

The Dark side of the Flavor

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E. Venturini

based on:

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

Outline

- The Flavor-hierarchy puzzle
- Yukawa couplings as effective couplings
- Dark sector origin of Flavor
- Exponentially spread Yukawa couplings
- Phenomenological implications
- New signatures at colliders
- Conclusions

Are we facing the LHC nightmare scenario ?

- Message from LHC new 13 TeV data, with $\sim 13 \text{ fb}^{-1}$ of Lum collected in both ATLAS and CMS in '15-'16
 - ➔ NO signal of New Physics (NP) (750 GeV diphoton hope vanished)
 - ➔ SM is in great shape (all data in good agreement with SM predictions)
 - ➔ NP scale is pushed up higher and higher (squarks, gluinos masses $> O(\text{TeV})$)
- naturalness criteria used so far to motivate and search for NP
 - ➔ SUSY, extended-technicolor, extra-dimensions, little-Higgs, composite Higgs (PNGB), where are they ?
 - ➔ plenty of discoveries expected at LHC 8-13 TeV with $O(\text{fb}^{-1})$ luminosity
- No mass hierarchy problem in SM Higgs sector :
 - radiative corrections to Higgs mass $\delta M^2_H \sim O(\alpha_W m^2_{\text{top}})$ same order as Higgs mass..(no terms $O(\alpha_W \Lambda^2_{\text{GUT}})$ if there is no GUT)
- desperately looking for new hints to invoke NP...

... rumors about theorists involved



8/22/2016

Fake human sacrifice filmed at Cern, with pranking scientists suspected | Science | The Guardian

the guardian

Fake human sacrifice filmed at Cern, with pranking scientists suspected

Spokeswoman at high temple of particle physics suggests 'scientific users' of the Geneva facility 'let their humour go too far' with staging of occult rite

Staff and agencies in Geneva

Thursday 18 August 2016 03.13 BST

The European Organisation for Nuclear Research (Cern) has launched an investigation into a video filmed at night on its Geneva campus depicting a mock ritual human sacrifice.

The video, which circulated online, shows several individuals in black cloaks gathering in a main square at Europe's top physics lab, in what appears to be a re-enactment of an occult ceremony.

The video includes the staged "stabbing" of a woman. It is filmed from the perspective of a secret viewer watching from a window above who, as the ceremony reaches its climax, lets out a string of expletives and flees with the camera still running.

The ceremony appears to have been staged in front of a statue of the Hindu deity Shiva that is on permanent display at the complex, home of the Large Hadron Collider.

SCIENCE / CERN

CERN Officially Distances Itself From Satan

LHC draws more than its fair share of conspiracy theorists



By **Arden Dier**, Newser Staff
Posted Apr 5, 2016 3:43 AM CDT
Updated Apr 10, 2016 7:53 AM CDT



A technician works in the Large Hadron Collider tunnel of CERN. (Laurent Gillieron/Keystone via AP)

335 comments

Comments

(NEWSER) – When CERN's Large Hadron Collider is fired up again at the end of April, physicists won't just be testing for unknown particles. They'll also be testing a [new FAQ page](#), and it's an unusual one that distances CERN from demons and Satan. Since the LHC began smashing particles together, conspiracy theorists have suggested physicists were about to open a door to another dimension, allowing apocalyptic forces to reach our planet, reports [the Wall Street Journal](#). An editorial in Michigan's [Daily Reporter](#) in September noted

filmed on our premises but without official permission or knowledge," a Cern Agence France-Presse in an email.

lone this type of spoof, which can give rise to misunderstandings about the our work."

under way was an "internal matter", she said.

1 questions about security on Cern's campus.

security procedures surrounding access to the campus, the Cern "Cern IDs are checked systematically at each entry to the Cern site whether it

d that those responsible for the prank had access badges.

ry year thousands of scientific users from all over the world and sometimes air humour go too far. This is what happened on this occasion," the email said.

was not available to comment the possible identity of those responsible.

AFP they had been in contact with Cern about the video but were not involved ation.

Flavor-hierarchy problem

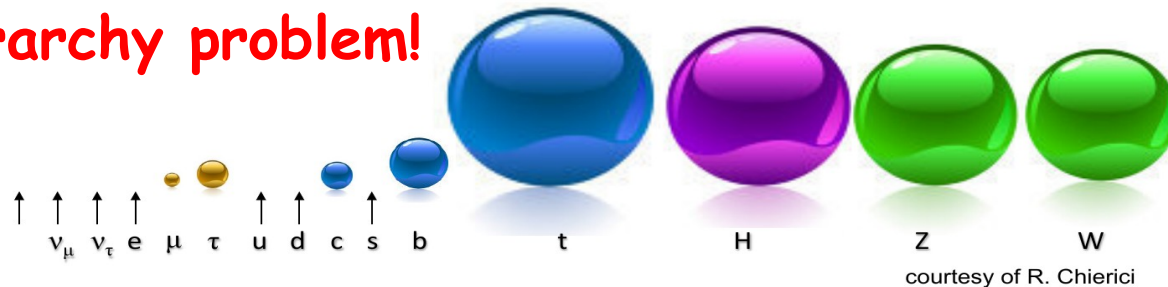
- The SM fermion mass sector contains too many free parameters, reflected in the structure of Yukawa couplings (**Ys**)

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...

The true hierarchy problem!



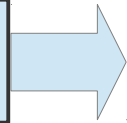
- good agreement with SM Higgs properties strongly supports the existence of SM Ys (to generate fermion masses)

- **Ys eigenvalues** are spanning from 6 order of magnitude for charged fermions, up to 12 if we include Dirac neutrino masses
- Unlike gauge interactions, **Ys not related to any symmetry** resembling random numbers rather than fundamental couplings.
- **What if Yukawas are low energy effective couplings ?**
→ easier to justify the large hierarchy (Froggatt-Nielsen mechanism)
- Recently, a natural solution to solve the Flavor-hierarchy problem was proposed
EG, M. Raidal, PRD 89 (2014)
- **A new paradigm:** Ys are effective couplings arising at 1-loop from interactions of SM fields with a Dark sector
- **Flavor hierarchy problem shifted to the ChSB of dark sector !**

The Dark Sector (DS) origin of Flavor

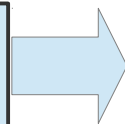
- Main assumption: **Chiral** and **Flavor Symmetry Breaking** reside in the Dirac masses of N_f dark fermions in Dark Sector
- Dark fermions : **SM singlet replica of SM fermions**
- Messenger fields: responsible to transmit the **ChSB** and **FSB** to the **SM** through radiatively generated Yukawa couplings
- Universal masses for messenger fields

perturbative dynamics



generate Yukawa couplings at 1-loop

non-perturbative dynamics



generate exponentially spread
Dirac masses for dark-fermions

Generation of Yukawa couplings

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

- Y_f are vanishing at the tree-level
- this can be enforced by some S symmetry ($H \rightarrow -H$, $S \rightarrow -S$)
- after SSB of S (typically a vev of a scalar) Y_s can be generated

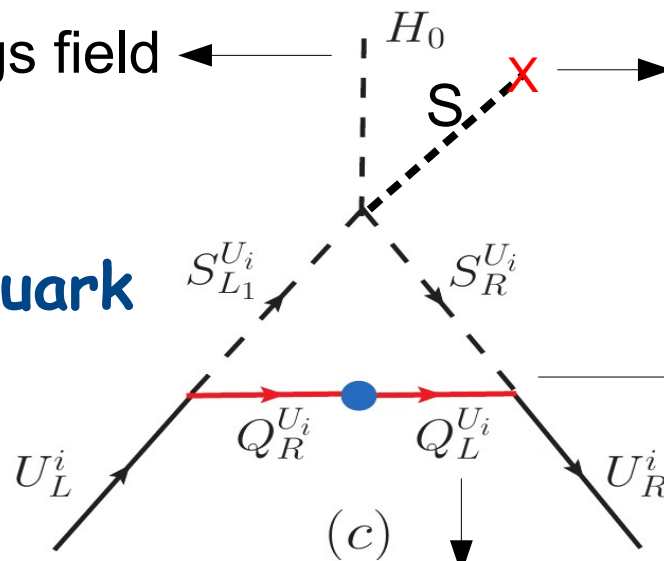
EG, M. Raidal, PRD 89 (2014)

Higgs Yukawa's radiatively generated at 1-loop

H_0 = Higgs field $\leftarrow$ H_0 $\xrightarrow{S}$ vev of $\langle S \rangle$

Yukawa coupling UP quark

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



messenger scalars
(same quantum numbers
of squarks and sleptons)

Dark-Fermions (singlets under SM gauge)

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

Mechanism for dark-fermion mass generation

- Yukawa couplings follows dark-fermion mass M_f hierarchy
- Non-perturbative dynamics in DS responsible of M_f hierarchy

ChSB induced by U(1) Lee-Wick term

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

Invariant under global chiral transformations and local U(1) gauge invariance

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

- fermion mass “ m ” arises as a non-trivial solution of the self-consistent mass gap equation (via Nambu-Jona-Lasinio mechanism) PR 122 (1961) 345, PR 124 (1961) 246

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

perturbative solution always there, corresponds to $m=0$
non trivial solutions $m \neq 0$ correspond to the true vacuum (lowest energy), which is a superposition of pair-states

$\Sigma \rightarrow$ Self-Energy induced at 1-loop by the interaction

Due to the presence of an indefinite metric and $U(1)_F$ gauge symmetry the one-loop contribution to SE evaluated on-shell is **finite and gauge invariant** and **proportional to fermion mass due to chirality**

photon long-distance contribution

ghost photon with mass $\sim \Lambda$
short-distance contribution

$$\Sigma(\hat{p}, m) = \text{diagram with red dashed arc (+)} + \text{diagram with magenta dashed arc (-)}$$

proportional to m

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

At low energy, it behaves as a local 4-fermion interaction (Ch. invariant) similar to the one of NJL model

In the weak coupling regime, non-trivial solution $m \neq 0$ exists only for $m \ll \Lambda$

$$1 = -\frac{\alpha}{2\pi} \int_0^1 dx (2-x) \log \left(\frac{m^2}{\Lambda^2} \frac{(1-x)^2}{x} \right) + \mathcal{O}(m^2/\Lambda^2)$$

- **minus sign** crucial for the existence of the solution
- it depends on the spin nature of the interaction ($g_{\mu\nu}$ metric)
- **scalars predicts +sign** → no solution in weak coupling regime

mass-gap solution (for 1 fermion)

$$m = \Lambda \exp \left\{ -\frac{2\pi}{3\alpha(\Lambda)} + \frac{1}{4} \right\} \quad \alpha = g^2/4\pi$$

truly non-perturbative solution as a function of α

• if we have N_f fermions coupled to $U(1)_F$

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

• if $U(1)_F$ charges q_f are non-universal $\rightarrow$ mass splitting generated

• but SM Y s are proportional to DF masses $\rightarrow$ exponentially spread

EG, M. Raidal, PRD 89 (2014)

$$Y^i \sim \exp \left\{ -\frac{\gamma}{\alpha q_i^2} \right\}$$

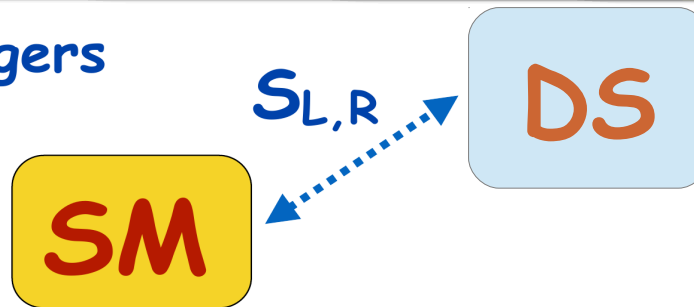


amazing matching with
observed spectrum for
 q_{DF} integers

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

■ heavy scalar messengers $S_{L,R}$

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



Messengers
(Scalars)

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

Dark Sector
(Fermions+Scalar)

- DM stability requires colored messengers to be heavy
messenger mass in the quark sector > 50 TeV
- EW messengers could be lighter < 1 TeV

Setting Yukawa couplings to zero

- We used discrete Z_2 symmetry ($H \rightarrow -H$, $S \rightarrow -S$)
- Yukawa operators are related to higher order operators O_Y

$$O_Y \sim \frac{1}{\Lambda_{eff}} (\bar{\psi}_L H_L) \psi_R S + h.c.$$

- **after SSB** of $S \rightarrow \langle S \rangle$ SM Yukawa operators are generated

- A new way to set $Y_f \rightarrow 0$, extending SM gauge to **LR symmetry**

$$SU(2)_L \times SU(2)_R \times U(1)_Y \quad \underbrace{(\bar{\psi}_L^f)}_{SU(2)_L} H_L \text{ and } (\psi_R^f) \underbrace{\hat{H}_R}_{SU(2)_R \text{ doublets}}$$

- **Theorem:** if there exists only one **H_R doublet** to break $SU(2)_R$, then Yukawa couplings are vanishing at tree-level due to gauge invariance

lowest dimensional operator gauge invariant $\longrightarrow \frac{1}{\Lambda_{eff}^f} (\bar{\psi}_L^f H_L) (H_R^\dagger \psi_R^f) + h.c.$

$\xrightarrow{H_R \rightarrow \langle H_R \rangle}$

- **Y_s generated at 1-loop by the Dark Sector + SSB of $SU(2)_R$!**

LR Gauge sector

EG, L.Marzola, M.Raidal, in preparation

- The hyper charges of RH doublets are set to the corresponding LH values

$$Q = I_3^L + I_3^R + Y$$

- Left-Right symmetry requires to set $g_L = g_R = g$

$$\mathcal{L} \supset (D_\mu H_R)^\dagger (D^\mu H_R) = (H_{uR}^*, H_{dR}^*) \left| \left[g \sum_i \frac{\tau^i}{2} W_{R\mu}^i + g' Y B_\mu \right] \right|^2 \begin{pmatrix} H_{uR} \\ H_{dR} \end{pmatrix}$$

v_L and **v_R** vevs of H_L and H_R , **assuming** $v_R \gg v_L$.

Charged gauge boson masses $M_{W_{L,R}}^2 = \frac{g^2 v_{L,R}^2}{4}$ **$Y = (B-L)/2$**

$$e = \frac{g' g}{\sqrt{2g'^2 + g^2}} = g \sin \theta_W = g' \sqrt{\cos 2\theta_W}$$

basis (B, W_L^3, W_R^3)

Neutral sector mass matrix

$$M^2 = \frac{1}{8} \begin{pmatrix} (v_L^2 + v_R^2)g'^2 & -v_L^2 g g' & -v_R^2 g g' \\ -v_L^2 g g' & v_L^2 g^2 & 0 \\ -v_R^2 g g' & 0 & -v_R^2 g^2 \end{pmatrix}$$

Radiative Yukawa model naturally predicts $v_R \gg v_L$. **(see next slides)**

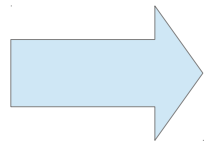
Mass gauge eigenstates at leading order in $\left(\frac{v_L}{v_R}\right)$ expansion

neutral sector

$$\begin{cases} M_A = 0 \\ M_{Z_L}^2 = \frac{(g^4 + 2g'^2 g^2)v_L^2}{4(g'^2 + g^2)} \\ M_{Z_R}^2 = \frac{(v_L^2 + v_R^2)g'^4 + 2g'^2 g^2 v_R^2 + g^4 v_R^2}{4(g'^2 + g^2)} \end{cases}$$

charged sector

$$M_{W_{L,R}}^2 = \frac{g^2 v_{L,R}^2}{4}$$



SM ρ parameter = $1 + \mathcal{O}((v_L/v_R)^2)$

$$\frac{M_{W_R}^2}{M_{Z_R}^2 (1 - \tan^2 \theta_W)} = 1 + \mathcal{O}((v_L/v_R)^2)$$

prediction $\rightarrow$

$$\begin{aligned} M_{W_R} &\simeq 0.84 M_{Z_R} \\ M_{W_L} &\simeq 0.88 M_{Z_L} \end{aligned}$$

Interaction Lagrangian in LR models

to generate Yukawa couplings

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

Dark fermions (pointing to $\bar{q}_L^i$)
 L-doublet messenger fields (pointing to $\hat{S}_L^{U_i}$ and $\hat{S}_L^{D_i}$)
 L-doublets quarks (pointing to $Q_R^{U_i}$ and $Q_R^{D_i}$)
 R-doublets quarks (pointing to $\bar{q}_R^i$)
 R-doublet messenger fields (pointing to $\hat{S}_R^{U_i}$ and $\hat{S}_R^{D_i}$)
 4-scalar coupling of Higgses to fermions (pointing to the λ term)

DM and Vacuum stability bounds

Messenger mass matrix

mass² eigenvalues

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

$$M_S^2 = \begin{pmatrix} m_L^2 & \Delta \\ \Delta & m_R^2 \end{pmatrix} \quad m_{\pm}^2 = \frac{1}{2} \left(m_L^2 + m_R^2 \pm [(m_L^2 + m_R^2)^2 + 4\Delta]^2 \right)^{1/2}$$

Flavor universality in the messenger mass matrix → same matrix for each flavor

LR symmetry → $m_L^2 = m_R^2 \equiv \bar{m}^2$ → mixing parameter $\xi = \Delta/\bar{m}^2$

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

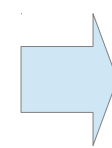
to avoid tachions (and potential color-charge breaking minima) $\xi < 1$

to avoid charged stable particle

(DM constraints)

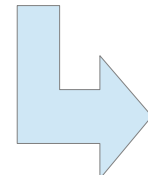
$$\bar{m} \geq m_t \left(\frac{16\pi^2}{g_L g_R} \right) F(\xi)$$

implying bounds on v_R



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

Lightest messenger heavier than the heaviest dark fermion Q_t



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

(see next slides for the origin of above relation)

Absolute lower bounds on v_R [TeV]

	v_R	W_R mass	lightest messenger mass	
ξ	$v_R^{\min}$ [TeV]	$M_{W_R}^{\min}$ [TeV]	$\bar{m}^{\min}$ [TeV]	$m_-^{\min}$ [TeV]
0.1	1581	169	554	526
0.2	799	85	279	249
0.3	529	56	185	155
0.5	293	31	107	75
0.7	164	17	67	37
0.8	110	12	52	23
0.9	57	6	35	11
0.95	30	3	25	6

Table 2: Minimum values allowed by vacuum stability and DM constraints, for the H_R vev $v_R^{\min}$, the W_R mass $M_{W_R}^{\min}$, the average messenger mass $\bar{m}^{\min}$, and the lightest *up-down* universal messenger mass eigenvalue $m_-^{\min} = \bar{m}^{\min} \sqrt{1 - \xi}$, versus some values of the mixing parameter ξ . Results are in unit of couplings, that is $g_{L,R} = \lambda = 1$.

■ large hierarchy among v_L and v_R predicted !

■ Colored-messenger masses naturally above 10 TeV for $\xi \sim 0.9$
and above 100 TeV for small mixing $\xi < 0.1$

Yukawa couplings (quark f)

prediction at 1-loop (in low energy approximation), exact in ξ

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

after EWSB: mass of dark-fermion M_{Q_f} as function of quark mass m_f

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

Loop function

$$f_1(x, \xi) = \frac{1}{2} \left[C_0\left(\frac{x}{1-\xi}\right) \frac{1}{1-\xi} + C_0\left(\frac{x}{1+\xi}\right) \frac{1}{1+\xi} \right]$$

$$C_0(x) = \frac{1 - x(1 - \log x)}{(1 - x)^2}$$

One-loop contribution to the Higgs mass

- for large mixing ξ and large g_L, g_R lower bounds on v_R can be relaxed

$$\delta m_H^2 \sim \frac{(\lambda v_R)^2}{16\pi^2} \log \left(\frac{\bar{m}^2}{m_H^2} \right) \longrightarrow \text{naturalness arguments favor large mixing } \xi \text{ and large } g_L, g_R$$

Phenomenological implications

- Dynamics responsible of dark-fermion masses predicts an unbroken $U(1)_F \rightarrow$ a massless dark-photon in the spectrum

- rich phenomenology at colliders [exploration just started]

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

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

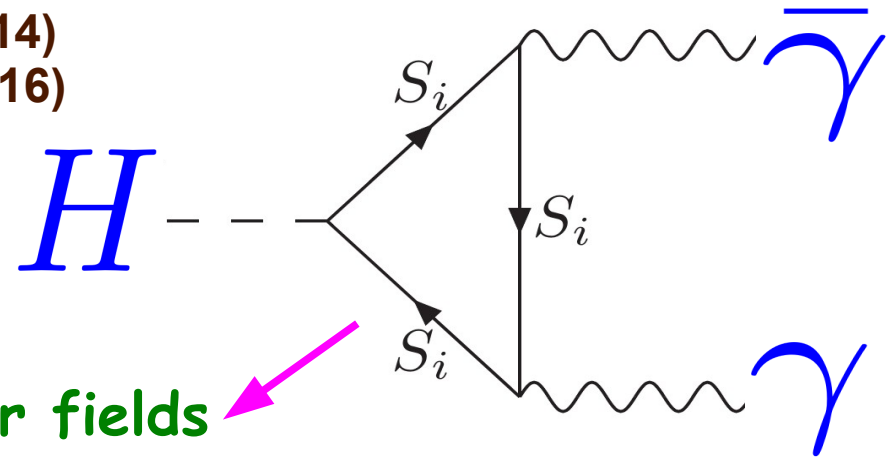
- not yet analyzed by CMS and ATLAS collaborations (only exp. analyses with a continuous massive system for the missing energy performed)
- although inspired by this scenario, the following analysis and results are fully model independent

Monophoton Exotic Higgs Signature @ LHC

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

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

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



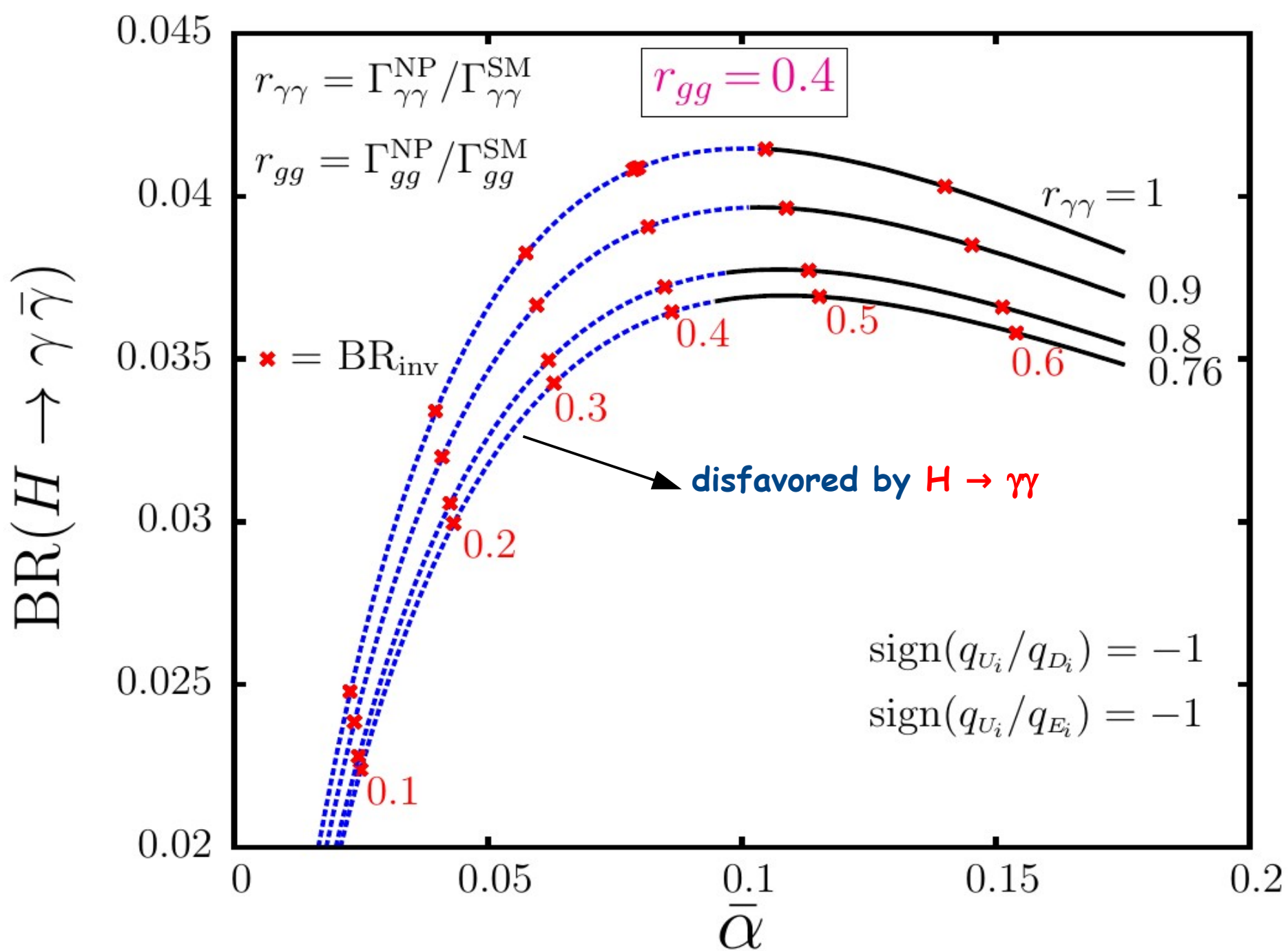
- Effective coupling has same structure as $H \rightarrow \gamma \gamma$

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

- Non-decoupling effect $\rightarrow \Lambda_{\gamma \bar{\gamma}}$ proportional to the Higgs VEV !!!
- DP coupling $\bar{\alpha}$ could be large (allowed if DP is massless)
astrophysical/cosmological constraints of massive DP do not hold

- potentially large rates expected in this scenario !

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



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

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

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

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

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

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

with 2 jets mainly
forward/backward

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

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

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

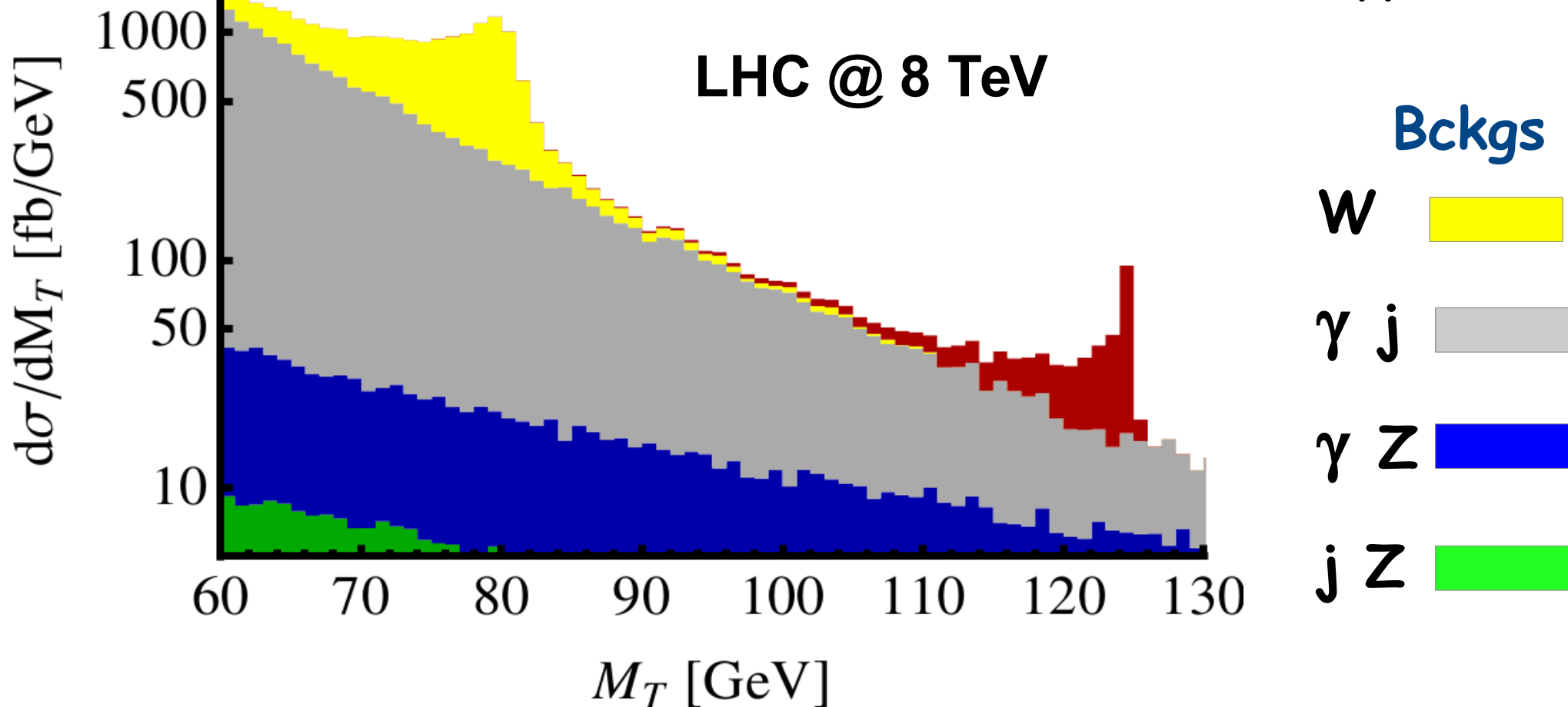
M_T distribution [fb/GeV]

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

Signal

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

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



- M_T distribution peaked at original M_H mass

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

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

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

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

Significance vs BR in gg and VBF mechanisms

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

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

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

Large discovery potential @ LHC 14 TeV
by gluon-gluon fusion up to BR $\sim 10^{-4}$ - 10^{-3}

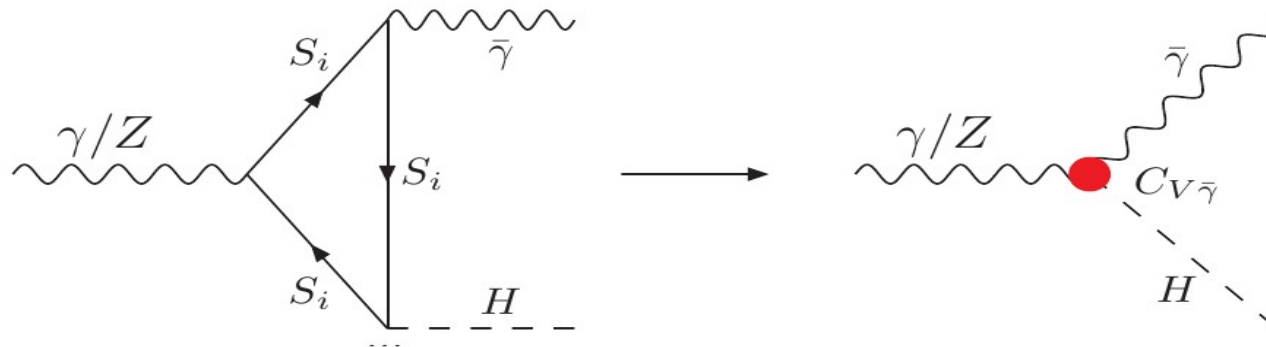
Implications of $H\bar{\gamma}$ and $H\bar{z}\bar{\gamma}$ at e^+e^- colliders

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

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

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

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



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

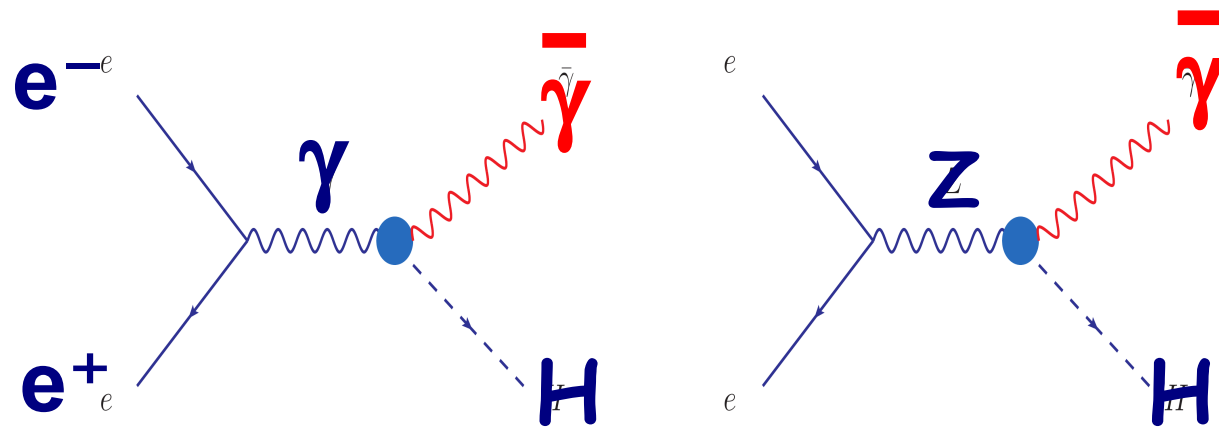
$$e^+e^- \rightarrow H\bar{\gamma} \rightarrow b\bar{b}\bar{\gamma}$$

Model independent analysis:

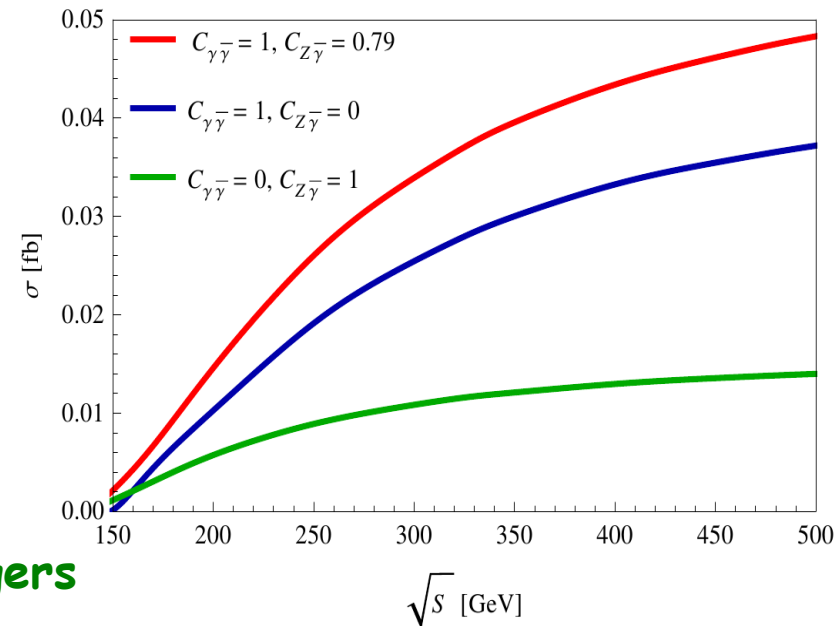
Effective Lagrangian parametrization

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

DP field strength



Total x-section



assuming mass degeneracy in Left and Right messengers

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

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

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

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

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

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

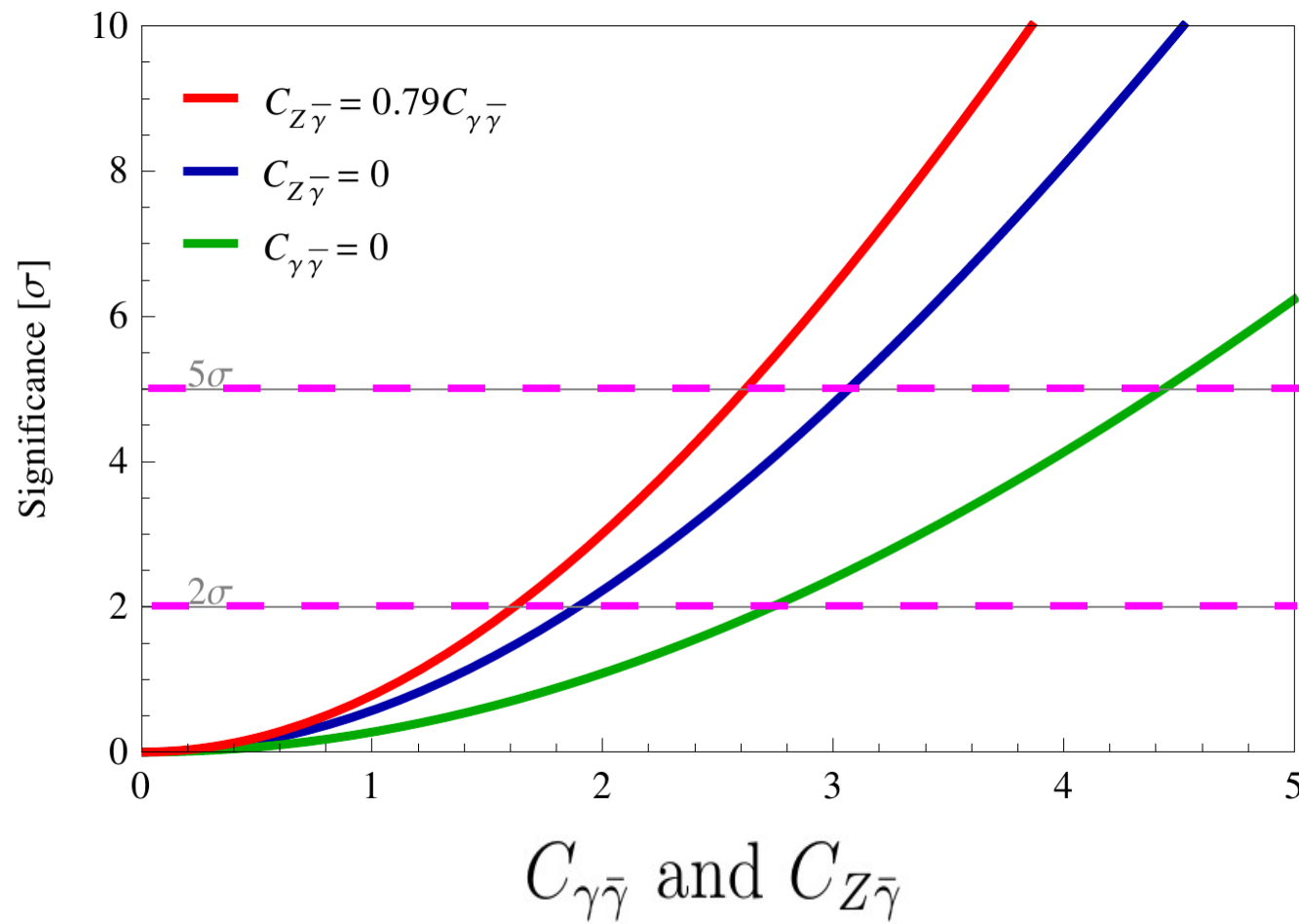
Irreducible

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

Reducible

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

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



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

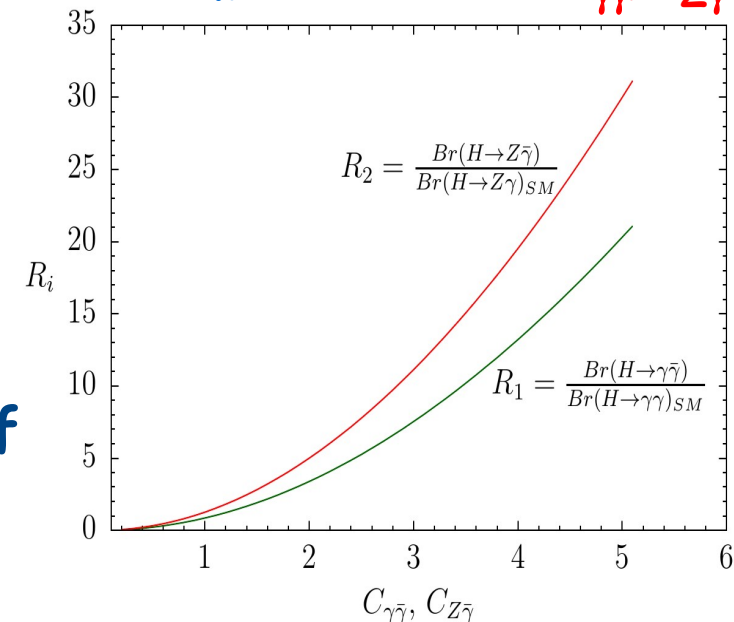
5 σ values of $C_{\gamma\bar{\gamma}}$ and $C_{Z\bar{\gamma}}$ in the natural range of predictions for the U(1)_F Flavor model

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

5 σ

2 σ

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



Searching for $H \rightarrow \gamma \bar{\gamma}$ decay at e^+e^-

We consider main Higgs production at $e^+e^- \rightarrow Z^* \rightarrow Z H \rightarrow \gamma \bar{\gamma}$

S.Biswas, EG, M.Heikeinheimo, B.Mele
in preparation

- we consider Z decays into $f\bar{f} = \mu^+\mu^-$, $j j$

- dark photon undetected: **signature** consists of $f\bar{f} + \gamma + E_{\text{miss}}$

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

- Model independent analysis

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

Final state: We are studying $e^+e^- \rightarrow ZH \rightarrow (\mu^+\mu^-) (\text{ph-dph})$. The final state therefore contains two oppositely charged muons, one isolated photon and missing energy.

We have used PYTHIA for the signal and MadGraph+PYTHIA interface for the backgrounds (ZZA, WWA and $2\mu 2\nu + \text{ph}$) analyses.

ISR/FSR effects are taken care of by PYTHIA. In addition, finite detector resolutions for the photon and muons have also been incorporated according to the ILD detector specification in Ref. [[arXiv:1605.00100](#)]

Basic Cuts:

- Jet veto with $p_t > 20 \text{ GeV}$
- $p_t(\mu, \text{ph}) > 10 \text{ GeV}$ and $|\eta(\mu, \text{ph})| < 2.5$
- $\Delta R(\text{ph-ph}, \mu-\mu, \text{ph}-\mu) > 0.2$

Other Cuts:

- $86 \text{ GeV} < M_{\ell\ell} < 96 \text{ GeV},$
- $120 \text{ GeV} < M_{\gamma\bar{\gamma}} < 130 \text{ GeV},$
- $M_{\text{miss}} < 20 \text{ GeV} (40 \text{ GeV}).$

Sequence of cuts:

In addition to the **basic cuts** the following set of cuts are applied in sequence

- Z-mass cut: $86 \text{ GeV} < M_{ll} < 96 \text{ GeV}$
- Higgs-mass cut: $120 \text{ GeV} < M_{\text{ph-dph}} < 130 \text{ GeV}$
- Missing mass cut: $< 20 \text{ GeV}$

Preliminary results

	XSEC (fb)	Basic cut (fb)	MZ cut (fb)	MH cut (fb)	M_miss cut (fb)
Signal	240.3	0.0653	0.0549	0.0497	0.0473
ZZA	21.1	0.243	0.231	0.055	-
WWA	264.4	2.603	0.218	0.032	0.0007
2mu2nu +ph	6.3*	4.996	0.573	0.109	0.0015

S.Biswas, EG, M.Heikeinheimo, B.Mele

Signal and background xsec before and after cuts

- * 2mu2nu+ph events are generated with basic cuts; WWA and ZZA with only cuts on photon.
- H->ph-dph BR is assumed to be 1% for the signal (from 3rd column onwards).
- The XSEC in 2nd column are at the level of undecayed Z/W/H (except 2mu2nu+ph).

Final state: We are studying $e^+e^- \rightarrow ZH \rightarrow (q \bar{q}) (\text{ph-dph})$. The final state therefore contains two oppositely dijet, one isolated photon and missing energy.

We have used PYTHIA for the signal and MadGraph+PYTHIA interface for the backgrounds (ZZA, WWA and $2\mu 2\nu + \text{ph}$) analyses.

ISR/FSR effects are taken care of by PYTHIA. In addition, finite detector resolutions for the photon and muons have also been incorporated according to the ILD detector specification in Ref. [[arXiv:1605.00100](#)]

Basic Cuts:

- Lepton veto with $p_t > 10 \text{ GeV}$ and $|\eta| < 2.5$
- $p_t(\text{ph}) > 10 \text{ GeV}$ and $|\eta(\text{ph})| < 2.5$
- $\Delta R(\text{ph-ph}, \mu\text{-}\mu, \text{ph-}\mu) > 0.2$
- $\Delta R(\text{ph-j}, \text{j-j}) > 0.4$
- Jet $p_t > 20 \text{ GeV}$, $|\eta(\text{j})| < 5.0$ and jet cone size $R=0.4$

Other Cuts: See next slide

Sequence of cuts:

In addition to the **basic cuts** the following set of cuts are applied in sequence

- Z-mass cut: $50 \text{ GeV} < M_{jj} < 90 \text{ GeV}$
- Higgs-mass cut: $120 \text{ GeV} < M_{\text{ph-dph}} < 130 \text{ GeV}$
- Missing mass cut: $< 20 \text{ GeV}$

S.Biswas, EG, M.Heikeinheimo, B.Mele

Preliminary results

	XSEC (fb)	Basic cut (fb)	MZ cut (fb)	MH cut (fb)	M_miss cut (fb)
Signal	240.3	0.8044	0.6687	0.1541	0.1098
2j+2nu+ph	7.48*	3.921	3.099	0.588	0.00022

Signal and background xsec before and after cuts

- * 2j+2nu+ph events are generated with basic cuts.
- H->ph-dph BR is assumed to be 1% for the signal (from 3rd column onwards).
- The XSEC in 2nd column are at the level of undecayed Z/W/H (except 2j2nu+ph).

Combining $\mu+\mu^-$ and hadronic channels, 5σ sensitivity on BR up to 10^{-3} for ab^{-1} of luminosity can be reached !

How to generate the CKM matrix

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

$$\begin{aligned}\tilde{\mathcal{L}}_{MS}^I = & \left\{ g_L \left(\sum_{i,j=1}^N \left[\bar{q}_L^i (X_L^U)_{ij} Q_R^{U_j} \right] \hat{S}_L^{U_j} + \sum_{i,j=1}^N \left[\bar{q}_L^i (X_L^D)_{ij} Q_R^{D_j} \right] \hat{S}_L^{D_j} \right) \right. \\ & \left. + g_R \left(\sum_{i,j=1}^N \left[\bar{u}_R^i (X_R^U)_{ij} Q_L^{U_j} \right] S_R^{U_j} + \sum_{i,j=1}^N \left[\bar{d}_R^i (X_R^D)_{ij} Q_L^{D_j} \right] S_R^{D_j} \right) \right\}\end{aligned}$$

radiative generation of Yukawa implies

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

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

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

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

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

possible to generate $\Delta^{U,D}$ at higher loops, explaining the CKM hierarchy
 $\rightarrow$ requires new scalar singlets with $Q_{ij} = \bar{e}_i - \bar{e}_j$ $U(1)_F$ charges

After rotation to quark-mass eigenstates $X_{L,R}^U \rightarrow \rho_{L,R}, \quad X_{L,R}^D \rightarrow \eta_{L,R}$

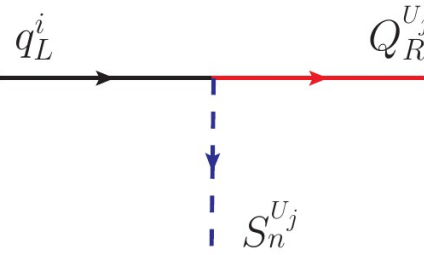
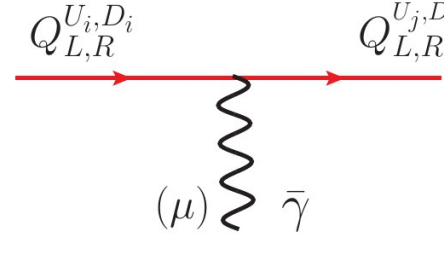
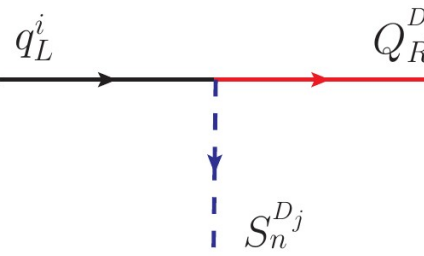
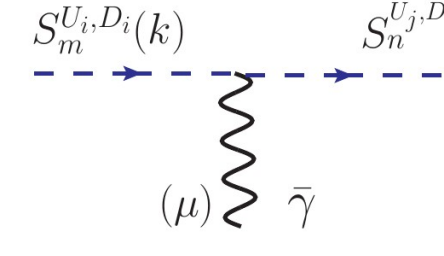
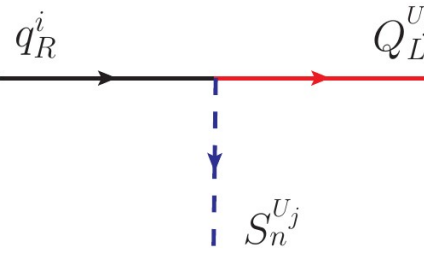
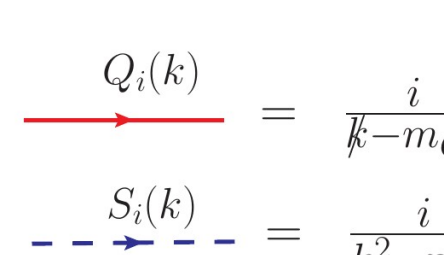
$$\rho_{L,R} \equiv V_{L,R}^{U \dagger} \cdot X_{L,R}^U \quad \eta_{L,R} \equiv V_{L,R}^{D \dagger} \cdot X_{L,R}^D$$

If $X_L^{U,D}$ are unitary matrices, then $V_{L,R}^{U,D} = (X_L^{U,D})^{-1}$

and $K = X_L^U \cdot X_L^{D \dagger}$ **implying** $\rho_{L,R}, \eta_{L,R} = \text{unity 1 matrices}$

but no reason why $X_L^{U,D}$ are unitary matrices $\Rightarrow \rho_{L,R}, \eta_{L,R}$ **general matrices**

Feynman rules for flavor-changing neutral vertices involving fermion(i)-darkfermion(j)-messengers(j)

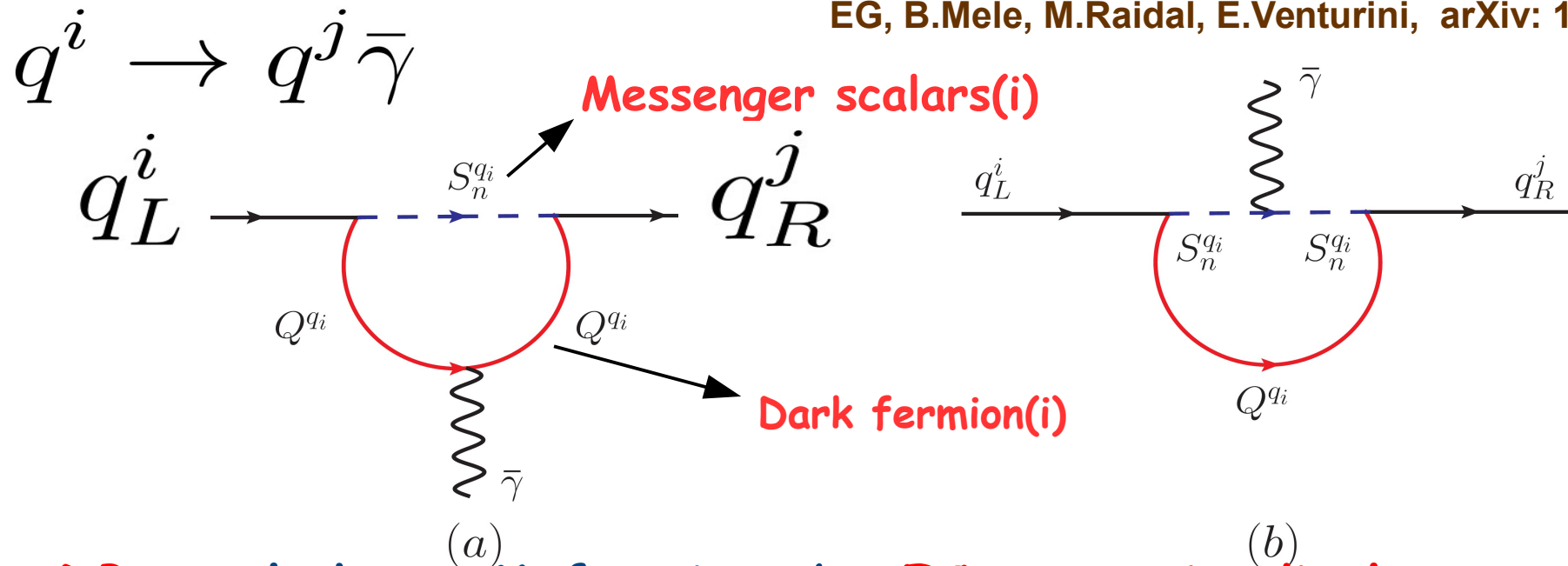
	=	$ig_L U(n, 1) (\rho_L^{ji})^*$		=	$i\delta_{ij} \bar{e} \bar{e}_{U_j, D_j} \gamma_{L, R}^\mu$
	=	$ig_L U(n, 1) (\eta_L^{ji})^*$		=	$i\delta_{ij} \delta_{mn} \bar{e} \bar{e}_{U_j, D_j} (k + k')^\mu$
	=	$ig_R U(n, 2) (\rho_R^{ji})^*$		=	$\frac{i}{\not{k} - m_{Q_i}}$ $\frac{i}{k^2 - m_{S_i}^2}$



resemble the FCNC couplings of **quarks-gluino-squarks**

FCNC decays of SM fermions into a Dark Photon

EG, B.Mele, M.Raidal, E.Venturini, arXiv: 1607.05928



■ 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

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

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

$$\left. \left. + \left(\frac{\bar{m}_U^2}{\bar{m}_D^2} \right) \bar{e}_k^D \eta_L^{jk} \eta_L^{ki} F_{LL}(x_k^D, \xi_D) \right) \right],$$

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

Effective scale proportional to the decaying fermion mass

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

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
lightest messenger
mass < 1 TeV

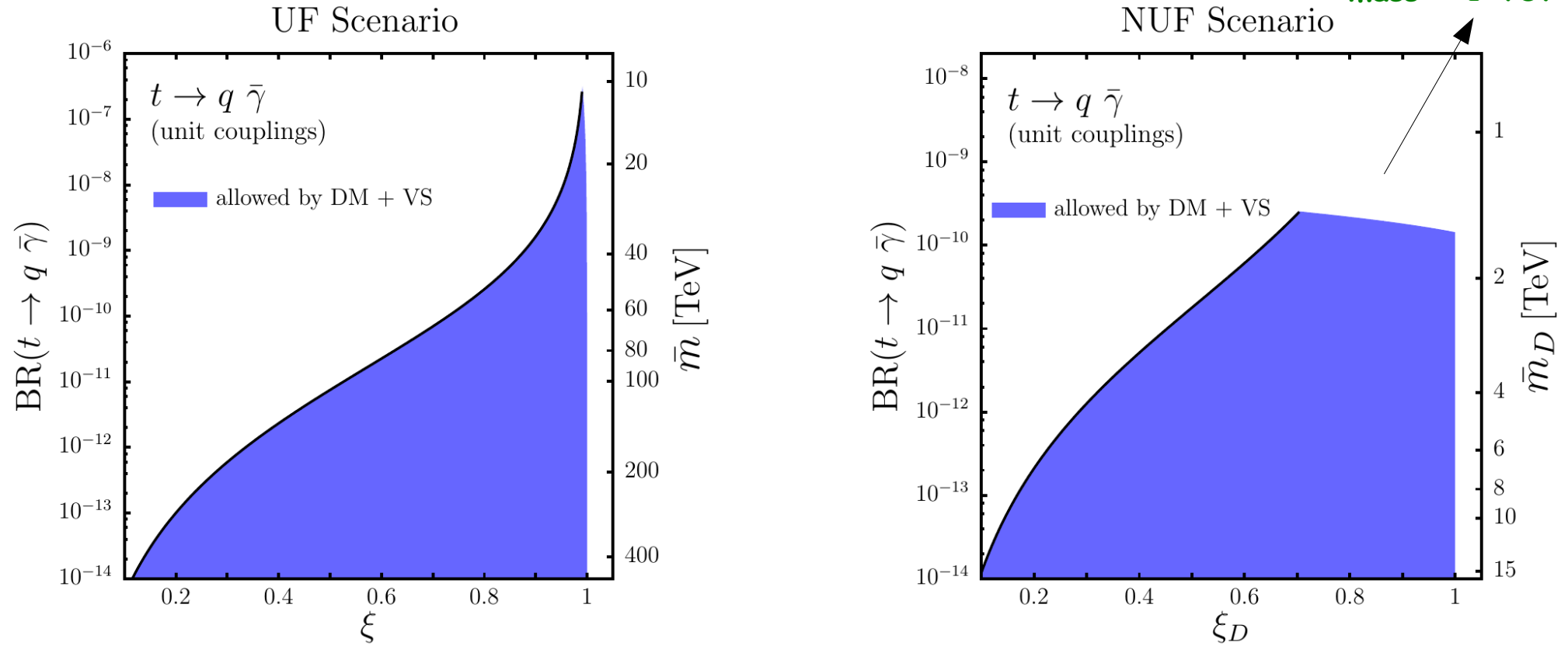


Figure 3: Allowed regions (colored areas) by DM and vacuum stability (VS) constraints for $\text{BR}(t \rightarrow q \bar{\gamma})$ and for the average messenger mass scales $\bar{m}$ and $\bar{m}_D$, versus the corresponding mixing ξ and ξ_D , in the UF (left) and NUF (right) scenarios, respectively.

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

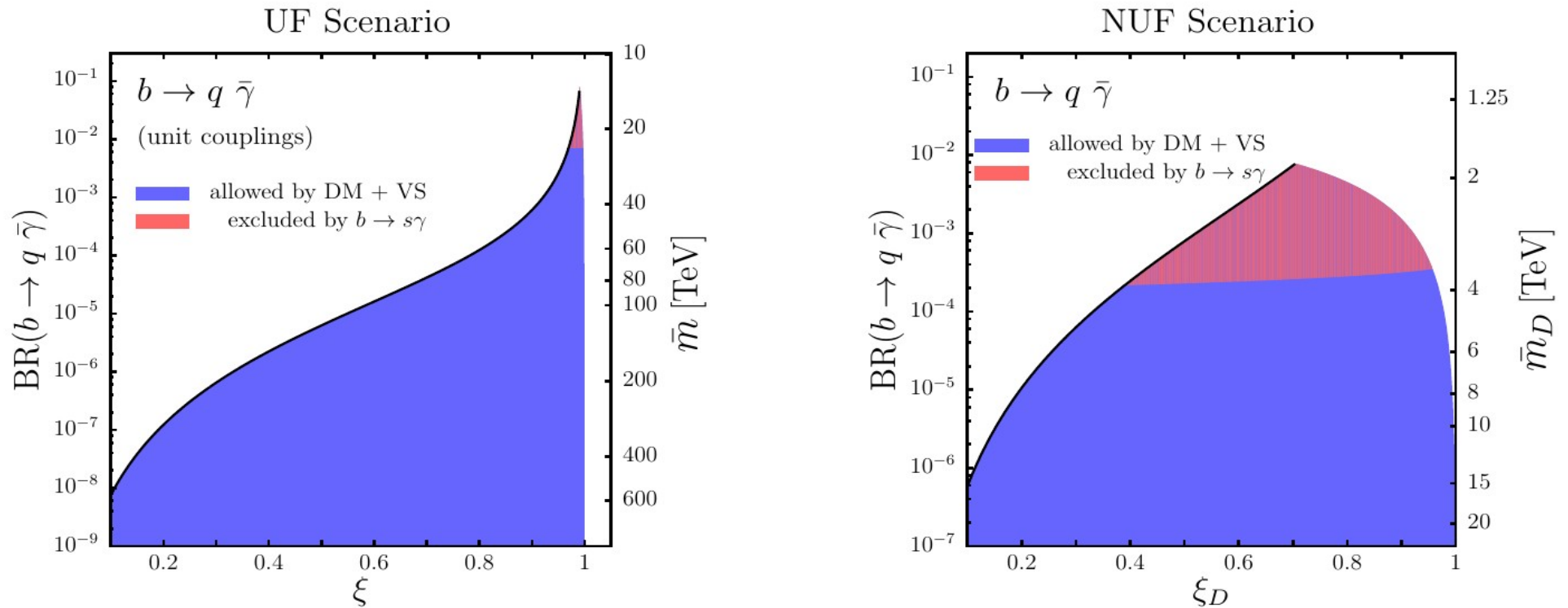


Figure 5: Allowed regions (colored areas) by DM and vacuum stability (VS) constraints for $\text{BR}(b \rightarrow q \bar{\gamma})$ and for the average messenger mass scales $\bar{m}$ and $\bar{m}_D$, versus the corresponding mixing ξ and ξ_D , in the UF (left) and NUF (right) scenarios, respectively. In the UF (NUF) scenario, we assume $\bar{e} \bar{e}_3^D \eta_L^{j3} / \eta_L^{33} = 1$ (0.1), with $j = 1, 2$.

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

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

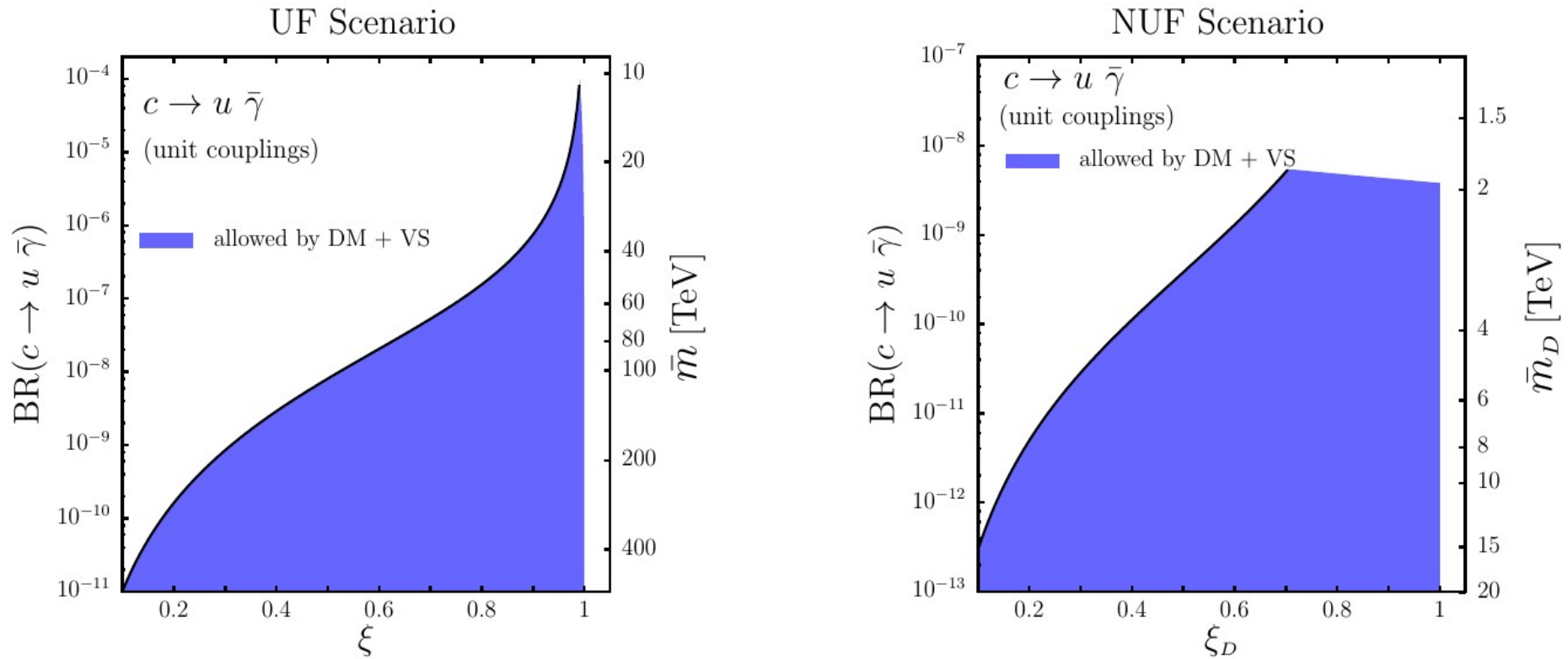


Figure 6: Allowed regions (colored areas) by DM and vacuum-stability (VS) constraints for $\text{BR}(c \rightarrow u \bar{\gamma})$ and for the average messenger mass scales $\bar{m}$ and $\bar{m}_D$, versus the corresponding mixing ξ and ξ_D , in the UF (left) and NUF (right) scenarios, respectively.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

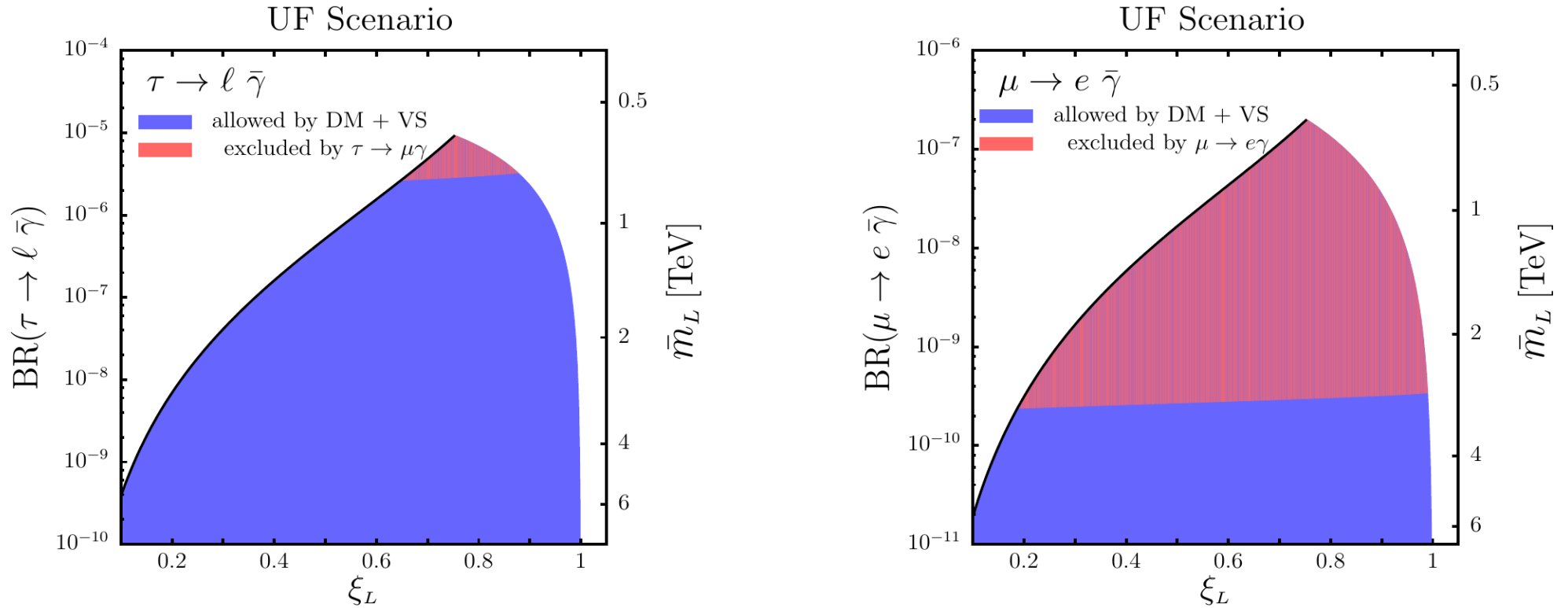


Figure 8: Regions allowed by DM and vacuum stability (VS) constraints for $\text{BR}(\tau \rightarrow \ell \bar{\gamma})$ (left) and $\text{BR}(\mu \rightarrow e \bar{\gamma})$ (right), and for the average messenger mass scale $\bar{m}_L$, versus the mixing ξ_L , in the UF scenario (blue areas). Superimposed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

FCNC decays of SM fermions into a Dark Photon

EG, B.Mele, M.Raidal, E.Venturini, arXiv: 1607.05928

- DP coupled to SM fermions by FC magnetic-dipole operators (suppressed by typical messenger mass scale)

- Eight new kind of FCNC signatures predicted !

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

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

- Large and possibly measurable BRs are allowed, up to

$$\begin{array}{ll} \text{BR}(b \rightarrow q \bar{\gamma}) \sim 10^{-4} - 10^{-3} & \text{BR}(t \rightarrow q \bar{\gamma}) \sim 10^{-10} - 10^{-7} \\ \text{BR}(c \rightarrow u \bar{\gamma}) \sim 10^{-8} - 10^{-4} & \\ \text{BR}(\tau \rightarrow l \bar{\gamma}) \sim 10^{-10} - 10^{-6} & \text{BR}(\mu \rightarrow e \bar{\gamma}) \sim 10^{-10} - 10^{-6} \end{array}$$

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

Outlook

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