The Dark side of Flavor

Emidio Gabrielli

University and INFN Trieste, Italy

NICPB, Tallinn, Estonia

in collaboration with: Marco Fabbrichesi, Luca Marzola, Barbara Mele, Martti Raidal, Elena Venturini

based on:

PRL 119 (2017) 031801 M. Fabbrichesi, EG, B.Mele

PRD 95 (2017) 035005 EG, M.Raidal, L.Marzola

PRD 94 (2016) 115013 EG, B.Mele, M.Raidal, E.Venturini

PRD 89 (2014) 015008 EG, M.Raidal

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Outline

- Flavor model: theoretical framework
  - Yukawa couplings as effective couplings
  - generated by a Dark Sector
  - solution to the flavor hierarchy problem
- Phenomenological implications
- New FCNC signatures
- Conclusions

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 → Froggat-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

Effective Yukawa: Theoretical framework

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

- **Main paradigm:** 4-dim Yukawa operators (Ys) forbidden by some symmetry Σ but can arise from operators of dim-5
- Assume existence of a Dark sector, with Dark-Fermions
- generate dark-chiral symmetry breaking non-perturbatively so that DF mass hierarchies exist
- Transfer DF mass hierarchy to SM using appropriate messenger sector (via renormalizable interact.)
- Effective Ys arise at 1-loop after SSB of Σ

From operators of dim-5 $\left(\bar{\psi}_L^f H_L \psi_R^f\right) S + h.c.$

SSB <S> vev

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

M_f → Dark fermion mass

Λ_{eff} → (almost) universal effective scale arising from loop

- for each SM fermion there exists a massive Dark-fermion in the Dark sector (~ rescaled SM fermion spectrum)

- Non-perturbative dynamics in Dark sector responsible of of generating M_f hierarchy (see next slides)

Dark-Fermions mass hierarchy

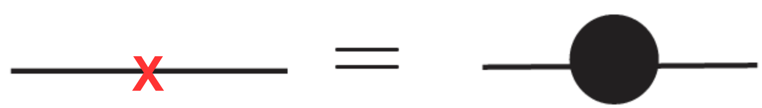
- Large hierarchy of Yukawa's suggests some non-perturbative, exponential mechanism for dark-fermion masses M_f

- Possible realization: via Nambu & Jona-Lasinio (NJL) mechanism

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

self-energy

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



perturbative solution m=0 always there

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

Lee-Wick mechanism for ChSB

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

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

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

$$D_\mu = \partial_\mu + igA_\mu \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

spin-1 ghost in the spectrum with mass ~ Λ

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.

Mass-gap solution

EG, PRD 77 (2008)
EG, Raidal, PRD 89 (2014)

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

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

$\Lambda \to$ Lee-Wick ghost mass

- non-universal U(1) charges → exponential mass spread

Masses M_f ⟺ U(1) charges q_f

- other mechanism based on Miransky scaling:

U(1) @ strong coupling → requires criticality ($\alpha > \alpha_c = \pi/3$)

Λ_c energy scale where U(1) becomes strong

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

embed this idea into effective Yukawa →

Yukawa hierarchy

EG, Raidal, PRD 89 (2014)

- requires exact U(1) gauge symmetry in Dark sector
- Dark fermions charged under U(1) in dark sector

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

α U(1) fine-structure c.
q_f U(1) quantum charges
$\gamma \sim$ anomalous dimension

- Yukawa's hierarchy related to U(1) charges

- A good matching of observed spectrum for charges O(1)

$\bar{\alpha}(\Lambda) = 0.14$, $q_{U_3} = 1$ and $q_{D_3} = 0.9$. $q_{E_3} = 1$

ψ:	U_2	D_2	U_1	D_1
q_ψ	0.88	0.82	0.77	0.76

ψ:	E_2	E_1	N_3	N_2	N_1
q_ψ	0.92	0.81	0.65	0.59	0.55

$m_{N_1} = 1$ eV, $m_{N_2} = 10^{-3}$ eV, and $m_{N_3} = 10^{-6}$ eV

Enforced by LR gauge symmetry

EG, Marzola, Raidal, PRD 95 (2015)

- $g_L = g_R = g$

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

$$H_L \qquad H_R$$

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)

$$\frac{1}{\Lambda_{\text{eff}}}\left(\bar{\psi}^f_L H_L\right)\left(H^\dagger_R \psi^f_R\right) + h.c.$$

- Yukawa's generated after SSB of $SU(2)_R$

- Strong CP problem automatically solved !

Interactions Lagrangian in LR models

required to generate Yukawa couplings

Dark fermions

SU(2)$_L$-doublet messenger fields

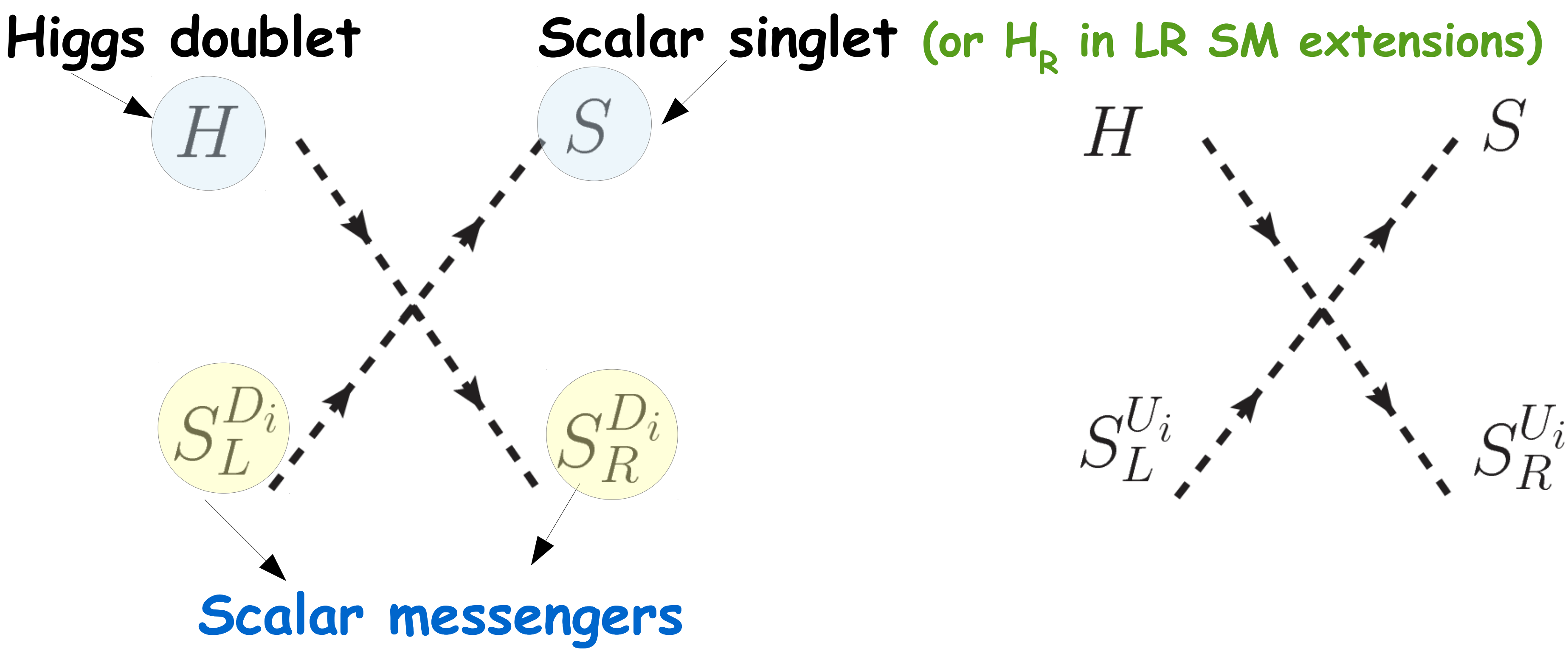
$$
\begin{aligned}
\mathcal{L}^{I}_{MS} \;=\;& g_L\left(\sum_{i=1}^{N}\left[\bar{q}^{i}_{L} Q^{U_i}_{R}\right]\hat{S}^{U_i}_{L} + \sum_{i=1}^{N}\left[\bar{q}^{i}_{L} Q^{D_i}_{R}\right]\hat{S}^{D_i}_{L}\right) \\
+\;& g_R\left(\sum_{i=1}^{N}\left[\bar{q}^{i}_{R} Q^{U_i}_{L}\right]\hat{S}^{U_i}_{R} + \sum_{i=1}^{N}\left[\bar{q}^{i}_{R}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

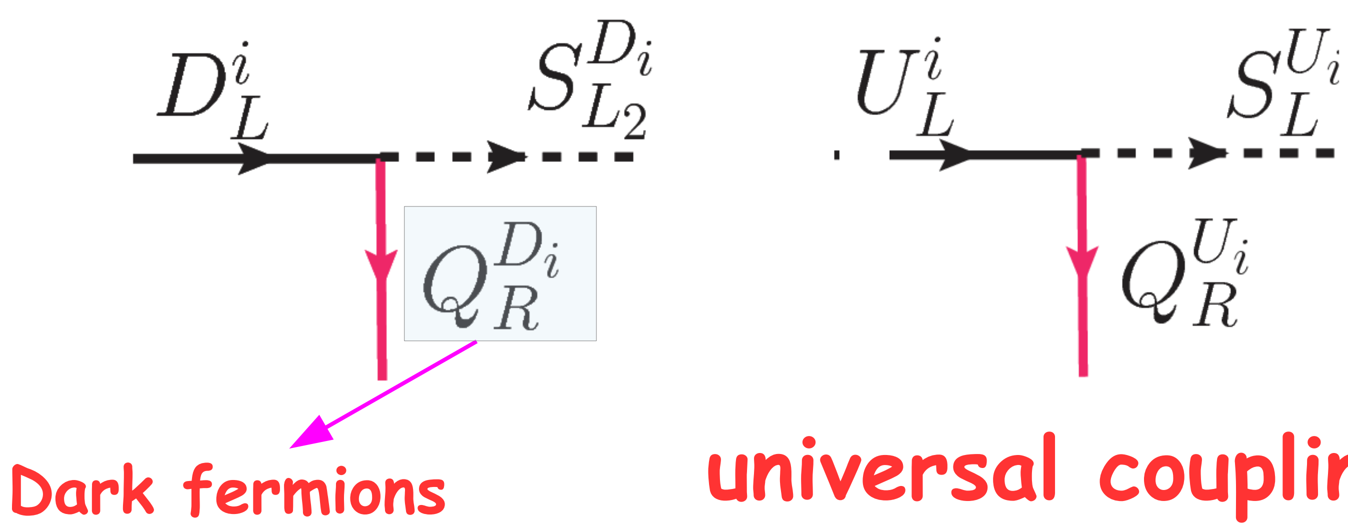
SU(2)$_R$-doublet messenger fields

4-scalar coupling of Higgses to fermions

(LR symmetry → gL=gR) SU(N) → $U(1)^N \times Z_N$ symmetry

Minimal set of new interactions





+ L ↔ R

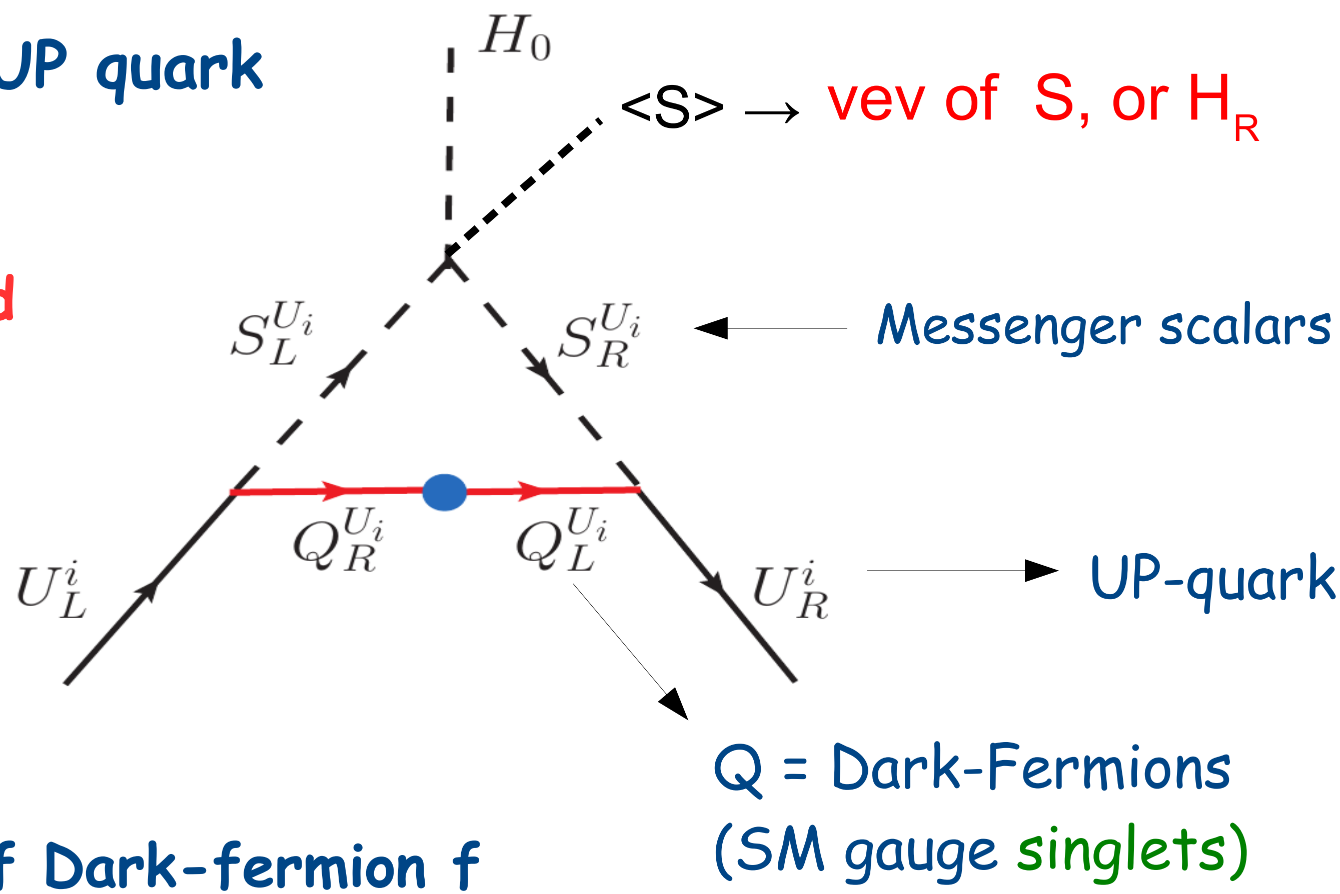
universal couplings → $U(1)^N \times Z_N$

Higgs Yukawa's radiatively generated at 1-loop

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

Yukawa coupling UP quark

H_0 = Higgs field



● → M_f = mass of Dark-fermion f

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

⇒ Yukawas follow M_f hierarchy !

Messenger mass matrix

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

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

Assume flavor universal structure

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

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

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

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

to avoid tachions

and color-charge breaking minima

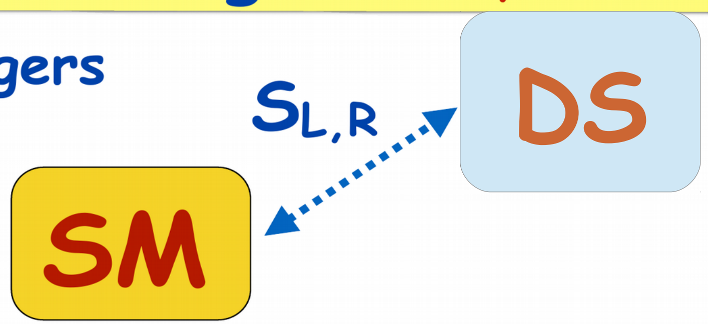
→ $0 < \xi < 1$

Summary of model's features

- **Dark fermions stable** [due to exact U(1)-dark gauge symmetry]
  - having long-range interactions mediated by a massless dark photon
  - 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 >> TeV scale

	Fields	Spin	$SU(2)_L$	$U(1)_Y$	$SU(3)_c$	$U(1)_F$
Messengers (Scalars)	$\hat{S}_L^{D_i}$	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	$-q_{U_i}$
Dark Sector (Fermions+Scalar)	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

Massless Dark photons

- Different from massive Dark photons scenarios
- On-shell massless DP can be fully decoupled from SM sector at tree-level B. Holdom, *Phys Lett.* 166 B (1986) 196
- 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 allowed

Massless Dark Photon signatures

- DP discovery channel in Higgs boson physics:

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

$$H \to \gamma\bar{\gamma}$$ → non-decoupling

- no results by CMS and ATLAS yet

Decoupling (suppressed by UV scale)

- 9 new FCNC processes $\mathsf{f} \to \mathsf{f}' \ \bar{\gamma}$ $\mathsf{f} = t, b, c, s, \tau, \mu$

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

- DP discovery channel in Kaon physics $K^+ \to \pi^+\pi^0\bar{\gamma}$

EG, Mele, Fabbrichesi, PRL 119 (2017)

- New Z boson decay $Z \to \gamma\bar{\gamma}$ (evading Landau-Yang Th.)

EG, Mele, Fabbrichesi, arXiv:1712.05412
To appear on PRL

FCNC fermion decays into dark photon

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

CKM matrix origin

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

$$\tilde{\mathcal{L}}^I_{MS} = \Bigg\{ g_L \left(\sum_{i,j=1}^{N} \left[\bar{q}^i_L (X^U_L)_{ij} Q^{U_j}_R \right] \hat{S}^{U_j}_L + \sum_{i,j=1}^{N} \left[\bar{q}^i_L (X^D_L)_{ij} Q^{D_j}_R \right] \hat{S}^{D_j}_L \right) + g_R \left(\sum_{i,j=1}^{N} \left[\bar{U}^i_R (X^U_R)_{ij} Q^{U_j}_L \right] S^{U_j}_R + \sum_{i,j=1}^{N} \left[\bar{D}^i_R (X^D_L)_{ij} Q^{D_j}_L \right] S^{D_j}_R \right)$$

radiative generation of Yukawa implies

$$Y^{U,D}_{ij} \sim \left(X^{U,D\,\dagger}_L \cdot \hat{Y}^{U,D} \cdot X^{U,D}_R \right)_{ij}$$

$$\hat{Y}^{U,D} = \mathrm{diag}[Y^{U,D}_1, Y^{U,D}_2, Y^{U,D}_3]$$

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

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

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

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

After rotation to quark-mass eigenstates

$$X_{L,R}^U \Rightarrow \rho_{L,R}, \qquad X_{L,R}^D \Rightarrow \eta_{L,R}$$

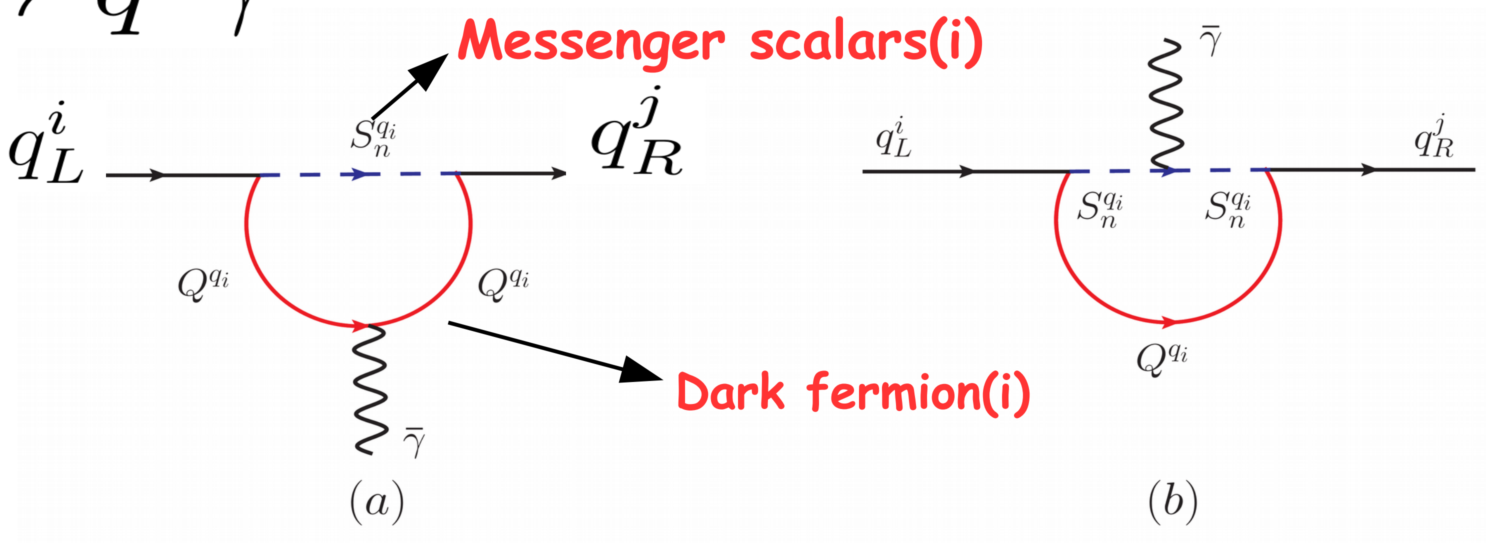
$$\rho_{L,R} \equiv V_{L,R}^{U\,\dagger} \cdot X_{L,R}^U \qquad \eta_{L,R} \equiv V_{L,R}^{D\,\dagger} \cdot X_{L,R}^D$$

$\rho_{L,R}, \eta_{L,R}$ ⇒ general matrices

FCNC decays of SM fermions into a Dark Photon

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

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



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

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

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

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

- Decay width

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

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

neglecting mass of final fermion

$$\frac{1}{(\Lambda_L^U)_{ij}} = \frac{\bar{e}\, m_{U_i}}{\overline{m}_U^2}\left[\bar{e}_i^U \frac{\rho_R^{ji}}{\rho_R^{ii}} F_{LR}(x_i^U, \xi_U) - \frac{g_R^2}{16\pi^2}\sum_{k=1}^{3} \bar{e}_k^U \rho_R^{jk}\rho_R^{ki} F_{RR}(x_k^U, \xi_U)\right]$$

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

$F_{RR}(x,\xi) = F_{LL}(x,\xi) \qquad F_{RL}(x,\xi) = F_{LR}(x,\xi)$ → Loop functions

- leading term → dark-fermion mass term absorbed into quark mass

Effective scale proportional to the decaying fermion mass

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

FCNC decays of SM fermions into a Dark Photon

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

- 9 new kind of FCNC signatures predicted !

top	$t \to c\,\bar{\gamma}\;,\; u\,\bar{\gamma}$	tau	$\tau \to \mu\,\bar{\gamma}\;,\; e\,\bar{\gamma}$
bottom	$b \to s\,\bar{\gamma}\;,\; d\,\bar{\gamma}$	muon	$\mu \to e\,\bar{\gamma}$
charm,s	$c \to u\,\bar{\gamma}\;,\; s \to d\,\bar{\gamma}$		

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

- Large and possibly measurable BRs are allowed, up to
  - $BR(b \to q\,\bar{\gamma}) \sim 10^{-4} - 10^{-3}$
  - $BR(c \to u\,\bar{\gamma}) \sim 10^{-8} - 10^{-4}$
  - $BR(t \to q\,\bar{\gamma}) \sim 10^{-10} - 10^{-7}$
  - $BR(\mu \to e\,\bar{\gamma}) \sim 10^{-10} - 10^{-9}$
  - $BR(\tau \to l\,\bar{\gamma}) \sim 10^{-10} - 10^{-6}$

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

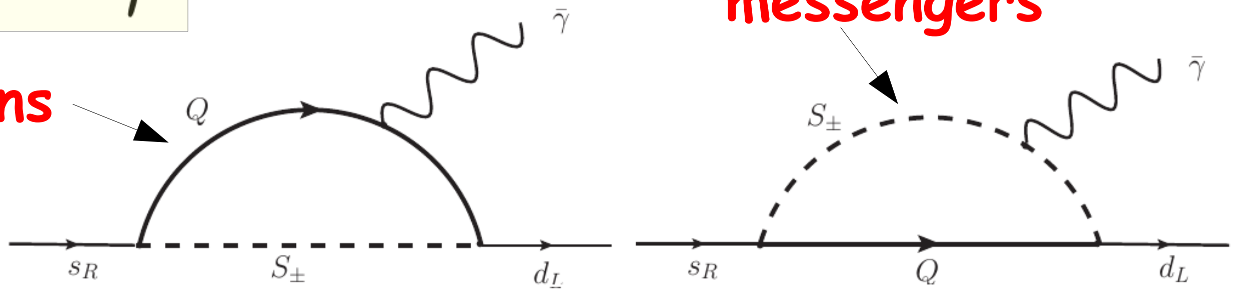
FCNC Kaon decay into a massless Dark photon

Fabbrichesi, EG, Mele, PRL 119 (2017)

$$s \to d\,\bar{\gamma}$$

Dark-fermions

messengers



Effective Hamiltonian

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

FC couplings $\xi = g_L g_R/2$

DF ~ messenger mass

$$K^+ \to \pi^+\,\pi^0\,\bar{\gamma}$$

FCNC magnetic-dipole operator

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

Dark-photon

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

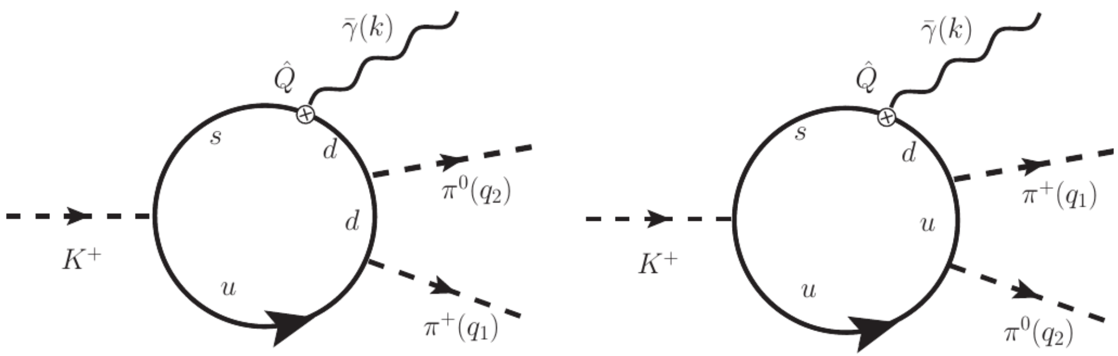
$$K^+(p) \to \pi^+(q_1)\,\pi^0(q_2)\,\bar{\gamma}(k)$$

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

$$\frac{\mathrm{d}^2\Gamma}{\mathrm{d}z_1\mathrm{d}z_2} = \frac{m_K}{(4\pi)^3}\,|M(z_1,z_2)|^2\,\{z_1z_2\,[1-2(z_1+z_2) - r_1^2 - r_2^2] - r_1^2 z_2^2 - r_2^2 z_1^2\}\;,$$

where $z_i = k\cdot q_i/m_K^2$ and $r_i = M_{\pi_i}/m_K$

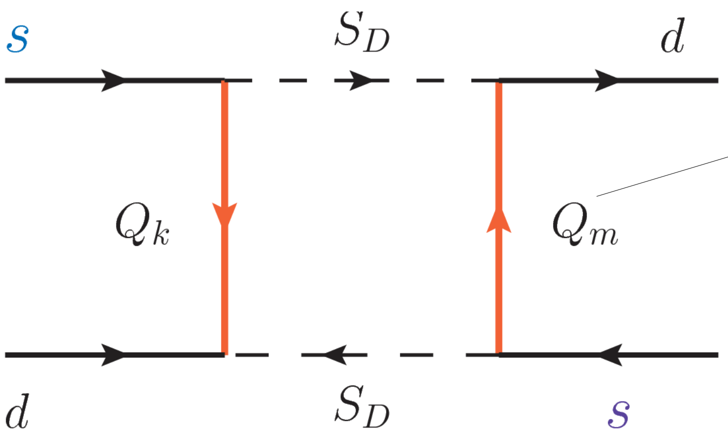
Matrix element estimated using the Chiral-Quark model



D_0, D_{00} usual PV functions

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

NLO contributions to ΔS=2 effective Hamiltonian



Dark-fermions

+ crossing diagrams

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

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

$\mu = 2$ GeV

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

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

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

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

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

- Λ → Dark sector mass scale

Fabbrichesi, EG, Mele, PRL 119 (2017)

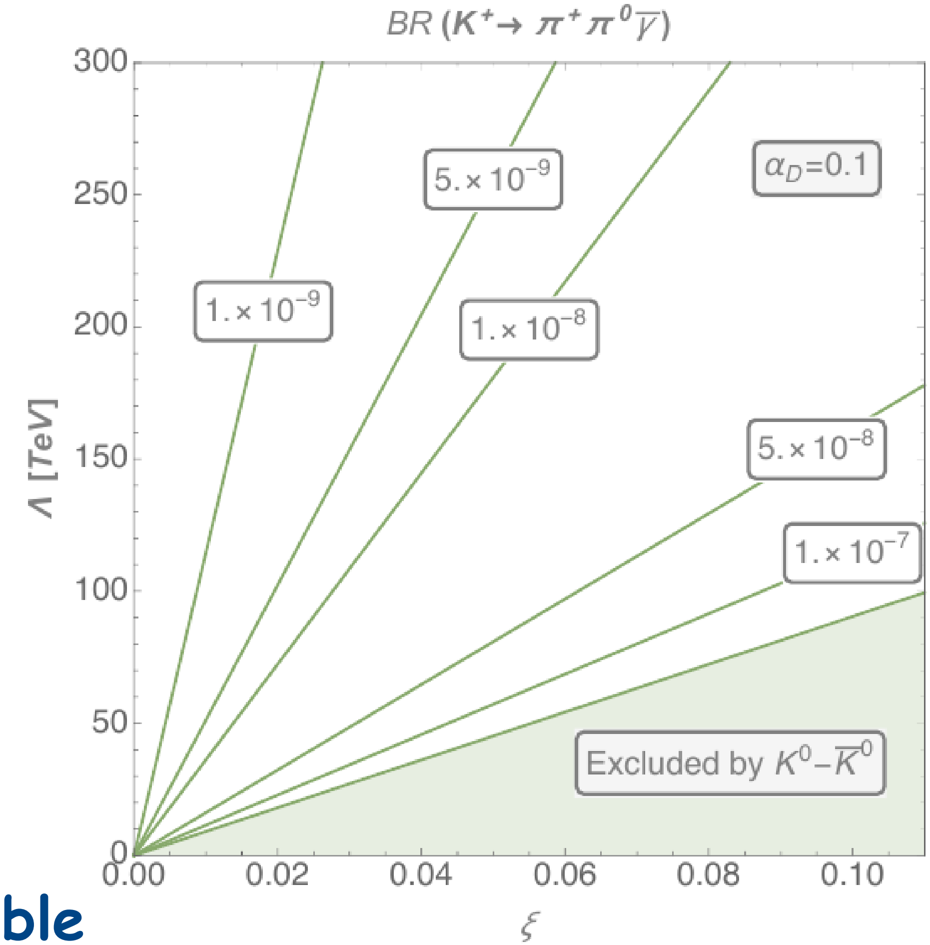
NLO K-$\bar{\text{K}}$ mixing constraints

[TeV]

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

[TeV]

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



Large BR of order 10^{-8}-10^{-7} possible

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

Conclusions

- Origin of Yukawa might require existence of a Dark Sector as predicted by a recent proposal to naturally explain Yukawa hierarchy

- Dark sector might have long distance interactions mediated by an unbroken $U(1)_F$ that forecasts a massless Dark Photon

- Higgs boson can be the SM portal to Dark Photons
  - rich phenomenological implications @ LHC and linear colliders
  - search for dark photons in $H \to \gamma \bar{\gamma}$, and $H \to Z \bar{\gamma}$

- In FCNC sector: new 9 processes predicted
  - $t \to (c,u)\, \bar{\gamma}$, $b \to (s,d)\, \bar{\gamma}$, $c \to u\, \bar{\gamma}$, $s \to d\, \bar{\gamma}$, $\tau \to l\, \bar{\gamma}$, $\mu \to e\, \bar{\gamma}$
  - not yet experimentally investigated

- FCNC $s \to d\, \bar{\gamma}$ transition: golden channel $K^+ \to \pi^+ \pi^0 + \bar{\gamma}$
  - large available rates BR ~ 10^{-8} - 10^{-7}
  - currently under consideration by NA62 @ CERN

Backup slides

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

$$x_{\rm f} = M^2_{Q_{\rm f}}/\bar{m}^2$$

- **After EWSB**

$$M_{Q_{\rm f}} = m_{\rm f}\left(\frac{16\pi^2}{g_L g_R}\right)\frac{1}{\xi f_1(x_{\rm f},\xi)}$$

Dark-fermion mass >> SM fermion mass

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

⇨ Dark fermion spectrum ~ rescaled spectrum of SM one

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)

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

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

implying lower bounds on v_R

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

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 → relaxed lower bound
- hierarchy among $SU(2)_L$ and $SU(2)_R$ naturally explained !

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

- from exp. upper bounds on BR($t \to q\,\gamma$)

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

$$\mathrm{BR}^{(t\to u\gamma)}(t \to u\,\bar{\gamma}) \quad < \quad 1.8 \times 10^{-2} \left(\frac{\bar{\alpha}}{0.1}\right)$$

$$\mathrm{BR}^{(t\to c\gamma)}(t \to c\,\bar{\gamma}) \quad < \quad 2.3 \times 10^{-1} \left(\frac{\bar{\alpha}}{0.1}\right)$$

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

$$\mathrm{BR}^{(t\to u\gamma)}(t \to u\,\bar{\gamma}) \quad < \quad 3.4 \times 10^{-2} \left(\frac{\bar{\alpha}}{0.1}\right)$$

$$\mathrm{BR}^{(t\to c\gamma)}(t \to c\,\bar{\gamma}) \quad < \quad 4.4 \times 10^{-1} \left(\frac{\bar{\alpha}}{0.1}\right)$$

large BR are allowed from BR($t \to q\,\gamma$)

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

Excluded by
lighest messenger
mass < 1 TeV

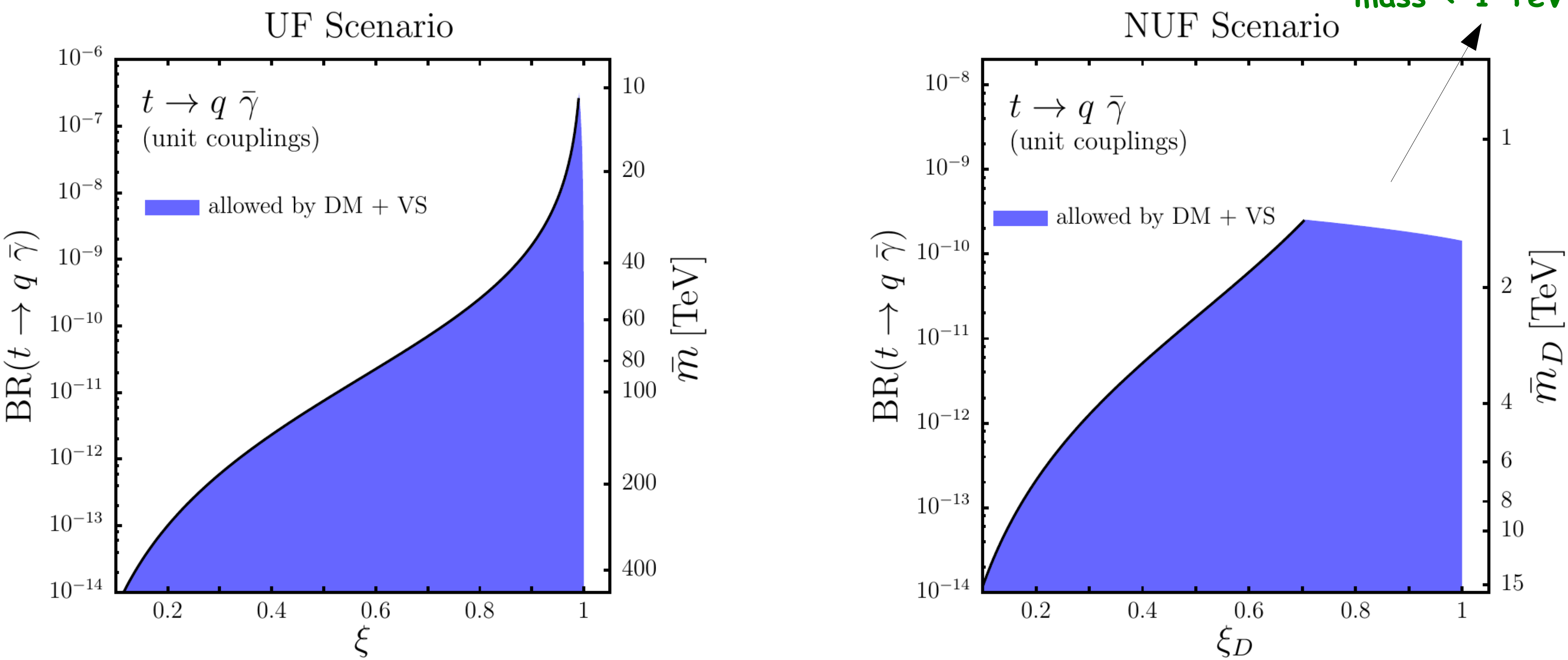
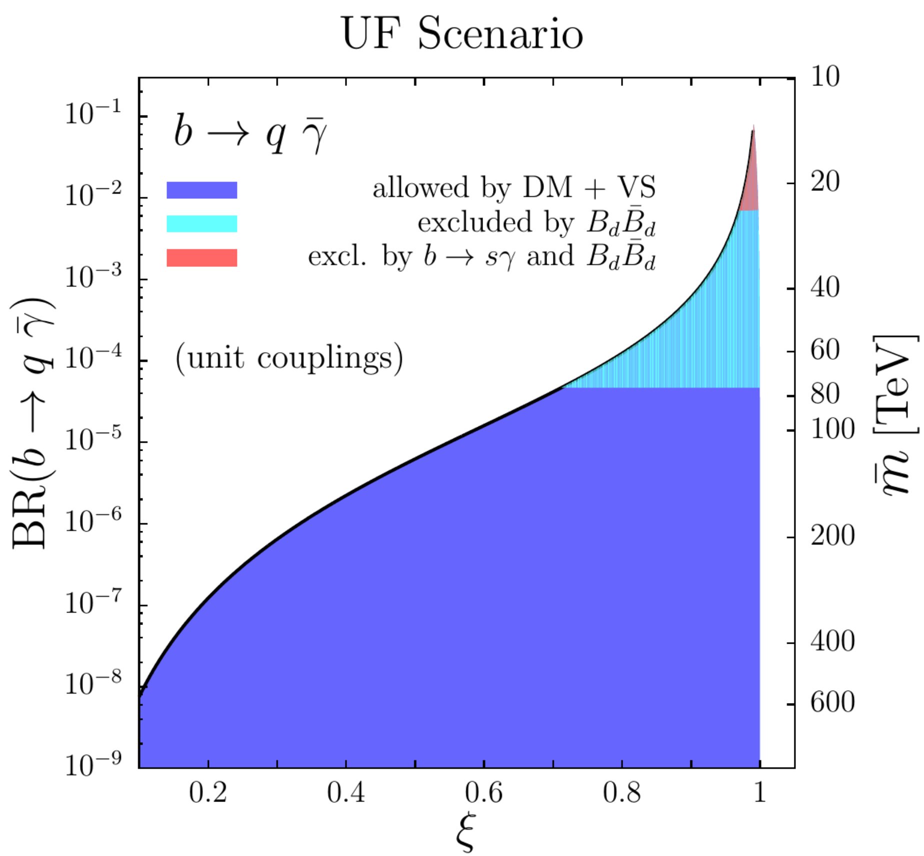


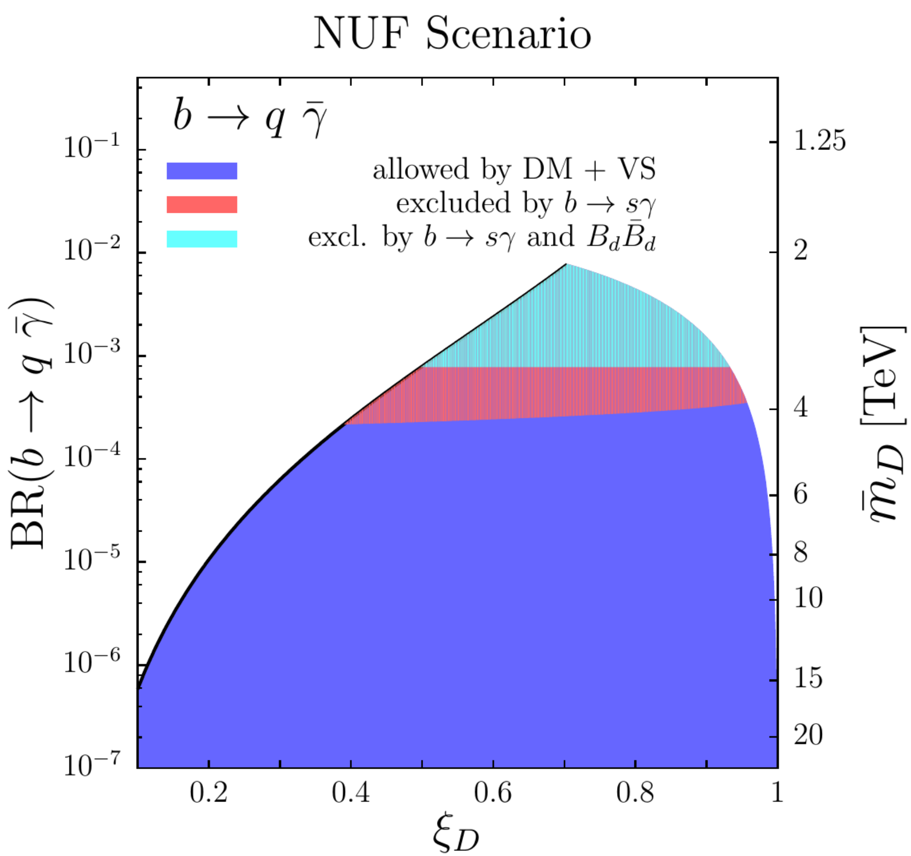
Figure 3: Allowed regions (colored areas) by DM and vacuum stability (VS) constraints for BR($t \to q\,\bar{\gamma}$) and for the average messenger mass scales $\bar{m}$ and $\bar{m}_D$, versus the corresponding mixing ξ and ξ_D, in the UF (left) and NUF (right) scenarios, respectively.

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 BR($b \to q\,\bar{\gamma}$)   (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 BR($c \to u\,\bar{\gamma}$)

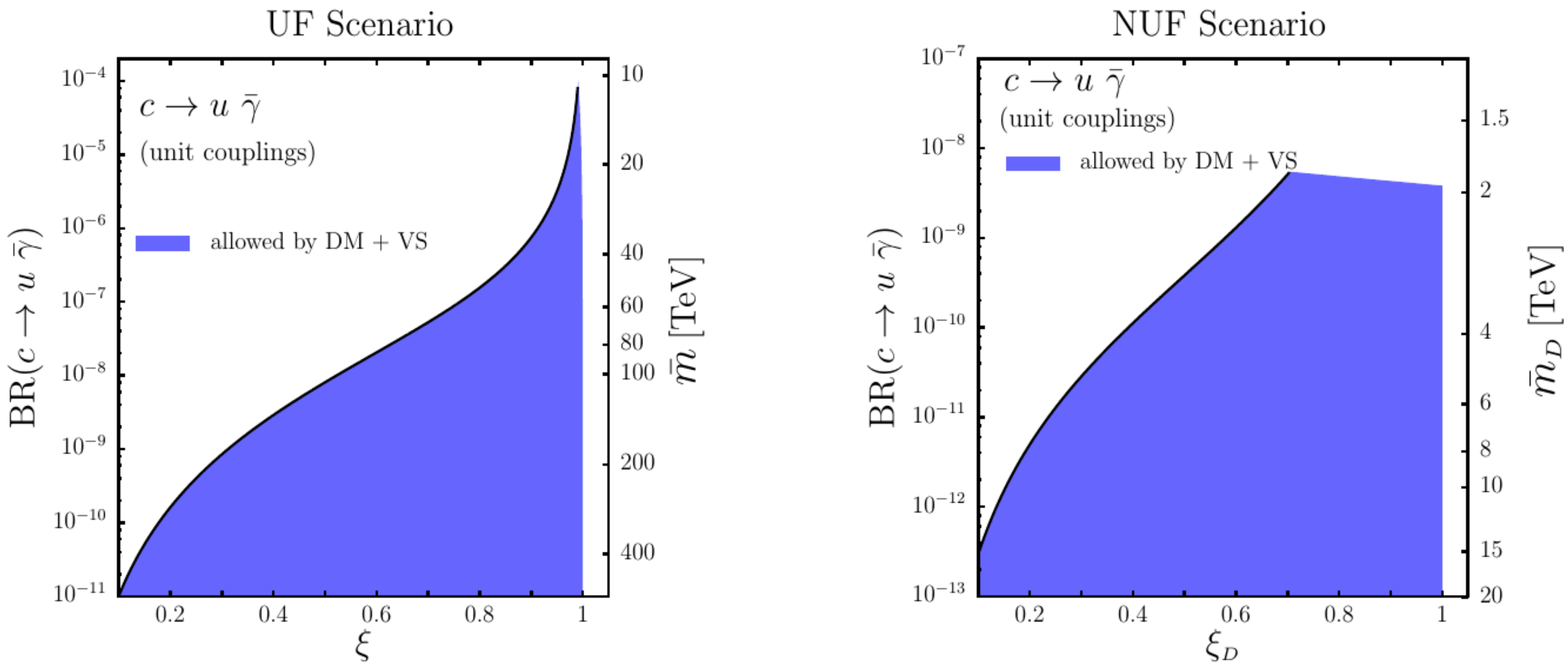


Figure 6: Allowed regions (colored areas) by DM and vacuum-stability (VS) constraints for $\mathrm{BR}(c \to u\,\bar{\gamma})$ and for the average messenger mass scales $\bar{m}$ and $\bar{m}_D$, versus the corresponding mixing ξ and ξ_D, in the UF (left) and NUF (right) scenarios, respectively. In the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

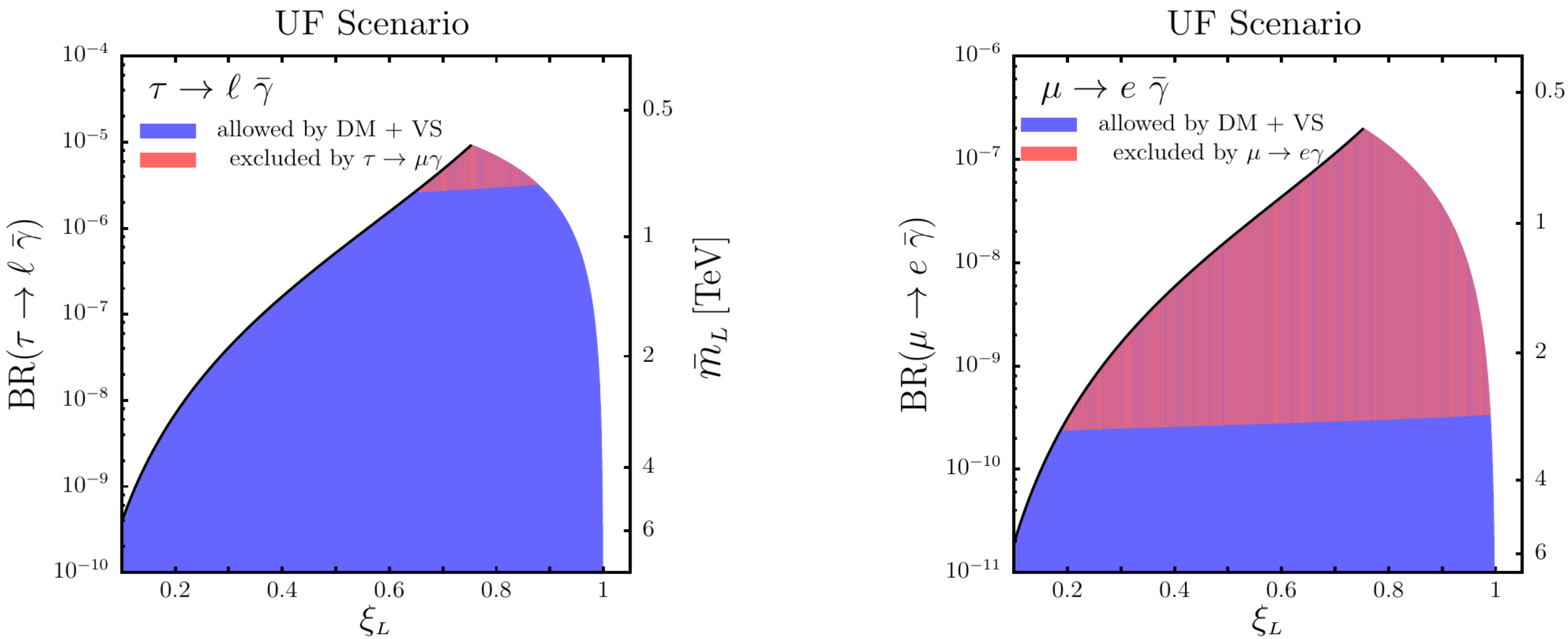


Figure 8: Regions allowed by DM and vacuum stability (VS) constraints for BR($\tau \to \ell\,\bar{\gamma}$) (left) and BR($\mu \to e\,\bar{\gamma}$) (right), and for the average messenger mass scale $\bar{m}_L$, versus the mixing ξ_L, in the UF scenario (blue areas). Superimposed red areas are the subregions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