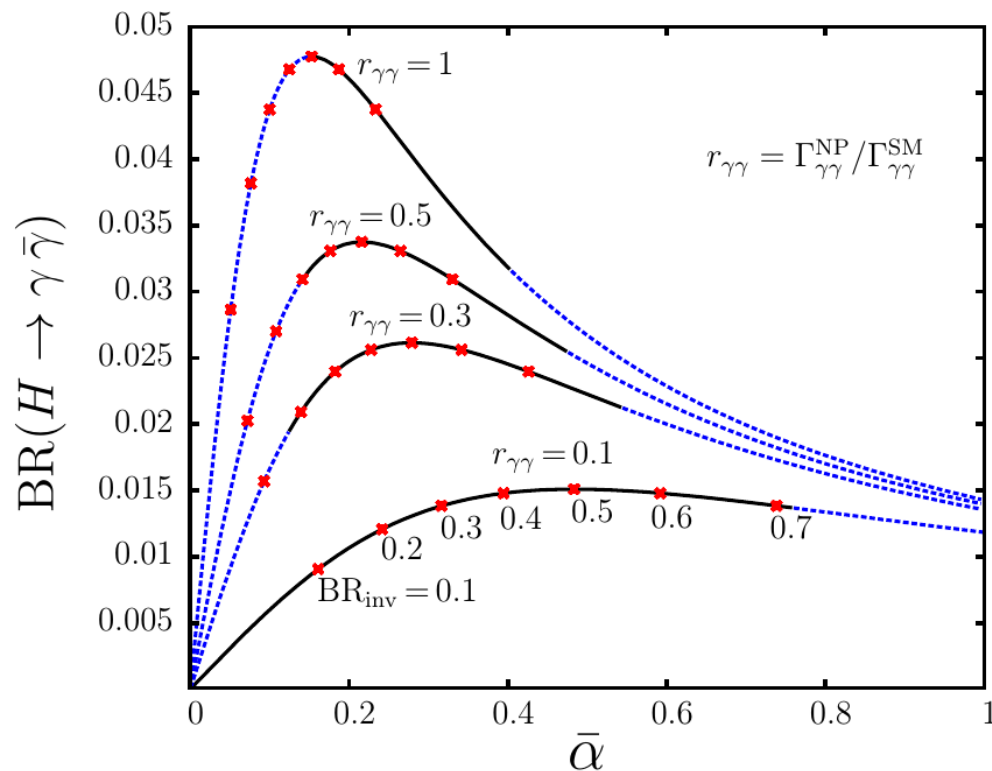


Figure 2: $\text{BR}(H \rightarrow \gamma \bar{\gamma})$ versus the dark U(1) fine structure constant $\bar{\alpha}$. The black solid lines show the allowed BR ranges as a function of the relative new physics contribution to the $H \rightarrow \gamma \gamma$ width, and of the $H \rightarrow \bar{\gamma} \bar{\gamma}$ contribution to the Higgs invisible BR [5].

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

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

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

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

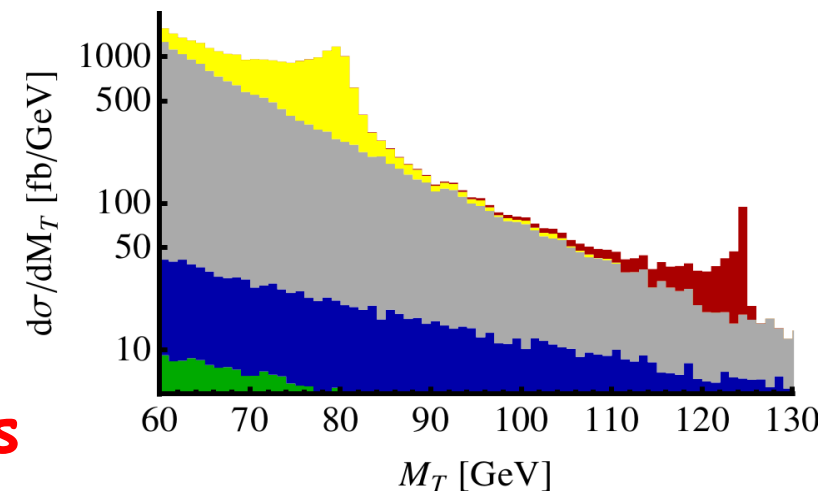
monochromatic photon $E_\gamma = m_H/2$ in the Higgs rest frame

- in Lab frame one can define the variable M_T as the transverse invariant mass of the $\gamma + \cancel{E}_T$ system

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

- M_T distribution peaked at M_H mass

- p_T^γ distribution exhibits similar structure at $M_H/2$



Significance vs BR in gg and VBF mechanisms

Improved analysis including parton shower effects and gg + VBF @ 14 TeV

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

BR $_{\gamma\bar{\gamma}}$ (%)	L= 100 fb $^{-1}$		L=300 fb $^{-1}$		L=3 ab $^{-1}$	
Significance	2σ	5σ	2σ	5σ	2σ	5σ
BR $_{\gamma\bar{\gamma}}$ (VBF)	0.76	1.9	0.43	1.1	0.14	0.34
BR $_{\gamma\bar{\gamma}}$ (ggF)	0.064	0.16	0.037	0.092	0.012	0.029

Table 1: Reach in BR($H \rightarrow \gamma\bar{\gamma}$) (in percentage) for a 95% C.L. exclusion and a 5σ discovery at the 14 TeV LHC, for a Higgs produced either in the VBF or in the gluon-fusion channels, for different integrated luminosities L.

■ large discovery potential @ LHC 14 TeV by gluon fusion

■ sensitivity on BR up to BR $\sim 10^{-3} \rightarrow 10^{-4}$ for L $\sim 0.3-3$ ab $^{-1}$

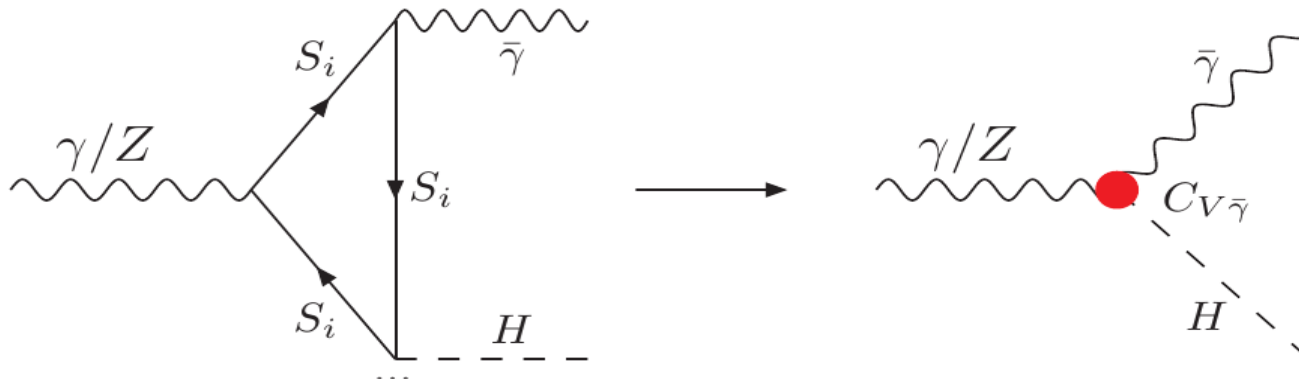
Implications of $H\gamma\bar{\gamma}$ and $HZ\bar{\gamma}$ @ e^+e^-

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 adopted

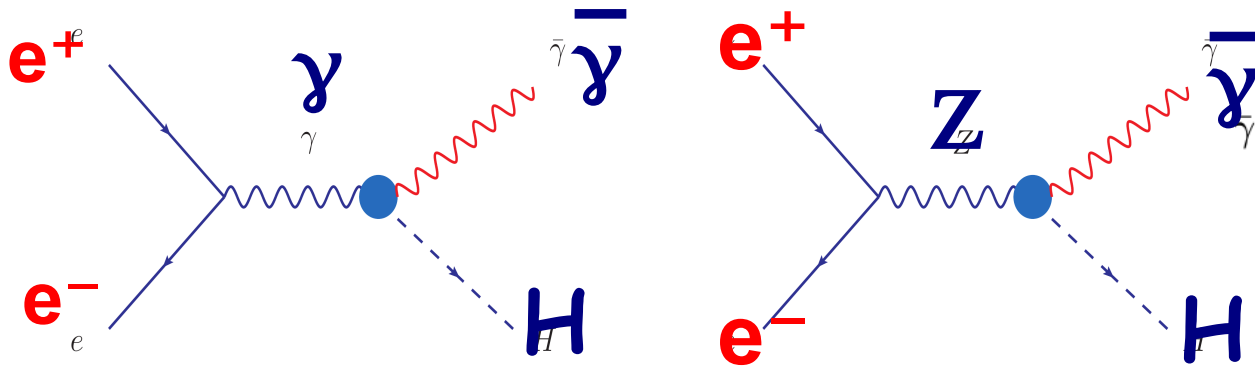
$$e^+e^- \rightarrow H\bar{\gamma} \rightarrow b\bar{b}\bar{\gamma}$$

Model independent analysis:

Effective Lagrangian parametrization

$\bar{\gamma}_{\mu\nu}$ DP field strength

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



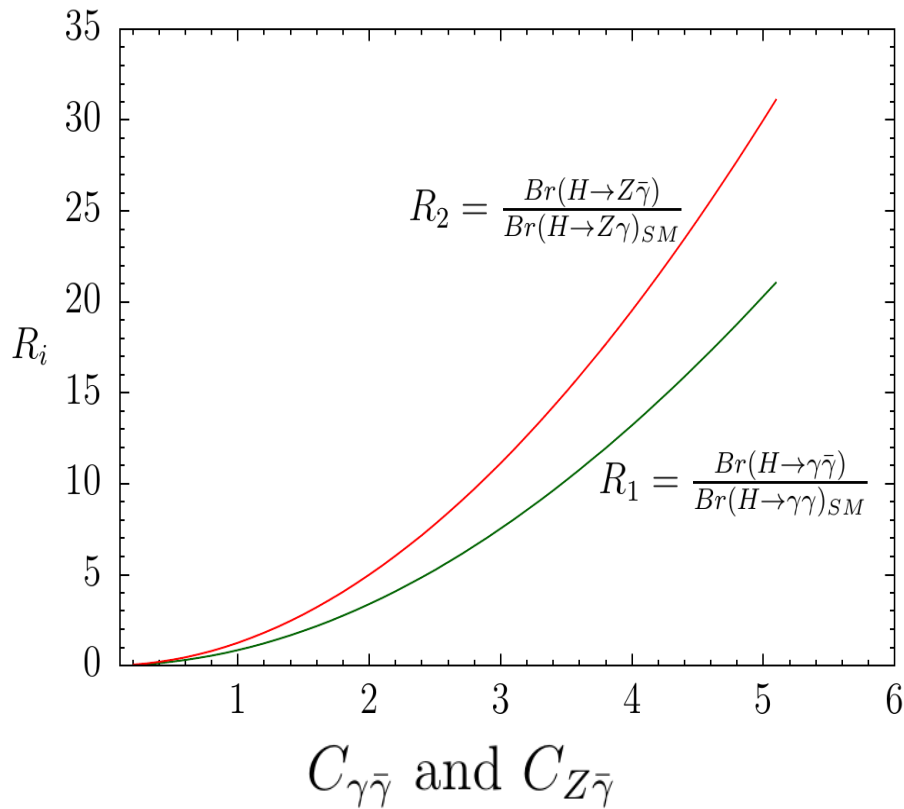
assuming mass degeneracy in Left and Right →
messengers (LR symmetry)

$$C_{Z\bar{\gamma}} = C_{\gamma\bar{\gamma}} R_{Z\gamma}$$

net result from a messenger doublet → $R_{Z\gamma}^{\tilde{q}} = \frac{R_{Z\gamma}^{\tilde{u}} + R_{Z\gamma}^{\tilde{d}}}{2} \approx 0.79$

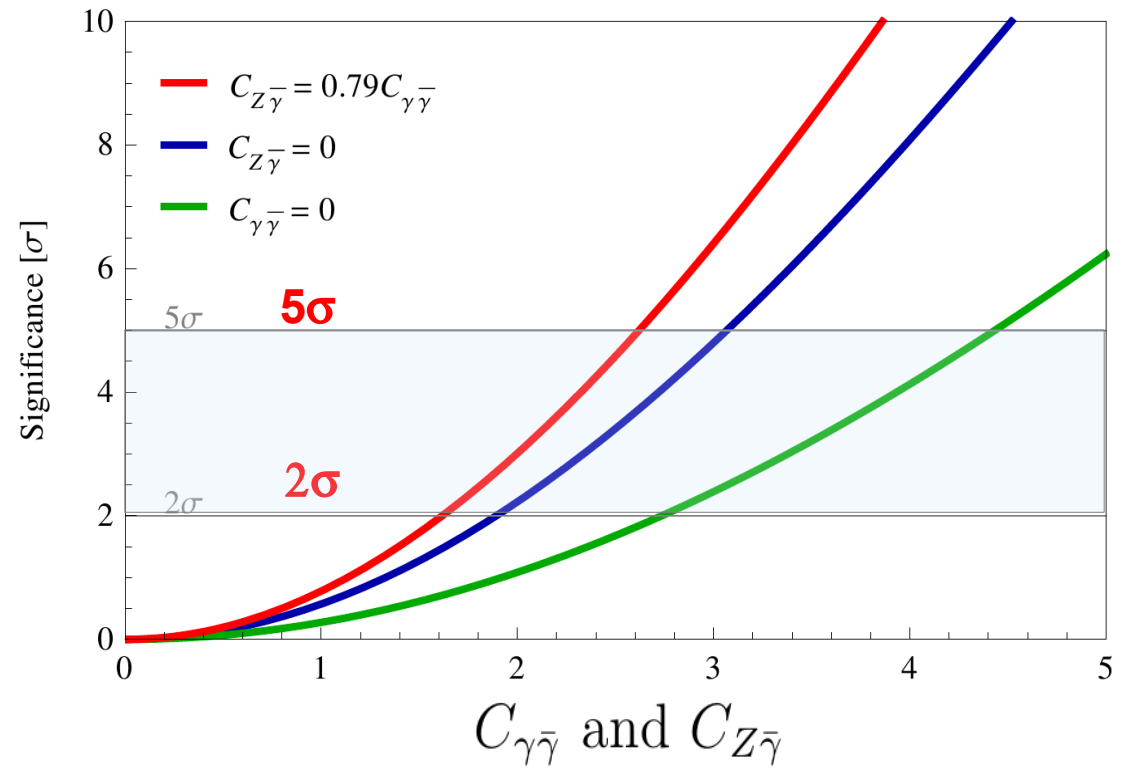
results for $\sqrt{s} = 240$ GeV

Normalized BRs to $\text{BR}_{SM}(\bar{\gamma} \rightarrow \gamma)$



Significance [σ]

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



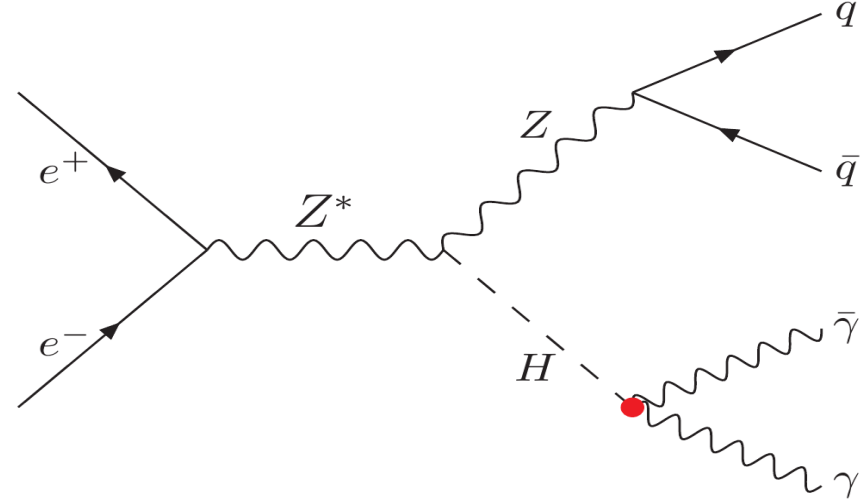
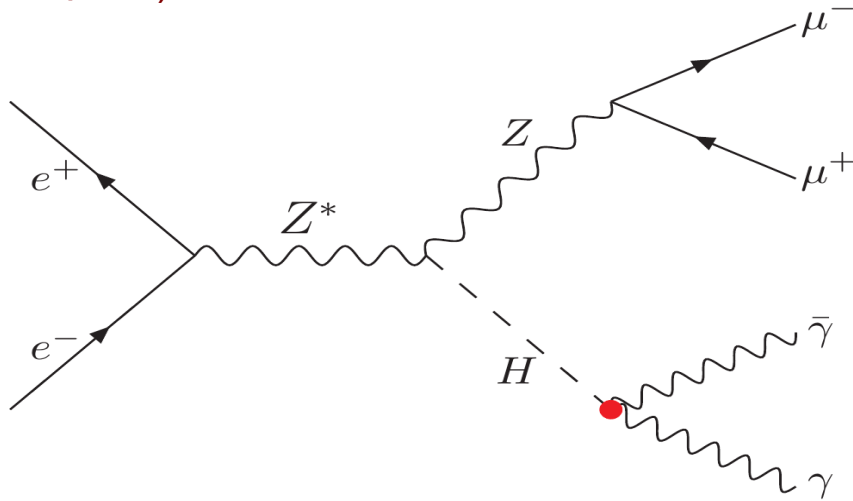
$$C_{\gamma\bar{\gamma}} > 1.9 \quad \Rightarrow \quad \text{BR}(H \rightarrow \gamma\bar{\gamma}) > 3 \text{ BR}_{SM}(H \rightarrow \gamma\gamma)$$

$$C_{Z\bar{\gamma}} > 2.7 \quad \Rightarrow \quad \text{BR}(H \rightarrow Z\bar{\gamma}) > 9 \text{ BR}_{SM}(H \rightarrow Z\gamma)$$

$\sim 6 \times 10^{-3}$

$$e^+e^- \rightarrow ZH \rightarrow (\mu^+\mu^-, q\bar{q})(\gamma\bar{\gamma})$$

Biswas, EG, Heikinen, Mele
PRD 96 (2017)



- model independent analysis → use of Higgs effective vertices
- can provide complementary information to $e^+e^- \rightarrow H\bar{\gamma}$
- requiring an invisible system with vanishing mass in the final state will help a lot in discriminating S/B

assumptions on detector performances

- Muon momentum resolution: $\Delta p/p = 0.1\% + p_T/(10^5 \text{ GeV})$ for $|\eta| < 1$, and 10 times poorer for $1 < |\eta| < 2.5$.
- Photon energy resolution: $\Delta E/E = 16.6\%/\sqrt{E/\text{GeV}} + 1.1\%$.
- Jet energy resolution: $\Delta E/E = 30\%/\sqrt{E/\text{GeV}}$
- Particle identification efficiency for muons and photons: 99% for $p_T > 10 \text{ GeV}$.

Channels considered

Leptonic channel: $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^-\gamma\bar{\gamma}$

Hadronic channel: $e^+e^- \rightarrow ZH \rightarrow q\bar{q}\gamma\bar{\gamma}$

(worst energy resolution for jets can be compensated by larger BR of $Z \rightarrow \text{hadrons}$)

e^+e^- channel less sensitive: $\rightarrow$ poorer electron momentum resolution and additional Z-neutral current t-channel bckg $e^+e^-\bar{\nu}\nu\gamma$

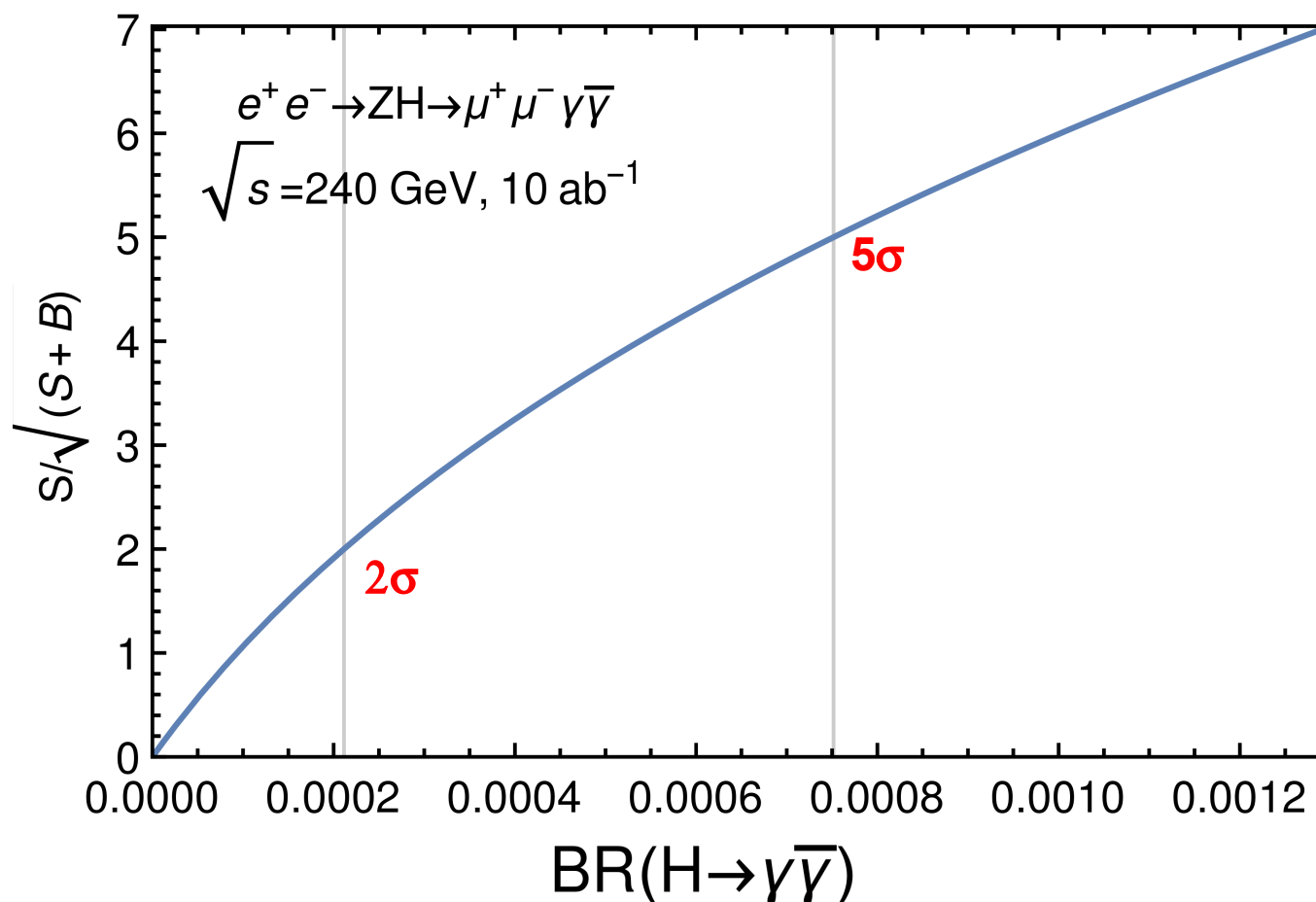
N. events corresponding to $L = 10 \text{ ab}^{-1}$

Process	Basic cuts	$M_{\ell\ell}$ cut	$M_{\gamma\bar{\gamma}}$ cut	M_{miss} cut
$\mu^+\mu^-\gamma\bar{\gamma}$ ($BR_{\gamma\bar{\gamma}} = 0.1\%$)	65.3	54.9	49.7	47.3
$\mu^+\mu^-\nu\bar{\nu}\gamma$	5.00×10^4	5.73×10^3	1.09×10^3	15

↓
main bckg

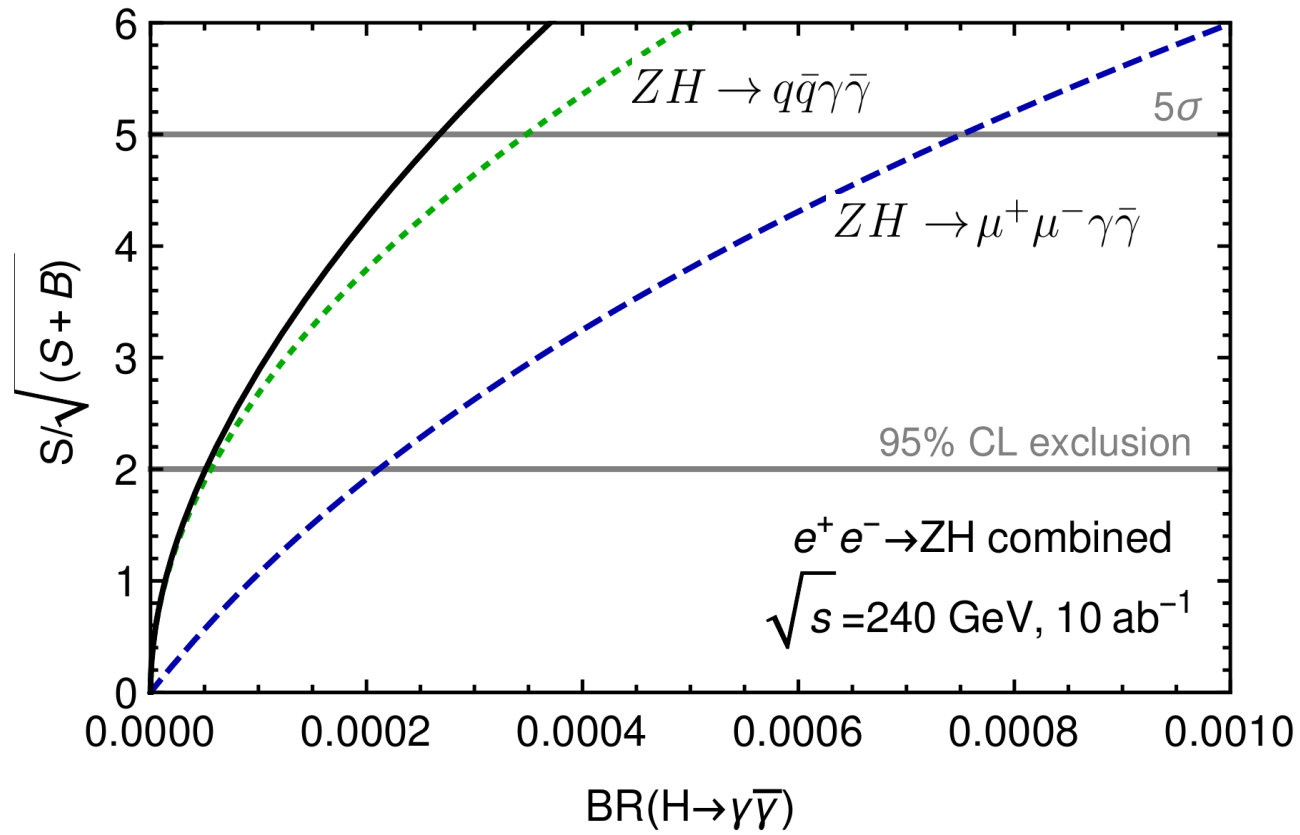
Significance vs BR

↓
very efficient cut



N. events corresponding to $L = 10 \text{ ab}^{-1}$

Process	Basic cuts	M_{jj} cut	$M_{\gamma\bar{\gamma}}$ cut	M_{miss} cut	$\cancel{E}$ cut
$jj\gamma\bar{\gamma}$ ($BR_{\gamma\bar{\gamma}} = 0.1\%$)	804	669	154	110	72
$jj\gamma$	3.39×10^7	2.26×10^7	1.47×10^5	6.5×10^4	—
$jj\nu\bar{\nu}\gamma$	3.9×10^4	3.1×10^4	5.9×10^3	2.2	—



FCNC fermion f decays into a dark photon

$$f \rightarrow f' \bar{\gamma}$$

CKM matrix origin

in the basis of weak-gauge eigenstates (no CKM mixing $X_{ij} \rightarrow \delta_{ij}$)

$$\mathcal{L}_{MS}^I \supset \hat{g}_L \left(\sum_{i,j=1}^N \left[\bar{q}_L^i (X_L^U)_{ij} Q_R^{Uj} \right] \hat{S}_L^{Uj} + \sum_{i,j=1}^N \left[\bar{q}_L^i (X_L^D)_{ij} Q_R^{Dj} \right] \hat{S}_L^{Dj} \right) \\ + \hat{g}_R \left(\sum_{i,j=1}^N \left[\bar{q}_R^i (X_R^U)_{ij} Q_L^{Uj} \right] \hat{S}_R^{Uj} + \sum_{i,j=1}^N \left[\bar{q}_R^i (X_R^D)_{ij} Q_L^{Dj} \right] \hat{S}_R^{Dj} \right)$$

radiative generation of Yukawa implies

$$Y_{ij}^{U,D} \sim \left(X_L^{U,D}{}^\dagger \cdot \hat{Y}^{U,D} \cdot X_R^{U,D} \right)_{ij}$$

$$\hat{Y}^{U,D} = \text{diag}[Y_1^{U,D}, Y_2^{U,D}, Y_3^{U,D}]$$

a “natural” way to generate X can require higher loops

EG, Marzola, Raidal, Veermae (in preparation)

Yukawas can be diagonalized as usual by a bi-unitary transformation

$$\text{diag}[Y^{U,D}] = V_{L,R}^{U,D \dagger} \cdot Y^{U,D} \cdot V_{L,R}^{U,D} \longrightarrow \text{CKM matrix } K = V_L^U \dagger \cdot V_L^D.$$

minimal flavor violation requires $\rightarrow X_{L,R}^{U,D} \sim \mathbf{1} + \Delta_{L,R}^{U,D} \quad |\Delta_{L,R}^{U,D}| \ll 1$

no reason why $X_L^{U,D}$ should be unitary

After rotation to quark-mass eigenstates

$$X_{L,R}^U \longrightarrow \rho_{L,R}, \quad X_{L,R}^D \longrightarrow \eta_{L,R}$$

$$\rho_{L,R} \equiv V_{L,R}^{U \dagger} \cdot X_{L,R}^U$$

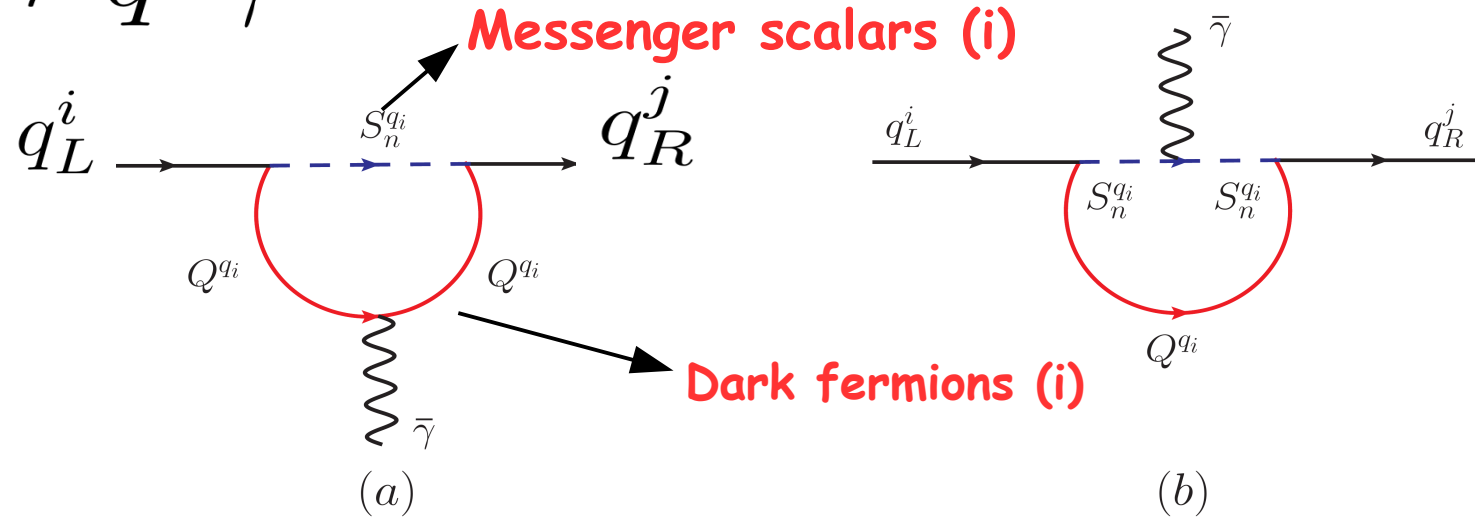
$$\eta_{L,R} \equiv V_{L,R}^{D \dagger} \cdot X_{L,R}^D$$

$\rho_{L,R}, \eta_{L,R} \longrightarrow$ matrices characterizing new FCNC interactions

FCNC decays of SM fermions into a Dark Photon

EG, Mele, Raidal, Venturini, PRD 94 (2016)

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



■ 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

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

Effective scales for UP-quark transitions (exact in ξ, x)

neglecting mass of final fermion

$$\begin{aligned} \frac{1}{(\Lambda_L^U)_{ij}} &= \frac{\bar{e} m_{U_i}}{\bar{m}_U^2} \left[\bar{e}_i^U \frac{\rho_R^{ji}}{\rho_R^{ii}} F_{LR}(x_i^U, \xi_U) - \frac{g_R^2}{16\pi^2} \sum_{k=1}^3 \bar{e}_k^U \rho_R^{jk} \rho_R^{ki} F_{RR}(x_k^U, \xi_U) \right] \\ \frac{1}{(\Lambda_R^U)_{ij}} &= \frac{\bar{e} m_{U_i}}{\bar{m}_U^2} \left[\bar{e}_i^U \frac{\rho_L^{ji}}{\rho_L^{ii}} F_{RL}(x_i^U, \xi_U) - \frac{g_L^2}{16\pi^2} \sum_{k=1}^3 \left(\bar{e}_k^U \rho_L^{jk} \rho_L^{ki} F_{LL}(x_k^U, \xi_U) \right. \right. \\ &\quad \left. \left. + \left(\frac{\bar{m}_U^2}{\bar{m}_D^2} \right) \bar{e}_k^D \eta_L^{jk} \eta_L^{ki} F_{LL}(x_k^D, \xi_D) \right) \right], \end{aligned}$$

$$F_{RR}(x, \xi) = F_{LL}(x, \xi) \quad F_{RL}(x, \xi) = F_{LR}(x, \xi) \rightarrow \text{Loop functions}$$

leading term $\rightarrow$ dark-fermion mass term absorbed into quark mass

Effective scale proportional to the decaying fermion mass

$$\Gamma(q^i \rightarrow q^j \bar{\gamma}) \sim \frac{m_{q_i}^5 \bar{\alpha}}{16\pi^3 \bar{m}_q^4} \times |\text{loop functions}|^2$$

FCNC decays of SM fermions into a Dark Photon

EG, Mele, Raidal, Venturini, PRD 94 (2016)

- 9 new kind of FCNC signatures predicted !

top	$t \rightarrow c \bar{\gamma} , u \bar{\gamma}$
bottom	$b \rightarrow s \bar{\gamma} , d \bar{\gamma}$
charm,s	$c \rightarrow u \bar{\gamma} , s \rightarrow d \bar{\gamma}$

tau	$\tau \rightarrow \mu \bar{\gamma} , e \bar{\gamma}$
muon	$\mu \rightarrow e \bar{\gamma}$

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

- Large and possibly measurable BRs are allowed, up to

- $\text{BR}(b \rightarrow q \bar{\gamma}) \sim 10^{-4} - 10^{-3}$

- $\text{BR}(c \rightarrow u \bar{\gamma}) \sim 10^{-8} - 10^{-4}$

- $\text{BR}(t \rightarrow q \bar{\gamma}) \sim 10^{-10} - 10^{-7}$

- $\text{BR}(\mu \rightarrow e \bar{\gamma}) \sim 10^{-10} - 10^{-9}$

- $\text{BR}(\tau \rightarrow l \bar{\gamma}) \sim 10^{-10} - 10^{-6}$

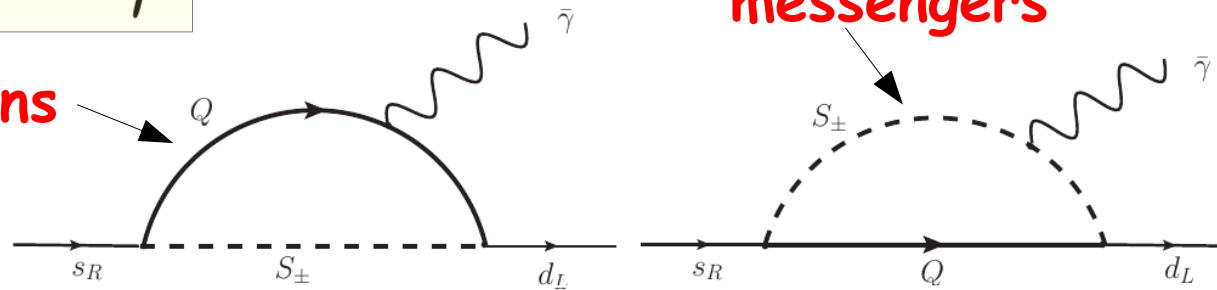
depending on various parameters and on flavor universality structure of messenger sector

FCNC Kaon decay into a massless Dark photon

Fabbrichesi, EG, Mele, PRL 119 (2017)

$$s \rightarrow d \bar{\gamma}$$

Dark-fermions



messengers

Effective Hamiltonian

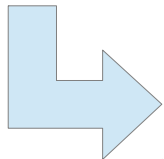
$$\mathcal{H}_{eff}^{\Delta S=1} = \frac{e_D}{64 \pi^2} \frac{\xi}{\Lambda} \hat{Q}$$

$\xi = g_L g_R / 2$ (FC couplings)
 Λ (DF ~ messenger mass)

FCNC magnetic-dipole operator

$$\hat{Q} = (\bar{s} \sigma^{\mu\nu} d) \bar{F}_{\mu\nu}$$

Dark-photon



$$K^+ \rightarrow \pi^+ \pi^0 \bar{\gamma}$$

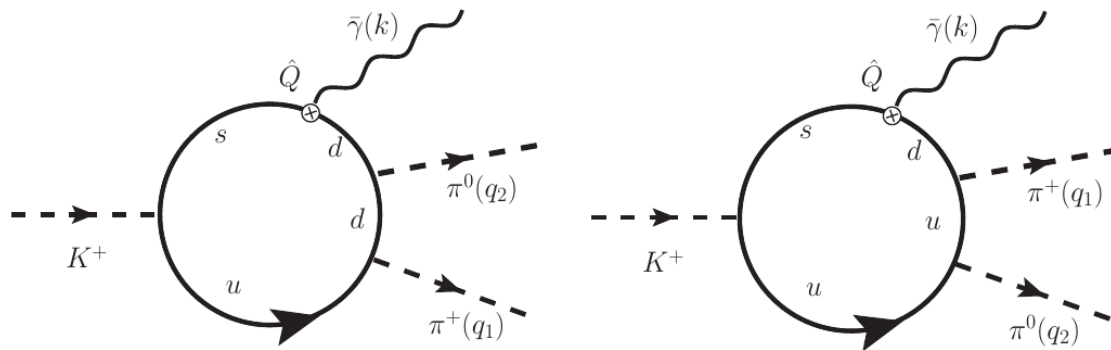
$K^+ \rightarrow \pi^+ \bar{\gamma} \Rightarrow$ for massless dark photon identically vanishes

$$K^+(p) \rightarrow \pi^+(q_1) \pi^0(q_2) \bar{\gamma}(k)$$

$$\langle \bar{\gamma} \pi^+ \pi^0 | \mathcal{H}_{eff}^{\Delta S=1} | K^+ \rangle = \frac{M(z_1, z_2)}{m_K^3} \varepsilon_{\mu\nu\rho\sigma} q_1^\nu q_2^\rho k^\sigma \varepsilon^\mu(k)$$

$$\frac{d^2\Gamma}{dz_1 dz_2} = \frac{m_K}{(4\pi)^3} |M(z_1, z_2)|^2 \{ z_1 z_2 [1 - 2(z_1 + z_2) - r_1^2 - r_2^2] - r_1^2 z_2^2 - r_2^2 z_1^2 \}, \quad \text{where } z_i = k \cdot q_i / m_K^2 \text{ and } r_i = M_{\pi_i} / m_K$$

Matrix element estimated using the Chiral-Quark Model



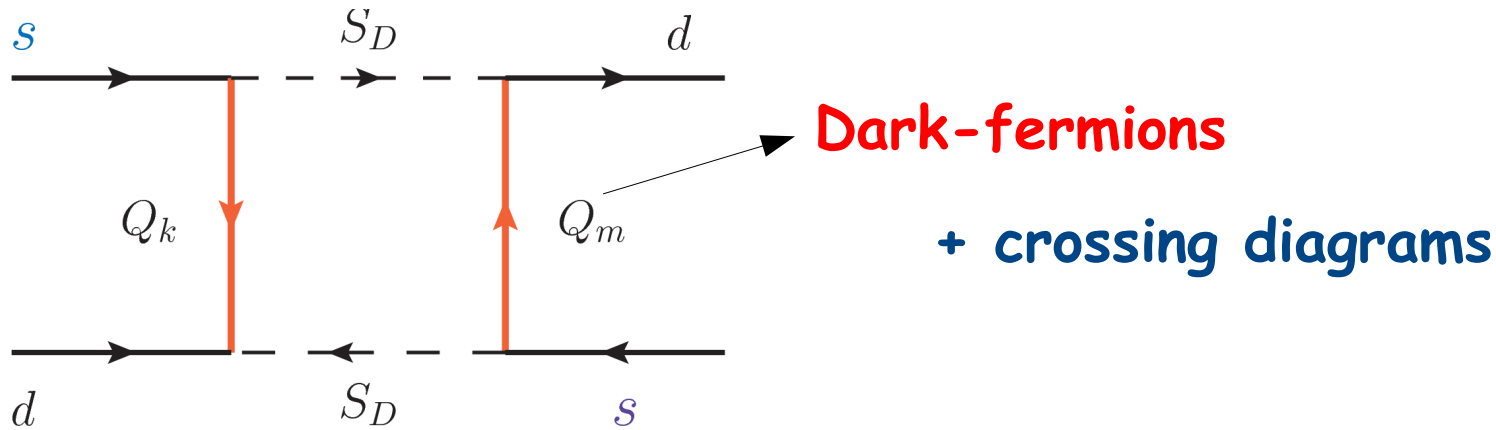
F. Gursey, Nuovo Cim. **16**, 230 (1960); J. A. Cronin, Phys. Rev. **161**, 1483 (1967); S. Weinberg, Physica A **96**, 327 (1979); A. Manohar and H. Georgi, Nucl. Phys. B **234**, 189 (1984); A. Manohar and G. W. Moore, Nucl. Phys. B **243**, 55 (1984).

D_0, D_{00} usual PV functions

$$\frac{M(z_1, z_2)}{m_K^3} = \frac{e_D}{32\pi^2} \frac{\xi}{\Lambda} \frac{M^3}{\pi^2 f^3} \left[M^2 D_0(0, m_\pi^2, m_\pi^2, m_K^2; 2m_K^2 z_1 + m_\pi^2, m_K^2(1 - 2z_1 - 2z_2); M, M, M, M) \right. \\ \left. - D_{00}(0, m_\pi^2, m_\pi^2, m_K^2; 2m_K^2 z_1 + m_\pi^2, m_K^2(1 - 2z_1 - 2z_2); M, M, M, M) + (z_1 \leftrightarrow z_2) \right].$$

QCD NLO contributions to $\Delta S=2$ effective Hamiltonian included

M. Ciuchini *et al.*, JHEP **9810**, 008 (1998) [[hep-ph/9808328](#)].



$$\mathcal{H}_{eff}^{\Delta S=2} = \sum_i^5 C_i Q_i + \sum_{i=1}^3 \tilde{C}_i \tilde{Q}_i$$

$\mu = 2 \text{ GeV}$

$$\langle Q_i \rangle = \langle K^0 | Q_i | \bar{K}^0 \rangle$$

	$Q_1, \tilde{Q}_1$	$Q_2, \tilde{Q}_2$	$Q_3, \tilde{Q}_3$	Q_4	Q_5
$\langle Q_i \rangle$	$\bar{d}_L^\alpha \gamma_\mu s_L^\alpha \bar{d}_L^\beta \gamma_\mu s_L^\beta, (L \leftrightarrow R)$	$\bar{d}_R^\alpha s_L^\alpha \bar{d}_R^\beta s_L^\beta, (L \leftrightarrow R)$	$\bar{d}_R^\alpha s_L^\beta \bar{d}_R^\beta s_L^\alpha, (L \leftrightarrow R)$	$\bar{d}_R^\alpha s_L^\alpha \bar{d}_L^\beta s_R^\beta$	$\bar{d}_R^\alpha s_L^\beta \bar{d}_L^\beta s_R^\alpha$
$C_i(\Lambda)$	$1/3 m_K f_K^2 B_1(\mu)$	$-5/2 X_K m_K f_K^2 B_3(\mu)$	$1/24 X_K m_K f_K^2 B_3(\mu)$	$1/4 X_K m_K f_K^2 B_4(\mu)$	$1/12 X_K m_K f_K^2 B_5(\mu)$
	$-1/24 C^2$	0	$1/12 C^2$	$1/6 C^2$	$1/6 C^2$

$$C^2 = \xi^2 / (16\pi^2 \Lambda^2) \quad \xi = g_L g_R / 2$$

$$X_K(\mu) = (m_K / (m_d(\mu) + m_s(\mu)))^2$$

A simplified model (1 dark-fermion + messenger fields)

$$\text{BR}(K^+ \rightarrow \pi^+ \pi^0 \bar{\gamma}) \simeq 1.31 \alpha_D \eta^2 \frac{\xi^2}{\Lambda^2}$$

■ $\Lambda \rightarrow$ Dark sector mass scale

Fabbrichesi, EG, Mele, PRL 119 (2017)

QCD ren. fact.

$\text{BR}(K^+ \rightarrow \pi^+ \pi^0 \bar{\gamma})$

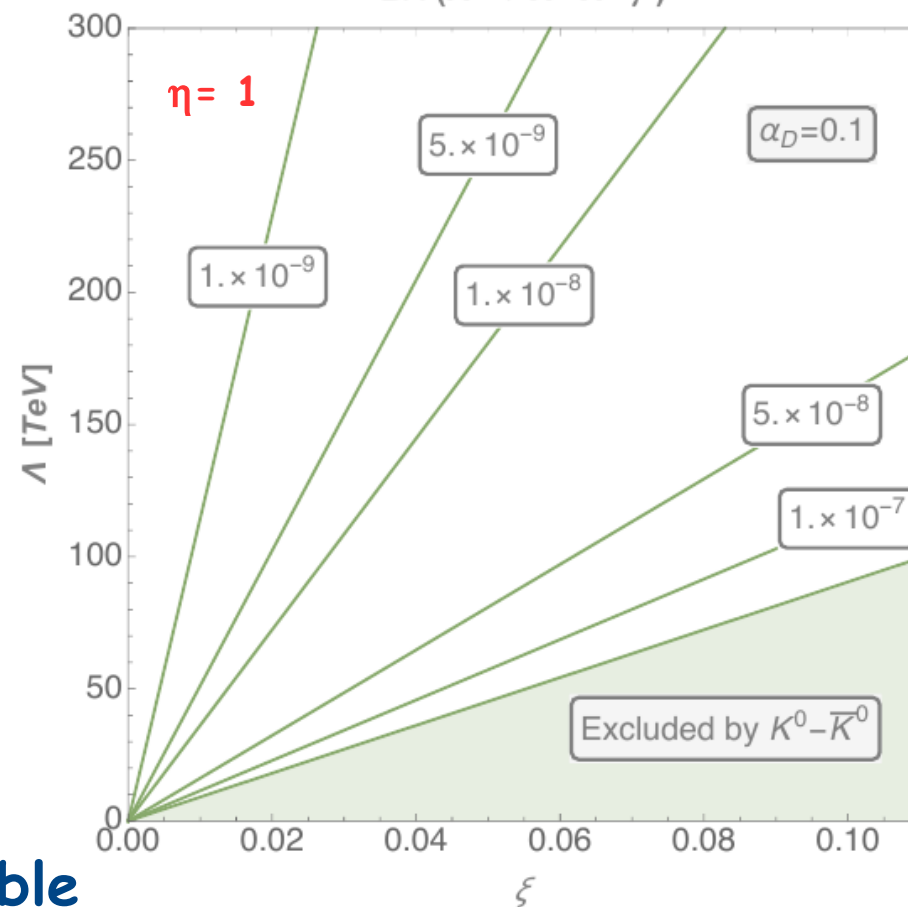
NLO K - $\bar{K}$ mixing constraints

[TeV]

$$\Delta M_K = 8.47 \times 10^{-13} \frac{\xi^2}{\Lambda^2}$$

[TeV]

$$\text{BR}(K^+ \rightarrow \pi^+ \pi^0 \bar{\gamma}) \lesssim 1.6 \times 10^{-7}$$



Large BR of order 10^{-8} - 10^{-7} possible
 $\rightarrow$ in the ballpark of NA62 exp.

FIG. 3: $\text{BR}(K^+ \rightarrow \pi^+ \pi^0 \bar{\gamma})$ as a function of the effective scale Λ and coupling $\xi = g_L g_R / 2$, for a representative choice of the coupling strength $\alpha_D = 0.1$.

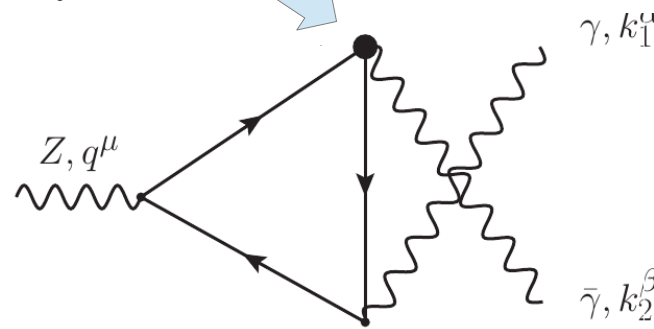
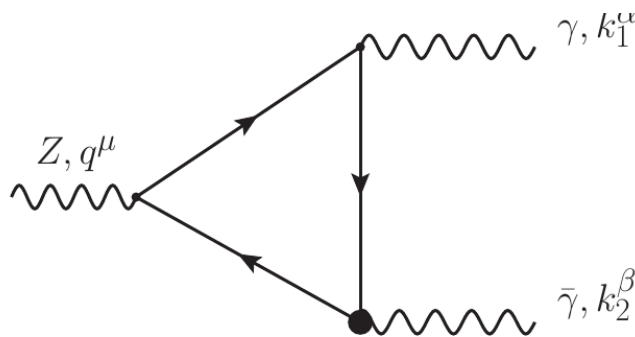
Z decay into photon + (massless) DP

$$Z(q) \rightarrow \gamma(k_1)\bar{\gamma}(k_2)$$

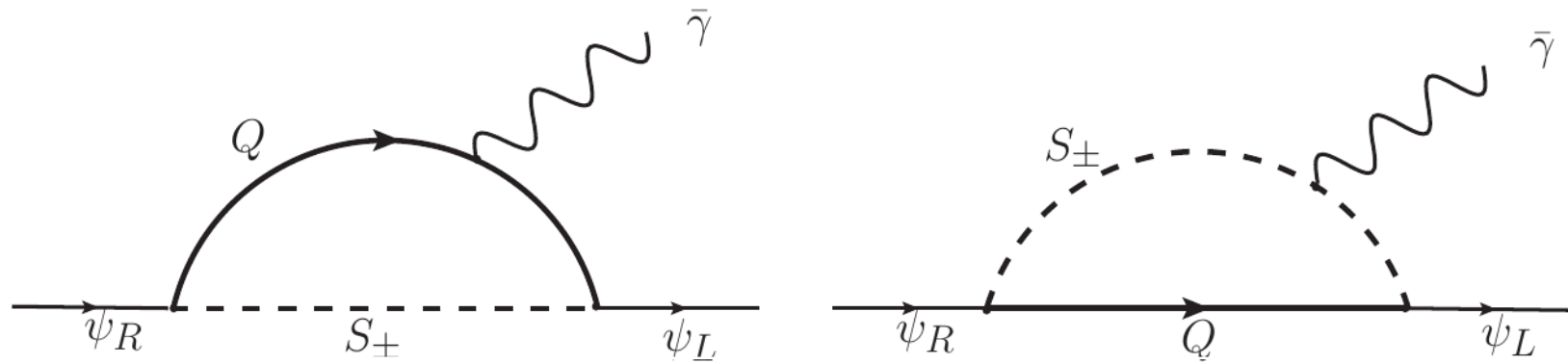
Landau-Yang theorem violated ?

- **NO** → does not apply if **massless spin1** states can be distinguished as the case of **photon + DP**
- but to bypass theorem photon and DP must couple differently to SM fermions in the loop
- massless DP have no tree-level couplings with SM fermions, but can have **dipole-like** couplings

$$\mathcal{L} = \sum_f \frac{e_D}{2\Lambda} \bar{\psi}_f \sigma_{\mu\nu} \left(d_M^f + i\gamma_5 d_E^f \right) \psi_f B^{\mu\nu}$$



quarks and leptons running in the loop



■ to simplify analysis we assume **common mass** = Λ for DF (Q) and messenger fields S.

■ matching Wilson coefficients at the scale Λ we e get

$$\mathcal{L} = \sum_f \frac{e_D}{2\Lambda} \bar{\psi}_f \sigma_{\mu\nu} \left(d_M^f + i\gamma_5 d_E^f \right) \psi_f B^{\mu\nu}$$

$$d_M^f = \frac{1}{2} \text{Re} \frac{g_L^f g_R^{f*}}{(4\pi)^2} \quad \text{and} \quad d_E^f = \frac{1}{2} \text{Im} \frac{g_L^f g_R^{f*}}{(4\pi)^2}$$

1-loop amplitude is finite and predictable

$$\mathcal{M}_M = \frac{e_D e}{4\pi^2} \sum_{i=1}^3 C_i Q_i^{\mu\alpha\beta} \epsilon_\mu^Z(q) \epsilon_\alpha(k_1) \bar{\epsilon}_\beta(k_2)$$



Magnetic contribution

$$\begin{aligned} Q_1^{\mu\alpha\beta} &= \varepsilon^{\alpha\beta\mu\lambda} k_{1\lambda} - \frac{2}{M_Z^2} \varepsilon^{\alpha\mu\lambda\rho} k_1^\beta k_{1\lambda} k_{2\rho} \\ Q_2^{\mu\alpha\beta} &= \varepsilon^{\alpha\beta\mu\lambda} k_{2\lambda} - \frac{2}{M_Z^2} \varepsilon^{\beta\mu\lambda\rho} k_2^\alpha k_{1\lambda} k_{2\rho} \\ Q_3^{\mu\alpha\beta} &= \frac{1}{M_Z^2} (k_1^\mu - k_2^\mu) \varepsilon^{\alpha\beta\lambda\rho} k_{1\lambda} k_{2\rho} \end{aligned}$$

$$C_1 = \sum_f \frac{r_f m_f d_M^f}{\Lambda} (2 + B_f + 2C_f M_Z^2)$$

$$C_2 = \sum_f \frac{r_f m_f d_M^f}{\Lambda} (3 + 2B_f - 2C_f m_f^2)$$

$$C_3 = \sum_f \frac{r_f m_f d_M^f}{\Lambda} (11 + 5B_f + 2C_f (m_f^2 + M_Z^2))$$

$$r_f = N_c^f g_A^f Q_f \quad g_A^f = g T_3^f / (2 \cos \theta_W)$$

$$B_f \equiv \text{Disc}[B_0(M_Z^2, m_f, m_f)],$$

$$C_f \equiv C_0(0, 0, M_Z^2, m_f, m_f, m_f)$$

$B_0, C_0 \rightarrow$ PV functions

all WI satisfied $\rightarrow$ strong check of computation

$$\Gamma(Z \rightarrow \gamma\bar{\gamma}) = \frac{\alpha_D \alpha M_Z}{24\pi^3} (|C_M|^2 + |C_E|^2)$$

$$C_{M,E} = \sum_f d_{M,E}^f \xi^f(m_f) \quad \xi^f(m_f) \equiv \frac{r_f m_f}{\Lambda} \left(3 + B_f + 2m_f^2 C_f \right)$$

SM fermion masses

$$\text{BR}_f = \alpha_D (|d_M^f|^2 + |d_E^f|^2) / (\Lambda/\text{TeV})^2 X_f$$

	<i>b</i>	<i>t</i>	<i>s</i>	<i>c</i>	τ	μ	
X_f	4.80	0.82	0.014	4.78	1.30	0.017	$\times 10^{-9}$

Present bounds from LEP , $\text{BR} < 10^{-7}$ bottom gives largest effect

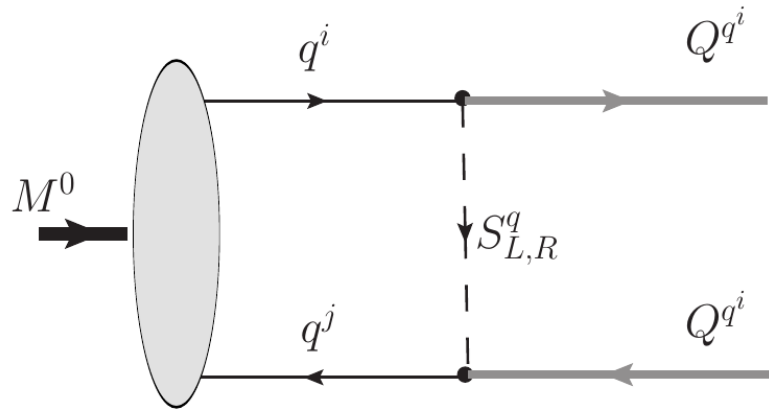
Future perspective

- ▶ **hadron colliders** → challenging to separate signal from bckg
→ boosted Z systems more promising
- ▶ $\text{BR}(Z \rightarrow \gamma\bar{\gamma}) \sim 10^{-9}$ expected for $\alpha_D \sim 1$, $\Lambda \sim 1 \text{ TeV}$
- ▶ **200 events** expected at HL-LHC with 3ab^{-1} of L
- ▶ **10⁴ events** expected at 100 TeV collider with 30ab^{-1} of L
- ▶ better opportunities @ **FCC-ee colliders**

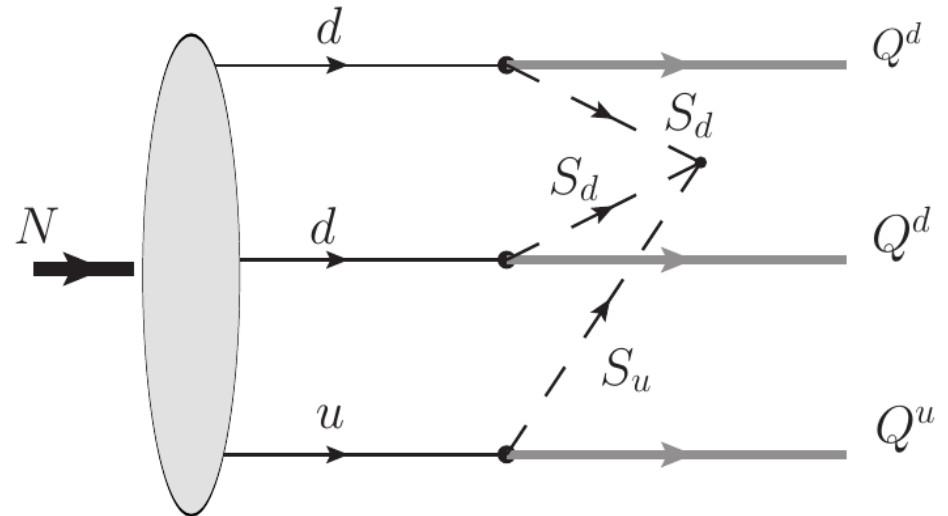
Neutral hadron disappearing into the darkness

Barducci, Fabbrichesi, EG, arXiv:1806.05678

Meson ($\bar{q}^j q^i$) $\rightarrow$ $\bar{Q}^i Q^i$



Neutron $\rightarrow$ $Q^d Q^d Q^u$



Relevant effective operators

$$\hat{Q}_L^{ij} = \bar{Q}_L^i \gamma^\mu Q_L^i \bar{q}_R^j \gamma_\mu q_R^i$$

$$\hat{Q}_R^{ij} = \bar{Q}_R^i \gamma^\mu Q_R^i \bar{q}_L^j \gamma_\mu q_L^i$$

$$\hat{Q}_1 = \varepsilon_{\alpha\beta\gamma} (\bar{Q}_R^U u_L^\alpha) (\bar{Q}_R^D d_L^\beta) (\bar{Q}_L^D d_R^\gamma)$$

$$\hat{Q}_2 = \varepsilon_{\alpha\beta\gamma} (\bar{Q}_L^U u_R^\alpha) (\bar{Q}_L^D d_R^\beta) (\bar{Q}_L^D d_R^\gamma)$$

If U(1) dark charges $q(Q^u) = -2 q(Q^d)$ as for EM charges of quarks, gauge invariance allows for N decay in DFs (general baryon number conservation)

Mesons decays

$$\left\{ \begin{array}{l} \Gamma(M_{ij}^0 \rightarrow Q^i \bar{Q}^i) = \frac{1}{8\pi} \frac{|\bar{\mathcal{M}}_{M^0}^{ij}|^2 |\vec{k}_i|}{m_{M^0}^2} S \left[\frac{q_i^2 \alpha_D}{v_i} \right] \longrightarrow \text{Sommerfeld factor} \\ \text{(relevant at treshold)} \\ |\mathcal{M}_{M^0}^{ij}|^2 = \frac{f_{M^0}^2 m_{M^0}^2 m_{Q^i}^2}{8m_S^4} P_{ij}^2 (g_L^2 + g_R^2)^2 \quad m_S \rightarrow \text{common messenger mass} \\ P_{ij}^{L,R} = \rho_{ij}^{L,R} \rho_{ii}^{L,R} \quad \text{FCNC couplings} \end{array} \right.$$

due to chirality $\rightarrow$ meson width proportional to DF masses m_{Q^i}

$$\bar{M}^0 M^0 \text{ mixing} \rightarrow \Delta m_{M^0} = \left[\frac{g_L^4 (\rho_{ij}^L)^2 \rho_{ii}^L \rho_{jj}^L + g_R^4 (\rho_{ij}^R)^2 \rho_{ii}^R \rho_{jj}^R}{m_S^2} \right] \frac{f_{M^0}^2 m_{M^0}}{192\pi^2}$$

$$\begin{aligned} m_{Q^s} &= 200 \text{ MeV} \quad g_L^i = g_R^i = \lambda \\ \text{BR}|_{K_L} &\simeq 3.0 \times 10^{-1} \lambda^4 P_{sd}^2 \left(\frac{1 \text{ TeV}}{m_S} \right)^4 \\ \text{BR}|_{K_L} &\lesssim 7.8 \times 10^{-5} \left(\frac{1 \text{ TeV}}{m_S} \right)^2 \end{aligned}$$

$$\begin{aligned} m_Q^b &= 2 \text{ GeV} \\ \text{BR}|_{B^0} &\simeq 1.4 \times 10^{-2} \lambda^4 P_{bd}^2 \left(\frac{1 \text{ TeV}}{m_S} \right)^4 \\ \text{BR}|_{B^0} &\lesssim 2.4 \times 10^{-5} \left(\frac{1 \text{ TeV}}{m_S} \right)^2 \end{aligned}$$

upper bounds on BR from mixing independent from couplings !

Neutron decays

■ Neutron puzzle: life time measured in two ways:

- by counting cooled neutron stored in a container (bottle method)
- protons coming from neutron decaying while traveling in a volume (beam method)

■ two measurements do not agree → 4σ discrepancy, beam result 8sec longer

■ new physics explanation: existence of an additional invisible decay of neutron (only beam method affected) B. Fornal and B. Grinstein, [arXiv:1801.01124](#) [hep-ph]

▶ decay channels studied so far: $N \rightarrow DF + \gamma, DS + DF, DF + \bar{\gamma}.$

J. M. Cline and J. M. Cornell, [arXiv:1803.04961](#) [hep-ph]

■ due to U(1) charge conservation, our model predicts

$$N(p) \rightarrow Q^U(k)Q^D(k_1)Q^D(k_2)$$

- 9-dim operators involved → naturally suppressed
- for light DF, neutron decay fully protected by a mass scale of ~ 100 TeV

■ constraints from nuclear physics (matter stability)

decay kinematically close to ${}^9\text{Be}$ decay into unstable isotope ${}^8\text{Be}$
 (largest energy difference) $937.9 \text{ MeV} < \sum_i m_{Q^i} < 939.565 \text{ MeV} = m_N$

borderline with perturbation theory $\rightarrow \eta\mu = 10 m_S$

$$m_{Q^U} = m_{Q^D} \simeq 313 \text{ MeV}$$

$$\Gamma_{N \rightarrow Q^U Q^D Q^D} \simeq 8.5 \times 10^{-35} S_N \left(\frac{\lambda\rho}{4\pi} \right)^6 \left(\frac{1 \text{ TeV}}{m_S} \right)^{10} \text{ GeV}$$

■ Neutron puzzle requires $\Gamma \sim 10^{-30} \text{ GeV} \rightarrow \text{extreme choices}$

Sommerfeld factor $S_N \sim 10^5$ or $m_S \sim 200 \text{ GeV}$ (if messeng. mainly decay $\rightarrow t + \text{DF}$)

What if DF are lighter than Beryllium constraints ?

■ Absence of inv. decay of Neutron in ${}^{16}\text{O}$ and ${}^{12}\text{C}$ from SNO and KamLaAND

$$\tau_N^{\text{inv}} \gtrsim 10^{29} \text{ years} \rightarrow \Gamma < 10^{-61} \text{ GeV} \quad m_{Q^U} = m_{Q^D} = 100 \text{ MeV}$$

$$\Gamma_{N \rightarrow \text{invisible}} \simeq 1.2 \times 10^{-61} \lambda^6 \rho^6 \left(\frac{100 \text{ TeV}}{m_S} \right)^{10} \text{ GeV}$$

$\rightarrow$ naturally satisfied by 100 TeV mass messengers !

Conclusions

■ Origin of Yukawa might require existence of a Dark Sector to explain Yukawa hierarchy → a new rich phenomenology predicted !

■ Higgs boson can be the SM portal to Dark Photons

- ▶ can be now tested @ LHC or at future linear colliders
- ▶ search for dark photons in $H \rightarrow \gamma \bar{\gamma}$, and $H \rightarrow Z \bar{\gamma}$

■ In FCNC sector: new 9 processes predicted

- ▶ $t \rightarrow (c,u) \bar{\gamma}$, $b \rightarrow (s,d) \bar{\gamma}$, $c \rightarrow u \bar{\gamma}$, $s \rightarrow d \bar{\gamma}$, $\tau \rightarrow l \bar{\gamma}$, $\mu \rightarrow e \bar{\gamma}$
- ▶ not yet experimentally investigated

■ a new Z decay predicted $Z \rightarrow \gamma \bar{\gamma} \rightarrow$ promising at e^+e^- colliders

■ FCNC $s \rightarrow d \bar{\gamma}$ transition: golden channel

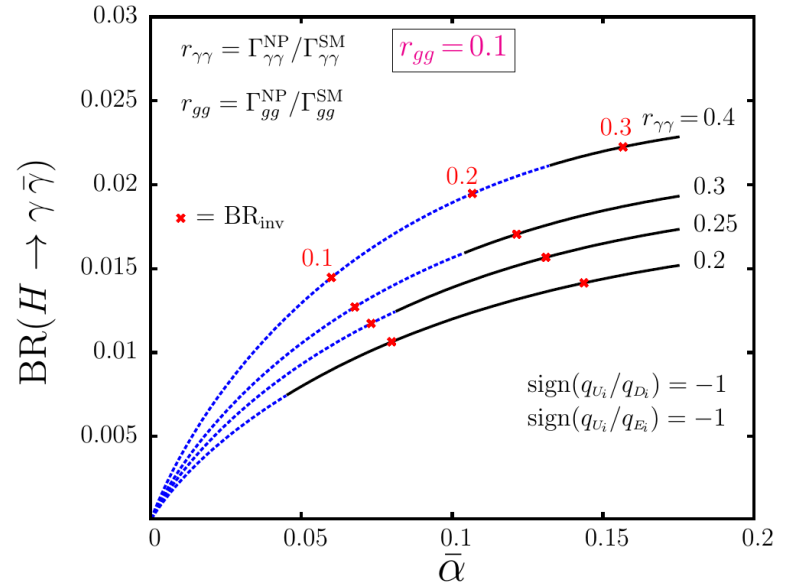
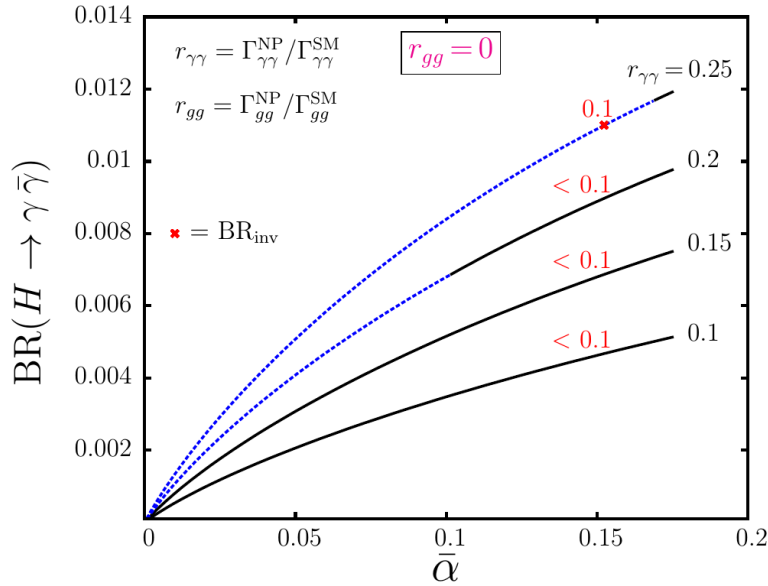
$$K^+ \rightarrow \pi^+ \pi^0 + \bar{\gamma}$$

- ▶ large available rates BR $\sim 10^{-8} - 10^{-7}$
- ▶ currently under consideration by NA62 @ CERN

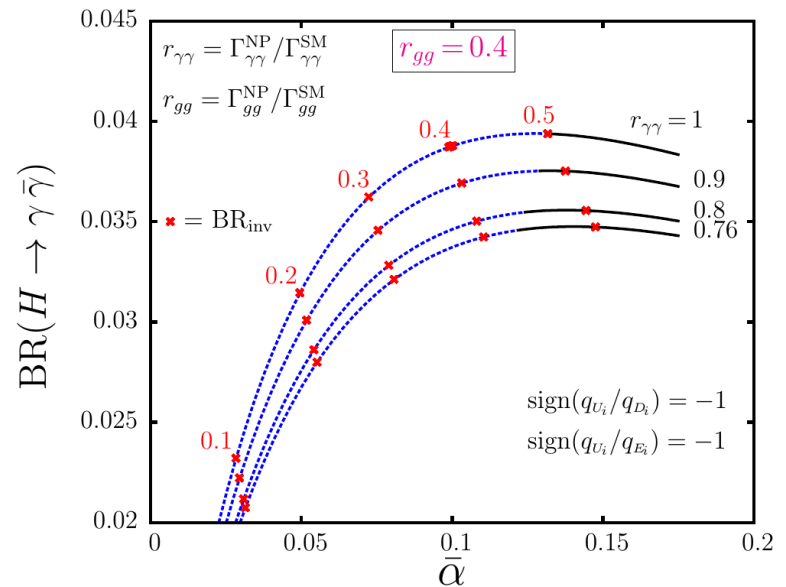
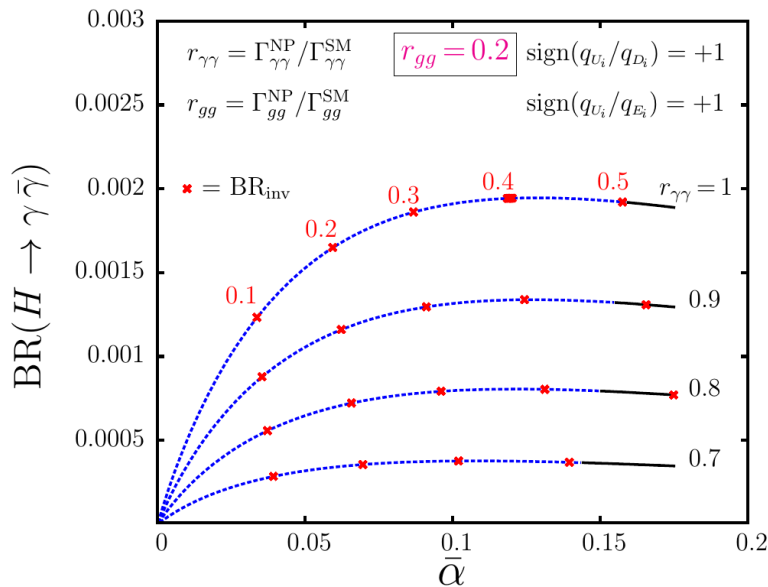
■ New processes to be explored → mesons and neutron decays in dark fermions

Backup slides

BR predictions in the full model for $H \rightarrow \gamma \bar{\gamma}$



dashed lines outside region $\frac{1}{2}\text{BR}_{\gamma\gamma}^{\text{SM}} < \text{BR}_{\gamma\gamma} < 2\text{BR}_{\gamma\gamma}^{\text{SM}}$



Lower bounds on messenger masses

■ at large ξ mixing

$$\bar{m}_U \geq \frac{(110 \text{ TeV}) K_t(\bar{m})}{g_L g_R} \sqrt{1 - \xi_U}$$

$$\bar{m}_D \geq \frac{(3 \text{ TeV}) K_b(\bar{m})}{g_L g_R} \sqrt{1 - \xi_D}$$

■ at small ξ mixing

$$\bar{m}_U \geq \frac{(55 \text{ TeV}) K_t(\bar{m})}{\xi_U g_L g_R}$$

$$\bar{m}_D \geq \frac{(1.5 \text{ TeV}) K_b(\bar{m})}{\xi_D g_L g_R}$$

$K_{t,b}$ renormalization factors $K_{t,b}(\bar{m}) < 1$

■ Colored-messenger masses naturally above TeV scale

■ EW messengers potentially lighter $\rightarrow$ relaxed lower bound

■ hierarchy among $SU(2)_L$ and $SU(2)_R$ naturally explained !

Top quark case $\text{BR}(t \rightarrow q \bar{\gamma})$ ($q=c,u$)

from exp. upper bounds on $\text{BR}(t \rightarrow q \gamma)$

- for $\xi_U = 0.1$, and $x_3^U = 0.8$ (small-mixing regime)

$$\text{BR}^{(t \rightarrow u \gamma)}(t \rightarrow u \bar{\gamma}) < 1.8 \times 10^{-2} \left(\frac{\bar{\alpha}}{0.1} \right)$$

$$\text{BR}^{(t \rightarrow c \gamma)}(t \rightarrow c \bar{\gamma}) < 2.3 \times 10^{-1} \left(\frac{\bar{\alpha}}{0.1} \right)$$

- for $\xi_U = 0.8$, and $x_3^U = 0.1$ (large-mixing regime)

$$\text{BR}^{(t \rightarrow u \gamma)}(t \rightarrow u \bar{\gamma}) < 3.4 \times 10^{-2} \left(\frac{\bar{\alpha}}{0.1} \right)$$

$$\text{BR}^{(t \rightarrow c \gamma)}(t \rightarrow c \bar{\gamma}) < 4.4 \times 10^{-1} \left(\frac{\bar{\alpha}}{0.1} \right)$$

large BR are allowed from $\text{BR}(t \rightarrow q \gamma)$

DM and Vacuum stability bounds on $\text{BR}(t \rightarrow q \bar{\gamma})$

Excluded by
highest messenger
mass < 1 TeV

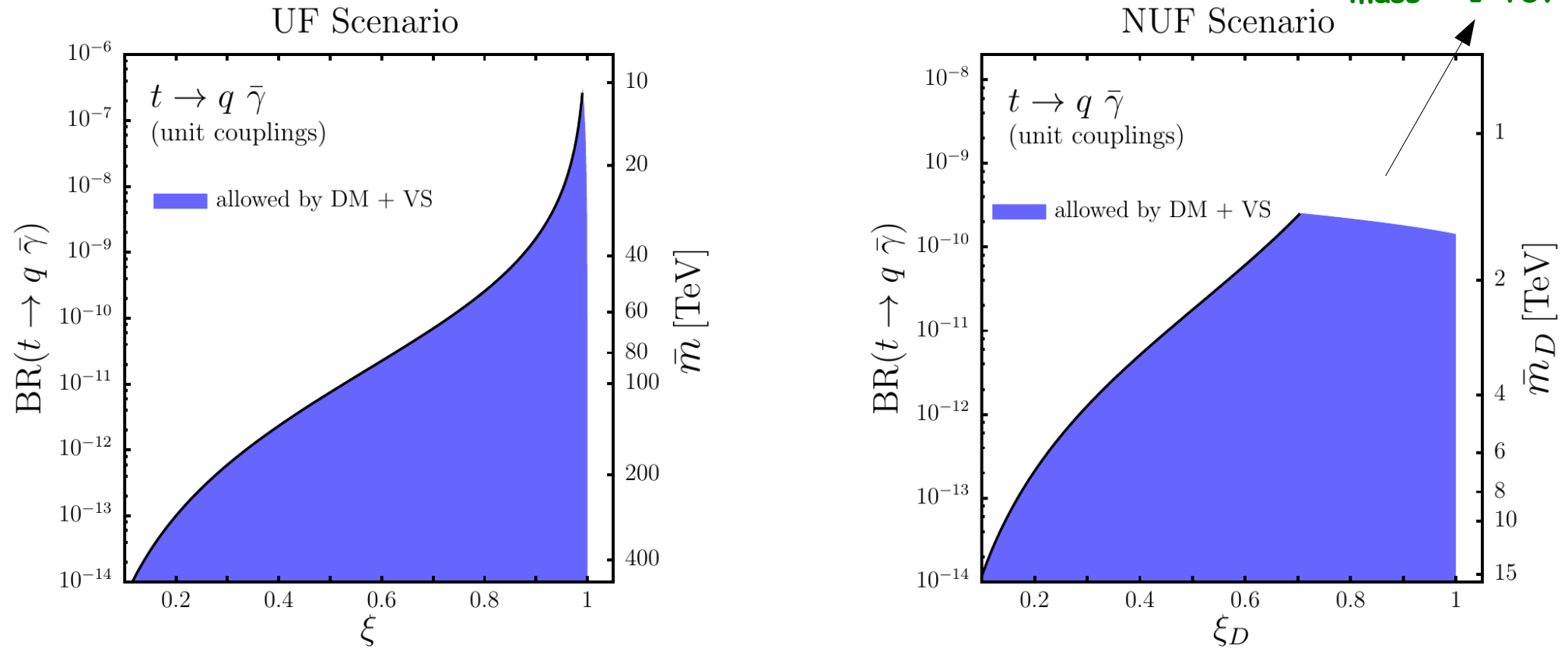
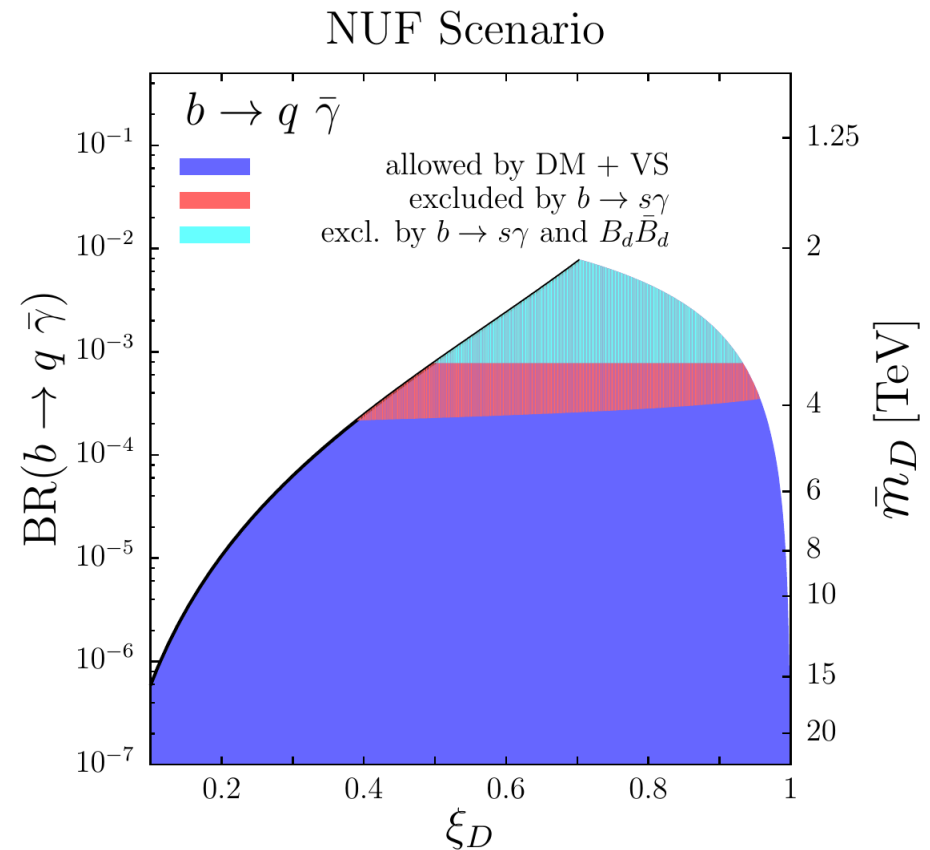
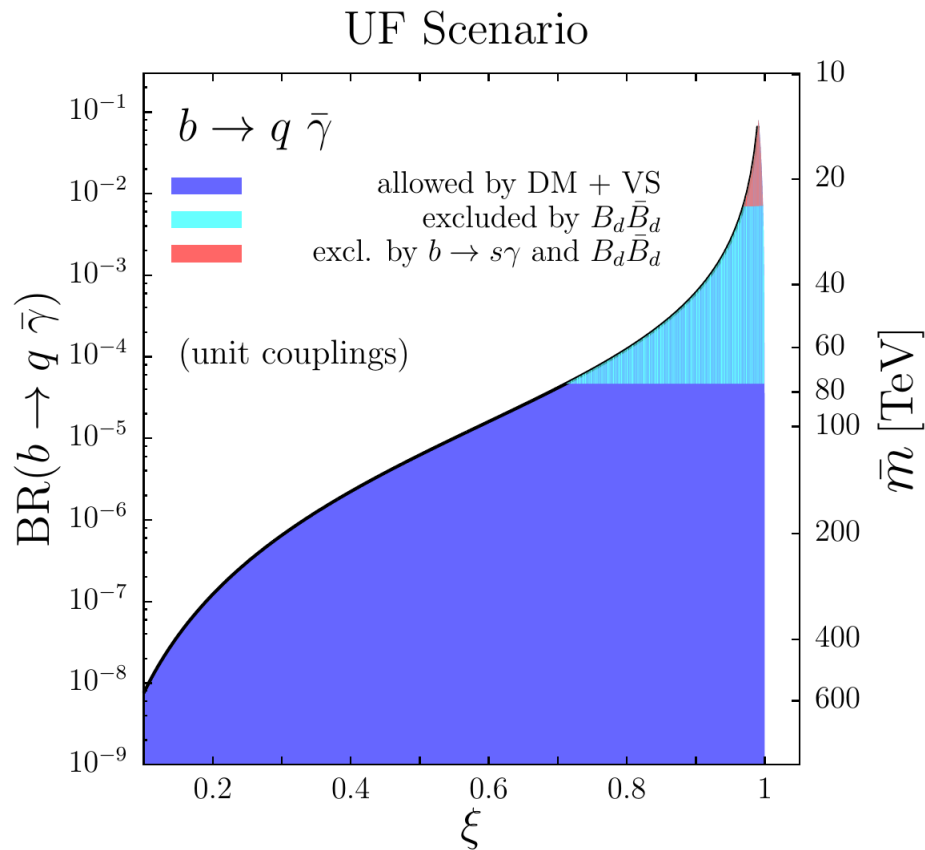


Figure 3: Allowed regions (colored areas) by DM and vacuum stability (VS) constraints for $\text{BR}(t \rightarrow q \bar{\gamma})$ and for the average messenger mass scales $\bar{m}$ and $\bar{m}_D$, versus the corresponding mixing ξ and ξ_D , in the UF (left) and NUF (right) scenarios, respectively.

DM and Vacuum stability can set very strong upper bounds on BR
(due to large width of top and lower bounds on $\bar{m}$ above TeV scale)

Bottom quark case $\text{BR}(b \rightarrow q \bar{\gamma})$ ($q=d,s$)



Large values of BR possible in both universal and non-universal flavor Scenario (enhancement due to the tiny width of b)

Charm quark case $\text{BR}(c \rightarrow u \bar{\gamma})$

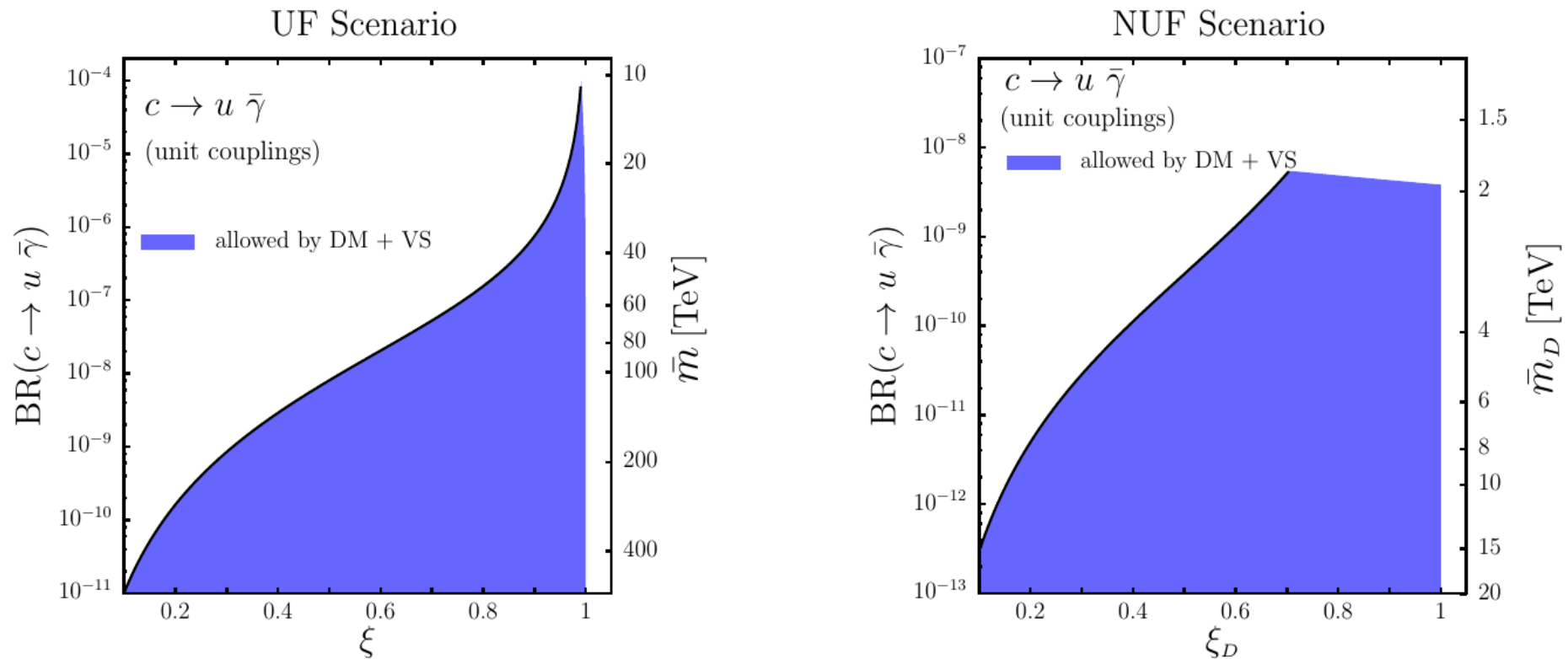


Figure 6: Allowed regions (colored areas) by DM and vacuum-stability (VS) constraints for $\text{BR}(c \rightarrow u \bar{\gamma})$ and for the average messenger mass scales $\bar{m}$ and $\bar{m}_D$, versus the corresponding mixing ξ and ξ_D , in the UF (left) and NUF (right) scenarios, respectively. In the left (right) plots we assume $\bar{e} \bar{e}_2^U \rho_L^{12} / \rho_L^{22} \simeq 1$ ($\bar{e} \bar{e}_2^D \eta_L^{12} / \eta_L^{22} \simeq 1$) with all other matrix elements of flavor matrices set to zero.

Large values of BR possible !

FV Leptonic decays $\text{BR}(\ell \rightarrow \ell' \bar{\gamma})$

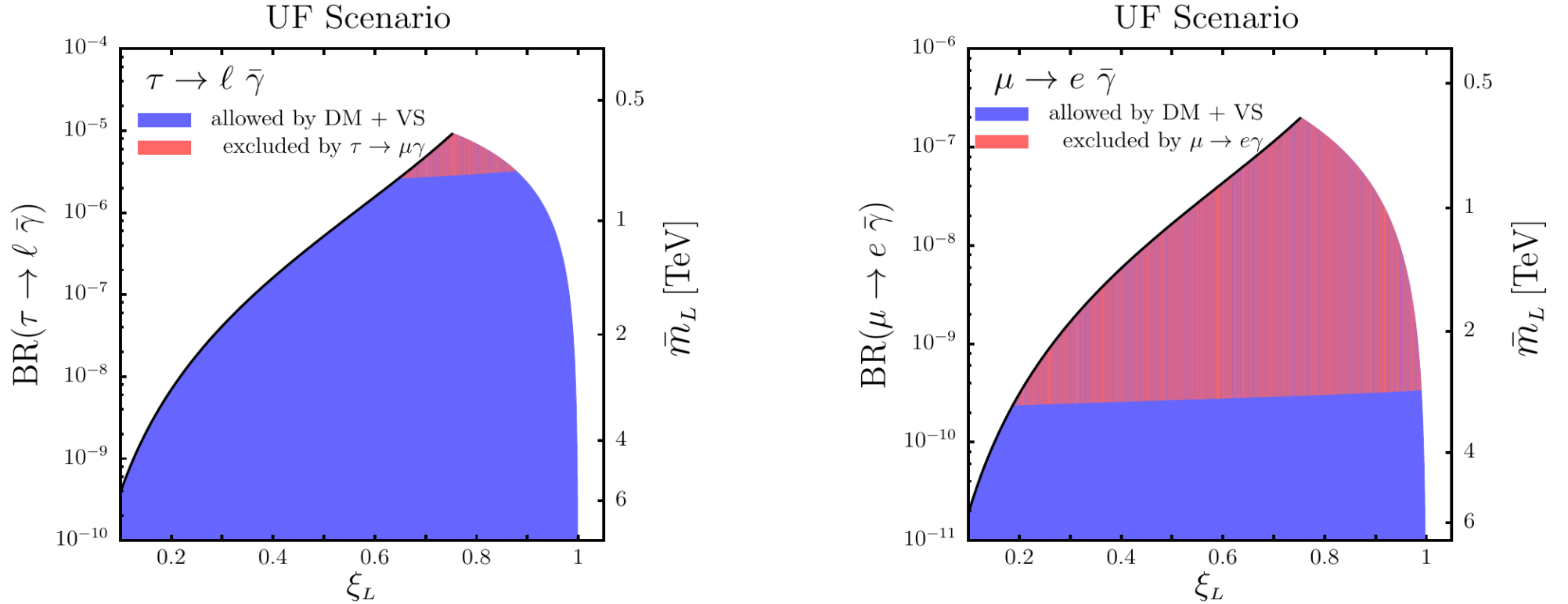


Figure 8: Regions allowed by DM and vacuum stability (VS) constraints for $\text{BR}(\tau \rightarrow \ell \bar{\gamma})$ (left) and $\text{BR}(\mu \rightarrow e \bar{\gamma})$ (right), and for the average messenger mass scale $\bar{m}_L$, versus the mixing ξ_L , in the UF scenario (blue areas). Superimposed red areas are the subregions excluded by direct constraints on $\text{BR}(\ell \rightarrow \ell' \gamma)$. In the left (right) plot, we assume $\bar{e} \bar{e}_3^L \tilde{\eta}_L^{j3} / \tilde{\eta}_L^{33} = 10^{-2}$ ($\bar{e} \bar{e}_3^L \tilde{\eta}_L^{12} / \tilde{\eta}_L^{22} = 10^{-4}$), with $j = 1, 2$.