

Searching for the Dark Sector

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

based on...

Model building

PRD 95 (2017) 035005	EG, M. Raidal, L. Marzola
PRD 89 (2014) 015008	EG, M. Raidal
PRD 77 (2008) 055020	EG

Phenomenology

PRD 98 (2018) 035049	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

Outline

- Theoretical framework
- Predictions for a Dark sector
- Phenomenological and astrophysics implications
- New Signatures (dark photons, dark-fermions)
- Conclusions

Dark Matter and Dark Sector

- Dark Matter origin is still unknown
- Five times more abundant in the Universe than ordinary barion matter
- Dark Matter could reside in a Dark Sector (DS)
- DS, that is weakly coupled to the SM, might possess rich internal structure and its own interactions
- could contain light or massless gauge bosons (**Dark Photons**) mediating long-range forces between Dark particles

Dark Photons

In Cosmology

D.N. Spergel, P.J. Steinhardt, PRL 84 (2000)
M.Vogelsberger, J.Zavala, A.Loeb, Mon.Not. Roy Astron 423 (2012)
L.G. Van den Aarssen, T. Bringmann, C. Pfrommer, PRL 109 (2012)
S. Tulin, H.B. Yu, K.M. Zurek, PRD 87 (2013)

- May solve the small-scale structure formation problems
- It can explain the dark discs of galaxies

J.Fan, A.Katz, L.Randall, M.Reece, PRL 110 (2013)

In Astroparticle physics

- May induce Sommerfeld enhancement of DM annihilation cross section needed to explain the PAMELA-Fermi-AMS2 positron anomaly

N.Arkani-Hamed, D.P. Finkbeiner, T.R. Slatyer, N.Weiner. PRD 79 (2009)

- May assist DM annihilations to the required magnitude making asymmetric DM scenarios viable

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

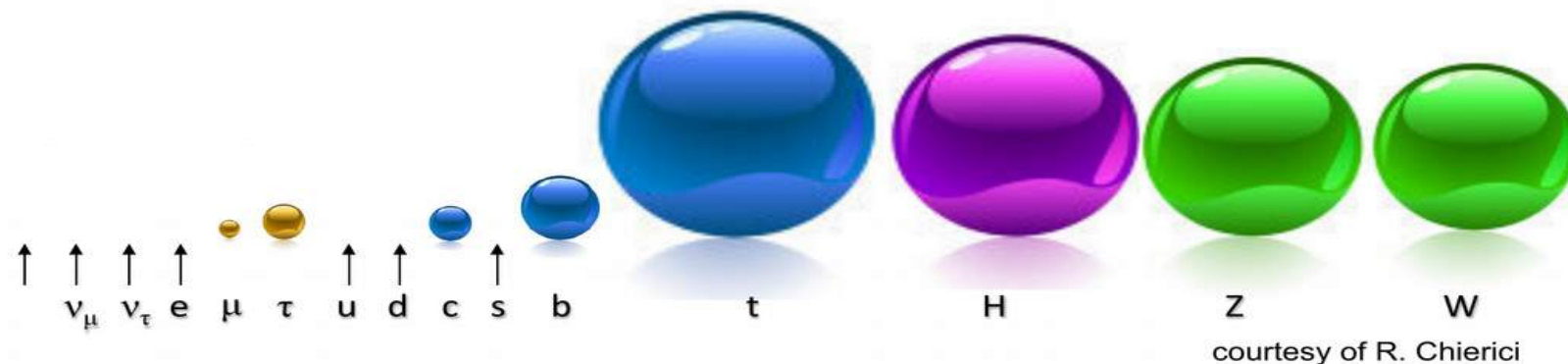
Predictions for a Dark Sector

- Dark sector, dark photons...if no predictions, who ordered them ?
- SM works very well ! ..but lack of DM candidate, and

Mystery in Hierarchy of SM Yukawa's

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

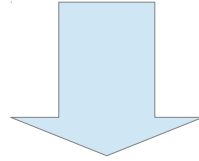
m_f 's span many orders of magnitudes...



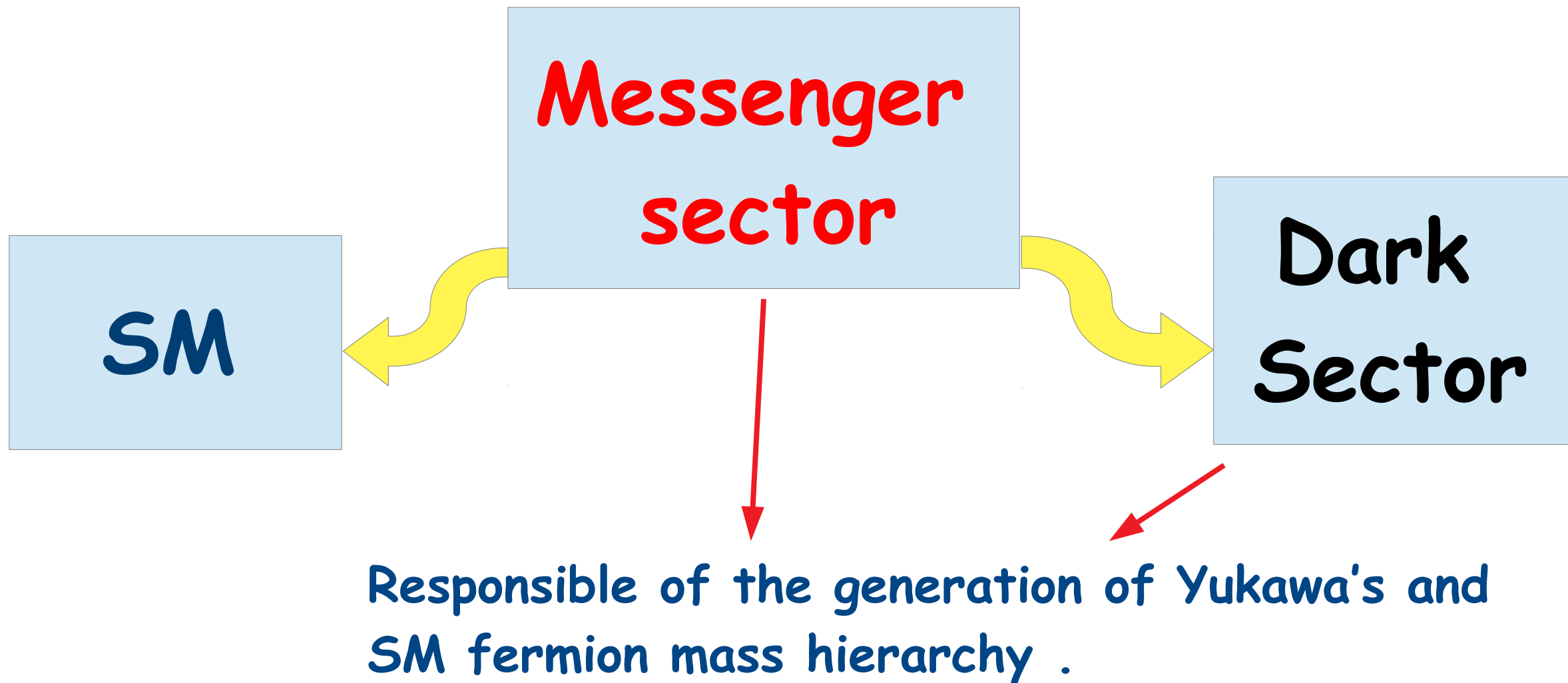
courtesy of R. Chierici

- fermion masses spanning from 6 orders of magnitude for charged fermions, up to 12 if we include (Dirac) neutrino masses
- we propose a solution to the Flavor hierarchy problem that can **predicts** the existence of a **Dark Sector → Dark Matter**

Solving the Flavor puzzle requires



Complete SM Theory



A solution to the Flavor hierarchy problem

- **Main paradigm:** Yukawa's as effective low energy couplings
- easier to justify the large hierarchy
- first attempt → Froggatt-Nielsen mechanism
- require ad-hoc high-dim operators → origin unknown

a new proposal:

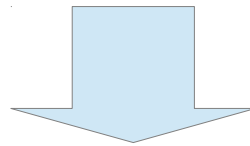
- effective Yukawa couplings generated by a renormalizable theory → require a Dark Sector

Theoretical Framework

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

- Yukawa operators **forbidden** by some symmetry S

- can arise at low energy as **effective couplings** from operators of **dim-5**, after spontaneous symmetry breaking of S



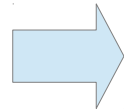
- ▶ **assume existence of a Dark sector** → Dark Fermions (DF) neutral under SM gauge interactions
- ▶ generate Dark-Chiral Symmetry Breaking **non-perturbatively** so that **DF** mass hierarchies arise
- ▶ transfer **DF** mass hierarchy to SM **dim-5 operators** using a universal messenger sector (**via renormalizable interactions**)

Lowest dimension operators
(dim 5)

$$\Rightarrow \left(\bar{\psi}_L^f H_L \psi_R^f \right) S + h.c.$$

SM scalar singlet

SSB $\langle S \rangle$ vev



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

Dark Fermion(f) Mass

~ universal effective scale
for universal messengers

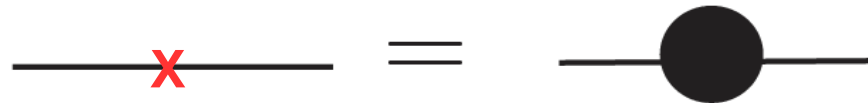
- SM fermion mass $\longleftrightarrow$ Dark fermion mass
(almost rescaled SM spectrum)
- shift the mass hierarchy problem to the DF sector
- non-perturbative dynamics in Dark sector responsible for dark-fermion mass hierarchy (see next slides)

Mechanisms for fermion mass hierarchy

- Large hierarchy of Yukawa's suggests some non-perturbative, exponential mechanism for dark-fermion masses M_f
- possible realization: via Nambu & Jona-Lasinio (NJL) mechanism
- dynamical mass "m" arises as a non-trivial solution of the self-consistent mass gap equation

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

↗ self-energy



perturbative solution $m=0$ always there

true ground state corresponds to non-trivial solution $m \neq 0$.

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.

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

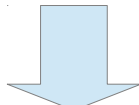
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

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

Dynamical fermion mass hierarchy

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

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

EG, PRD 77 (2008)

EG, Raidal, PRD 89 (2014)

Mass-gap solution

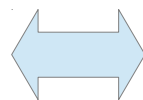
$$M_f = \Lambda \exp \left\{ -\frac{2\pi^2}{3\alpha(\Lambda)q_f^2} + \frac{1}{4} \right\}$$

valid for weak coupling regime $\alpha \ll 1$

$\Lambda \rightarrow$ Lee-Wick ghost mass

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

Masses M_f



$U(1)$ charges q_f

- another possible mechanism based on **Miransky scaling** (based on U(1) @ strong coupling, no Lee-Wick ghosts)
- 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 ChSB phase transition happens

- different charges are required to make large splitting

Yukawa hierarchy summary

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

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

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

Flavor hierarchy problem solved !

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 $q_{U_3} = 1$ $q_{D_3} = 0.9 \rightarrow m_t$ 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

good matching of SM spectrum also for integer charges ($q=1,2,3,\dots,6$)

above charges for neutrinos correspond to benchmark masses

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

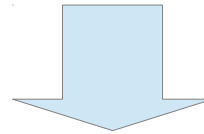
no need for seesaw mechanism $\rightarrow$ neutrino masses are Dirac type

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

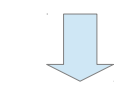
How to generate effective Yukawa → (technical aspects)

$Y_f = 0 \rightarrow$ 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)

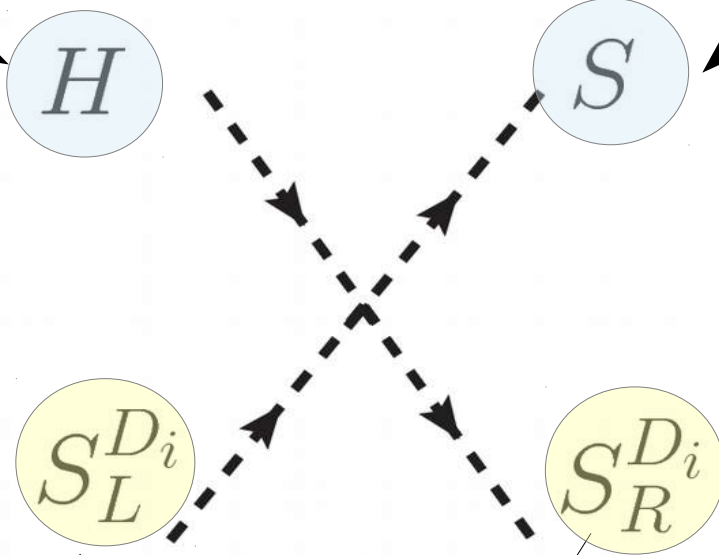
$$\frac{1}{\Lambda_{\text{eff}}} \left(\bar{\psi}_L^f H_L \right) \left(H_R^\dagger \psi_R^f \right) + h.c.$$

- Yukawa's generated after SSB of $SU(2)_R$
- no strong CP problem $\rightarrow$ axions not required

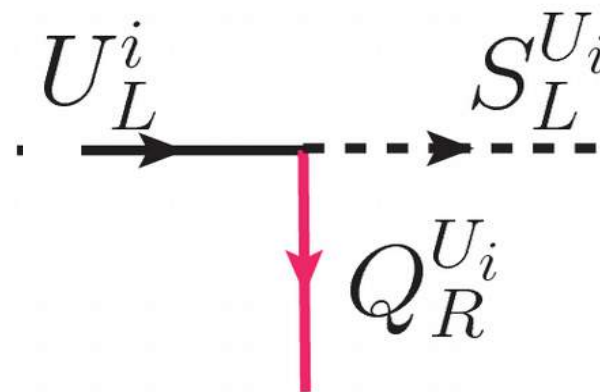
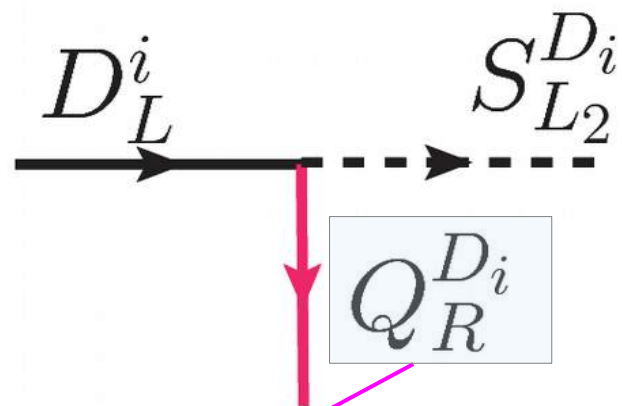
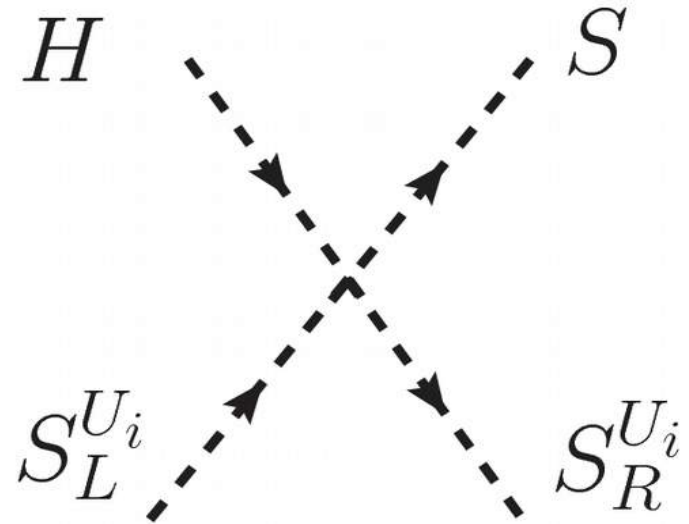
Minimal set of new interactions

Higgs doublet

Scalar singlet (or H_R in LR SM extensions)



Scalar messengers



+ $L \leftrightarrow R$

Dark fermions

universal couplings $\rightarrow U(1)^N \times Z_N$

Higgs Yukawa's radiatively generated at 1-loop

Via higher order dim. operators $\rightarrow$

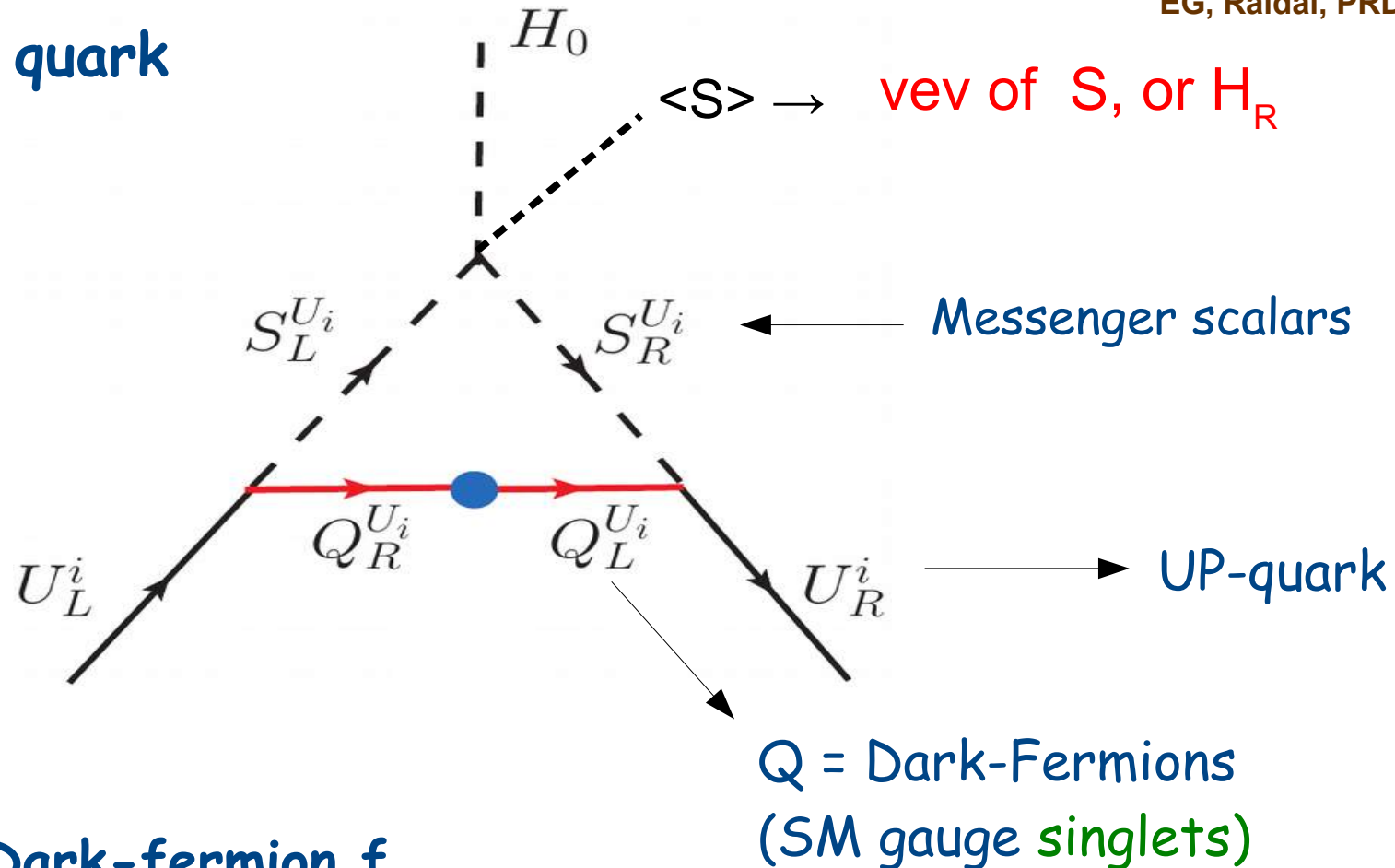
$\bar{U}_L U_R H S$ at any order

EG, Raidal, PRD 89 (2014)

Yukawa coupling UP quark

H_0 = Higgs field

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



$\langle S \rangle \rightarrow$ vev of S , or H_R

Messenger scalars

UP-quark

$Q = \text{Dark-Fermions}$
(SM gauge singlets)

$\bullet \rightarrow M_f = \text{mass of Dark-fermion } f$

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



Yukawas follow M_f hierarchy !

Interaction Lagrangian to generate Yukawa

charged under $U(1)_F$

Dark fermions

$SU(2)_L$ -doublet messenger fields

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

4-scalar coupling of Higgses to fermions

(LR symmetry $\rightarrow g_L = g_R$)

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

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

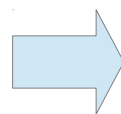
LR symmetry requires $\rightarrow m_L^2 = m_R^2 \equiv \bar{m}^2$

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

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 (exact in ξ)

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

loop function

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

■ 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

➡ Dark fermion spectrum $\sim$ rescaled SM spectrum

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

heavy scalar messengers $S_{L,R}$

▶ heavy scalar messengers (squark/slepton-like)



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

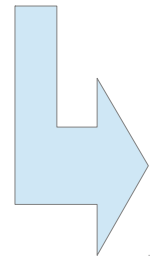
Messengers (Scalars)

Dark Sector (Fermions+Scalar)

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

EW messengers could be lighter, below TeV scale

- a massless dark-photon in the spectrum



neutrino-like signature in a collider experiment

A new source of DM predicted

- possibility to form stable neutral “Dark-Atoms”
(for quantized $U(1)$ charges)
- Dark-atoms $\rightarrow$ good candidates for Dark Matter
- expected DM emission of photon lines in the KeV range

Phenomenology of massless Dark Photons

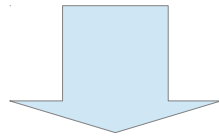
- different from massive Dark photons scenarios

(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 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)

+ First results by CMS ! ATLAS coming soon...

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.)

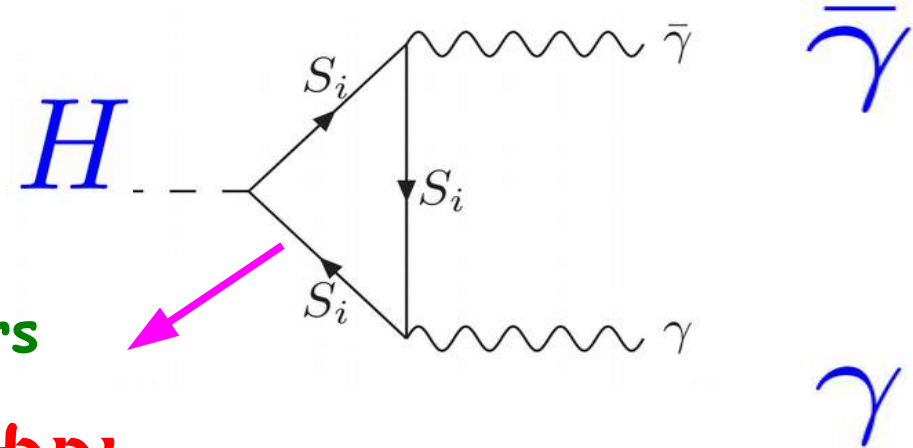
EG, Mele, Fabbrichesi, PRL 120 (2018)

Monophoton Exotic Higgs Signature

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

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

scalar messengers



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

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

DP field strength

model indep. parametrization

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

R = product of U(1) charges

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

- DP coupling $\bar{\alpha}$ could be large (allowed only 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 $H \rightarrow \gamma \bar{\gamma}$

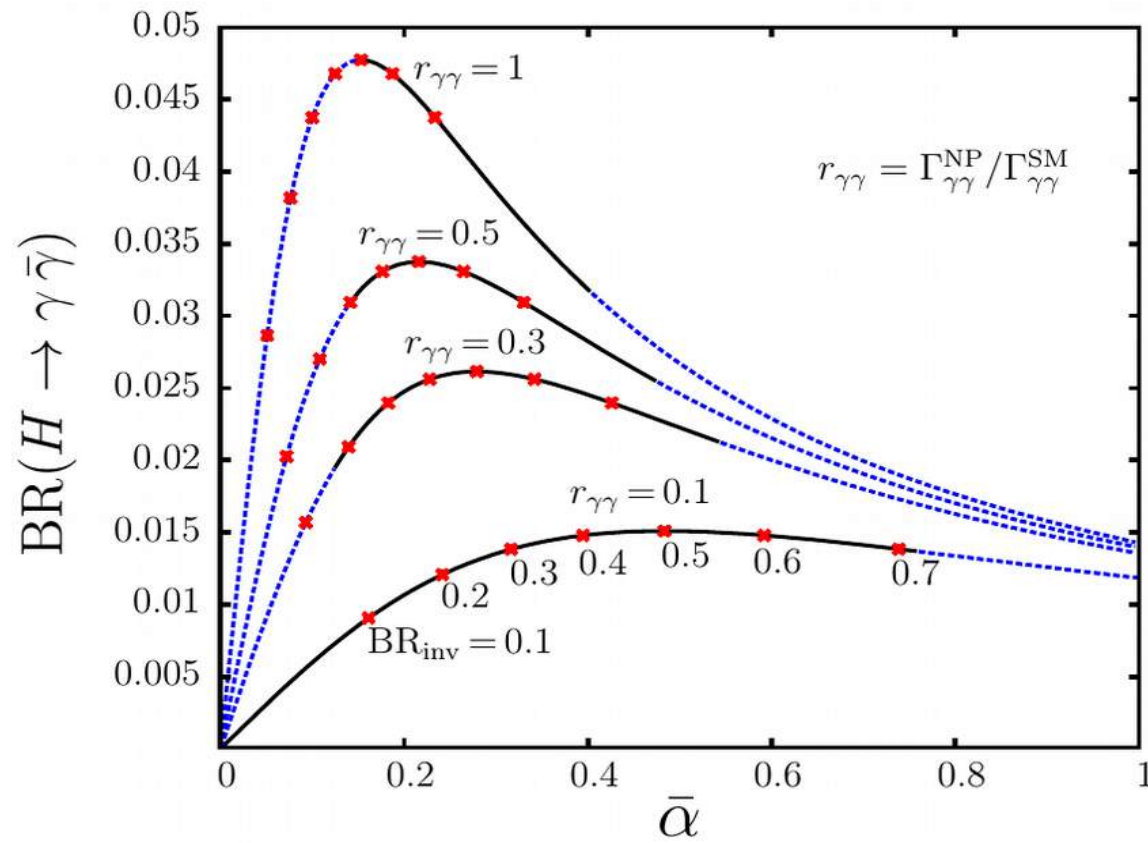


Figure 2: $\text{BR}(H \rightarrow \gamma \bar{\gamma})$ versus the dark U(1) fine structure constant $\bar{\alpha}$. The black solid lines show the allowed BR ranges as a function of the relative new physics contribution to the $H \rightarrow \gamma\gamma$ width, and of the $H \rightarrow \bar{\gamma}\bar{\gamma}$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

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

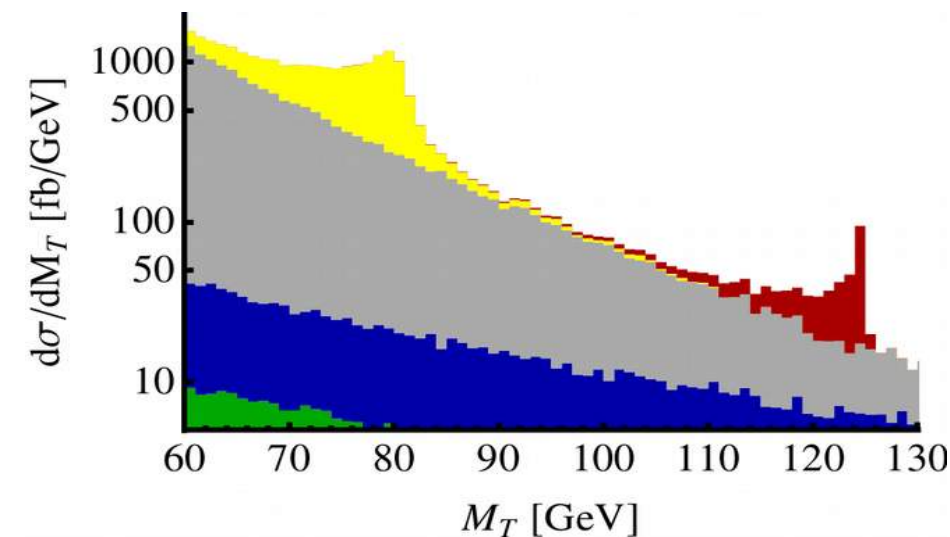
monochromatic photon $E_\gamma = m_H/2$ in the Higgs rest frame

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

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

- 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	2 σ	5 σ	2 σ	5 σ	2 σ	5 σ
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 5 σ 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 (but difficult)
- sensitivity on BR up to BR $\sim 10^{-3} \rightarrow 10^{-4}$ for L $\sim 0.3-3$ ab⁻¹
- FIRST results from CMS analysis via ZH production (bckg more under control) . ATLAS results appearing soon.

CMS Physics Analysis Summary

Contact: cms-pag-conveners-exotica@cern.ch

2019/05/17

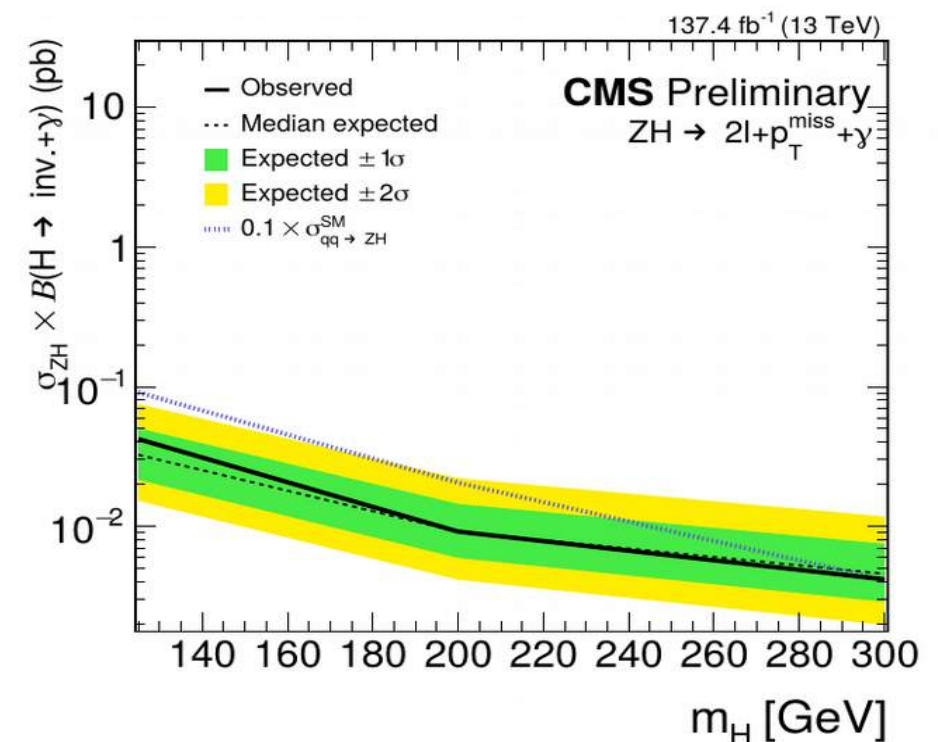
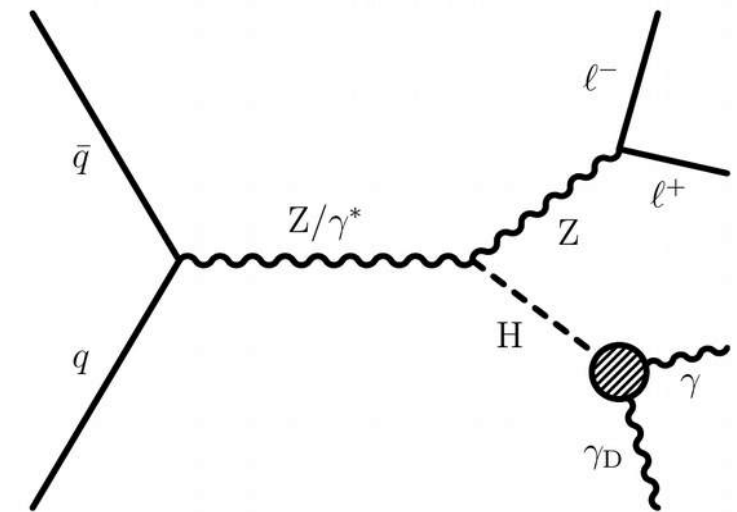
Search for Dark Photons in ZH Decays at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A search is presented for decays of a Higgs boson to an invisible particle together with an isolated photon, using the CMS experiment at the Large Hadron Collider. The Higgs boson is produced in association with a Z boson. The analysis is performed using a dataset recorded in 2016-18 corresponding to an integrated luminosity of 137.4 fb^{-1} , at a center-of-mass energy of 13 TeV. No significant excess of events above the standard model expectation is found, and the results are interpreted to place limits on the cross section times branching fraction of such decays of the Higgs boson.

The observed and expected 95% CL upper limits at $m_H = 125$ GeV assuming the SM production rate on $\mathcal{B}(H \rightarrow \text{invisible} + \gamma)$ is 4.6% and 3.6%, respectively.



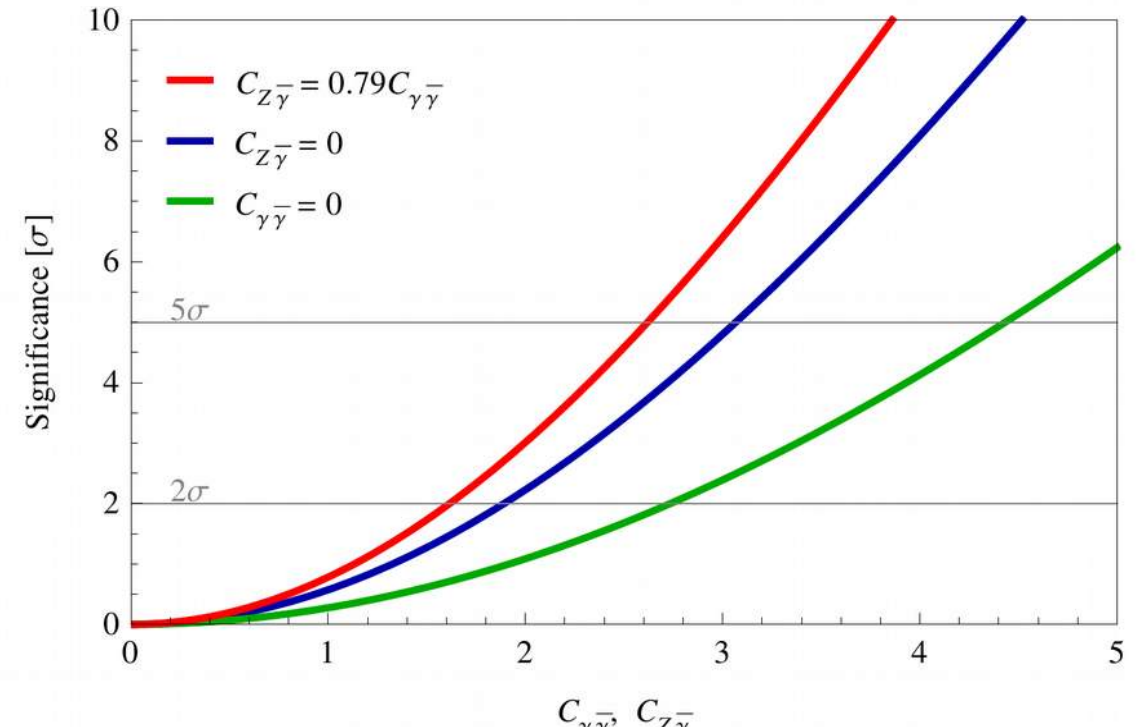
More statistics required to check the BR regions where the signal could hide. Be tuned!

Dark photon searches @ e+e- colliders

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

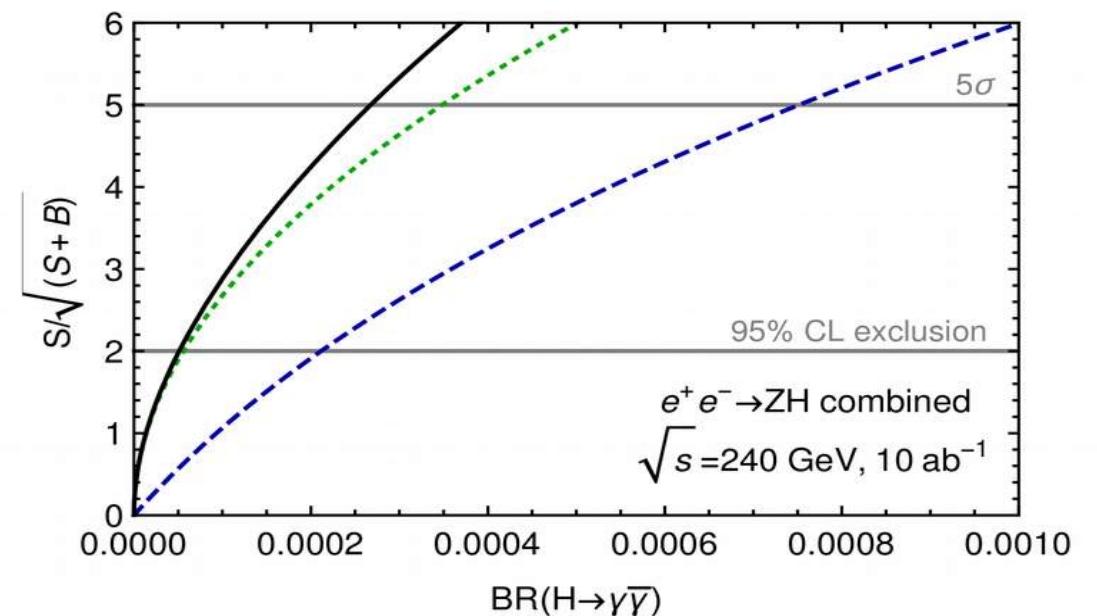
$$e^+e^- \rightarrow H\bar{\gamma} \rightarrow b\bar{b}\bar{\gamma}$$

Biswas, EG, Heikeinheimo, Mele, **PRD 93 (2016)**



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

Biswas, EG, Heikeinheimo, Mele, **PRD 96 (2017)**



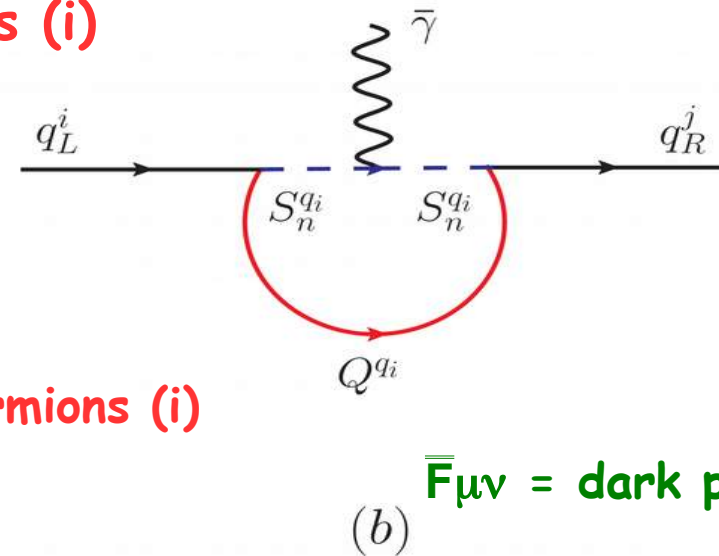
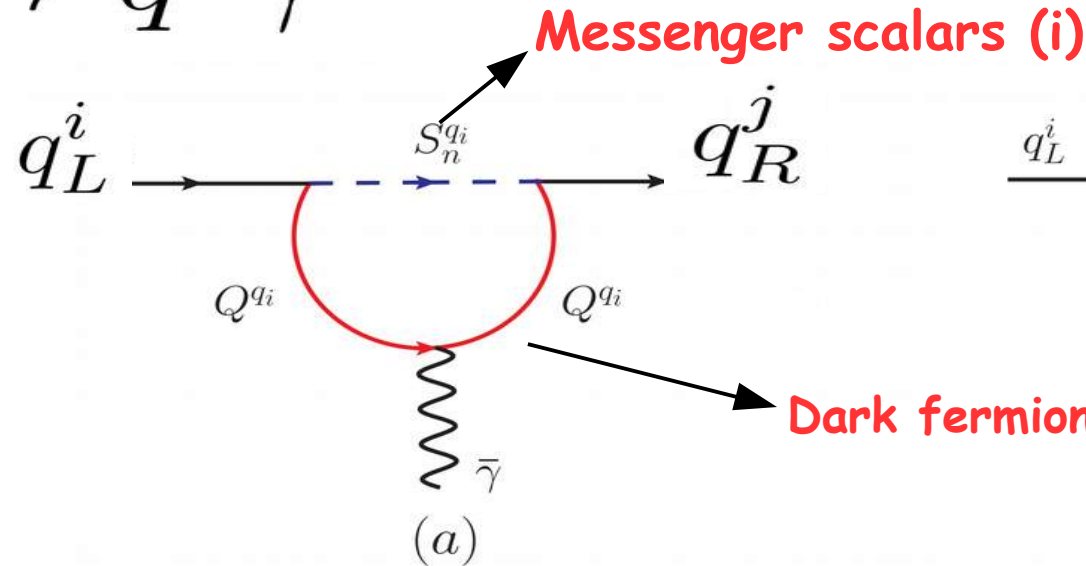
FCNC fermion f decays into a dark photon

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

FCNC decays of SM fermions into a Dark Photon

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

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



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

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

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

■ 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

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

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

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

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

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

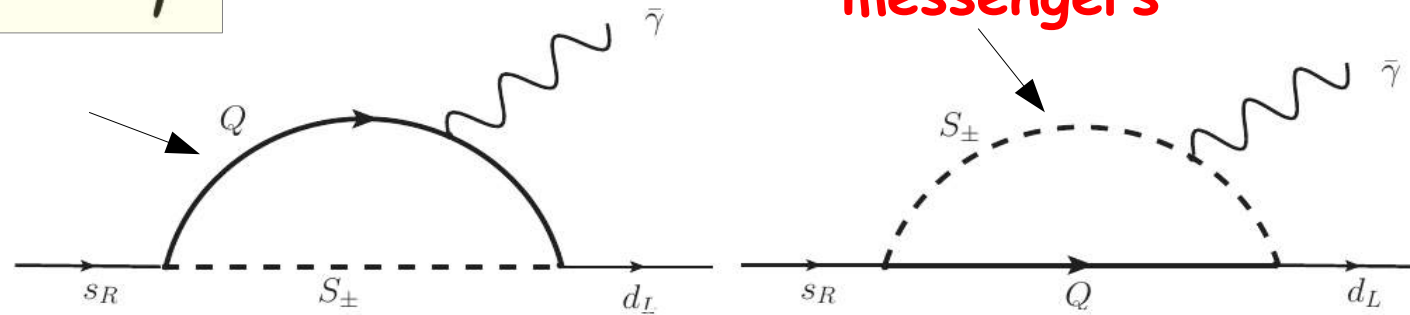
depending on various parameters and on flavor universality structure of messenger sector

FCNC Kaon decay into a massless Dark photon

Fabbrichesi, EG, Mele, PRL 119 (2017)

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

Dark-fermions



Effective Hamiltonian

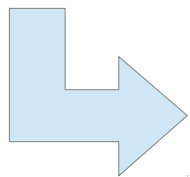
$$\mathcal{H}_{eff}^{\Delta S=1} = \frac{e_D}{64 \pi^2} \frac{\xi}{\Lambda} \hat{Q}$$

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

FCNC magnetic-dipole operator

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

Dark-photon



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

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

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)

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.

QCD ren. fact.

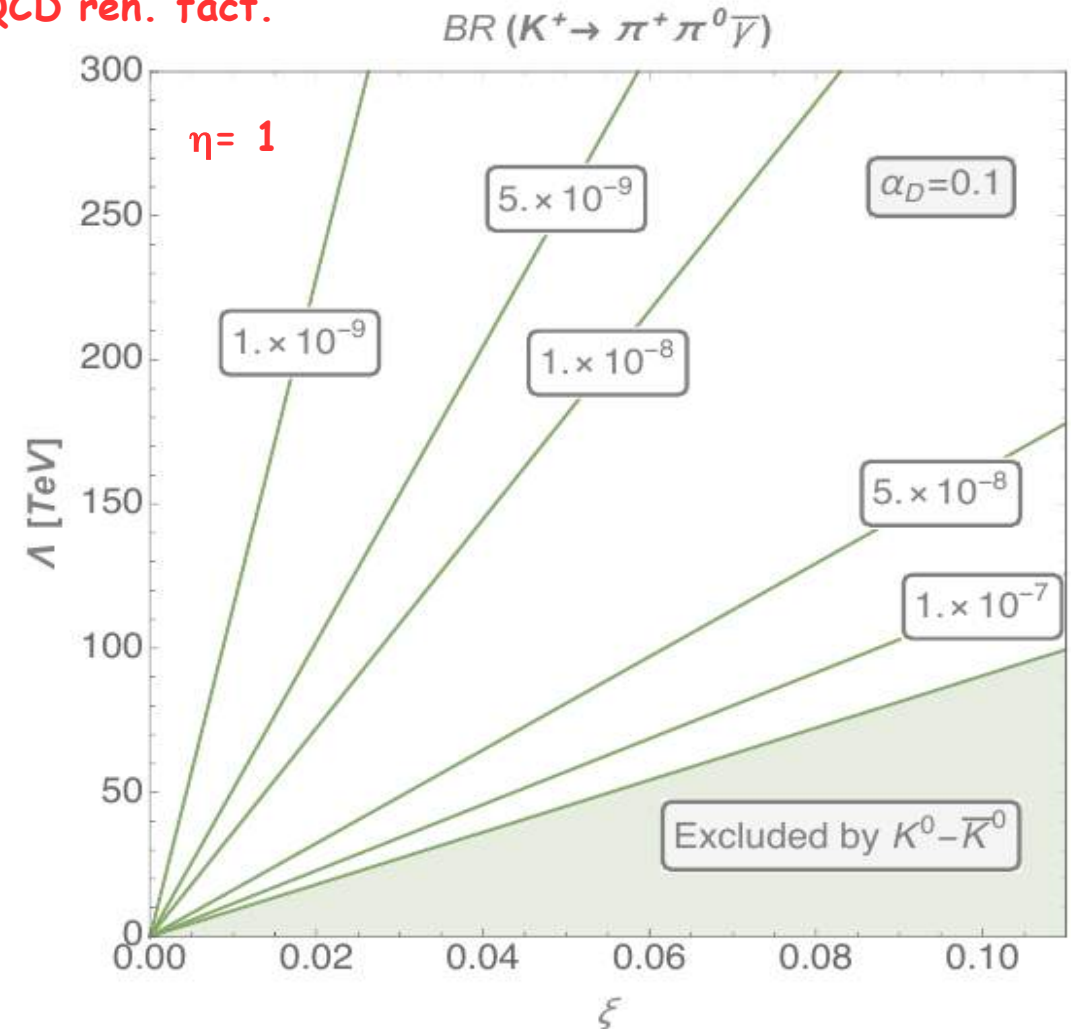
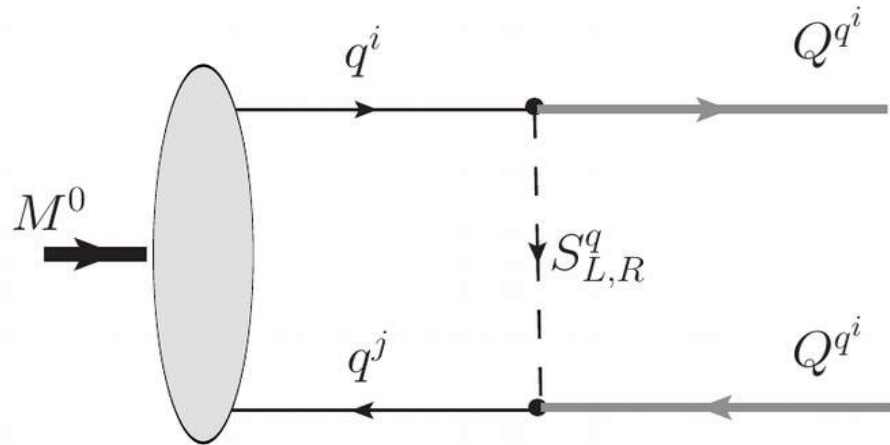


FIG. 3: $\text{BR}(K^+ \rightarrow \pi^+ \pi^0 \bar{\gamma})$ as a function of the effective scale Λ and coupling $\xi = g_L g_R / 2$, for a representative choice of the coupling strength $\alpha_D = 0.1$.

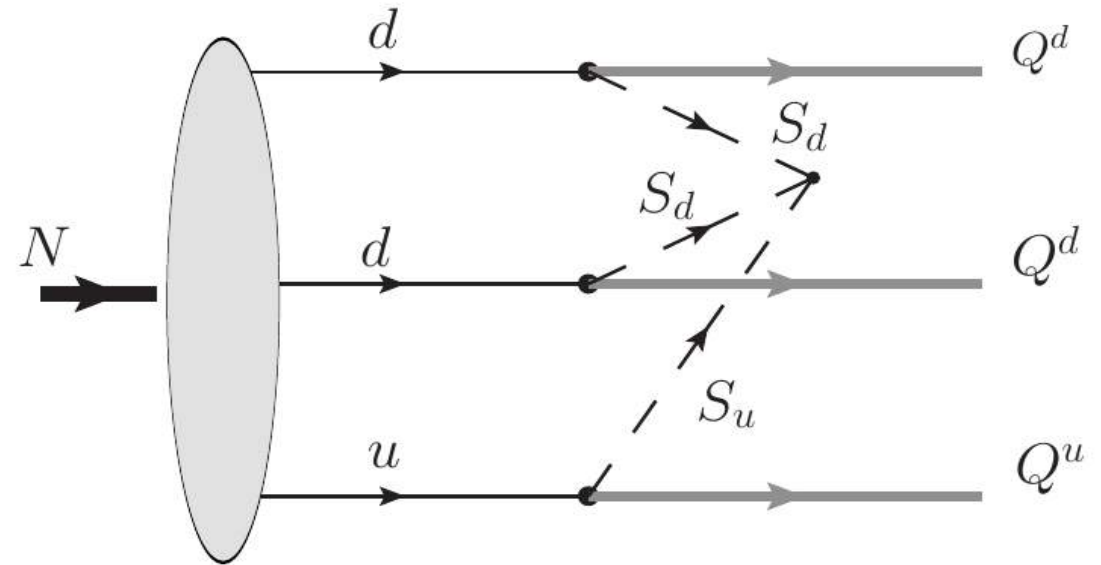
Neutral hadron disappearing into the darkness

Barducci, Fabbrichesi, EG, PRD 98 (2018)
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

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

$$P_{ij}^{L,R} = \rho_{ij}^{L,R} \rho_{ii}^{L,R} \quad \text{FCNC couplings}$$

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

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

$$g_L^i = g_R^i = \lambda$$

$$\text{BR}|_{K_L} \simeq 3.0 \times 10^{-1} \lambda^4 P_{sd}^2 \left(\frac{1 \text{ TeV}}{m_S} \right)^4$$

$$\text{BR}|_{K_L} \lesssim 7.8 \times 10^{-5} \left(\frac{1 \text{ TeV}}{m_S} \right)^2$$

$$m_{Q^s} = 200 \text{ MeV}$$

**Upper bound from
the $K\bar{K}$ mixing**

$$\text{BR}|_{B^0} \simeq 1.4 \times 10^{-2} \lambda^4 P_{bd}^2 \left(\frac{1 \text{ TeV}}{m_S} \right)^4$$

$$\text{BR}|_{B^0} \lesssim 2.4 \times 10^{-5} \left(\frac{1 \text{ TeV}}{m_S} \right)^2$$

$$m_Q^b = 2 \text{ GeV}$$

**Upper bound from
the $B\bar{B}$ mixing**

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 is 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

$$N(p) \rightarrow Q^U(k)Q^D(k_1)Q^D(k_2) \quad \text{Charge conservation prevents proton decay}$$

- 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): sufficient to keep kinematically closed the ${}^9\text{Be}$ decay into its 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 $\Rightarrow \eta\mu = 10 m_S$
trilinear messenger S^3 coupling
messenger mass

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

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

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

Sommerfeld factor $S_N \sim 10^5$ or $m_S \sim 200 \text{ GeV}$

(still allowed by LHC if messenger mainly decays $\rightarrow t + \text{DF}$)

- Astrophysical bounds from the dynamics of neutron stars do not rule out it because of Pauli blocking. (N decay stopped after 1 out of 10^5 N have decayed)

What if DF are lighter than Beryllium constraints ?

- Absence of inv. decay of Neutron in ^{16}O and ^{12}C from SNO and KamLAND

$$\tau_N^{\text{inv}} \gtrsim 10^{29} \text{ years} \quad \rightarrow \Gamma < 10^{-61} \text{ GeV}$$

$$m_{Q_U} = m_{Q_D} = 100 \text{ MeV}$$

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

→ naturally satisfied by 100 TeV mass messengers !

Conclusions

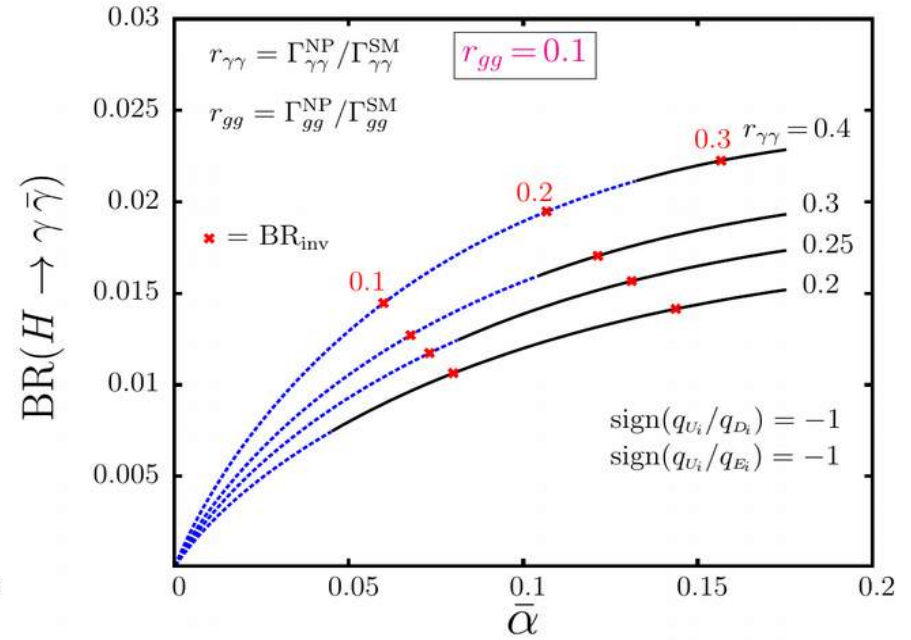
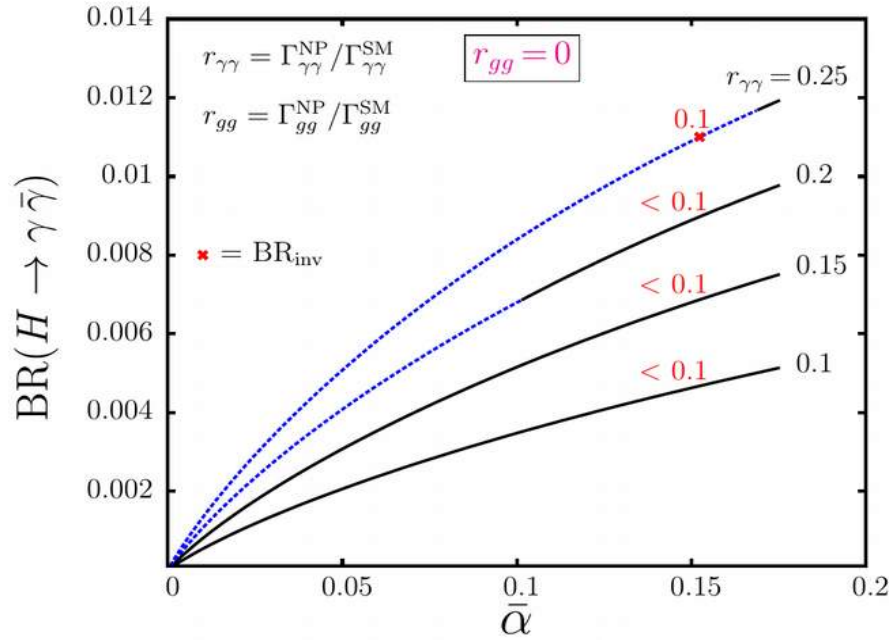
- Origin of fermion masses might require existence of a Dark Sector to explain Yukawa hierarchy → a new rich phenomenology predicted !
- Higgs boson can be the SM portal to Dark Photons
 - ▶ can be now tested @ LHC or at future linear colliders
 - ▶ search for dark photons in $H \rightarrow \gamma \bar{\gamma}$ just started → CMS first results
- 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
- 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
- New Dark matter scenario (dark atoms, dark fermions with long distance interactions)
- New DM search strategies required

voyage into the dark sector..



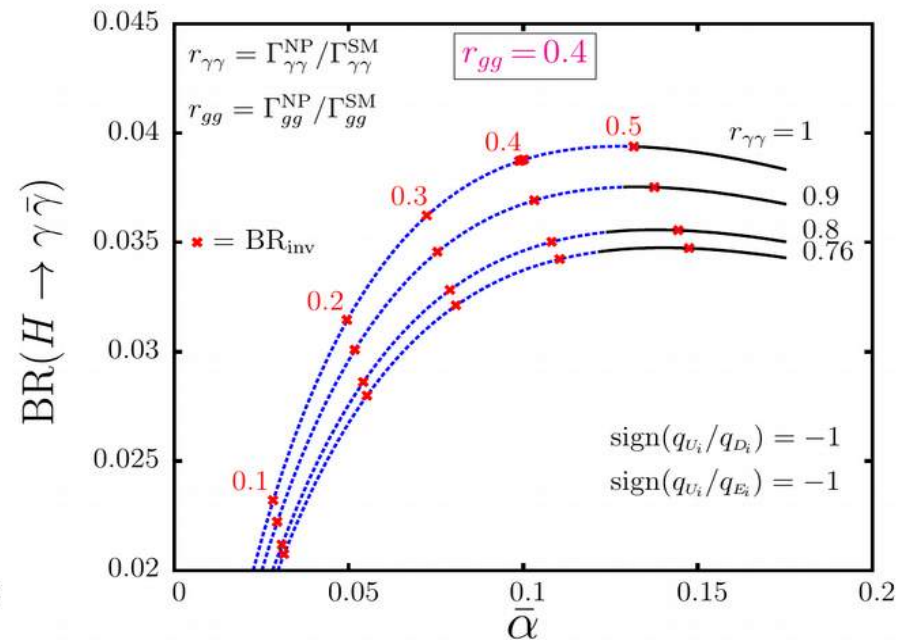
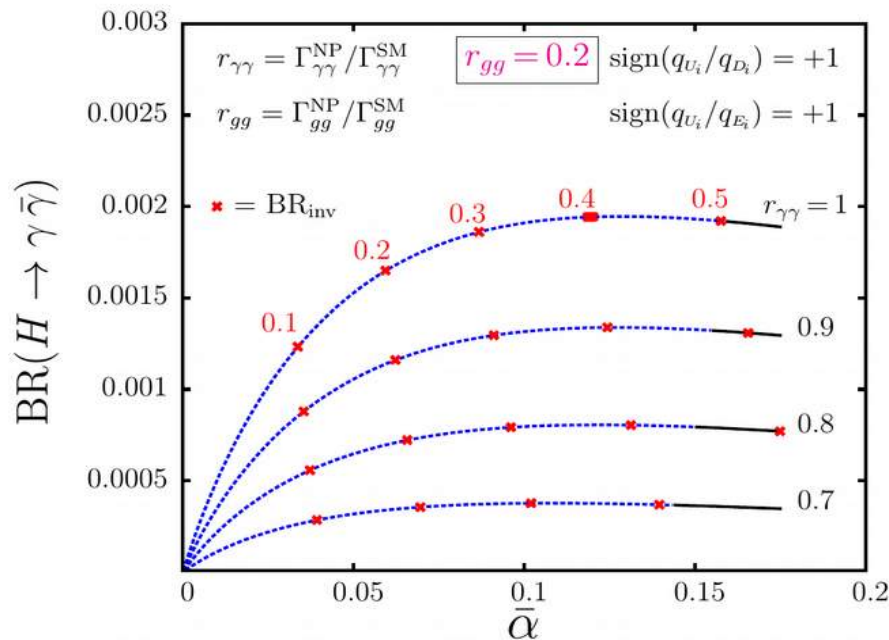
Backup slides

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

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

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

■ at small ξ mixing

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

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

$K_{t,b}$ renormalization factors

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

■ Colored-messenger masses naturally above TeV scale

■ EW messengers potentially lighter → 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

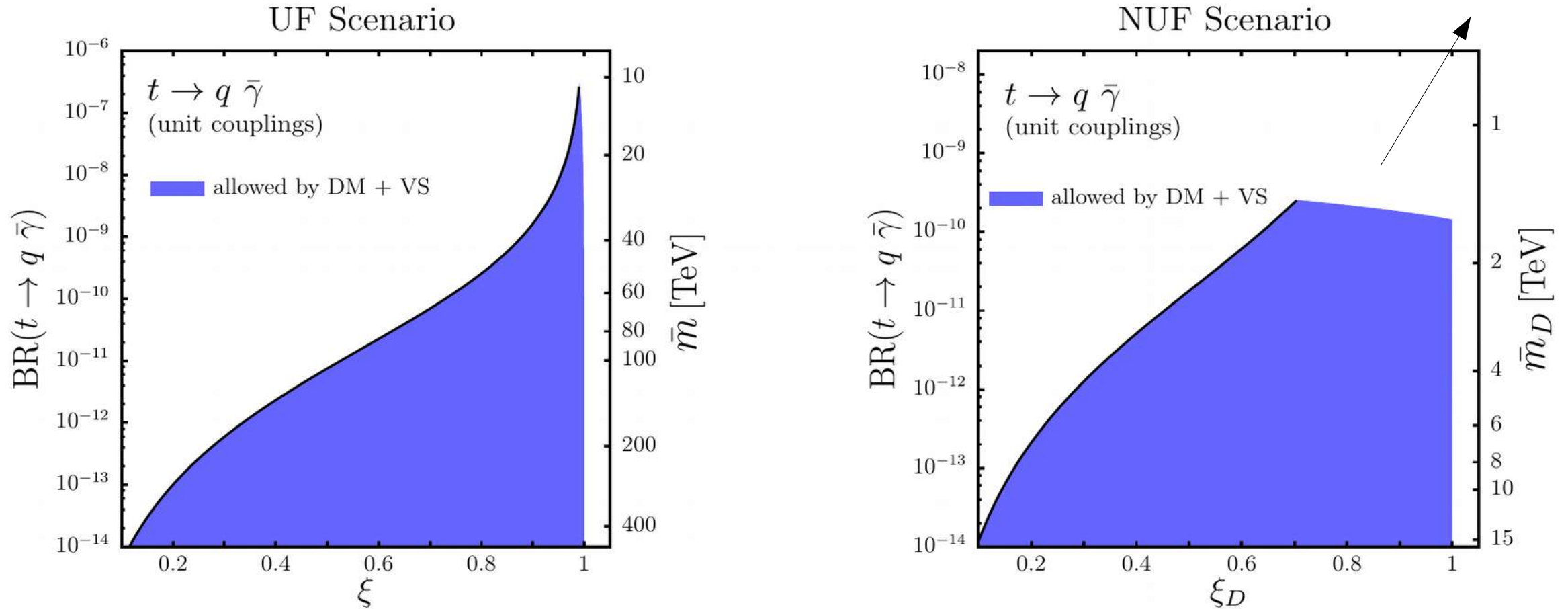
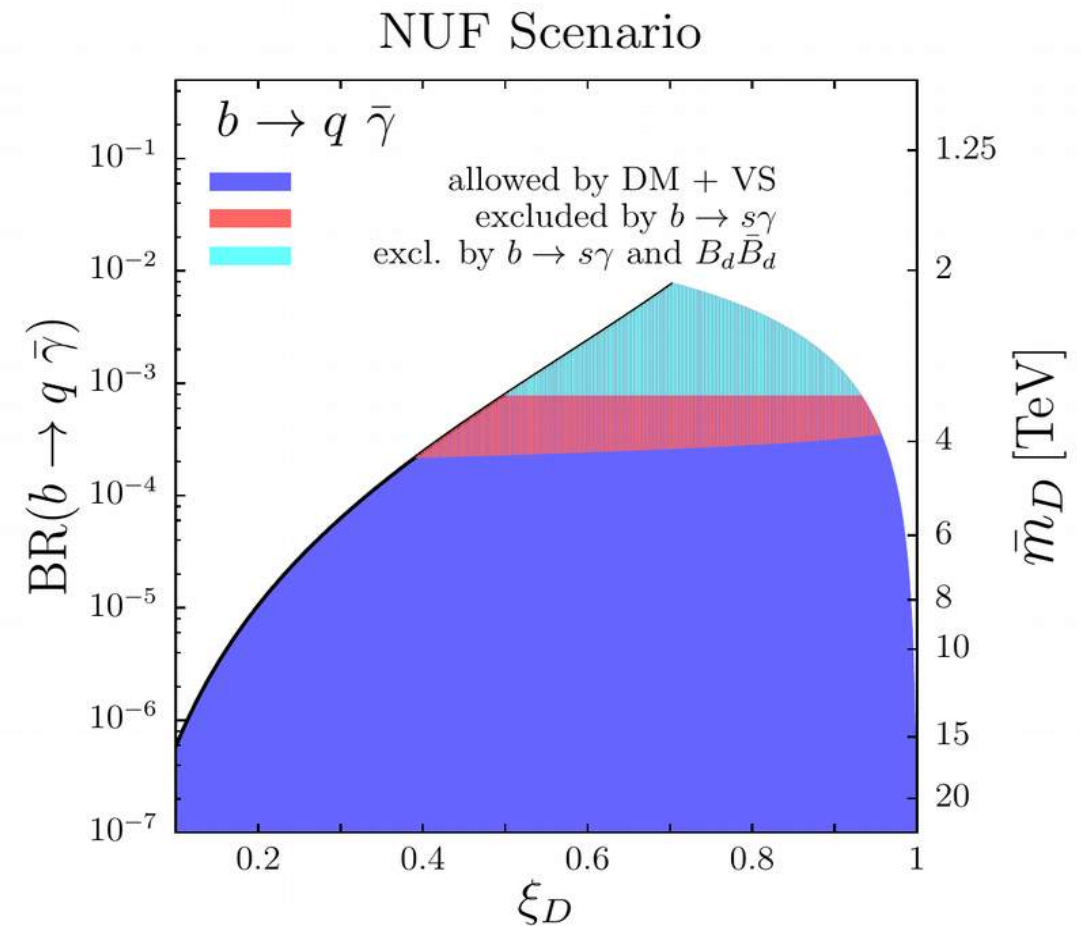
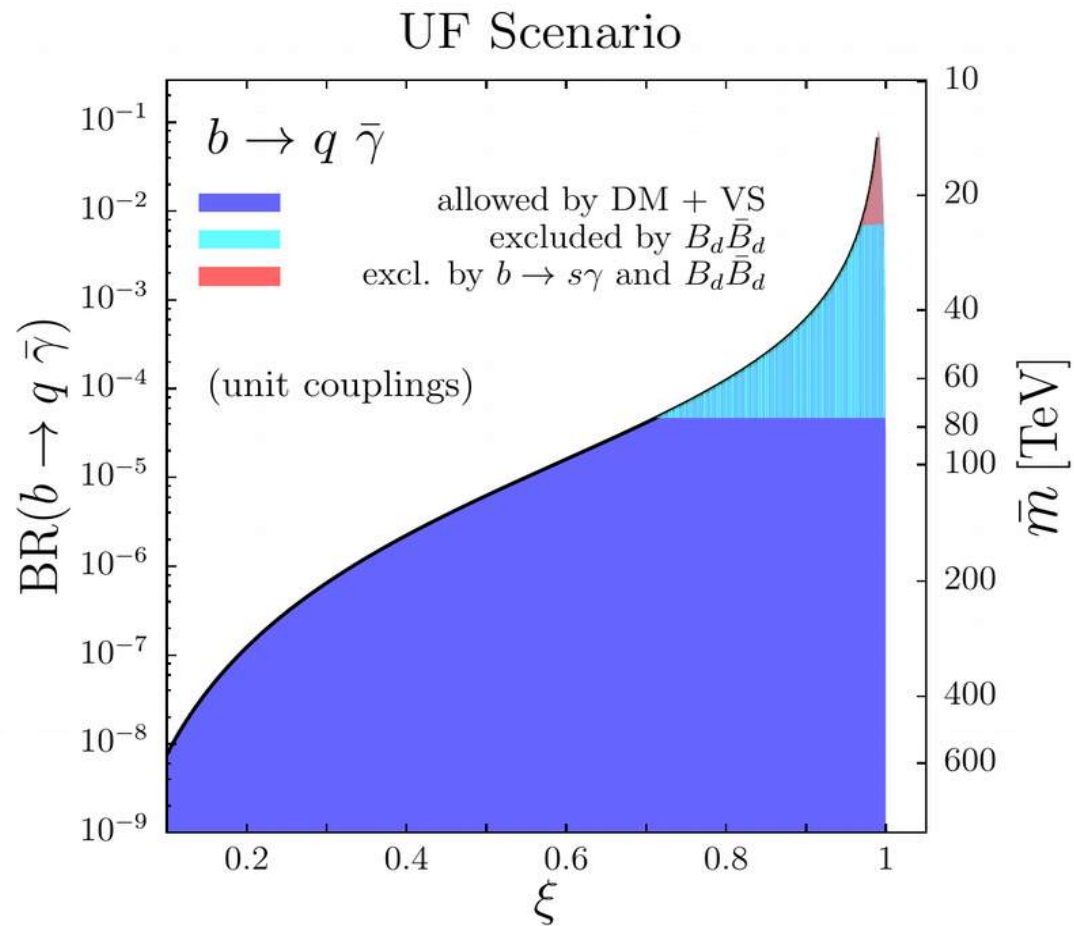


Figure 3: Allowed regions (colored areas) by DM and vacuum stability (VS) constraints for $\text{BR}(t \rightarrow q \bar{\gamma})$ and for the average messenger mass scales $\bar{m}$ and $\bar{m}_D$, versus the corresponding mixing ξ and ξ_D , in the UF (left) and NUF (right) scenarios, respectively.

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

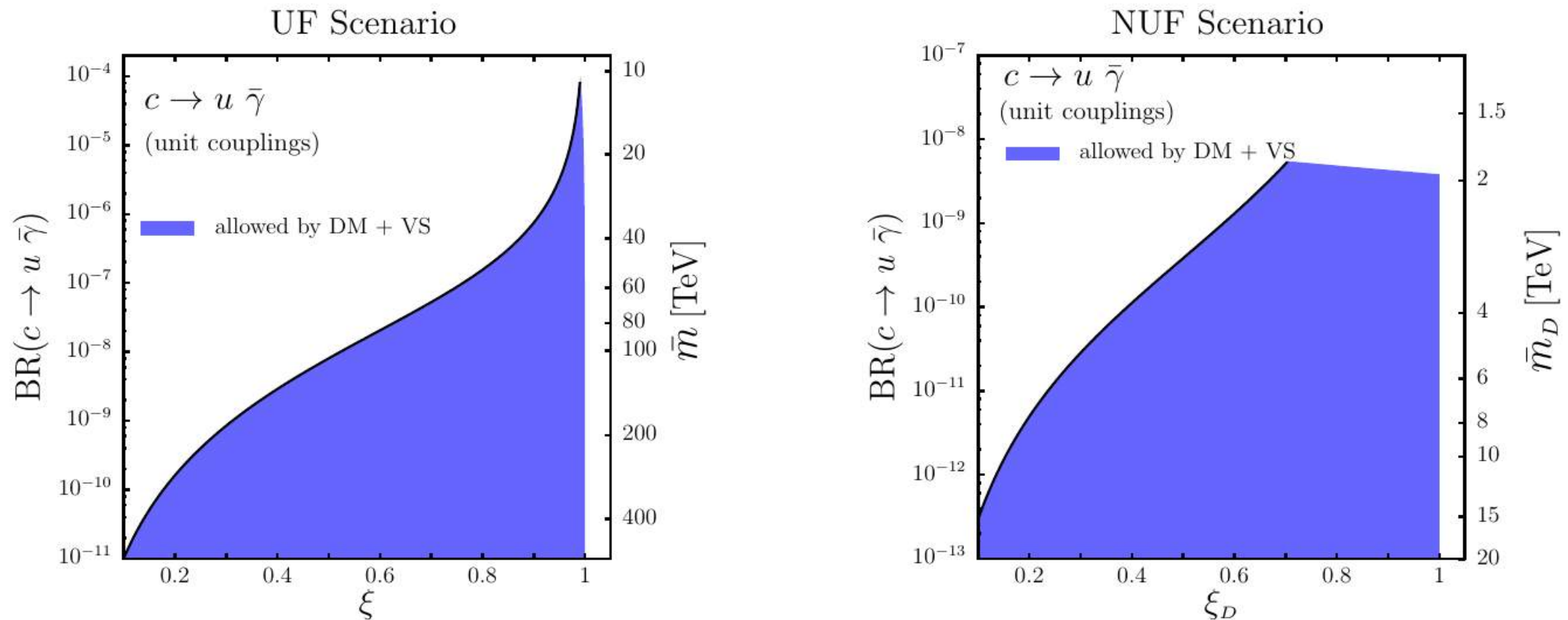


Figure 6: Allowed regions (colored areas) by DM and vacuum-stability (VS) constraints for $\text{BR}(c \rightarrow u \bar{\gamma})$ and for the average messenger mass scales $\bar{m}$ and $\bar{m}_D$, versus the corresponding mixing ξ and ξ_D , in the UF (left) and NUF (right) scenarios, respectively. 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 $\text{BR}(\ell \rightarrow \ell' \bar{\gamma})$

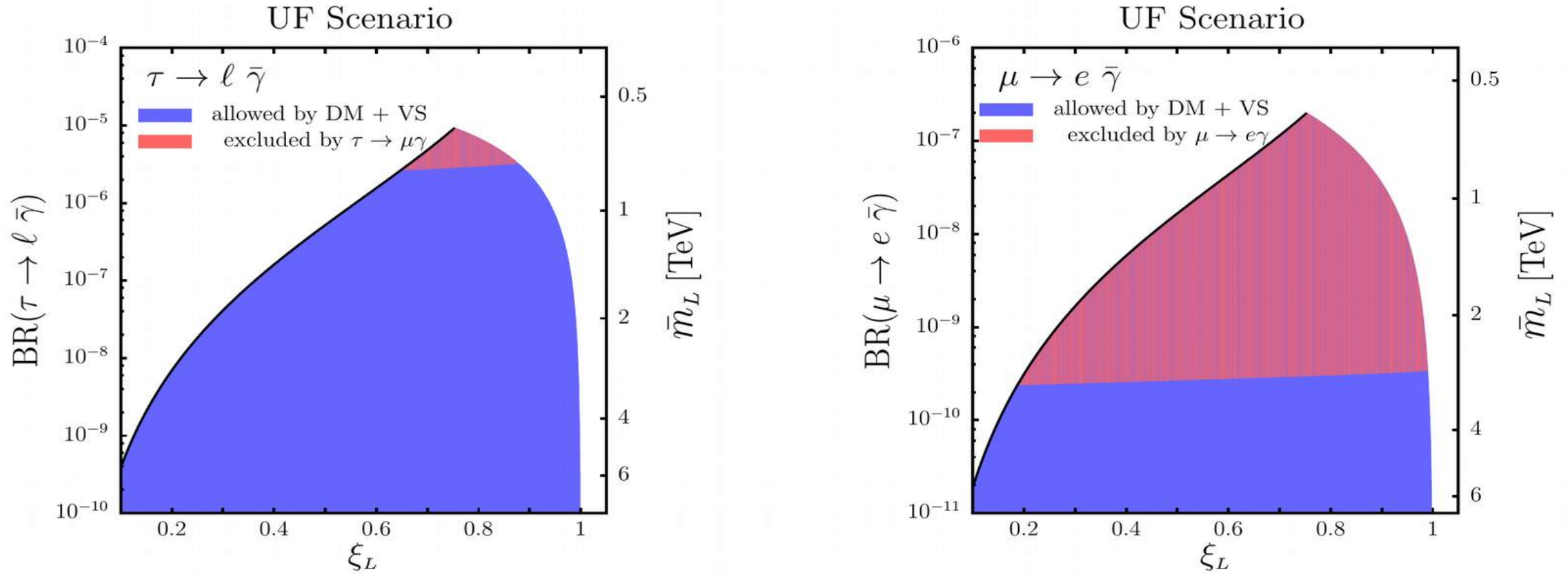


Figure 8: Regions allowed by DM and vacuum stability (VS) constraints for $\text{BR}(\tau \rightarrow \ell \bar{\gamma})$ (left) and $\text{BR}(\mu \rightarrow e \bar{\gamma})$ (right), and for the average messenger mass scale $\bar{m}_L$, versus the mixing ξ_L , in the UF scenario (blue areas). Superimposed 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 $j = 1, 2$.

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

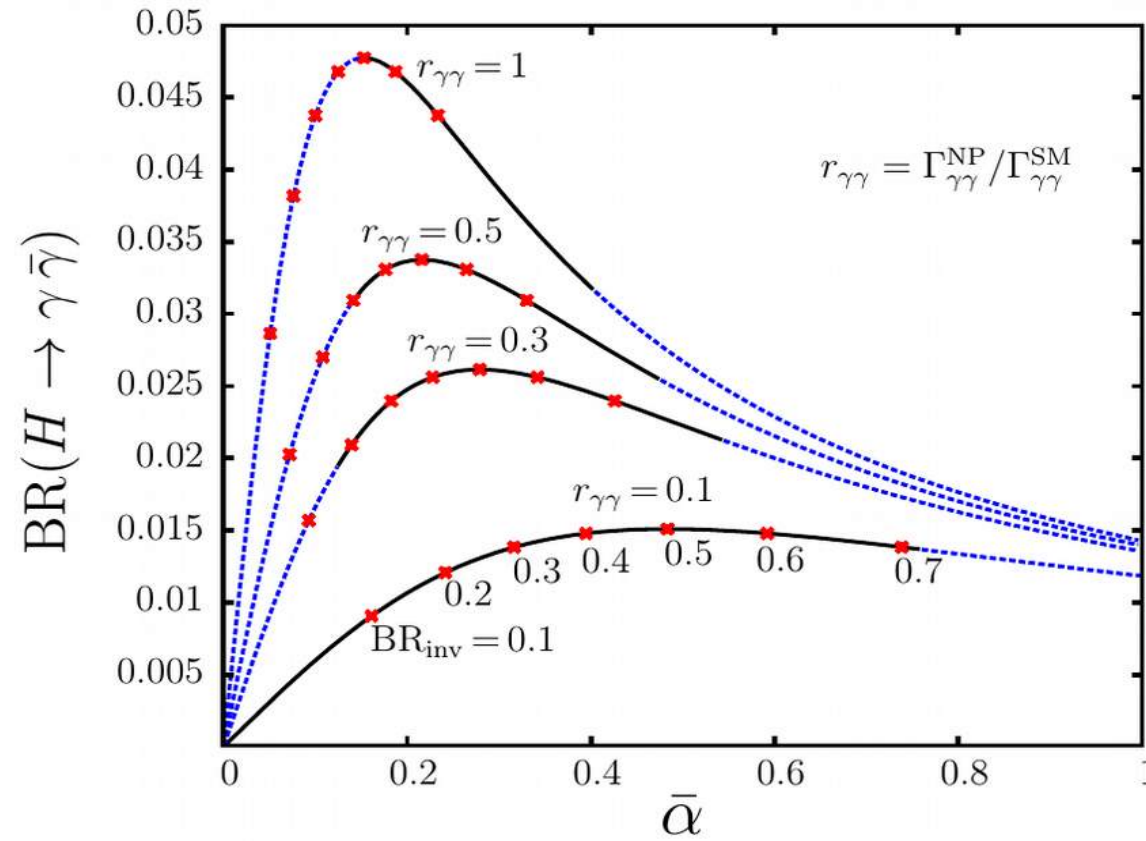


Figure 2: $\text{BR}(H \rightarrow \gamma \bar{\gamma})$ versus the dark U(1) fine structure constant $\bar{\alpha}$. The black solid lines show the allowed BR ranges as a function of the relative new physics contribution to the $H \rightarrow \gamma\gamma$ width, and of the $H \rightarrow \bar{\gamma}\bar{\gamma}$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