

Dark Photon searches via Higgs production @ FCC-ee

Emidio Gabrielli

University and INFN Trieste, Italy
NICPB, Tallinn, Estonia

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

based on:	arXiv: 1703.00402	Biswas, EG, Heikinheimo, Mele
	JHEP 1506 (2015) 102	Biswas, EG, Heikinheimo, Mele
	PRD 90 (2014) 055032	EG, Heikinheimo, Mele, Raidal
	PRD 89 (2014) 015008	EG, Raidal

Theoretical motivations for Dark Photons

- Dark Matter origin is unknown, not explained by SM
- possible origin in a **Hidden Sector (HS)** → **neutral** under SM
gauge interactions $SU(2)_L \times U(1)_Y \times SU(3)_C$
- **HS** might contain light or massless gauge bosons (**Dark Photons**)
mediating long-range forces in the HS
- Massive (light) **DP** mainly introduced **ad hoc** to improve astroparticle and cosmological models
Arkani-Hamed, Finkbeiner, Slatyer, Weiner, PRD 79 (2009)
Fan, Katz, Randall, Reece, PRL 110 (2013)
Agrawal, Cyr-Racine, Randall, arXiv:1610.04611
- Recent proposal aiming to naturally solve the Flavor hierarchy problem → predicts **interacting DM candidates via Dark Photon**

EG, M. Raidal, PRD 89 (2014)

A natural solution to the Flavor (hierarchy) problem

EG, M. Raidal, PRD 89 (2014)

- Require Hidden Sector charged under an unbroken $U(1)_F$
- HS contains N_f Dark Fermions (potential Dark Matter candidates) charged under an unbroken $U(1)_F$ ($\rightarrow$ massless Dark Photon)
- DF masses are generated non-perturbatively $\rightarrow$ exponentially spread (via higher derivative term in $U(1)$ sector $\rightarrow$ Lee-Wick theory)

EG, PRD 77 (2008)

$$M_{D_f} \sim \exp\left(-\frac{\kappa}{q_{D_f}^2 \bar{\alpha}}\right)$$

anom. dim.

DP coupling

Exponentially Spread Yukawa couplings

EG, M. Raidal, PRD 89 (2014)

■ $Y_f = 0$ at tree-level (enforced by some symmetry S)

■ Y_f 's low energy couplings → radiatively generated
(after SSB of S)

■ requires scalar messenger fields S_L

■ Y's follow DF mass hierarchy

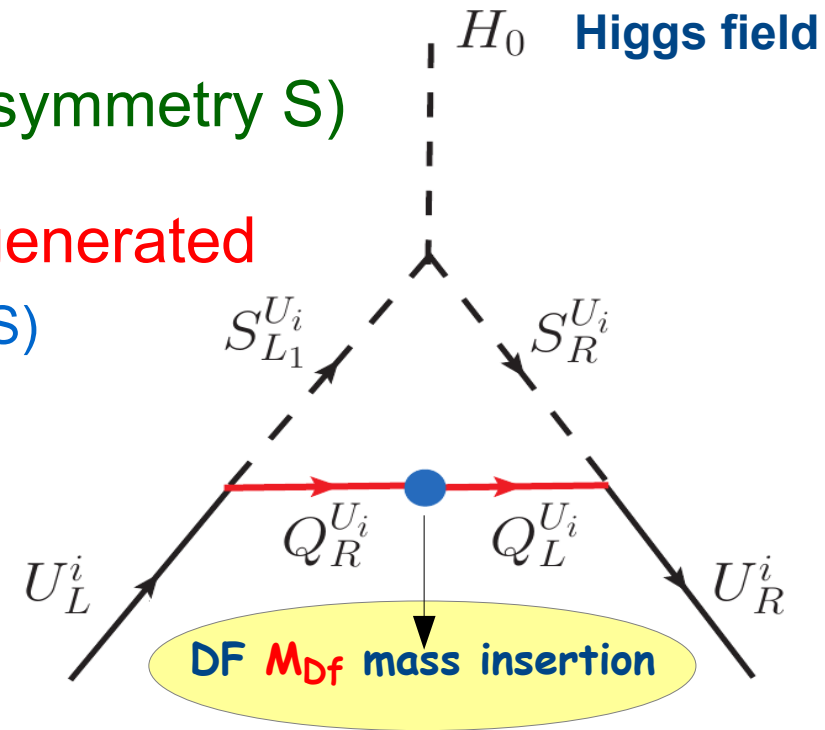
$$Y_f \sim M_{D_f} \sim \exp\left(-\frac{\kappa}{q_{D_f}^2 \bar{\alpha}}\right)$$

Flavor



Non-Universal q_{Df}

charges of same order
can generate large splitting



heavy scalar messengers $S_{L,R}$

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



Messengers
(Scalars)

Dark Sector
(Fermions+Scalar)

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

Barbara Mele

Milano, 12 February 2015

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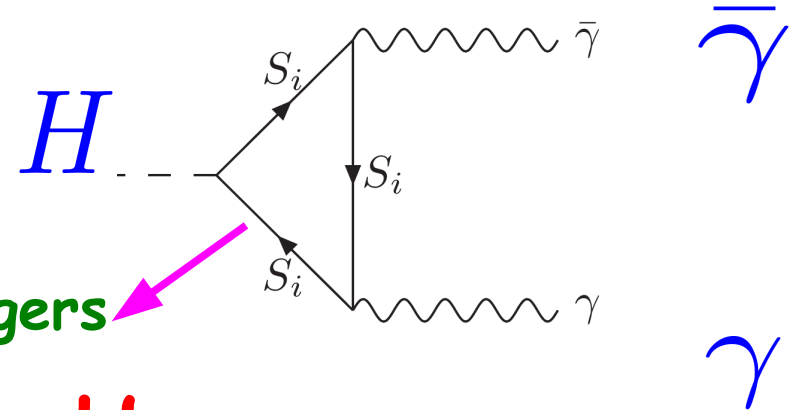
- **Dark Fermions** are lighter than messengers → stability due to $U(1)$ gauge invariance → potentially **multi-DM candidates**
- **DF** spectrum almost rescaled from SM-fermion spectrum
[DF associated to light SM fermions could be potentially very light]
- rich phenomenology at colliders [exploration just started]
- in the meantime:
 - one straightforward new signature in Higgs decays involving **Dark Photon couplings to Higgs boson...**

Monophoton Exotic Higgs Signature

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

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

scalar messengers



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

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

model indep. parametrization

- non-decoupling effect $\rightarrow \Lambda_{\gamma \bar{\gamma}}$ proportional to Higgs vev !
- DP coupling ($\bar{\alpha}$) could be large (allowed if DP is massless)
- potentially large rates expected !

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

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

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

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

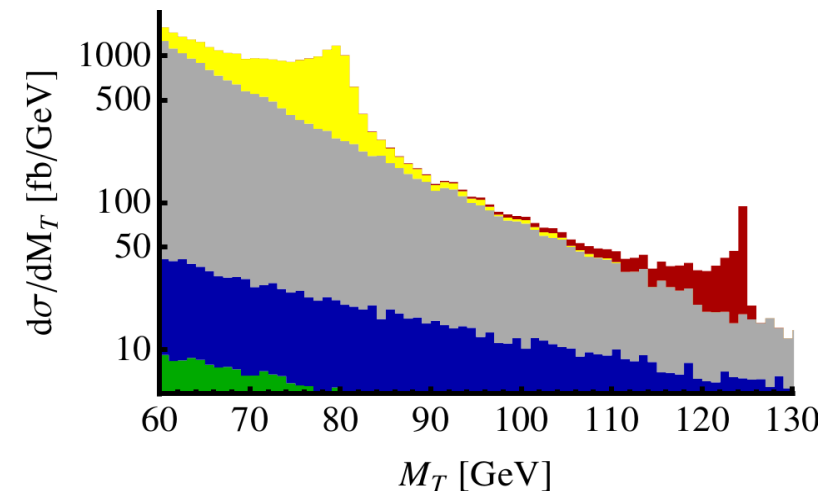
monochromatic photon $E_\gamma = m_H/2$ in the Higgs rest frame

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

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

- M_T distribution peaked at M_H mass

- P_T^γ distribution exhibits similar structure at $M_H/2$



Significance vs BR in gg and VBF mechanisms

Improved analysis including parton shower effects and gg + VBF @ 14 TeV

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

BR $_{\gamma\bar{\gamma}}$ (%)	L=100 fb $^{-1}$		L=300 fb $^{-1}$		L=3 ab $^{-1}$	
Significance	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 fusion
- sensitivity on BR up to BR $\sim 10^{-3} \rightarrow 10^{-4}$ for L $\sim 300 - 3000$ fb $^{-1}$

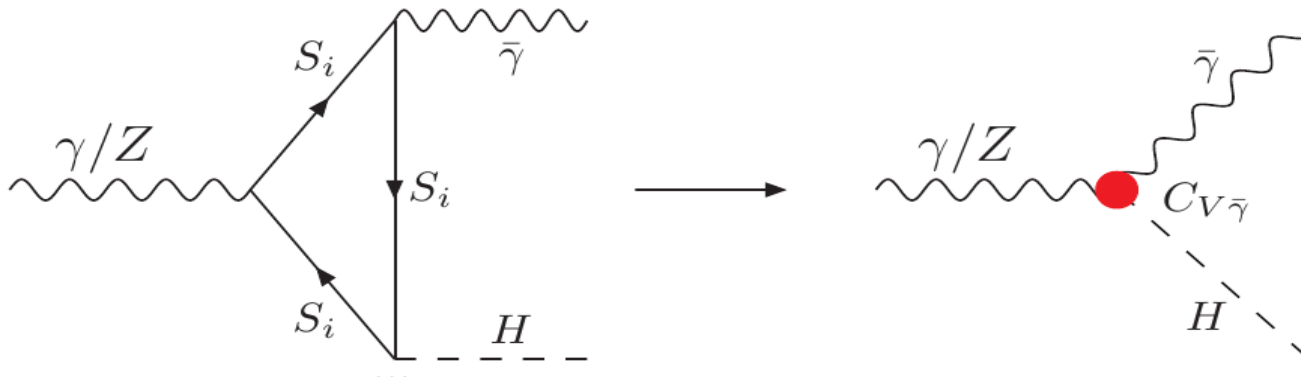
Implications of $H\gamma\bar{\gamma}$ and $HZ\bar{\gamma}$ @ e^+e^-

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

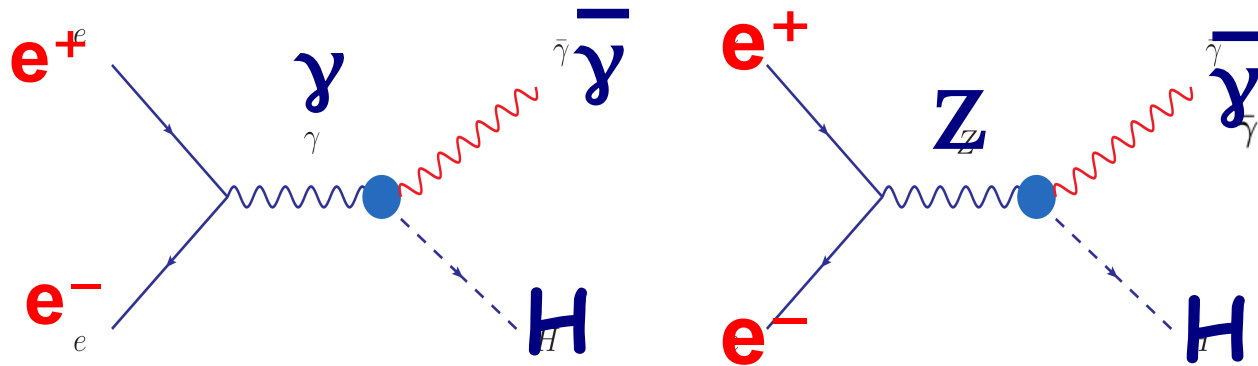
$$e^+e^- \rightarrow H\bar{\gamma} \rightarrow b\bar{b}\bar{\gamma}$$

Model independent analysis:

Effective Lagrangian: useful parametrization

$\bar{\gamma}_{\mu\nu}$ DP field strength

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



assuming mass degeneracy in Left and Right messengers (LR symmetry) $\rightarrow$

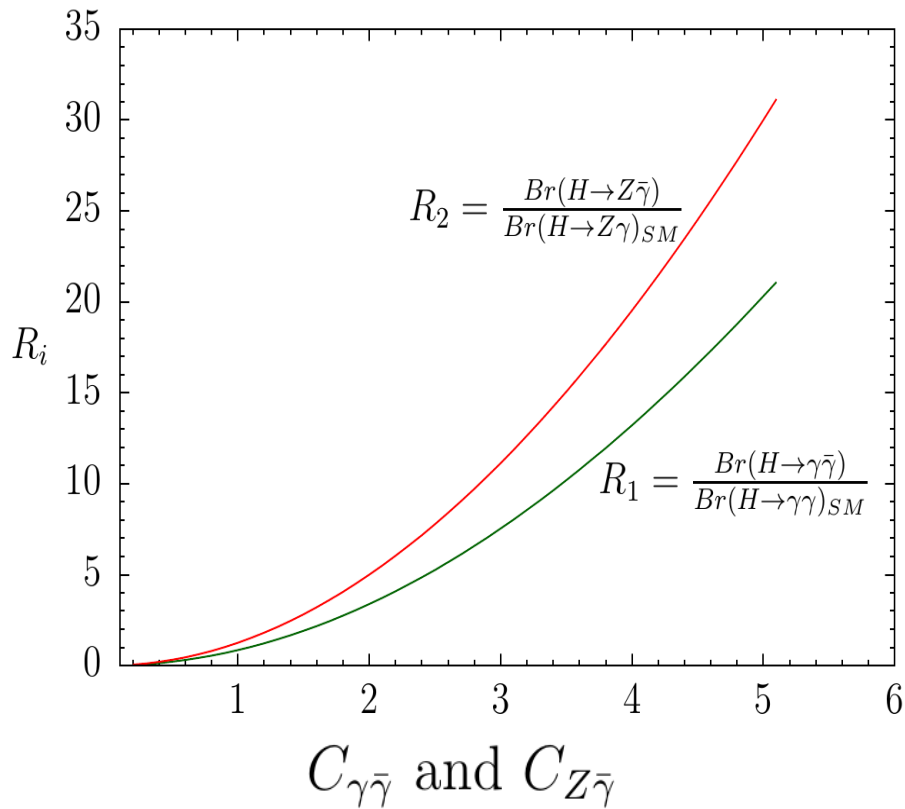
$$C_{Z\bar{\gamma}} = C_{\gamma\bar{\gamma}} R_{Z\gamma}$$

net result from a messenger doublet $\rightarrow$

$$R_{Z\gamma}^{\tilde{q}} = \frac{R_{Z\gamma}^{\tilde{u}} + R_{Z\gamma}^{\tilde{d}}}{2} \approx 0.79$$

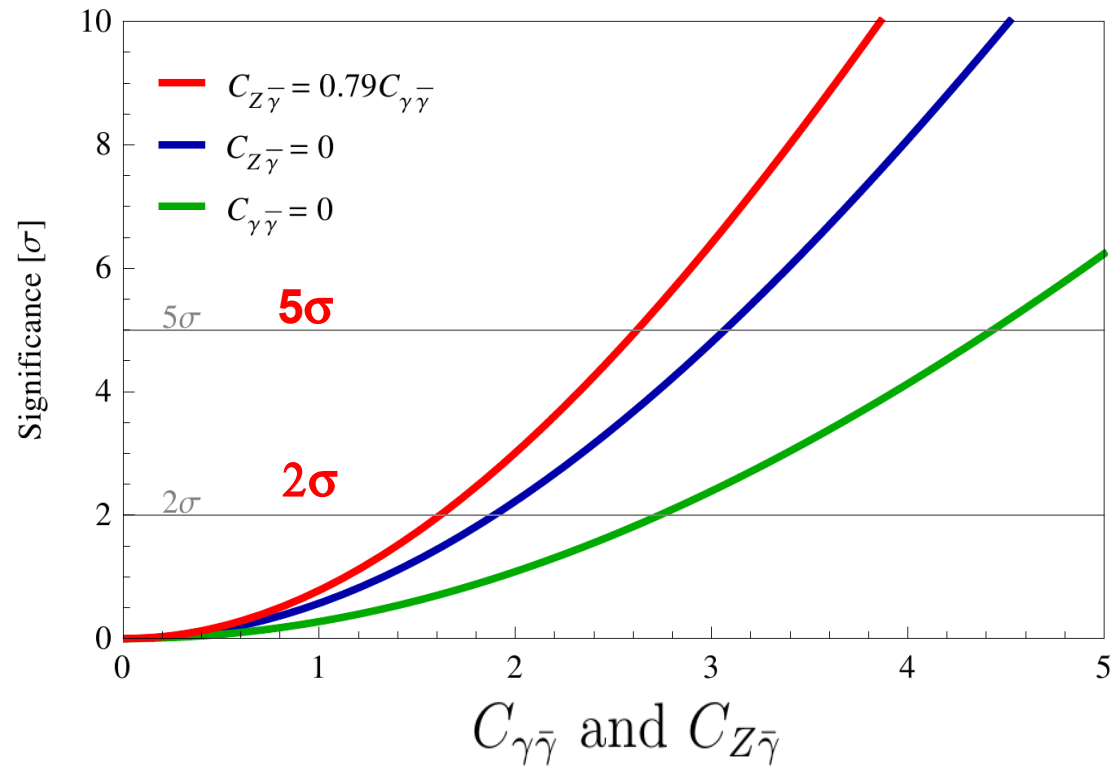
results for $\sqrt{s} = 240$ GeV

Normalized BRs to $\text{BR}_{SM}(\bar{\gamma} \rightarrow \gamma)$



Significance [σ]

$L=10\text{ab}^{-1}$



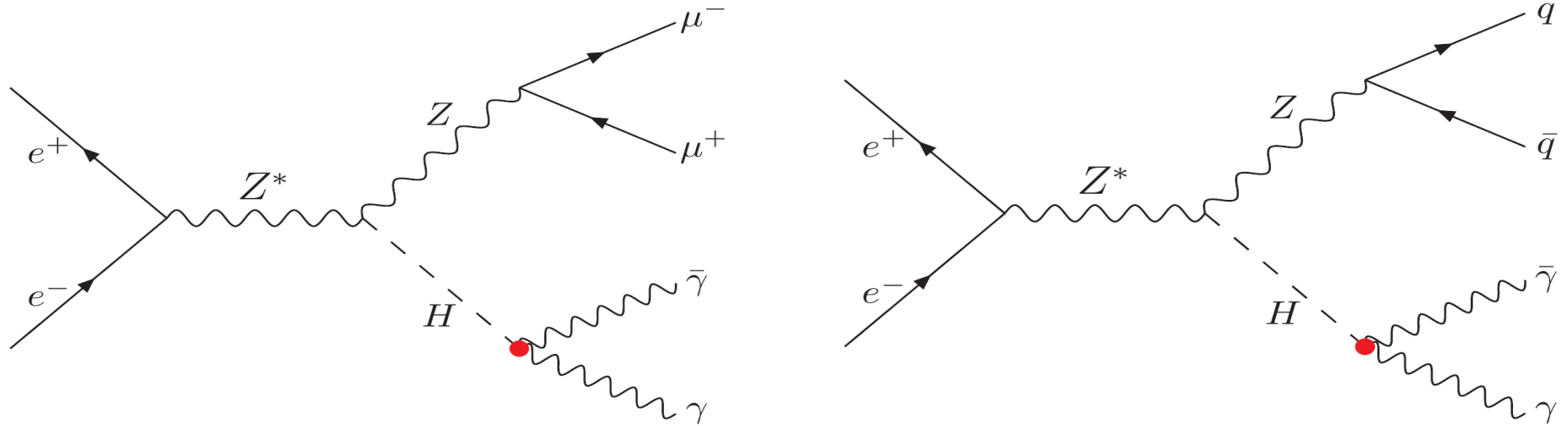
$$C_{\gamma\bar{\gamma}} > 1.9 \quad \Rightarrow \quad \text{BR}(H \rightarrow \gamma\bar{\gamma}) > 3 \text{ BR}_{SM}(H \rightarrow \gamma\gamma)$$

$$C_{Z\bar{\gamma}} > 2.7 \quad \Rightarrow \quad \text{BR}(H \rightarrow Z\bar{\gamma}) > 9 \text{ BR}_{SM}(H \rightarrow Z\gamma)$$

$\sim 6 \times 10^{-3}$

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

Biswas, EG, Heikeinheimo, Mele
arXiv :1703.00402



- model independent analysis → use of Higgs effective vertices
- can provide complementary information to $e^+e^- \rightarrow H\bar{\gamma}$
- requiring an invisible system with vanishing mass in the final state will help a lot in discriminating S/B

assumptions on detector performances

- Muon momentum resolution: $\Delta p/p = 0.1\% + p_T/(10^5 \text{ GeV})$ for $|\eta| < 1$, and 10 times poorer for $1 < |\eta| < 2.5$.
- Photon energy resolution: $\Delta E/E = 16.6\%/\sqrt{E/\text{GeV}} + 1.1\%$.
- Jet energy resolution: $\Delta E/E = 30\%/\sqrt{E/\text{GeV}}$
- Particle identification efficiency for muons and photons: 99% for $p_T > 10 \text{ GeV}$.

Channels considered

Leptonic channel: $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^-\gamma\bar{\gamma}$

Hadronic channel: $e^+e^- \rightarrow ZH \rightarrow q\bar{q}\gamma\bar{\gamma}$
(worst energy resolution for jets can be compensated by larger BR of $Z \rightarrow \text{hadrons}$)

e+e ch. not so sensitive: $\rightarrow$ due to poorer electron momentum resolution and
 $\rightarrow$ additional Z-neutral current t-channel bckg $e^+e^- \bar{\nu}\nu\gamma$

$$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^-\gamma\bar{\gamma}$$

- signal consists of pair of muons + photon + missing energy

$$M_{\text{miss}} = 0, \quad M_{\gamma\bar{\gamma}} = m_H \quad M_{\ell\ell} = M_Z$$

- signal and SM bckg simulated with MadGraph5_aMC@NLO interfaced with PYTHIA to include initial and final radiation and hadronization effects

Basic cuts

- muon and photon transverse momentum with $p_T^\mu, p_T^\gamma > 10 \text{ GeV},$
- muon and photon pseudorapidity in the range $|\eta^\mu|, |\eta^\gamma| < 2.5,$
- missing energy with $\cancel{E} > 10 \text{ GeV}.$
- angular separation between any two objects with $\Delta R > 0.2,$
- jet veto for $p_T^j > 20 \text{ GeV}.$

Main backgrounds for

$$ZH \rightarrow \mu^+ \mu^- \gamma \bar{\gamma}$$

Irreducible

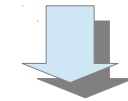
$$\mu^+ \mu^- \nu \bar{\nu} \gamma \left\{ \begin{array}{l} ZZ\gamma \\ WW\gamma \\ \nu \bar{\nu} Z\gamma \text{ (t-channel)} \end{array} \right.$$

optimized cuts

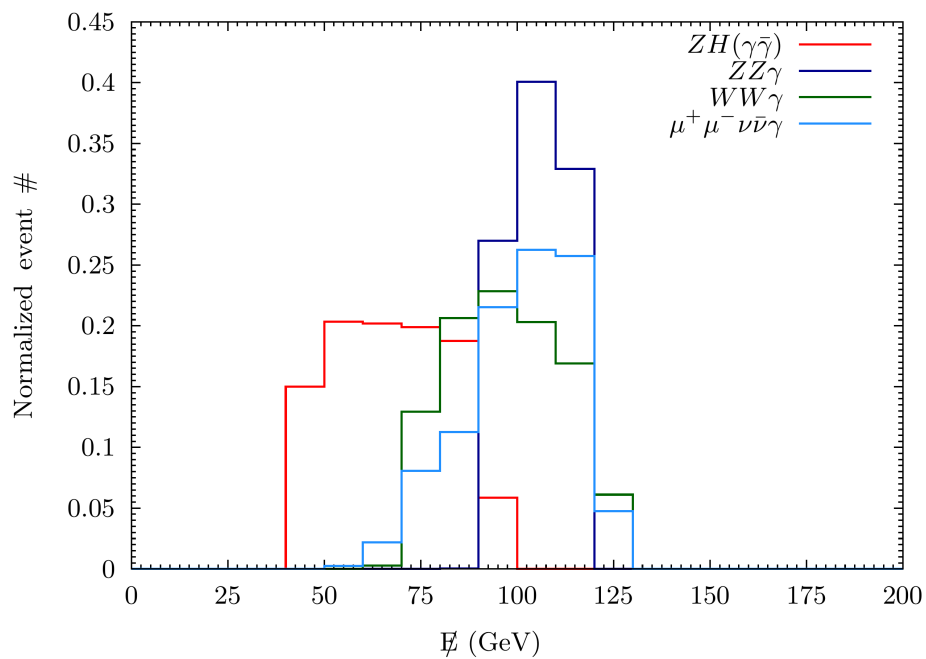
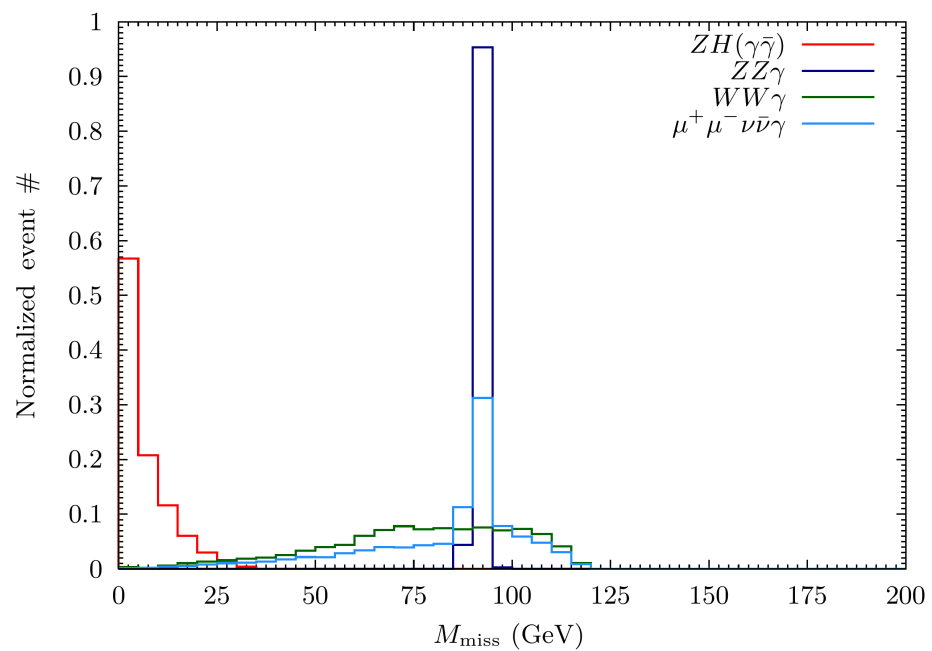
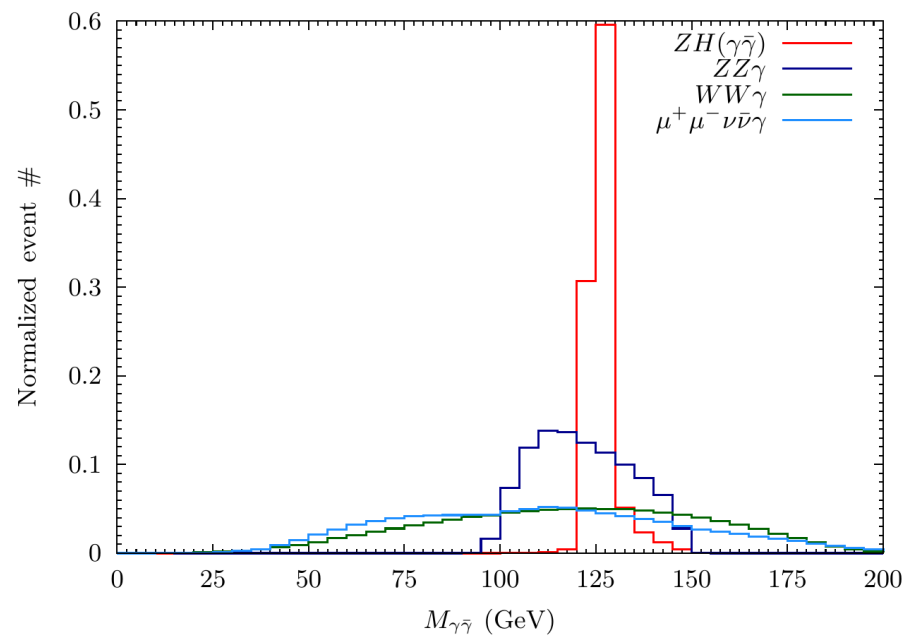
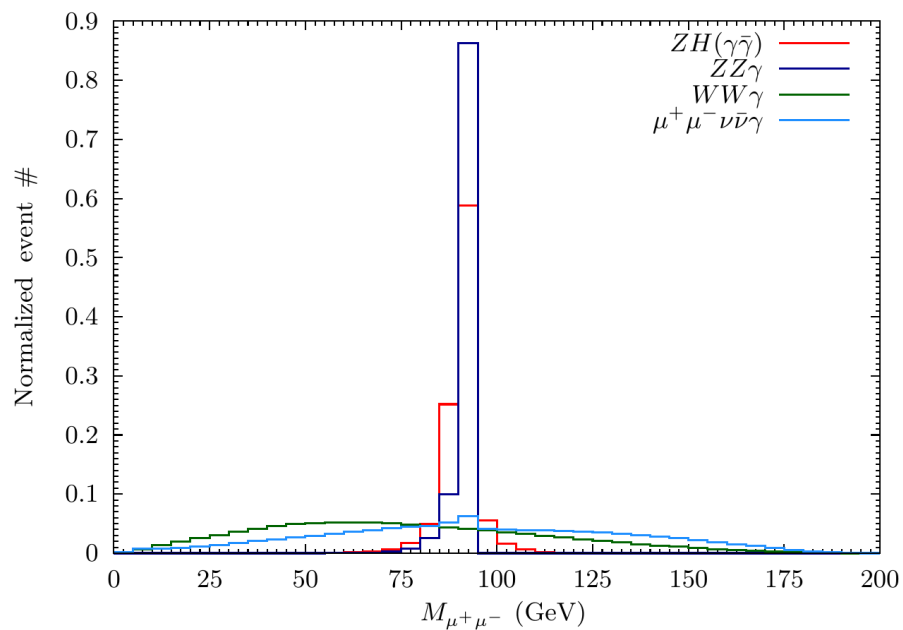
- Z mass cut: $86 \text{ GeV} < M_{\mu^+ \mu^-} < 96 \text{ GeV},$
- Higgs mass cut: $120 \text{ GeV} < M_{\gamma \bar{\gamma}} < 130 \text{ GeV}.$
- Missing mass cut: $M_{\text{miss}} < 20 \text{ GeV}$

Reducible

$$Z\gamma + \text{fake } E_{\text{Miss}}$$



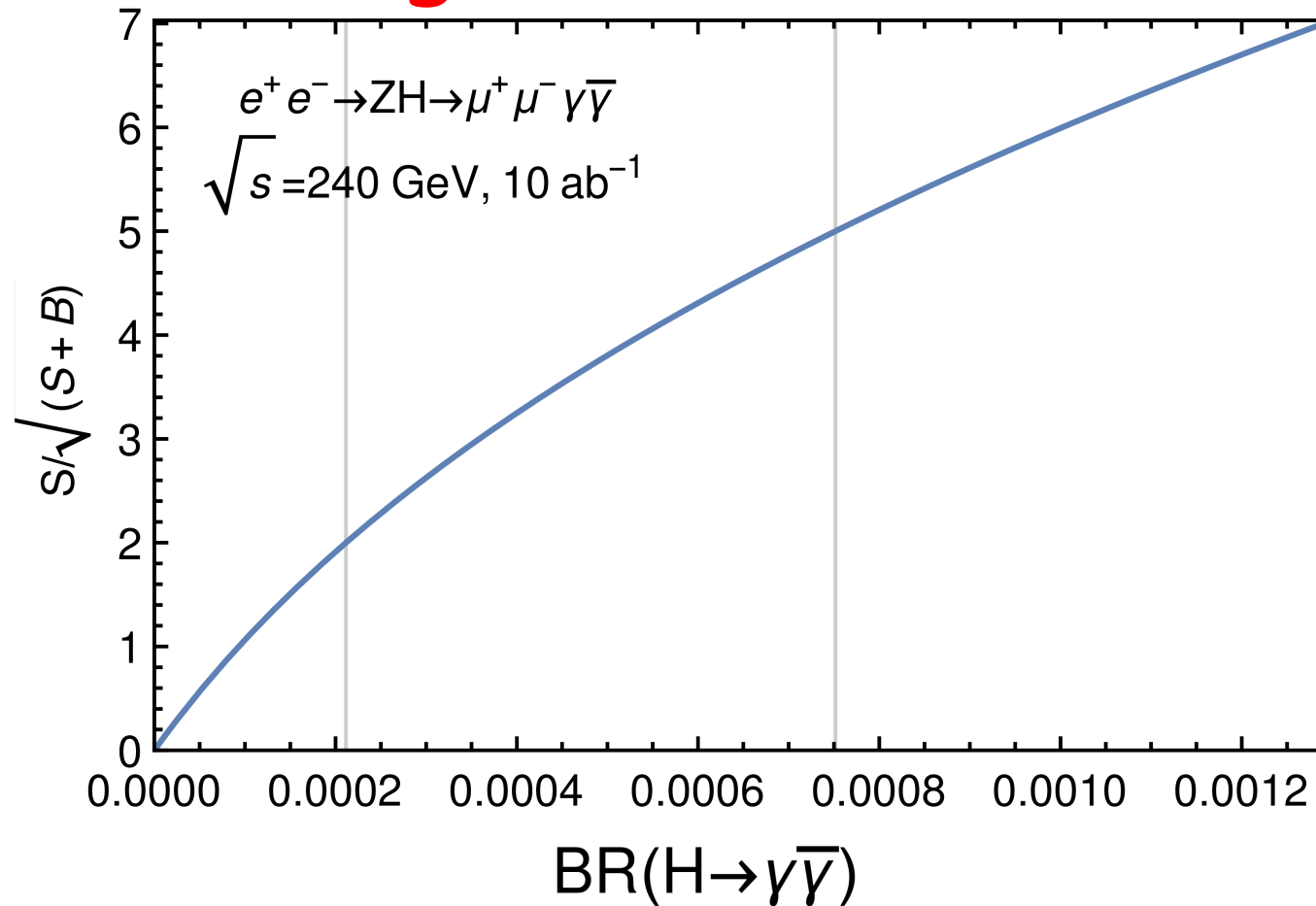
- IS rad./bremsstrahlung
- mismeasurement of photon/electron momenta
- missed final states
i.e. $ZH \rightarrow \mu^+ \mu^- \gamma \gamma$
(expected to be very small)



N. events corresponding to $L = 10 \text{ ab}^{-1}$

Process	Basic cuts	$M_{\ell\ell}$ cut	$M_{\gamma\bar{\gamma}}$ cut	M_{miss} cut
$\mu^+\mu^-\gamma\bar{\gamma}$ ($BR_{\gamma\bar{\gamma}} = 0.1\%$)	65.3	54.9	49.7	47.3
$\mu^+\mu^-\nu\bar{\nu}\gamma$	5.00×10^4	5.73×10^3	1.09×10^3	15

Significance vs BR



$$e^+e^- \rightarrow ZH \rightarrow q\bar{q}\gamma\bar{\gamma}$$

Signal consists of 2 jets + photon + missing energy ($M_{\text{miss}}=0$)

$$M_{\text{miss}} = 0, \quad M_{\gamma\bar{\gamma}} = m_H \quad M_{jj} = M_Z$$

■ signal and SM bckg simulated with MadGraph5_aMC@NLO interfaced with PYTHIA to include initial and final radiation and hadronization effects

■ jets clustered with cone size $R=0.4$ and $p_T > 20$ GeV

Basic cuts

- lepton veto for $p_T^\ell > 10$ GeV and $|\eta^\ell| < 2.5$,
- for the photon transverse momentum and pseudorapidity: $p_T^\gamma > 10$ GeV, $|\eta^\gamma| < 2.5$,
- for the jet transverse momentum and pseudorapidity: $p_T^j > 20$ GeV, $|\eta^j| < 5.0$,
- for the missing energy: $\cancel{E} > 10$ GeV.
- for the angular separation between any pair of visible objects: $\Delta R > 0.4$.

Main backgrounds for

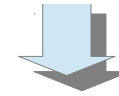
$$ZH \rightarrow q\bar{q}\gamma\bar{\gamma}$$

Irreducible

$$q\bar{q}\nu\bar{\nu}\gamma \left\{ \begin{array}{l} ZZ\gamma \\ WW\gamma \end{array} \right. \quad \text{(with Z,W} \rightarrow \text{had. modes)}$$

Reducible

$$q\bar{q}\gamma \rightarrow jj\gamma + \text{fake } E_{\text{Miss}}$$



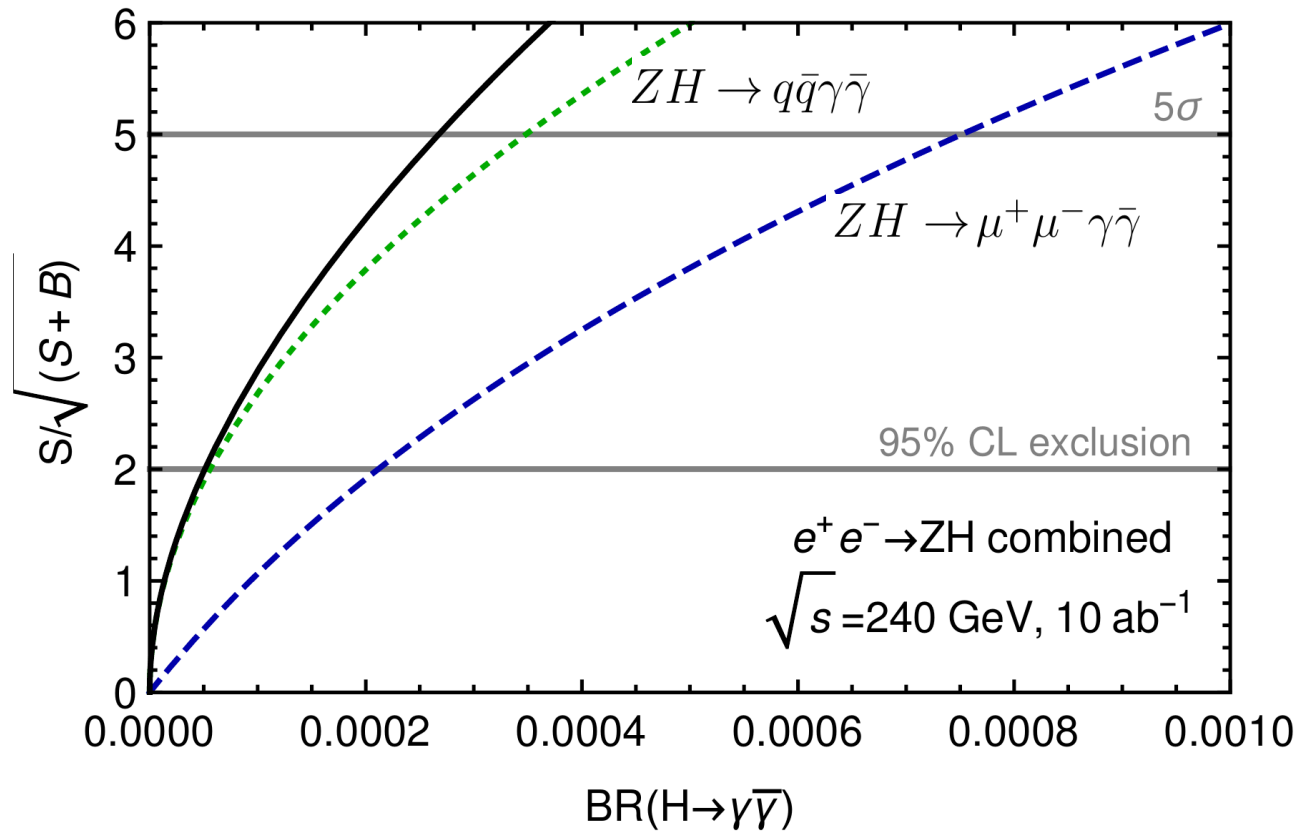
- Jet energy mismeasurement
- neutrinos from Heavy Flavor decays in jets

optimized cuts

- Higgs mass cut: $120 \text{ GeV} < M_{\gamma\bar{\gamma}} < 130 \text{ GeV}$
- Missing mass cut: $M_{\text{miss}} < 20 \text{ GeV}$ → very effective to reduce irred. bckg
- $\cancel{E} > 59 \text{ GeV}$ → very effective to reduce red. bckg $q\bar{q}\gamma$

N. events corresponding to $L = 10 \text{ ab}^{-1}$

Process	Basic cuts	M_{jj} cut	$M_{\gamma\bar{\gamma}}$ cut	M_{miss} cut	$\cancel{E}$ cut
$jj\gamma\bar{\gamma}$ ($BR_{\gamma\bar{\gamma}} = 0.1\%$)	804	669	154	110	72
$jj\gamma$	3.39×10^7	2.26×10^7	1.47×10^5	6.5×10^4	—
$jj\nu\bar{\nu}\gamma$	3.9×10^4	3.1×10^4	5.9×10^3	2.2	—



Summary

- Hidden sector might have long distance interactions mediated by $U(1)_F$ gauge $\rightarrow$ Dark Photon $\bar{\gamma}$.
 $\rightarrow$ New effective vertices can appear: $H Z \bar{\gamma}$, $H \gamma \bar{\gamma}$
- rich phenomenological implications expected
 - $\rightarrow$ search for $H \rightarrow \gamma \bar{\gamma}$, and $H \rightarrow Z \bar{\gamma}$ (golden channels @ LHC)
 - $\rightarrow$ potentially large rates due to non-decoupling effects in Higgs
 - $\rightarrow$ sensitivity @ LHC on $BR(H \rightarrow \gamma \bar{\gamma})$ can reach $10^{-3} \rightarrow 10^{-4}$
- we analyzed the potential of $e^+e^- \rightarrow HZ$ with $H \rightarrow \gamma \bar{\gamma}$ in both $Z \rightarrow \mu^+\mu^-$ and $Z \rightarrow qq$ (fully model independent analysis!)
- 5 σ sensitivity reached for $BR(H \rightarrow \gamma \bar{\gamma}) \sim 3 \times 10^{-4}$ 3 times better than LHC @ 300 fb $^{-1}$.
- ~ 100 times better (@ 95 C.L.) than $e^+e^- \rightarrow H(\rightarrow bb) \gamma \bar{\gamma}$ in probing the $H \rightarrow \gamma \bar{\gamma}$ vertex

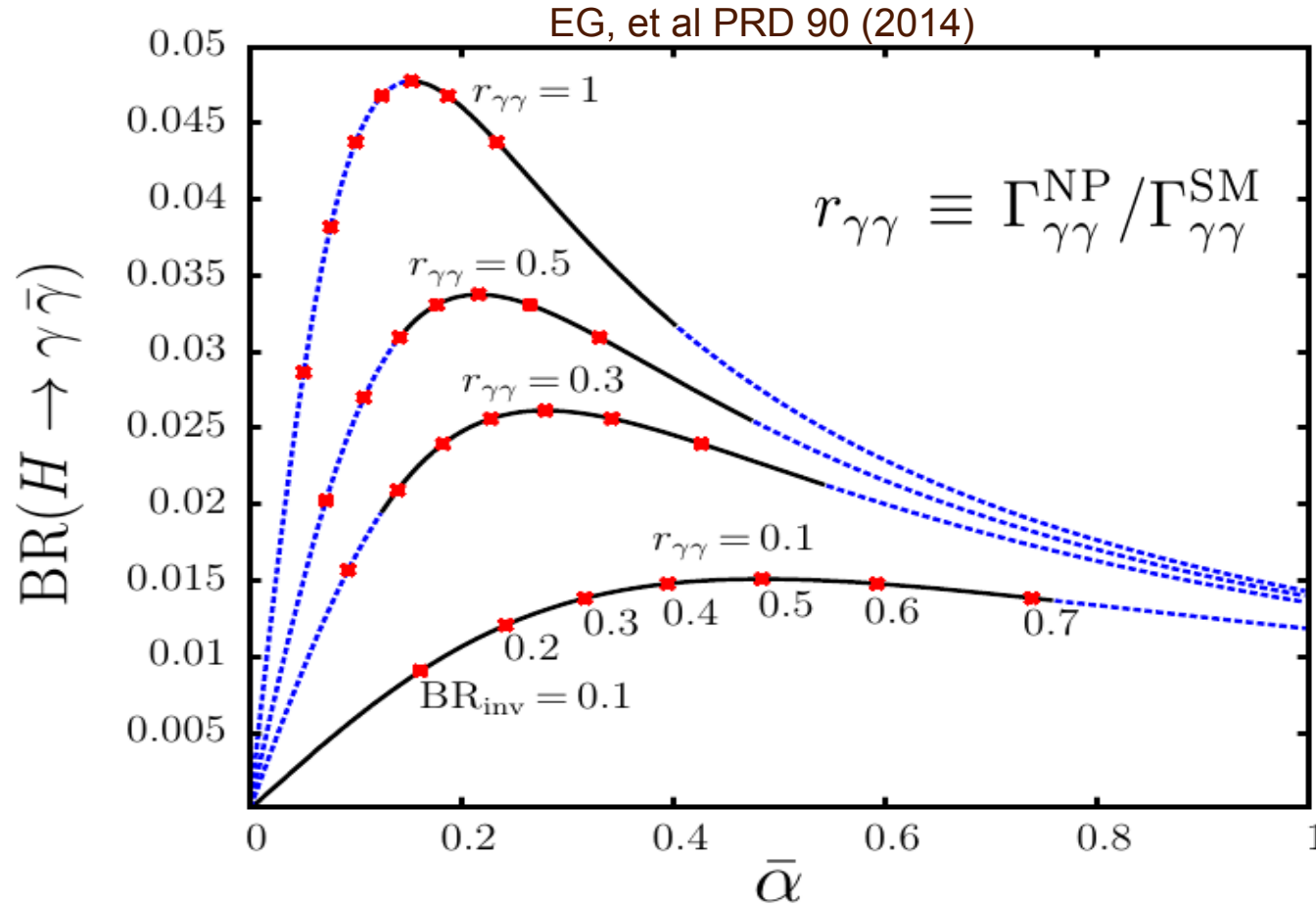
Backup slides

Model independent predictions for $\text{BR}(H \rightarrow \gamma \bar{\gamma})$

(simplified model 1 messenger only)

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

→ full lines

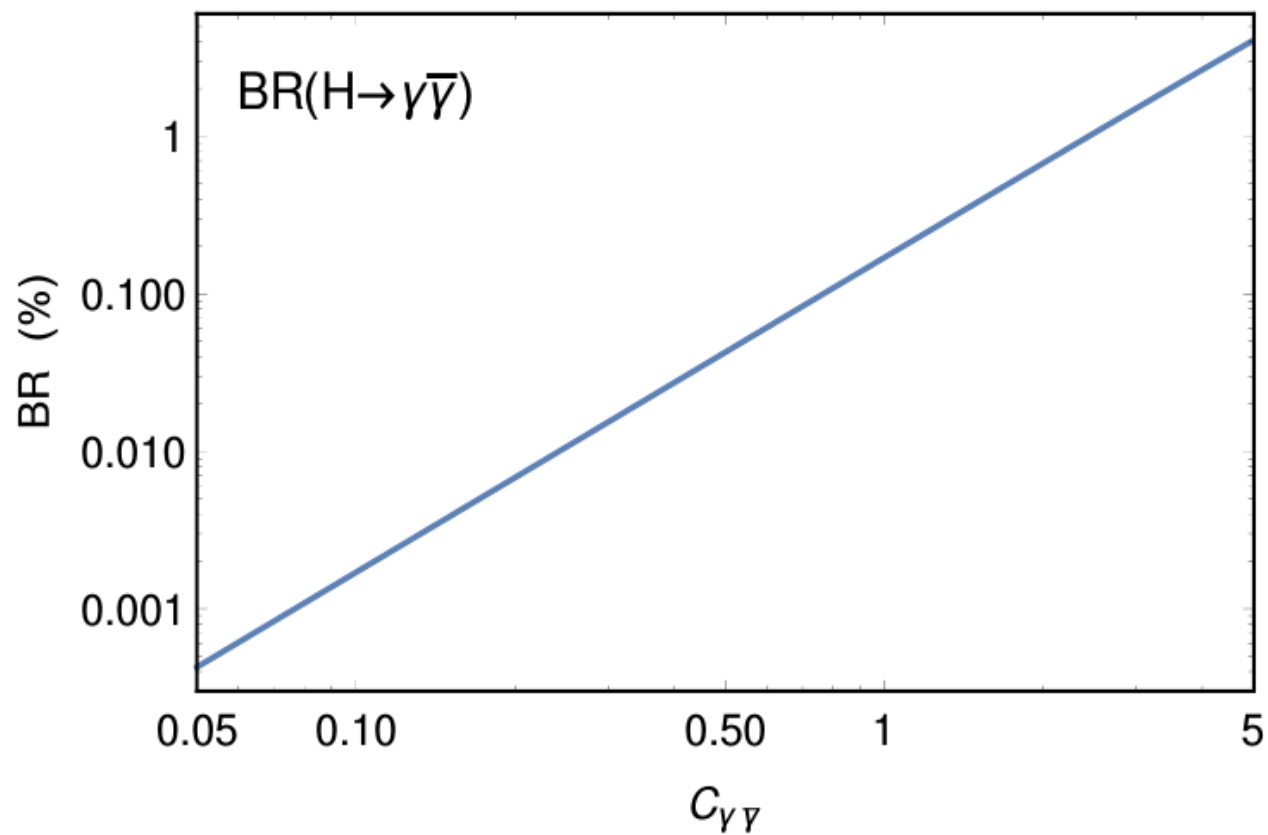


$$\text{BR}_{\gamma\gamma}^{\text{SM}} = 2.28 \times 10^{-3}$$

● $\text{BR}(H \rightarrow g\bar{g})$ can be as large as 5% consistently with all LHC constraints

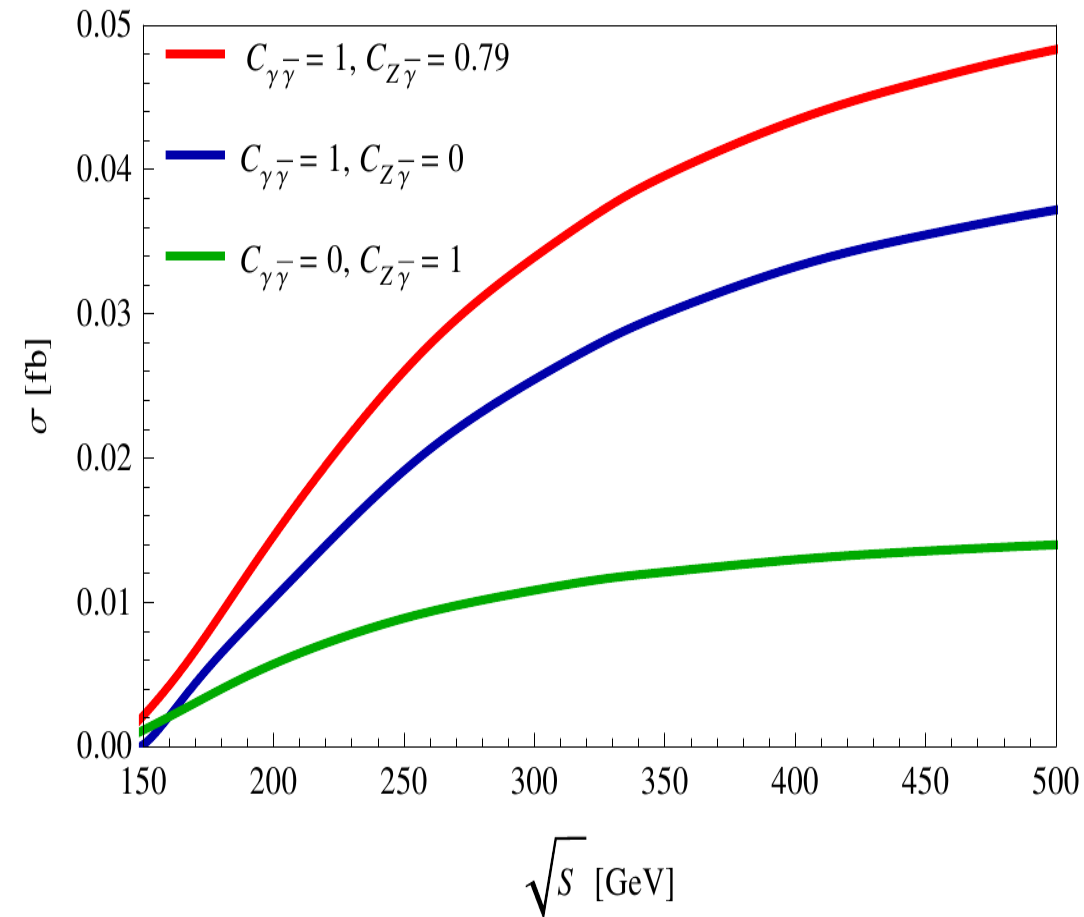
● our Flavor scenario naturally predicts large BRs ~ O(few %)

$$\Gamma(H \rightarrow \gamma\bar{\gamma}) = \frac{m_H^3 \alpha^2 |C_{\gamma\bar{\gamma}}|^2}{8\pi^3 v^2}$$

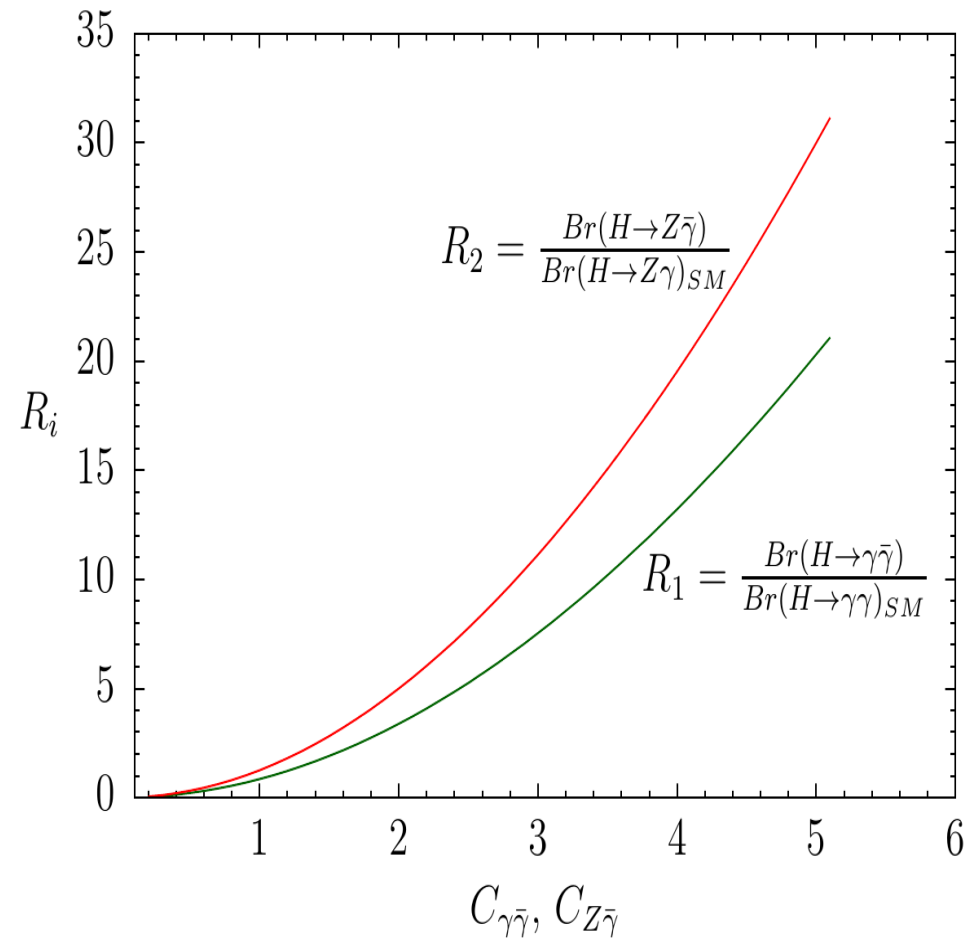


$$e^+e^- \rightarrow H\bar{\gamma} \rightarrow b\bar{b}\bar{\gamma}$$

Total cross section [fb]



Normalized Brs to SM

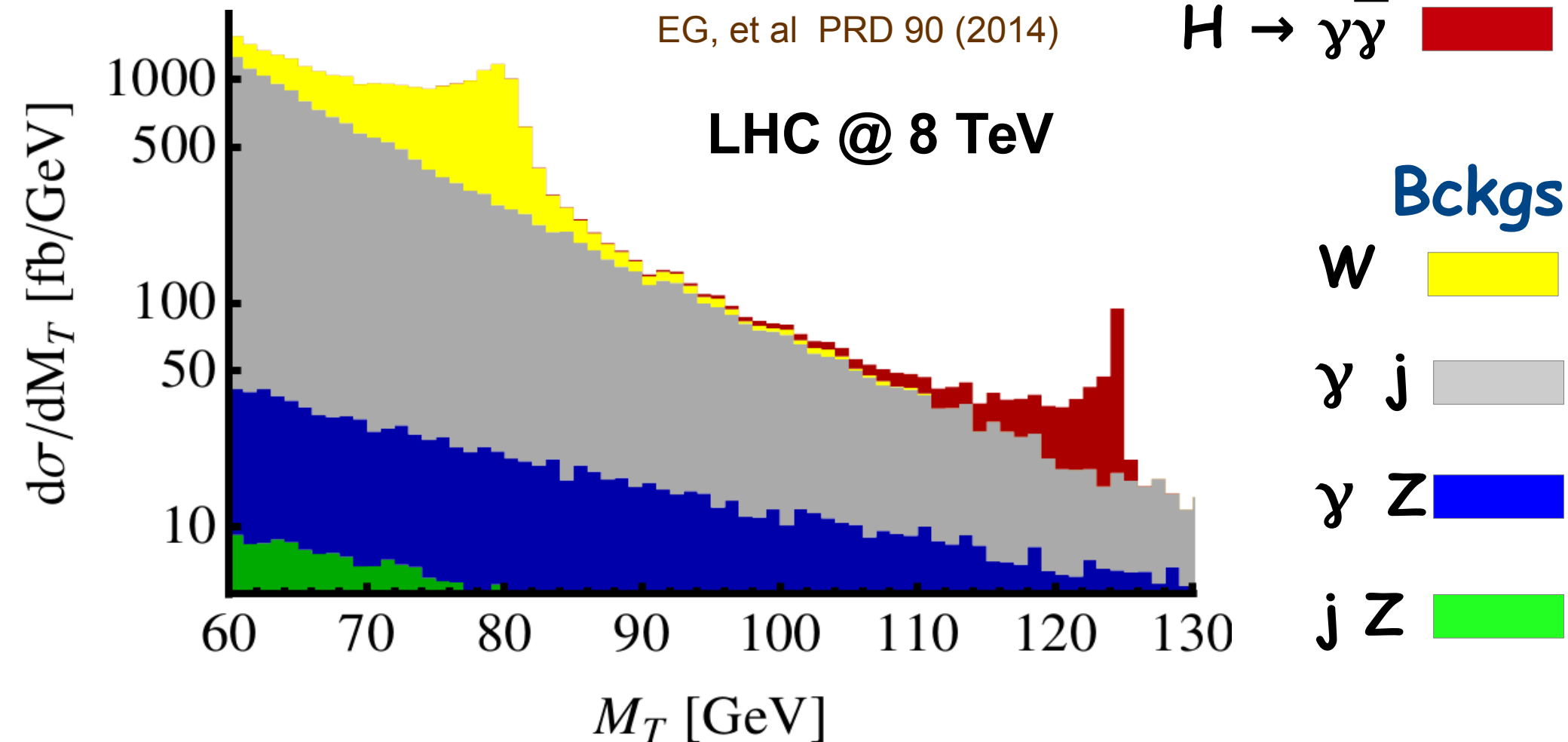


M_T distribution [fb/GeV]

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

Signal

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



M_T distribution peaked at original M_H mass

P_T^γ distribution exhibits similar structure at $M_H/2$