

Search for Dark Photons at Colliders

Emidio Gabrielli

University and INFN, Trieste, Italy

NICPB, Tallinn, Estonia

In collaboration with: M. Raidal, M. Heikinheimo, B. Mele, S. Biswas

based on: PRD 90 (2014) 055032 , PRD 89 (2014) 015008

Outline

- Motivations for Dark Photons ($\bar{\gamma}$)
- Effective couplings to Higgs boson $H \gamma \bar{\gamma}$, $H \bar{\gamma} \bar{\gamma}$
- Model independent analysis of $H \rightarrow \gamma \bar{\gamma}$ at LHC
- Implications of $H \gamma \bar{\gamma}$ and $H Z \bar{\gamma}$ at e^+e^- colliders
- A model of Flavor with Dark sector and Dark Photon
- Conclusions

Dark Matter and Dark Photons

- Dark Matter origin is still unknown
- Five times more abundant in the Universe than ordinary barion matter
- Dark Sector, weakly coupled to the SM, might possess rich internal structure and interactions
- Dark Sector 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)

Two U(1)'s and ε charge shift

B. Holdom, PLB 166 (1986)

One U(1) $\rightarrow$ ratios of charges preserved by WI at any scale

Two U(1) $\rightarrow$ effective theory at low energy can mix the two U(1)
 $\rightarrow$ non-diagonal WF renormalization

$$U(1)_1 \times U(1)_2$$

charges

masses

EFT scales

Light fields

Heavy fields

$$f_1$$

$$f_2$$

$$f_{12}$$

$$f'_{12}$$

$$(e_1, 0), (0, e_2), (e_1, e_2), (e_1, -e_2)$$

$$m_1 \sim m_2 < m_{12} < m'_{12}$$

$$\Lambda$$

$$\Lambda'$$

Effective theory for f_1 and f_2 at scale up to Λ

$$-4\mathcal{L}_{\text{kin}}(\Lambda) = \chi_1 (F_1^{\mu\nu})^2 + \chi_2 (F_2^{\mu\nu})^2 + 2\chi F_1^{\mu\nu} F_{2\mu\nu}$$

$$\chi = (e_1 e_2 / 6\pi^2) \log(m'_{12} / m_{12})$$

$\chi_{1,2} \sim 1$ Contain the usual logs of ratios of Λ , Λ' , m_{12} and m'_{12}

After diagonalizing and rescaling to canonical kin term $\longrightarrow \hat{A}_1^\mu \quad \hat{A}_2^\mu$

$$e_1 J_\mu(f_1) A_1^\mu + e_2 J_\mu(f_2) A_2^\mu$$

we can identify $\mathbf{J}_1$ with ordinary matter and $\mathbf{J}_2$ with matter in hidden sector

$$e_1 A_1^\mu = \hat{e}_1 \hat{A}_1^\mu$$

$$e_2 A_2^\mu = \hat{e}_2 \left(\hat{A}_2^\mu \cos \theta - \hat{A}_1^\mu \sin \theta \right)$$

to lowest order in $\chi \longrightarrow \sin \theta = \chi \quad \hat{e}_1 = e_1 \chi_1^{-1/2} \quad \hat{e}_2 = e_2 \chi_2^{-1/2}$

$\hat{A}_1^\mu$ photon $\rightarrow$ couple to both $\mathbf{f}_1$ (ordinary matter) and $\mathbf{f}_2$ (hidden sector)
ratio between $\mathbf{f}_2$ and $\mathbf{f}_1$ coupling $\epsilon = -\hat{e}_2 \chi / \hat{e}_1 \rightarrow$ millicharge

$\hat{A}_2^\mu$ dark photon $\rightarrow$ couple only to hidden sector $\mathbf{f}_2$

In the case of one massive U(1)

not possible to diagonalize simultaneously kinetic term and mass term

$\rightarrow$ dark photon couples also to ordinary matter $\rightarrow$ oscillations (for ultralight U(1))

Massive dark-photon scenarios more constrained !

Phenomenological implications of massless DP scenarios

- assume existence of **messenger fields** = charged under SM gauge and $U(1)_{DP}$
- couplings of massless DP to ordinary matter → **higher dimensional operators** (communicated by loops of messenger fields)
- effective couplings of higher dimensional operators suppressed by:
 - Λ scale of New Physics ($\sim$ **mass of messenger fields**)
 - coupling of DP to dark sector (**less constrained than massive DP case**)
- Higgs boson couplings special case: **potential non-decoupling effects !**
- SM examples : $H \rightarrow \gamma\gamma$ and $H \rightarrow gg$
- New Higgs couplings to ordinary **photon** and **dark photon**
- **potential non-decoupling effects, depending on the messenger sector**

Effective Higgs couplings to light sector

$$\mathcal{L}_{\text{eff}}^H = \overset{\text{EM field}}{\frac{\alpha}{\Lambda_{\gamma\gamma}} [H F_{\mu\nu} F^{\mu\nu}]} + \overset{\text{Gluon field}}{\frac{\alpha_S}{\Lambda_{gg}} [H G_{\mu\nu}^a G^{a\mu\nu}]}$$

- sending the mass of SM fermions circulating in the loop to infinity
the scale Λ tends to the Higgs vev $\lim_{m_f \rightarrow \infty} \Lambda_{\gamma\gamma, gg} \sim \langle H \rangle = v$
- expected to hold also for NP contributions (see SUSY models)
(depending if messengers carry same $SU(2)_L$ QN of quarks and leptons)
- **New contributions** induced by messenger fields directly at 1-loop

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

$\bar{\alpha} \rightarrow$ fine structure constant of $U(1)_{\text{DP}}$ $\bar{F}_{\mu\nu} \rightarrow$ DP field strength

- non-decoupling phenomena $\rightarrow \lim_{M_{\text{mess}} \rightarrow \infty} \Lambda_{\gamma\bar{\gamma}, \bar{\gamma}\bar{\gamma}, \bar{\gamma}Z} \sim \langle H \rangle = v$
- **Observable new signatures in the Higgs sector if $\bar{\alpha}$ not too small!**

Dark photons and Flavor hierarchy problem

- Most **dark photon** proposals are introduced ad hoc to improve Astroparticle/Cosmological model phenomenology

- recently, a new paradigm for a natural solution of the SM Flavor hierarchy puzzle has been proposed

EG, M. Raidal, PRD 89 (2014)

- this requires the existence of a **dark sector** containing

- **dark fermions:** SM singlets (multi DM candidates) with non-universal $U(1)_F$ charges → **rescaled spectrum of SM fermions**
- **(massless) dark photon:** gauge boson of local $U(1)_F$ gauge theory
- **messenger scalars:** very heavy, same QN of squarks and sleptons
potential non-decouplings effects in Higgs sector
- **Higgs boson:** SM portal to the Dark Sector

New signature in the Higgs boson physics

PHYSICAL REVIEW D **90**, 055032 (2014)

Dark photons and resonant monophoton signatures in Higgs boson decays at the LHC

Emidio Gabrielli,^{1,2} Matti Heikinheimo,¹ Barbara Mele,³ and Martti Raidal^{1,4}

arXiv:1405.5196 [hep-ph]

..not yet analyzed by CMS and ATLAS collaborations

Higgs boson search, where are we ?

- a new particle (resonance) has been discovered at the LHC with a mass in the range **125-126 GeV**
- consistent with the long-awaited **SM Higgs boson**
- **fully confirmed in all its most sensitive channels**
 $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$, $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ and $H \rightarrow b\bar{b}$

Combined best fit signal strength with SM Higgs

ATLAS-CONF-2014-009

ATLAS

(mH=125.5 GeV)

$$\mu = 1.30 \pm 0.12 \text{ (stat)} {}^{+0.14}_{-0.11} \text{ (sys)}$$

$$\mu^{bb,\tau\tau} = 1.09 \pm 0.24 \text{ (stat)} {}^{+0.27}_{-0.21} \text{ (sys)}$$

evidence for decay into fermions @ 3.7 σ

CMS

(mH=125.03 GeV)

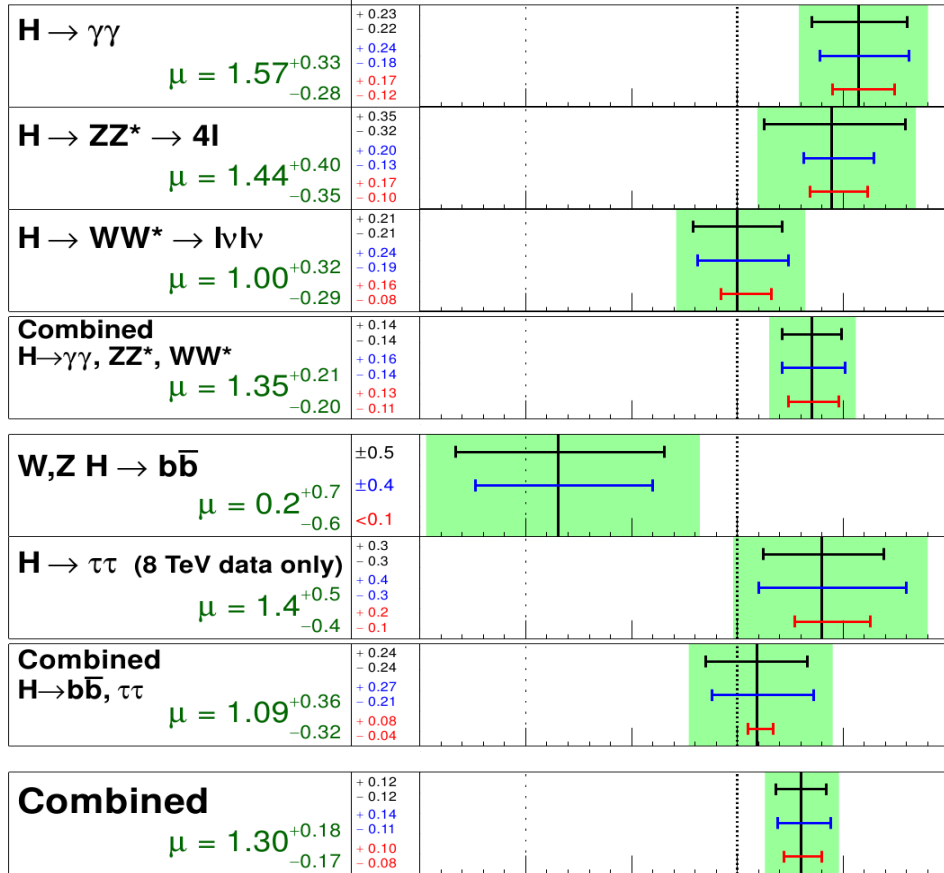
$$\mu = 1.00 \pm 0.09 \text{ (stat)} \pm 0.07 \text{ (sys)}$$

Compatibility with SM Higgs hypothesis

ATLAS Prelim.

$m_H = 125.5 \text{ GeV}$

— $\sigma(\text{stat.})$
— $\sigma(\text{theory})$
— $\sigma(\text{sys inc.})$
Total uncertainty
■ $\pm 1\sigma$ on μ

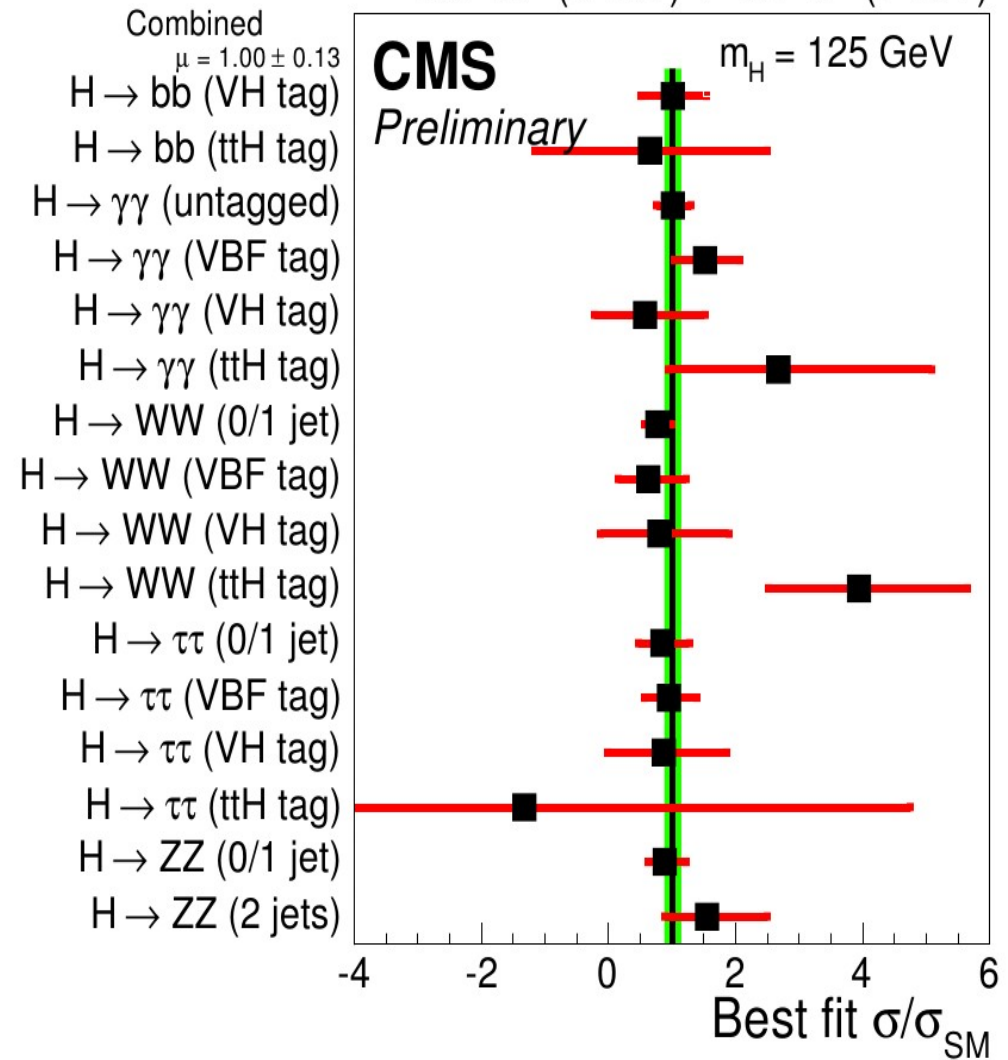


$\sqrt{s} = 7 \text{ TeV} \int \mathcal{L} dt = 4.6\text{-}4.8 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV} \int \mathcal{L} dt = 20.3 \text{ fb}^{-1}$

Signal strength (μ)

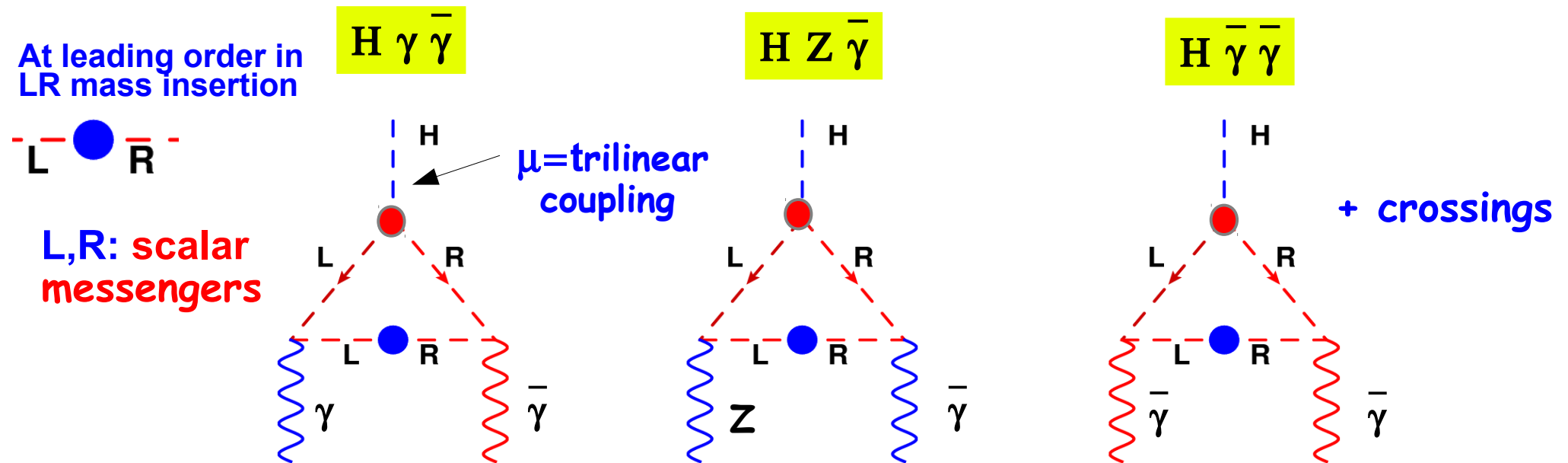
19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)



Di-photon enhancement seen only in ATLAS ($\mu=1.57$), CMS well agrees with SM expectations, although there is a depletion in $H \rightarrow \gamma\gamma$ (VBF tag)

Impact on Higgs radiative decays

- Loop of messenger fields can modify the SM Higgs boson vertices:
 $H \gamma \gamma$, $H \gamma Z$, and $H g g$ ($g \rightarrow$ gluons)
- but can induce also new effective vertices $H \gamma \bar{\gamma}$, $H Z \bar{\gamma}$ and $H \bar{\gamma} \bar{\gamma}$



$$M_S^2 = \begin{pmatrix} m_L^2 & \Delta \\ \Delta & m_R^2 \end{pmatrix} \rightarrow \text{L and R messenger mass matrix}$$

$\Delta = \langle H \rangle \mu$, is the LxR scalar mixing

Impact on Higgs radiative decays

arXiv:1405.5196

- Model independent parametrization of $H \rightarrow \gamma(k_1) \bar{\gamma}(k_2)$ amplitude

$$M_{\gamma\bar{\gamma}} = \frac{1}{\Lambda_{\gamma\bar{\gamma}}} T_{\mu\nu}(k_1, k_2) \varepsilon_1^\mu(k_1) \varepsilon_2^\nu(k_2)$$

$$T^{\mu\nu}(k_1, k_2) \equiv g^{\mu\nu} k_1 \cdot k_2 - k_2^\mu k_1^\nu$$

- If loop is mediated by scalars $\rightarrow$ **non-decoupling effect**

Δ turns out to be proportional to the Higgs vev !

$\bar{\alpha}$ = fine-structure constant of $U(1)_F$

$$\xi = \Delta / \bar{m}^2$$

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

v = Higgs vev
 $U(1)_F$ charges

$$R = N_c \sum_{i=1}^3 (e_U q_{U_i} + e_D q_{D_i})$$

mixing parameter $\xi < 1$ to avoid tachions

$\bar{m} = m_L \sim m_R$ messenger average mass

- Large mixing ξ can give a large effect, independently on mess. masses

Corresponding scales for $H \rightarrow \gamma\gamma$ and $H \rightarrow \bar{\gamma} \bar{\gamma}$

$$\Lambda_{\gamma\gamma} = \Lambda_{\gamma\bar{\gamma}} \frac{R}{R_0} \sqrt{\frac{\bar{\alpha}}{\alpha}},$$

$$\Lambda_{\bar{\gamma}\bar{\gamma}} = \Lambda_{\gamma\bar{\gamma}} \sqrt{\frac{\alpha}{\bar{\alpha}}} \frac{R}{R_1}$$

$$R_0 = 3N_c(e_U^2 + e_D^2)$$

$$R_1 = N_c \sum_{i=1}^3 (q_{U_i}^2 + q_{D_i}^2)$$

this suggests a model independent parametrization of BRs

$$r_{\gamma\gamma} \equiv \Gamma_{\gamma\gamma}^{\text{NP}} / \Gamma_{\gamma\gamma}^{\text{SM}}$$

$$\text{BR}_{\gamma\gamma} = N \left(1 \pm \sqrt{r_{\gamma\gamma}}\right)^2$$

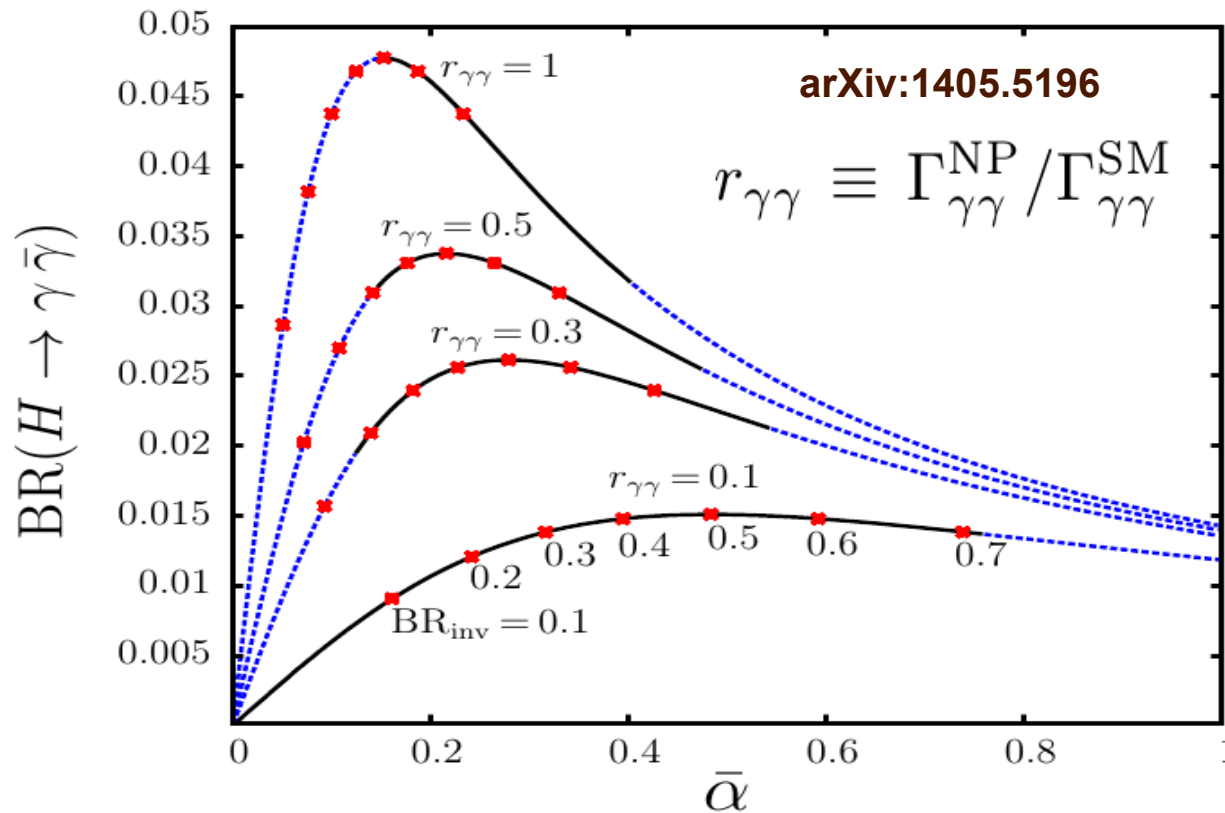
$$N = \text{BR}_{\gamma\gamma}^{\text{SM}} / (1 + r_{\bar{\gamma}\bar{\gamma}} \text{BR}_{\gamma\gamma}^{\text{SM}})$$

$$\text{BR}_{AB} = N r_{AB}$$

$$AB \equiv \{\gamma\bar{\gamma}, \bar{\gamma}\bar{\gamma}\}$$

$$r_{\gamma\bar{\gamma}} = 2 r_{\gamma\gamma} \frac{R^2}{R_0^2} \left(\frac{\bar{\alpha}}{\alpha}\right), \quad r_{\bar{\gamma}\bar{\gamma}} = r_{\gamma\gamma} \frac{R_1^2}{R_0^2} \left(\frac{\bar{\alpha}}{\alpha}\right)^2$$

Model independent predictions for $\text{BR}(H \rightarrow \gamma\bar{\gamma})$, for 1 messenger, with QED and $U(1)_F$ unity charges, as function of $\bar{\alpha}$



$$\text{BR}_{\gamma\gamma}^{\text{SM}}/2 \leq \text{BR}_{\gamma\gamma} \leq 2\text{BR}_{\gamma\gamma}^{\text{SM}}$$

→ full lines

$$\text{BR}_{\gamma\gamma}^{\text{SM}} = 2.28 \times 10^{-3}$$

- $\text{BR}(H \rightarrow \gamma\bar{\gamma})$ can be as large as 5% (more than 1 order of magnit. larger than $\text{BR}^{\text{SM}}(H \rightarrow \gamma\bar{\gamma})$) consistently with all LHC constraints
- Large values of $\bar{\alpha} \gg \alpha$ and mixing ξ are naturally expected in the scenario of exponentially spread Yukawa couplings ! (see following slides)

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

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

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

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

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

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

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

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

- Like in $W \rightarrow e \nu$, the M_T observable features the narrow peak at the original particle mass (in this case m_H)
- Also the p_T^γ distribution will be peaked at $m_H/2$
- This allows for a very efficient (simple) cut-based search strategy
 - Looking for events with a single photon and missing energy (no jets or leptons)
 - cutting around the expected maximum of M_T and p_T^γ distributions
- Peaks could be relatively easy to pinpoint on top of the continuous relevant background, for sufficiently large $H \rightarrow \gamma\bar{\gamma}$ rates

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

- One isolated photon with $50 \text{ GeV} < p_T^\gamma < 63 \text{ GeV}$ and $|\eta^\gamma| < 1.44$.
- Missing transverse momentum with $\cancel{E}_T > 50 \text{ GeV}$.
- Transverse mass in $100 \text{ GeV} < M_T < 126 \text{ GeV}$.
- No isolated jets or leptons.

Most relevant background for $\gamma + \cancel{E}_T$

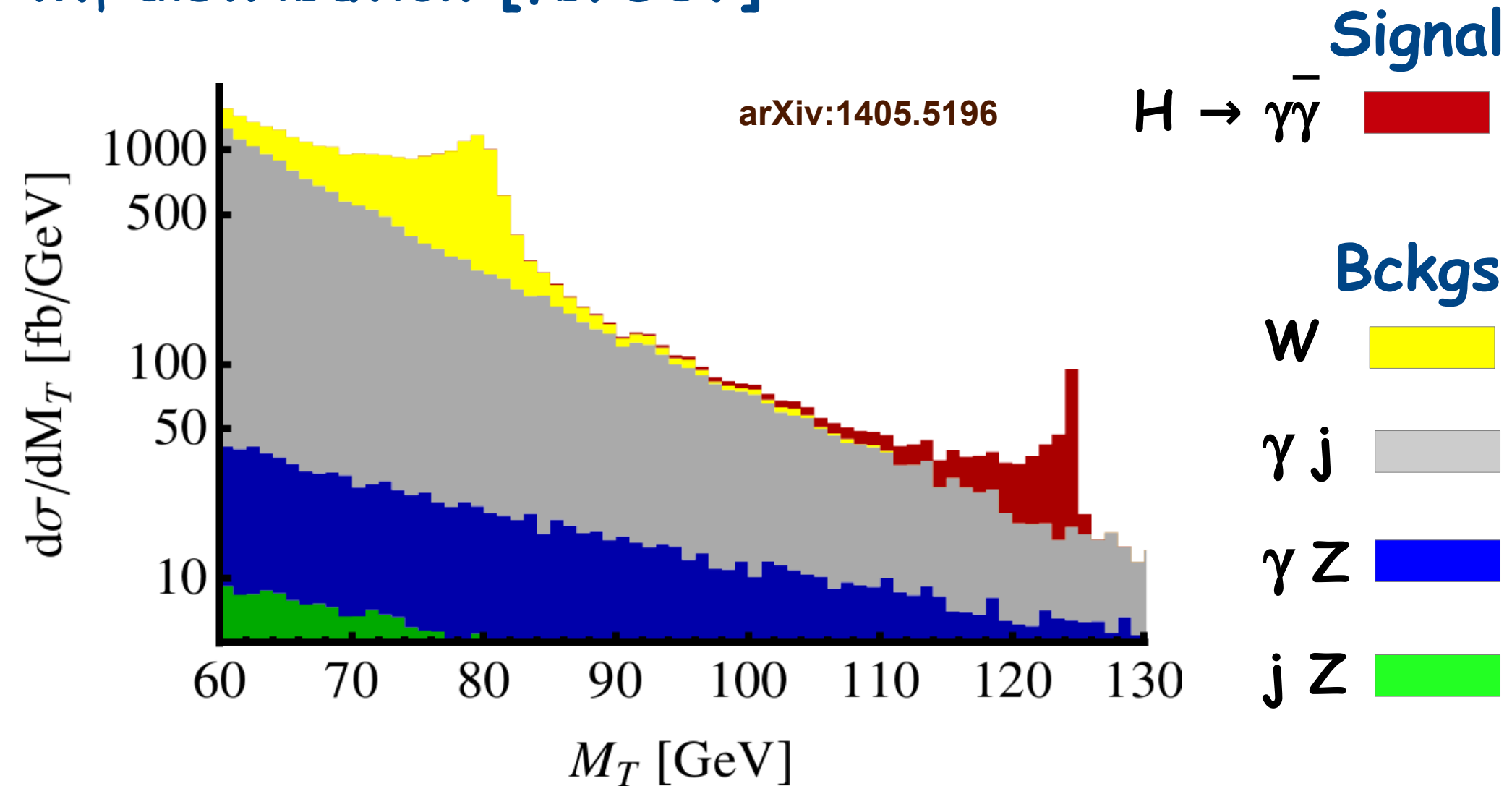
1. $pp \rightarrow \gamma j$, where large apparent $\cancel{E}_T$ is created by a combination of real $\cancel{E}_T$ from neutrinos in heavy quark decays and mis-measured jet energy.
2. $pp \rightarrow \gamma Z \rightarrow \gamma \nu \bar{\nu}$ (irreducible background);
3. $pp \rightarrow j Z \rightarrow j \nu \bar{\nu}$, where the jet is misidentified as a photon;
4. $pp \rightarrow W \rightarrow e \nu$, where the electron (positron) is mis-identified as a photon;
5. $pp \rightarrow \gamma W \rightarrow \gamma \ell \nu$, where the lepton is missed;
6. $pp \rightarrow \gamma \gamma$, where one of the photons is missed.

Background analysis

- $pp \rightarrow \gamma j$ is expected to be the dominant background
→ difficult to estimate without detailed information about the detector performance
- we evaluated the bckg $pp \rightarrow \gamma j$ by simulating events with one photon and one jet, treating jets with $|\eta| > 4.0$ as missing energy
- the other backgrounds are estimated through parton level simulation, with a probability 10^{-3} and $1/200$ to misidentify jet and an electron respectively, as a photon

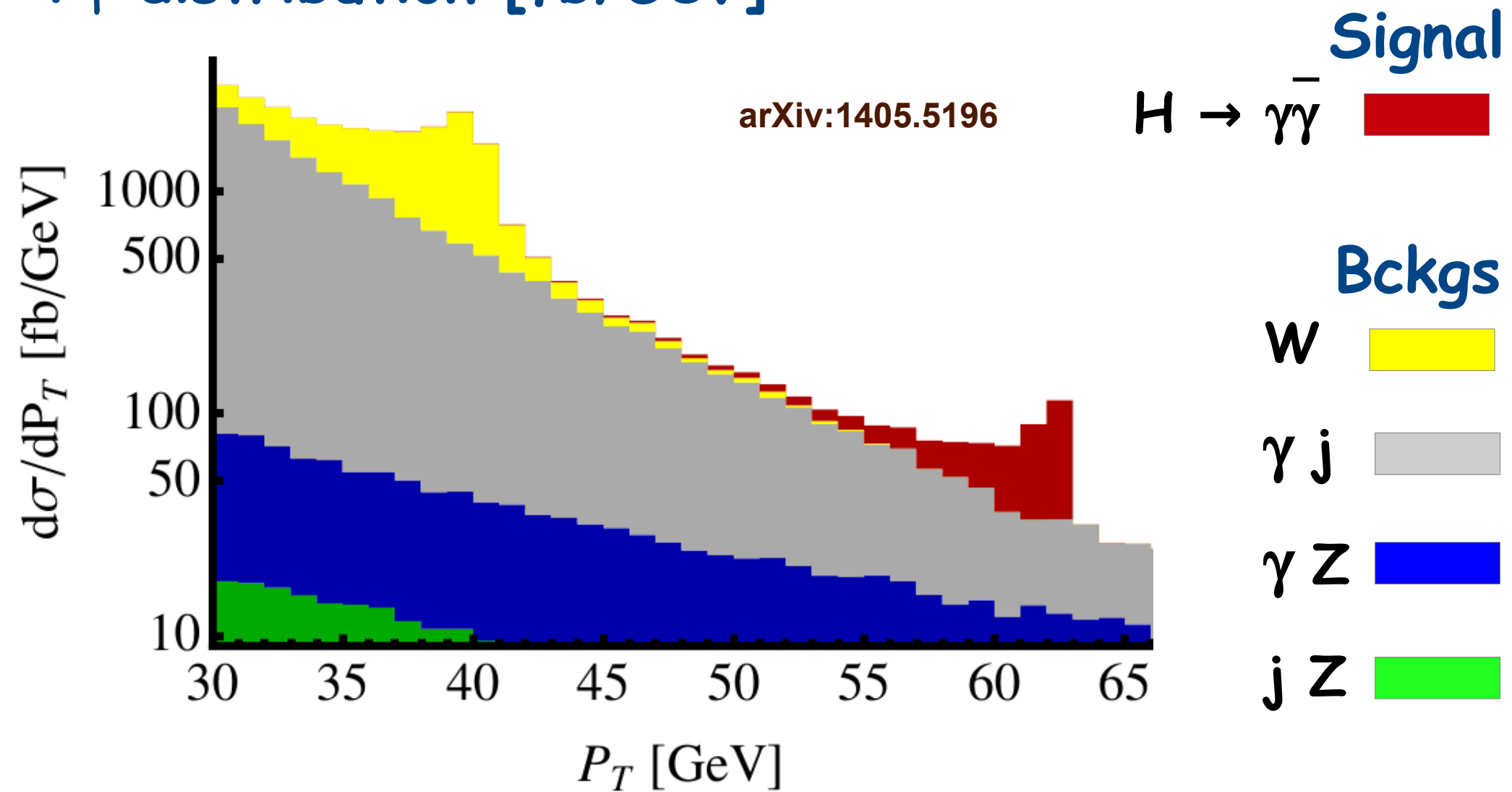
C.Peterson, A.Romagnoni, R.Torre,
JHEP 1210, 016 (2010)

M_T distribution [fb/GeV]



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

P_T distribution [fb/GeV]



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

Cross section X acceptance [fb]

arXiv:1405.5196	$\sigma \times A_1$	$\sigma \times A_2$
Signal $\text{BR}_{H \rightarrow \gamma \bar{\gamma}} = 1\%$	65	34
γj	715	65
$\gamma Z \rightarrow \gamma \nu \bar{\nu}$	157	27
$j Z \rightarrow j \nu \bar{\nu}$	63	11
$W \rightarrow e \nu$	22	0
Total background	957	103
$S/\sqrt{S+B}$ ($\text{BR}_{H \rightarrow \gamma \bar{\gamma}} = 1\%$)	9.1	13.0
$S/\sqrt{S+B}$ ($\text{BR}_{H \rightarrow \gamma \bar{\gamma}} = 0.5\%$)	4.6	6.9

acceptance include previous cuts and:

$$A_1 : 50 \text{ GeV} < p_T^\gamma < 63 \text{ GeV} \quad A_2 : 60 \text{ GeV} < p_T^\gamma < 63 \text{ GeV}$$

■ significance $S/\sqrt{S+B}$ corresponds to $L=20 \text{ fb}^{-1}$

■ 5 x sigma sensitivity on $\text{BR}(H \rightarrow \gamma \bar{\gamma}) \sim 0.5 \% !$

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

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

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

S. Biswas, EG, M. Heikeineimo, B. Mele
(in preparation)

• we look at Higgs decay in $H \rightarrow b\bar{b}$

• dark photon undetected: signal consists of $b\bar{b}$ + missing energy

Model independent analysis: effective Lagrangian parametrized as

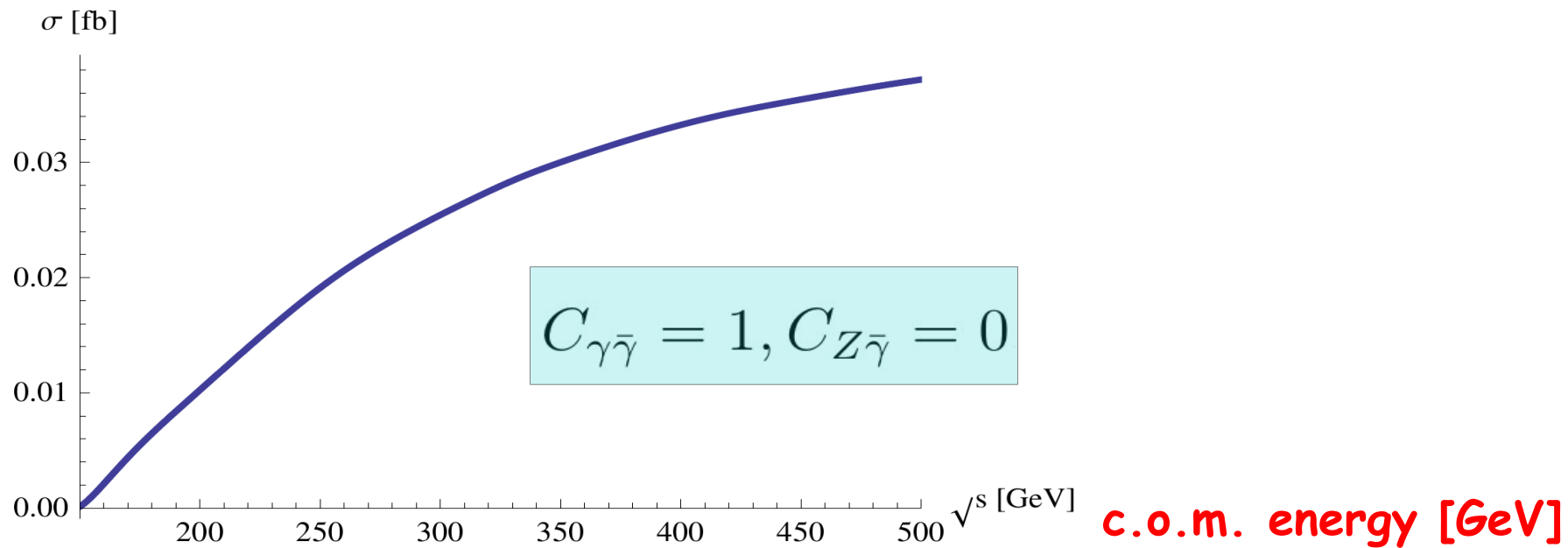
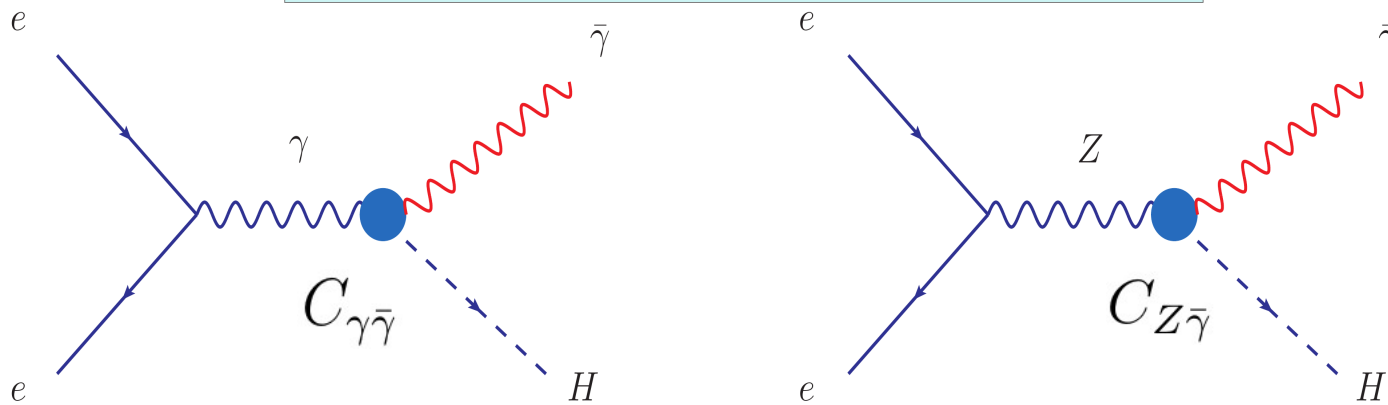
$$\mathcal{L}_{\text{DPH}} = \frac{\alpha}{\pi} \left(\frac{C_{\gamma\bar{\gamma}}}{v} \gamma^{\mu\nu} \bar{\gamma}_{\mu\nu} H + \frac{C_{Z\bar{\gamma}}}{v} Z^{\mu\nu} \bar{\gamma}_{\mu\nu} H + \frac{C_{\bar{\gamma}\bar{\gamma}}}{v} \bar{\gamma}^{\mu\nu} \bar{\gamma}_{\mu\nu} H \right)$$

assuming mass degeneracy in messengers L and R $\rightarrow$

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

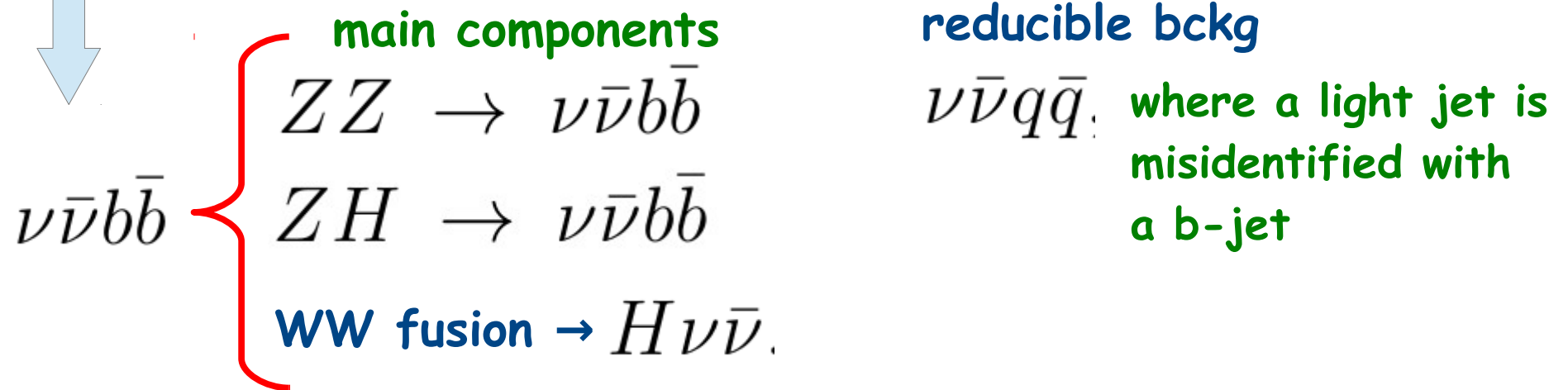
net result from a squark doublet $\rightarrow R_{Z\gamma}^{\tilde{q}} = \frac{R_{Z\gamma}^{\tilde{u}} + R_{Z\gamma}^{\tilde{d}}}{2} \approx 0.79$

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



- simulate signal with **MADGRAPH** using effective Lagrangian
- passed these events to **PYTHIA** to account for parton showering, hadronization, and initial state radiation

Main irreducible bckg for $b\bar{b} + \cancel{E}$ final states (with $\cancel{E}$ missing energy)

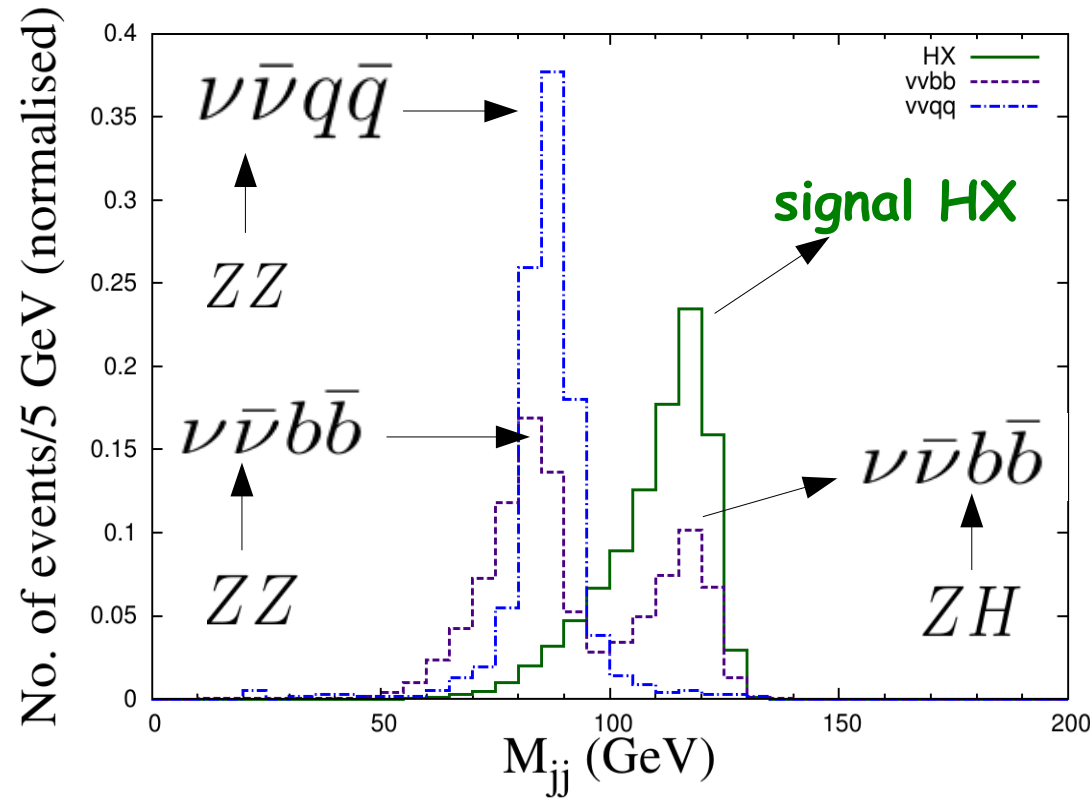


initial cuts to define the events

$$\begin{aligned} p_T^b &> 20 \text{ GeV} \\ |\eta_b| &< 2.5 \\ \Delta R(bb) &> 0.4 \\ \cancel{E} &> 40 \text{ GeV}. \end{aligned}$$

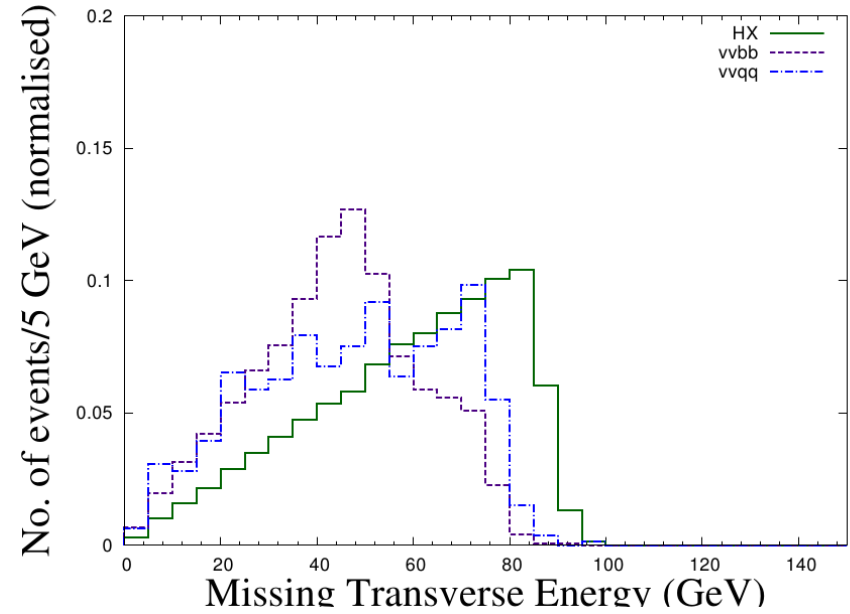
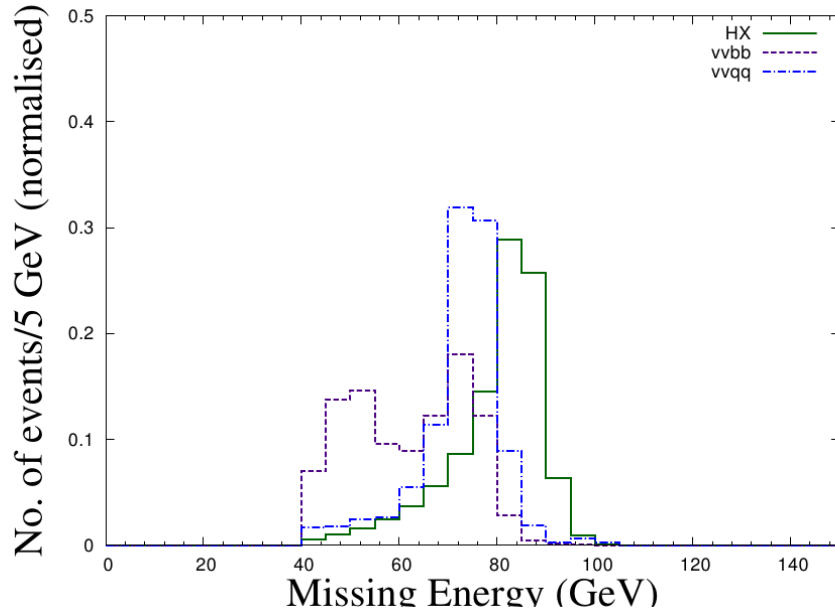
Assume: b-tagging efficiency of 80%
fake b-jet rejection factor 1/100

M_{jj} distribution of two highest pT jets (x-sections normalized to 1)
after PYTHIA showering hadronization and jet energy resolution



S. Biswas, EG, M. Heikeineimo, B. Mele
(preliminary)

Signal well separated from the main bckgs ZZ



A comparison of the missing energy ($\cancel{E}$) and the missing transverse energy ($\cancel{E}_T$) distributions for the signal (green) and the backgrounds $\nu\bar{\nu}b\bar{b}$ (blue) and $\nu\bar{\nu}q\bar{q}$ (indigo), where the $\cancel{E}$ (and $\cancel{E}_T$) have been reconstructed using visible particles after PYTHIA showering, hadronization and jet energy resolution effect. For illustration purposes, all cross sections are normalized to one.

- Potentially large values of $BR(H \rightarrow \gamma\bar{\gamma})$ require large values of DP coupling $\bar{\alpha}$ and scalar LR mixing parameter ξ
- We consider now a potential scenario where large values of $\bar{\alpha}$ and ξ are naturally expected
- Remarkably, this scenario arises as a natural solution to the Flavor Hierarchy problem
- DP not introduced ad hoc but as origin of the dynamics responsible for the Flavor hierarchy
- It requires the existence of a dark sector containing a strongly coupled (but still perturbative) massless dark photon,
- plus messenger scalar fields and Dark Fermions (DF) ($\rightarrow$ stable)
- DF $\rightarrow$ Dark Matter candidates with long distance interactions

The Flavor Puzzle

- After the discovery of the Higgs boson at the LHC, the only unexplained sector of SM is the Flavor sector
- **SM Yukawa couplings:** not to be connected to any known local or global symmetry.
- resemble arbitrary dimensionless couplings spanning over 6 order of magnitude for charged fermions and at least 12 if we include Dirac neutrinos

Three main approaches so far

- **Froggat-Nielsen Mechanism** C.D. Froggat, H.B. Nielsen, NPB 147 (1979)
- **Fermions in different branes of Extradimensions**
N. Arkani-Hamed, M. Schmaltz, PRD 61 (2000)
- **Radiative fermion masses or Yukawas**
S. Weinberg PRL 29 (1972) and many others..

Froggat-Nielsen Mechanism

- Introduces $U(1)_F$ Flavor symmetric non-renormalizable operators involving a large number of scalar **Flavon fields** ϕ that are suppressed by a large cut-off scale Λ .
- When the **Flavon field** ϕ obtains a vacuum expectation value $\langle \phi \rangle$, effective Yukawa couplings Y_s are induced as powers of the expansion parameter $\lambda \sim \langle \phi \rangle / \Lambda$ as $Y_s \sim \lambda^n$ depending on the $U(1)$ quantum numbers
- Since $\lambda \sim 0.2$ to explain Cabibbo angle, to generate Y_s of 6 or more order of magnitudes requires constructing operators with very high dimensionality
- It is not clear what underlying physics is responsible for those operators and whether this paradigm is testable

Extra-dimensions

- Confining different Fermions in different branes that are located in different places in extra-dimensions.
- Yukawa couplings are induced due to overlaps of the fermion wave-functions with the Higgs wave-functions in extra-dimensions.
- This scenario allows for an exponential parameterisation of Y_s
- Requires extra-dimensions, no evidence so far...and it does not explain why the values of the Yukawas are what they are

Radiative fermion masses

- Based on idea that zero order masses or Yukawa vanishes and are generated at higher orders in perturbation theory
- difficult to generate mass splitting of many orders of magnitude...

Exponentially spread dynamical Yukawa couplings

Theoretical framework

EG and M. Raidal, PRD 89 (2014) 015008

E. Ma, PRL 112 091801

S. Fraser and E. Ma, Arxiv 1402.6415

- Dark Sector as origin of Chiral and Flavor symmetry breaking
- Sources of ChSB identified with the masses of Dark Fermions (DF), singlets of SM gauge group $\rightarrow$ Flavor breaking shows up in DF mass spectrum
- Chiral and Flavor SB communicated to the SM by some Higgs portal type of Messenger Fields (scalars simplest choice + Flavor universality)
- Yukawa coupling (set to zero at tree level by a Z_2 symmetry $H \rightarrow -H$) after SSB of Z_2 , radiatively generated by exchange of messengers fields
- Y_s proportional to Dark-fermion masses times (almost) universal factor
- Dark Fermions (lightest states) are stable $\rightarrow$ Dark matter candidates
- Higgs boson as portal field to the Dark sector

Dark Fermion Sector

- Assume that for each SM fermion there is a singlet fermion replica in the dark sector

$$\mathcal{L}_{DF} = i \sum_f \bar{Q}_f (\partial_\mu \gamma^\mu + i M_{Q_f}) Q_f$$

EG, M. Raidal, PRD 89 (2014)

- we will show later the dynamics that generates M_{Q_f}
- Messenger sector → scalar fields carrying same QN as squarks and sleptons of SUSY models
- We require $SU(N_f)$ Flavor universality of tree-level messenger mass sector
- Separate universality for messengers in the quark and lepton sector

Lagrangian of Messenger sector

EG, M. Raidal
PRD 89 (2014)

- $2N_f$ complex scalar $SU(2)_L$ doublets: $\hat{S}_L^{U_i}$ and $\hat{S}_L^{D_i}$,
- $2N_f$ complex scalar $SU(2)_L$ singlets: $S_R^{U_i}$ and $S_R^{D_i}$,
- one real $SU(2)_L \times U(1)_Y$ singlet scalar: S_0 ,

$$\begin{aligned}\mathcal{L}_{MS}^I = & g_L \left(\sum_{i=1}^{N_f} [\bar{q}_L^i Q_R^{U_i}] \hat{S}_L^{U_i} + \sum_{i=1}^{N_f} [\bar{q}_L^i Q_R^{D_i}] \hat{S}_L^{D_i} \right) + \\ & + g_R \left(\sum_{i=1}^{N_f} [\bar{U}_R^i Q_L^{U_i}] S_R^{U_i} + \sum_{i=1}^{N_f} [\bar{D}_R^i Q_L^{D_i}] S_R^{D_i} \right) + \\ & + \lambda_S S_0 \left(\tilde{H}^\dagger S_L^{U_i} S_R^{U_i} + H^\dagger S_L^{D_i} S_R^{D_i} \right) + h.c.,\end{aligned}$$

Interactions that generate Yukawa couplings

g_L, g_R universal flavor couplings

$SU(2)_L \times U(1)_Y \times SU(3)_c$ quantum numbers of new fields

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

- The new interactions can radiatively generate all SM Yukawas
- After SSB of $\langle S \rangle = \mu \rightarrow$ Yukawa couplings can arise at 1-loop and turn out to be finite at any order in pert. theory
- Y_s proportional to DF masses $\rightarrow$ hierarchy problem shifted to the dark fermion mass sector

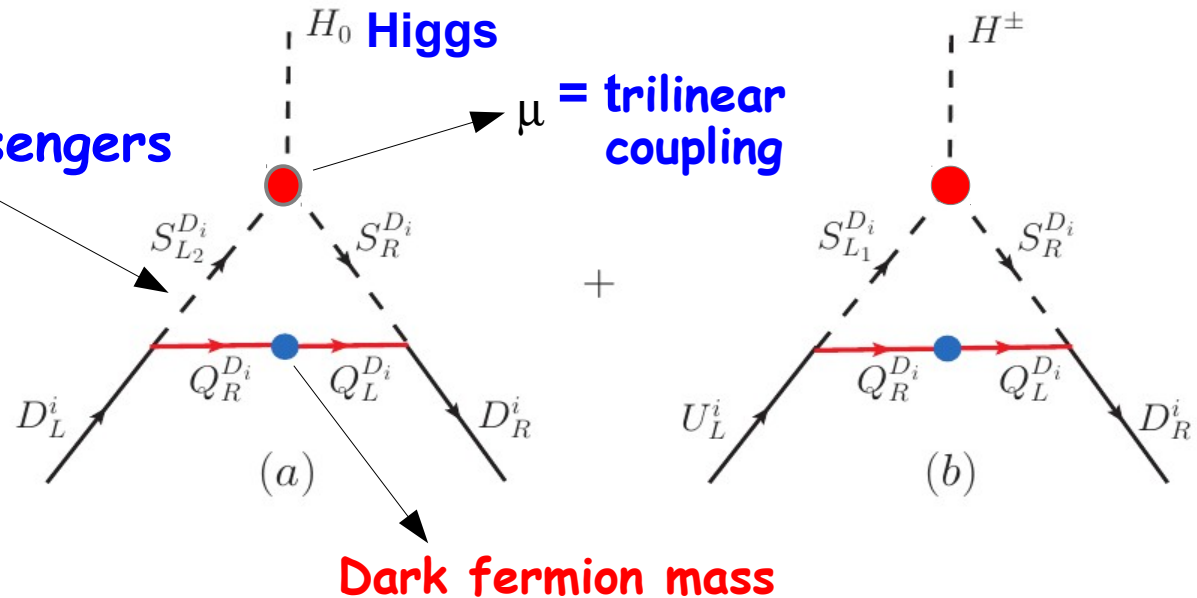
Radiative Yukawa couplings at 1-loop

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

scalar messengers

Yukawa of down quarks

Analogous diagrams
for Yukawa of up-quarks



Yukawa couplings are finite $\rightarrow$ predictivity !

Dark Fermion mass $\rightarrow$ $Y_i \sim \frac{M_i \mu}{\bar{m}^2}$ $\leftarrow$ Higgs-trilinear coupling

$\bar{m}^2$ $\rightarrow$ Average Messenger mass

● Messenger mass sector assumed to be universal

$\rightarrow$ Yukawa hierarchy given by Dark Fermion mass hierarchy !

example UP-Yukawa coupling

Assuming flavor universality in the $m_L \sim m_R = \bar{m}$
messenger masses and Higgs mass $M_H \ll \bar{m}$

$$Y^{U_i} = \frac{\lambda_S g_L g_R \mu M_{Q^{U_i}}}{16\pi^2 \bar{m}^2} C_0(x_i)$$

CO(x) loop function: $C_0(x) = \frac{1 - x(1 - \log x)}{(1 - x)^2}$

$$C_0(x) \simeq 1 + (1 + \log(x))x + \mathcal{O}(x^2)$$

$$C_0(1) = 1/2$$

$$x_i = M_{Q^{U_i}}^2 / \bar{m}^2$$

after EWSB

quark(i) mass

$$\frac{m_i}{v} = \frac{L \lambda_S \mu M_{Q_i}}{\bar{m}^2} C_0(x_i)$$

$$L \equiv \frac{g_L g_R}{16\pi^2}$$

Vacuum stability bounds

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

$$m_L = m_R = \bar{m} \quad (\text{to avoid stable charged particles} \rightarrow \bar{m} > M_{qi})$$

To avoid tachions in the spectrum

$$\Delta = v\mu_S < \bar{m}^2$$

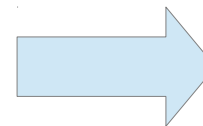


$$M_{Q_i} > \frac{m_i}{LC_0(x_i)}$$

m_i = quark(i) masses

Loop factors $L \sim g_L g_R / 16\pi^2$

$$M_{Q_t} \gtrsim \left(\frac{55}{g_L g_R} \right) \text{TeV}$$



$$\bar{m} > M_{Qt} > 55 \text{ TeV}$$

One-loop contribution to the Higgs mass

$$\delta m_H^2 \sim \bar{m}^2 / (g_L g_R)^2$$



naturalness arguments
suggest large g_L, g_R

Dynamics of Flavor and ChSB in the Dark Sector

- Main ingredients: $U(1)_F$ gauge theory + Lee-Wick term, coupled to massless Dirac fermions

EG, M. Raidal, PRD 89 (2014)

Dark photon

- Lee-Wick term is a higher derivative kinetic term
→ suppressed by a characteristic scale Λ

T.D. Lee, G.C. Wick, PRD 3 (1971)

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

- Λ interpretation → associated to the mass of a ghost “resonance” (unitarity issues solved if the ghost has a non-vanishing decay width)

T.D. Lee, G.C. Wick, PRD 3 (1971)
R.E. Cutkosky, et al NPB 12 (1969)

- Main result: the Lee-Wick term can trigger ChSB in the weak coupling regime (proved by solving the NJL mass-gap equation)

EG, PRD 77 (2008)

- Mass-gap solution is non-perturbative → gives rise to an exponential dependence by the $U(1)_F$ fermion quantum charge !

Lee-Wick theories

T.D.Lee and G.C.Wick NP B 9 (1969) 209 , PRD 2 (1970) 1033

- In these seminal papers Lee-Wick proposed a new approach to QFT
- This prompted the construction of more general theories in which the S -matrix is fully unitary, although the Lagrangian is not Hermitian
- This required the introduction of **negative-norm states** which are associated with massive **unstable** particles
- **Despite the presence of an indefinite metric, unitarity can be recovered, provided the negative norm states are massive and have a finite decay width**
- Recently this idea has been extended to the SM theory, allowing to naturally solve the scalar hierarchy problem (alternative way to SUSY)

B.Grinstein, D.O' Connell and M.B. Wise PRD 77 (2008) 025012

- To make sense of these theories → modify usual contour prescription for momentum integrals
- LW prescription is equivalent to imposing the boundary condition that there are no outgoing exponentially growing modes → this violates causality at microscopic scale (the decay products of a LW ghost appear at a time before the LW particle is created)
- It is believed that this theory does not produce violations of causality or other paradoxes at macroscopic scales

Due to the presence of a massive negative-norm state a new interesting phenomena appears:

Chiral Symmetry Breaking can be triggered by a $U(1)$ Lee-Wick term

This mechanism can be used to generate fermion masses in the Dark sector → true ground state is not the perturbative vacuum

ChSB induced by U(1) Lee-Wick term: a toy model

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

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

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

Consider the NJL mechanism for the generation of fermion masses

Y.Nambu, G. Jona-Lasinio PR 122 (1961) 345, PR 124 (1961) 246

fermion mass “m” arises as a non-trivial solution of the self-consistent mass gap equation

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

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

perturbative vacuum always gives the trivial solution $m=0$

non-trivial solution $m \neq 0$ corresponds to the true vacuum $\Omega \rightarrow$ lowest energy

Ω (in terms of zero-mass particles) is a superposition of pair states

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**

photon long-distance contribution

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

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

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

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 interaction
- **scalars predicts +** → no solution in weak coupling regime

Solution

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

Resummation of large corrections $\alpha^n \log^n(\Lambda/m)$ suggests


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

or equivalently, by requiring m to be RGE invariant ($dm/d\mu=0$)

$$m = \Lambda \exp \left\{ -\frac{2\pi}{3\alpha(\mu)} + \frac{1}{4} \right\} \left(\frac{\Lambda}{\mu} \right)^{\frac{4}{9}}$$

truly non-perturbative solution as a function of α

Mechanism for fermions mass splitting

● Universal charges  mass degeneracy

EG, PRD 77 (2008)

● if $U(1)_F$ charges q_f are non-universal

Lee-Wick scale

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

$\bar{\alpha}(\Lambda)$ fine-structure constant of $U(1)_F$ at Λ scale

Mass degeneracy removed $\rightarrow$ mass splitting exponentially spread

If we apply this mechanism to dark-sector $\rightarrow$ SM Yukawa couplings turn out to be proportional to DF masses and so exponentially spread

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

EG, M. Raidal, PRD 89 (2014)

 a natural solution to the hierarchy flavor problem !

Yukawas sum rules

$$Y^{U_j} = Y^{U_i} \exp \left\{ \frac{2\pi \left(q_{U_j}^2 - q_{U_i}^2 \right)}{3\bar{\alpha} q_{U_i}^2 q_{U_j}^2} \right\} \frac{C_0(x_j)}{C_0(x_i)}$$

$$x_i = M_{Q^{U_i}}^2 / \bar{m}^2$$

after EWSB $\rightarrow \langle H \rangle = v$

SM fermion masses

$$m_i = \Lambda_{\text{eff}} \exp \left(-\frac{2\pi}{3\bar{\alpha} q_i^2} \right)$$

$$\Lambda_{\text{eff}} \sim \left(\frac{v\mu\Lambda}{\bar{m}^2} \right) \frac{\lambda_S g_L g_R C(x_i)}{16\pi^2}$$

U(1)_F gauge invariance + Lee-Wick term required

EG, M. Raidal, PRD 89 (2014)

$$\mathcal{L}_{DS} = i \sum_i (\bar{Q}^{U_i} \mathcal{D}_\mu \gamma^\mu Q^{U_i} + \bar{Q}^{D_i} \mathcal{D}_\mu \gamma^\mu Q^{D_i}) + \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{\Lambda^2} \partial^\mu F_{\mu\alpha} \partial_\nu F^{\nu\alpha}, \rightarrow [\bar{Q}_i \textcolor{red}{M}_{Qi} Q_i]$$

• Dark-fermion mass term $\textcolor{red}{M}_{qi}$ dynamically generated $\rightarrow$ exponentially spread

• Messenger fields must be also charged under U(1)_F

Using 1-loop U(1)_F β -function and approx $\bar{m} \sim \textcolor{green}{M}_{Qi}$

$$\bar{\alpha}(\Lambda) = \bar{\alpha}(\bar{m}) \left(1 + R_2^q \left(\frac{4 + 3N_c^2}{9N_c} \right) + R_2^l \frac{7}{9} \right)$$

$$R_2^l \equiv \sum_{i=1}^3 (q_{E_i}^2 + q_{\nu_i}^2)$$

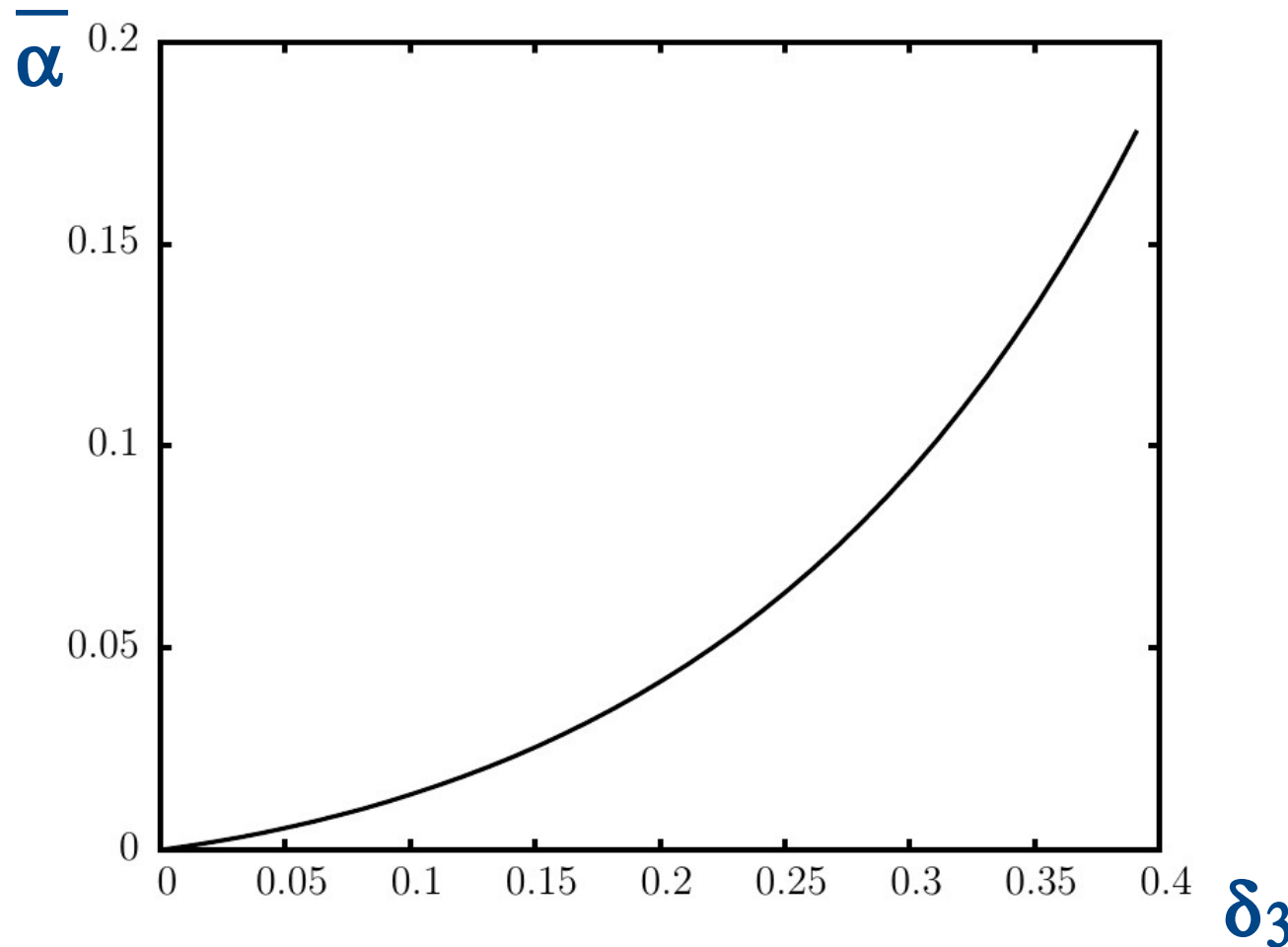
$$R_2^q \equiv N_c \sum_{i=1}^3 (q_{U_i}^2 + q_{D_i}^2)$$

Assuming Flavor universality in messenger sector

$$1/\bar{\alpha}(\Lambda) \sim \frac{3}{2\pi} \frac{q_{Q_i}^2}{1 - q_{Q_i}^2} \log \frac{m_t}{m_i} \longrightarrow \text{charges can be predicted as a function } \bar{\alpha}$$

charge of dark-fermion $\textcolor{red}{q}_{U3}=1$ associated to top-quark normalized to 1

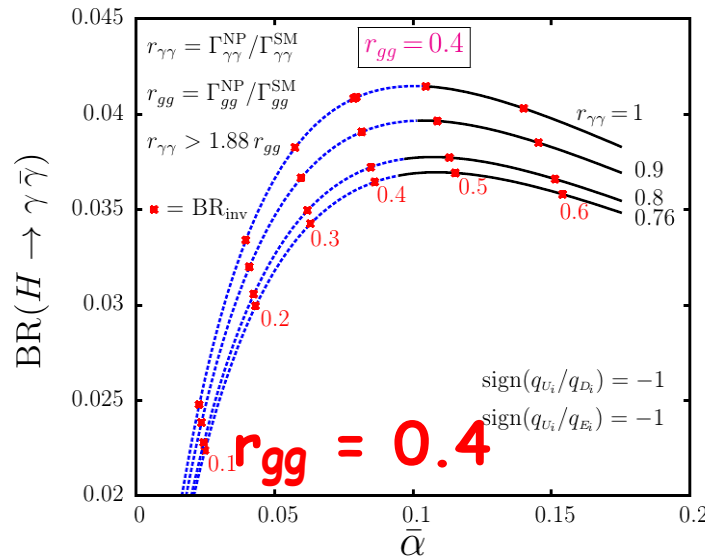
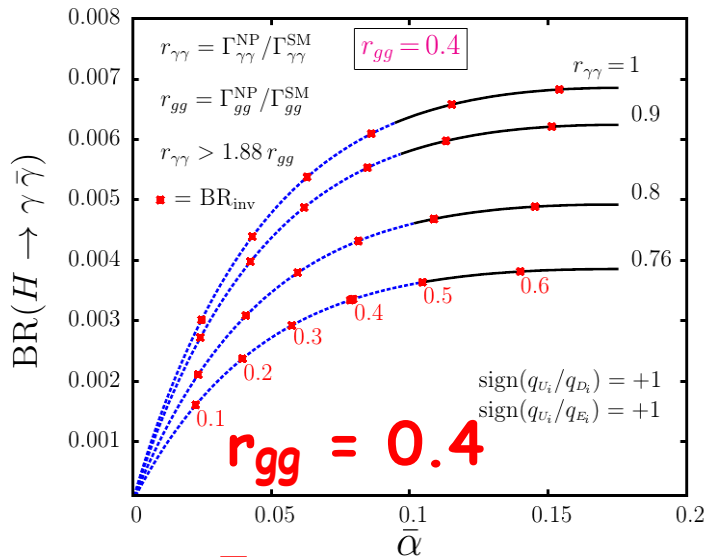
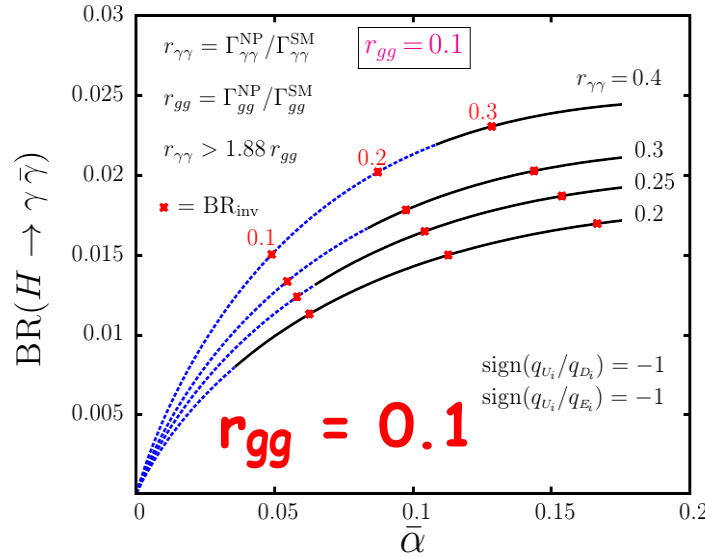
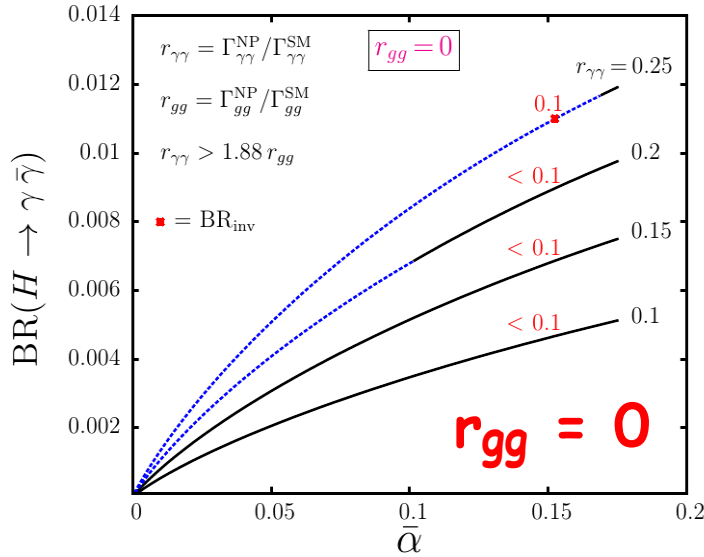
Predictions of $\overline{\alpha}$ at low energy (messenger average-mass scale)
 as a function of charge splitting δ_3 in UP and Down third DF generation



$$q_{Q_{D_3}} = q_{Q_{U_3}} (1 - \delta_3)$$

If we require charges not too fine tuned (i.e. $\delta_3 > 20\%$) then $\overline{\alpha}$ at low energy could be between $0.05 < \overline{\alpha} < 0.18$ ($\rightarrow \overline{\alpha}(\Lambda) \sim 1$)

Predictions for $\text{BR}(H \rightarrow \gamma\bar{\gamma})$ in full model versus $\bar{\alpha}$ ($\bar{m}$)



continuous lines

$$\frac{1}{2} \text{BR}_{\gamma\gamma}^{\text{SM}} < \text{BR}_{\gamma\gamma} < 2 \text{BR}_{\gamma\gamma}^{\text{SM}}$$

$$\text{BR}_{\gamma\gamma}^{\text{SM}} = 2.28 \times 10^{-3}$$

Same sign of $U(1)_F$ charges and EM charges

$$r_{gg} \equiv \frac{\Gamma_{gg}^{\text{M}}}{\Gamma_{gg}^{\text{SM}}}$$

$\text{BR}(H \rightarrow \gamma\bar{\gamma}) > 0.5\%$ requires $0.1 < \bar{\alpha} < 0.18 \rightarrow$ natural value if $\delta_3 > 20\%$

Conclusions

- Cosmological and particle physics hints suggest that massless $U(1)$ dark photons might exist together with a non-trivial dark sector
- motivated by these hints, we have analysed in a model independent way the $H \rightarrow \gamma \bar{\gamma}$ decay at LHC
- at LHC this decay shows as single photon plus E_T signature, with both energies peaked at $m_H/2$
- we estimate (at parton level) that a 5σ discovery can be reached with the existing 8 TeV LHC datasets if $BR(H \rightarrow \gamma\gamma) \sim 0.5\%$
- such large BRs can be easily obtained in dark $U(1)_F$ models explaining the origin and hierarchy of SM Yukawa couplings
- detector-level studies are required in order to draw realistic conclusions on the LHC sensitivity to dark photons
- Interesting implications of this scenario at future e^+e^- colliders and 100 TeV hadron colliders