

Dark Photon search at LHC in Higgs decays

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based on: arXiv:1405.5196 and PRD 89 (2014) 015008**

Outline

- Introduction to dark photons
- Dark photon effective couplings to Higgs
- Impact on Higgs decays $H \rightarrow \gamma \bar{\gamma}$, $\gamma \gamma$, $\bar{\gamma} \bar{\gamma}$
- Model independent analysis of $H \rightarrow \gamma \bar{\gamma}$ at LHC
- A model of Flavor with dark sector and a 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)

Dark photons and Flavor 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
- 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**
 - ➔ **a (massless) dark photon**: gauge boson of exact $U(1)_F$ gauge group
 - ➔ **messenger scalars**: very heavy, same QN of squarks and sleptons
 - ➔ **Higgs boson**: SM portal to the Dark Sector

EG, M. Raidal, PRD 89 (2014)

New signature in the Higgs boson physics

Dark photons and resonant mono-photon signatures in Higgs boson decays at the LHC

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(Dated: May 21, 2014)

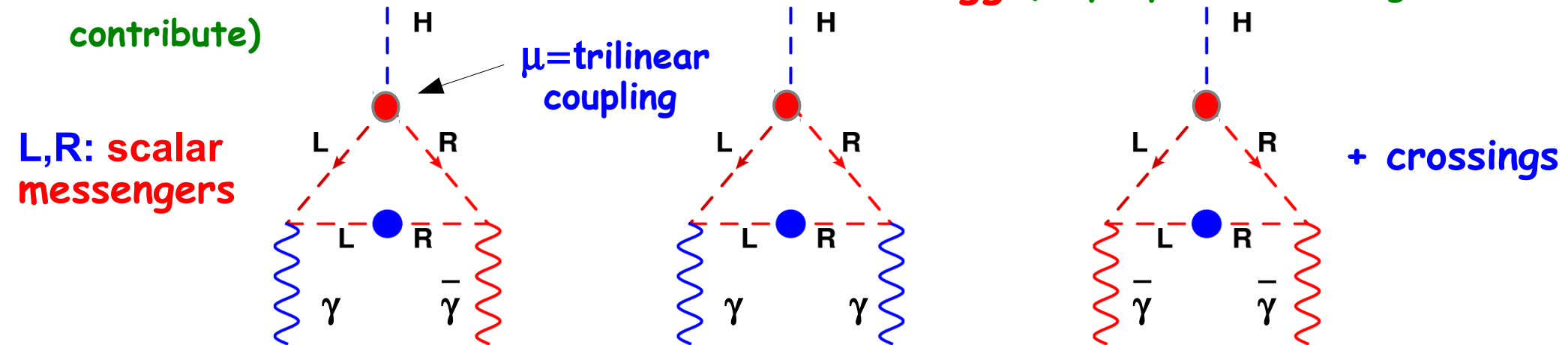
arXiv:1405.5196 [hep-ph]

(short notations for Dark Photon: **DP** and $\bar{\gamma}$)

Impact on Higgs radiative decays

- Loop of messenger fields can modify the Higgs boson decays:
 $H \rightarrow \gamma\gamma$ and $H \rightarrow gg$, but can generate also $H \rightarrow \gamma \bar{\gamma}$ and $H \rightarrow \bar{\gamma} \bar{\gamma}$

- We assume a small modification of $H \rightarrow gg$ (only squarks messengers contribute)



- In photon/DP production run both slepton and squark type of messengers
- DP detected as missing energy
- Model independent contribution: fixed by SM and $U(1)_F$ gauge invariance

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

$$-L - \bullet - \bar{R} - \rightarrow \Delta = \langle H \rangle \mu, \text{ is the LxR scalar mixing}$$

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 :
 Λ turns out to be proportional to the Higgs vev !

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

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

v = Higgs vev

$U(1)_F$ charges

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



Mixing parameter $\xi < 1$ to avoid tachions

$\bar{m} = m(L)$ and $m(R)$ average mass

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

- Large mixing ξ can give a large effect, independently on scalar 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

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

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

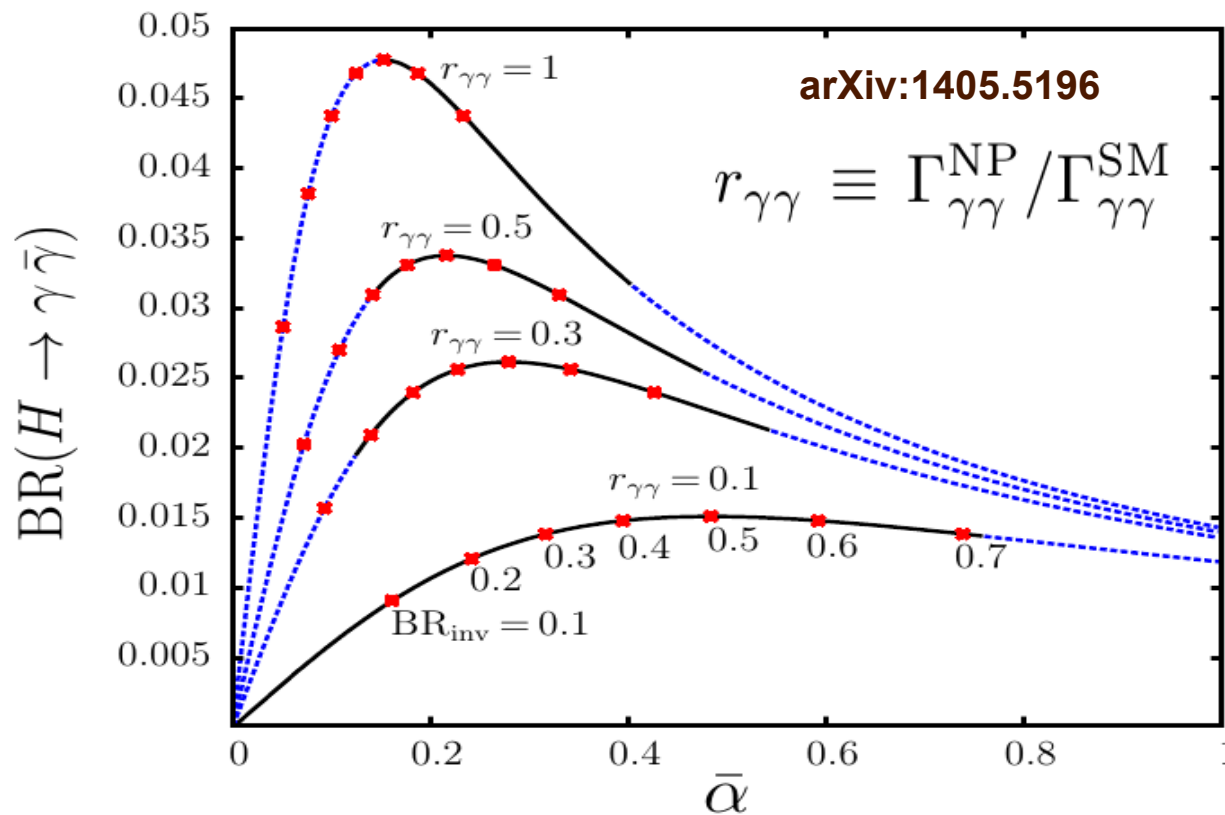
$$N = \text{BR}_{\gamma\gamma}^{\text{SM}} / (1 + r_{\bar{\gamma}\bar{\gamma}} \text{BR}_{\gamma\gamma}^{\text{SM}})$$

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

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

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

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 $\gamma + \cancel{E}_T$

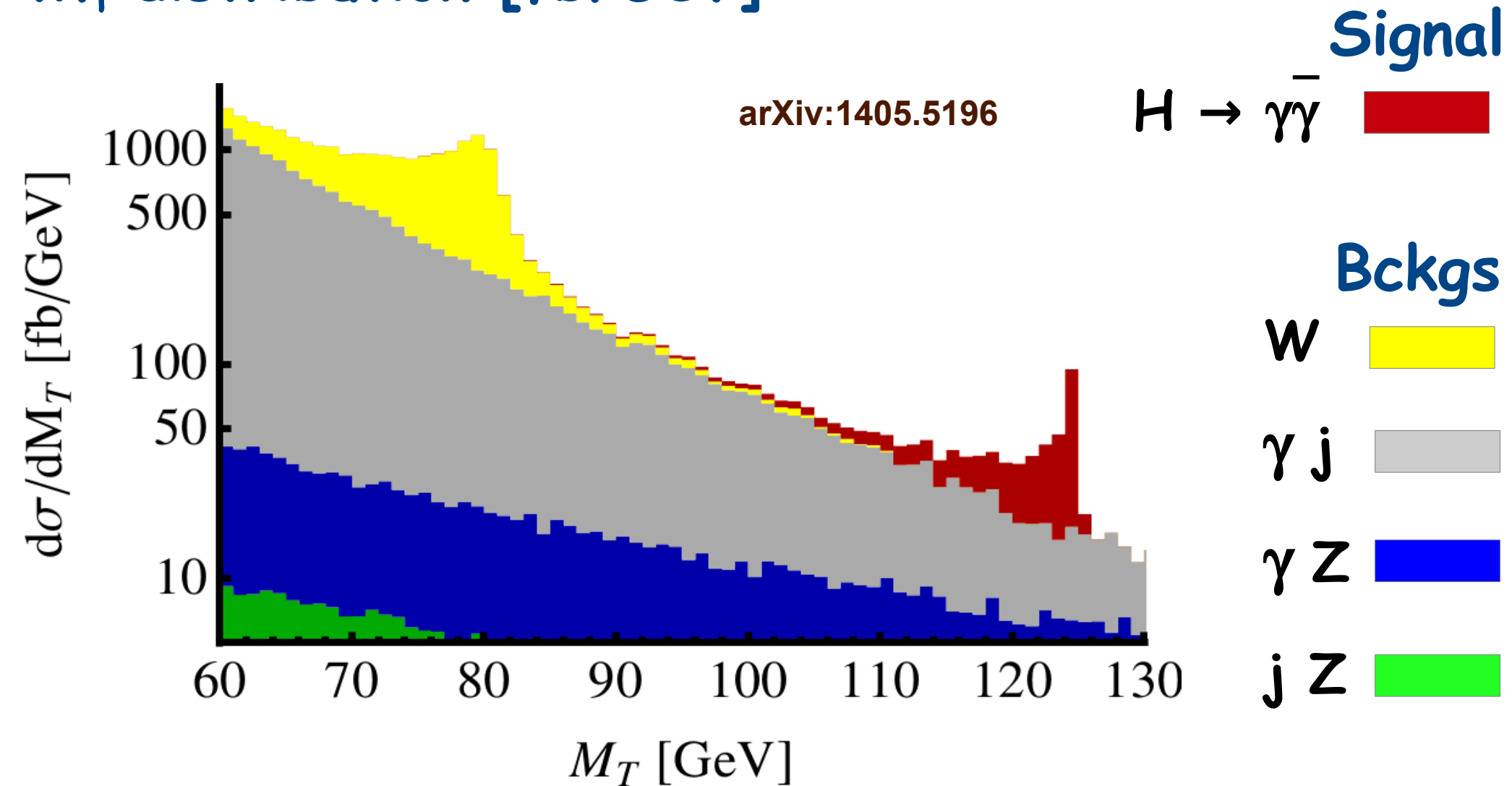
1. $pp \rightarrow \gamma j$, where large apparent $\cancel{E}_T$ is created by a combination of real $\cancel{E}_T$ from neutrinos in heavy quark decays and mis-measured jet energy.
2. $pp \rightarrow \gamma Z \rightarrow \gamma \nu \bar{\nu}$ (irreducible background);
3. $pp \rightarrow j Z \rightarrow j \nu \bar{\nu}$, 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

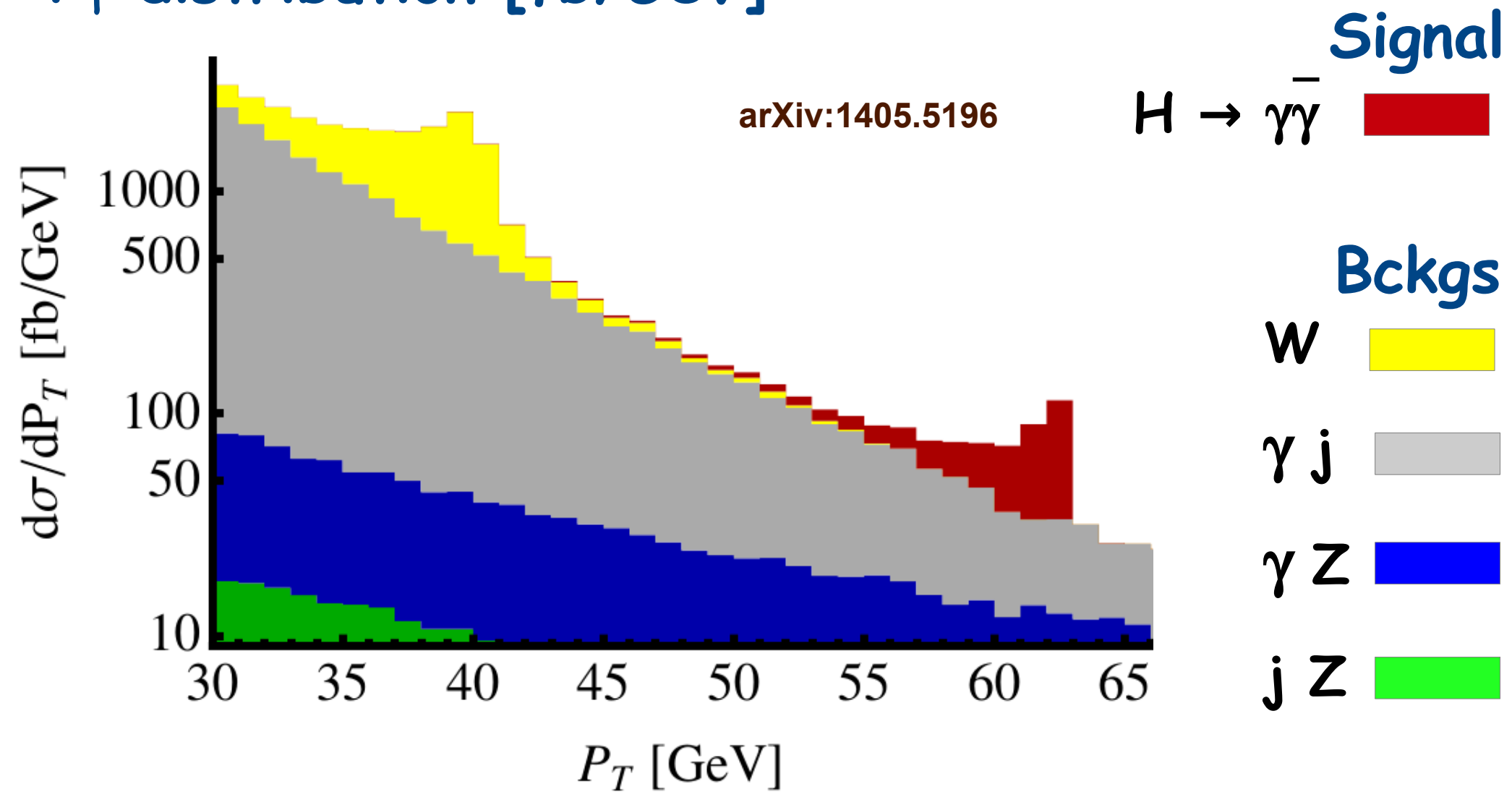
C.Peterson, A.Romagnoni, R.Torre,
JHEP 1210, 016 (2010)

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:

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

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

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

- 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 !
- It requires the existence of a dark sector containing a strongly coupled (but still perturbative) massless dark photon, messenger scalar fields, and dark fermions as natural candidates for Dark Matter !

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

Two 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)

Froggat-Nielsen Mechanism

introduces $U(1)_F$ flavour symmetric non-renormalizable operators involving a large number of scalar flavon fields that are suppressed by a large cut-off scale Λ . When the flavon ϕ obtains a vacuum expectation value (VEV) $\langle\phi\rangle$, effective Yukawa couplings Y are induced as powers of the expansion parameter $\lambda \sim \langle\phi\rangle/\Lambda$ as $Y \sim \lambda^n$.

Extra-dimensions

fermions in different branes that are located in different places in extra dimensions [7]. The Yukawa couplings are induced due to overlaps of the fermion wave-functions with the Higgs wave-function in extra dimensions. This scenario allows for exponential parameterisation of the measured Yukawa couplings.

Exponentially spread dynamical Yukawa couplings

PHYSICAL REVIEW D **89**, 015008 (2014)

Exponentially spread dynamical Yukawa couplings from nonperturbative chiral symmetry breaking in the dark sector

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Exponentially spread dynamical Yukawa couplings

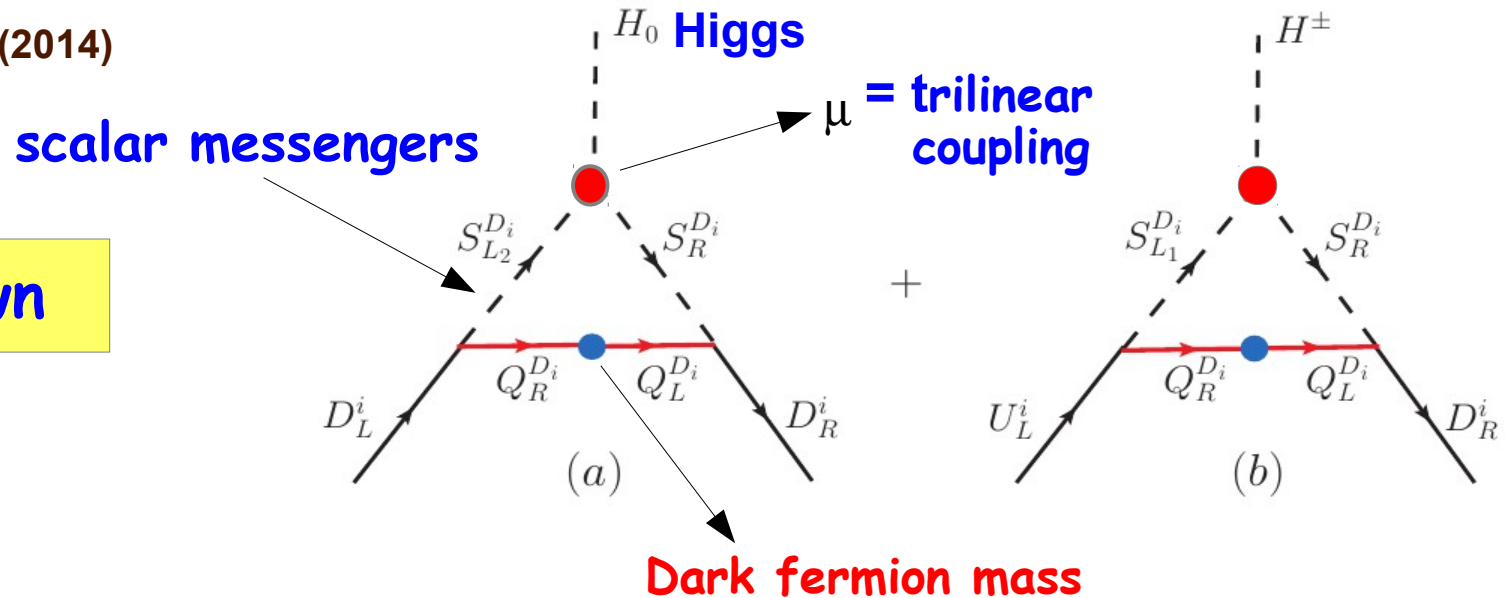
- Dark sector as origin of Chiral and Flavor symmetry breaking
- Vanishing Yukawa couplings at tree level ($H \rightarrow -H$ symmetry !)
- SSB of Z_2 ($H \rightarrow -H$) $\rightarrow$ Yukawa couplings Y_f are radiatively generated: finite result at any order in pert.th. $\rightarrow$ predictivity
- Y_f proportional to “ChSB parameters” $\times$ universal factor
- ChSB parameters = masses of Dark Fermions
- Messenger fields (squarks and sleptons) required to communicate the ChSB to the observable SM sector
- Higgs boson as a portal field to the Dark sector

SSB and ChSB: spontaneous and
Chiral Symmetry Breaking

Radiative Yukawa couplings at 1-loop

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

Yukawa down



Yukawas are finite (by power counting) → predictivity !

$$Y_i \sim \frac{M_i \mu}{\bar{m}^2}$$

Dark Fermion mass M_i (points to numerator), Higgs-trilinear coupling μ (points to numerator), Average Messenger mass $\bar{m}^2$ (points to denominator)

- Messenger mass sector assumed to be universal
→ Yukawa hierarchy given by Dark Fermion mass hierarchy !
- Dark sector dynamics responsible for the SM mass hierarchy !

Dynamics of Flavor and ChSB in the Dark Sector

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

Dark photon

EG, M. Raidal, PRD 89 (2014)

- 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 !

Mechanism for fermions mass splitting

EG, PRD 77 (2008)

- Universal charges  mass degeneracy
- 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

SM Yukawa couplings turn out to be also 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 !

- Messengers lighter than Dark Fermions (due to DM constraints)
- Dark Fermions spectrum $\sim$ rescaled version of SM fermion spectrum
- $U(1)_F$ gauge invariance and non-universality of charges imply that all Dark Fermions (if lighter than messengers) are all stable particles and all DM candidates !
- Non trivial DM scenario, that can have dramatic impacts in cosmology
- In order to generate top Yukawa coupling, LR ξ mixing is expected to be large, while vacuum stability bounds require:
 - mass of colored (squarks) messengers > 55 TeV !
 - however, mass of EW (sleptons) messengers could be lighter
- quark and lepton mass sum rules naturally predicts a strongly coupled (but still perturbative) dark photon, with $\alpha \sim O(0.2-0.3)$
- If dark photon is massless, kinetic mixing with photon can be tuned away $\rightarrow$ all astrophysical constraints can be circumvented !

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 $\cancel{E}_T$** 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