Higgs + Dark Photon @ FCC-ee

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

Dark sector origin of Dark Matter

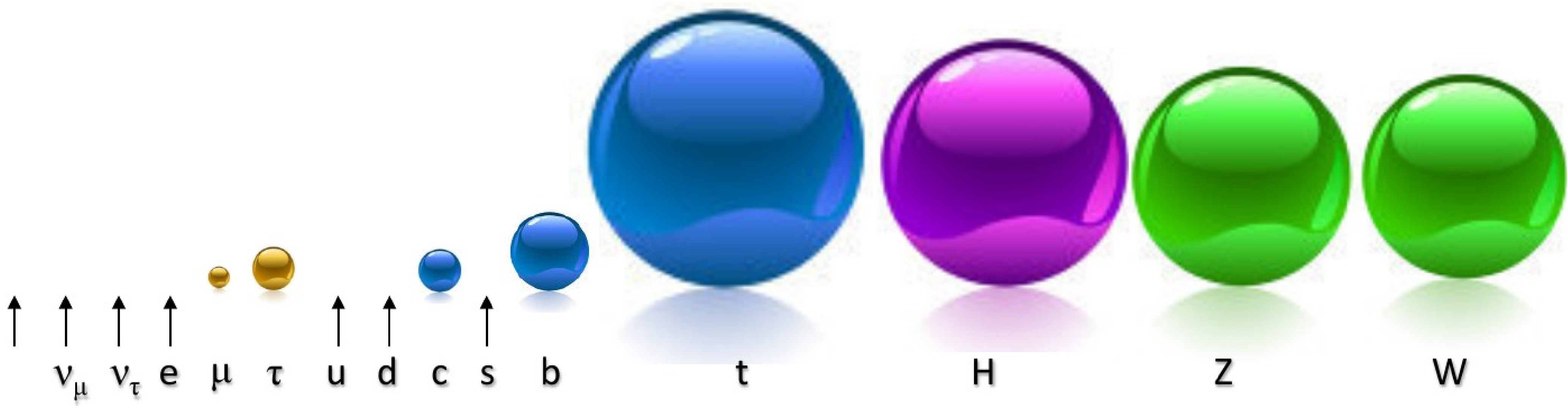
- Dark Matter origin is unknown, not explained by SM
- Possible origin in a Hidden Sector (HS), neutral under SM gauge interactions
- HS can have weakly effective coupling with SM particles , if there exist messenger fields HS ↔ SM
- HS could contain light or massless gauge bosons (Dark Photons) mediating long-range forces in the HS
- Massive (light) Dark Photons 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)**

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...



courtesy of R. Chierici

- recent proposal aiming to naturally solve the Flavor hierarchy problem (predicting DM candidates and Dark Photons)

A natural solution to the Flavor Hierarchy

- Require Hidden Sector + Dark unbroken $U(1)_F$

EG, M. Raidal, PRD 89 (2014)

- HS containing N_f Dark Fermions (Dark Matter candidates) charged under an unbroken $U(1)_F$ (massless Dark Photon)

- ChSB in HS via non-perturbative effects (via high derivative in DP field $\sim 1/\Lambda$ → Lee-Wick ghosts)

- Dark Fermions get mass M_{Df} depending on their $U(1)_F$ charge q_{Df}

anom. dim.

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

DP coupling

EG, PRD 87 (2008)
EG, M. Raidal, PRD 89 (2014)

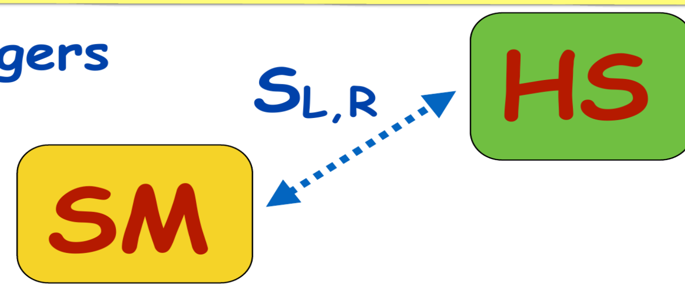
- Ex: exponential hierarchy in M_{Df} for integer $q_{Df}=1,2,3,..$

Flavor and Chiral Symmetry Breaking in HS → transferred at one-loop to visible-sector Yukawa couplings via squarks/slepton-like scalar messengers !

heavy scalar messengers $S_{L,R}$

→ heavy due to vacuum stability bounds

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



- Colored messenger heavy M > 55 TeV
  EW ones could be lighter
- Flavor broken only by q_{DF} charges → Flavor universality of messenger masses

	Fields	Spin	$SU(2)_L$	$U(1)_Y$	$SU(3)_c$	$U(1)_F$
Messengers (Scalars)	$\hat{S}_L^{D_i}$	0	1/2	1/3	3	$-q_{D_i}$
	$\hat{S}_L^{U_i}$	0	1/2	1/3	3	$-q_{U_i}$
	$S_R^{D_i}$	0	0	-2/3	3	$-q_{D_i}$
	$S_R^{U_i}$	0	0	4/3	3	$-q_{U_i}$
Dark Sector (Fermions+Scalar)	Q^{D_i}	1/2	0	0	0	q_{D_i}
	Q^{U_i}	1/2	0	0	0	q_{U_i}
	S_0	0	0	0	0	0

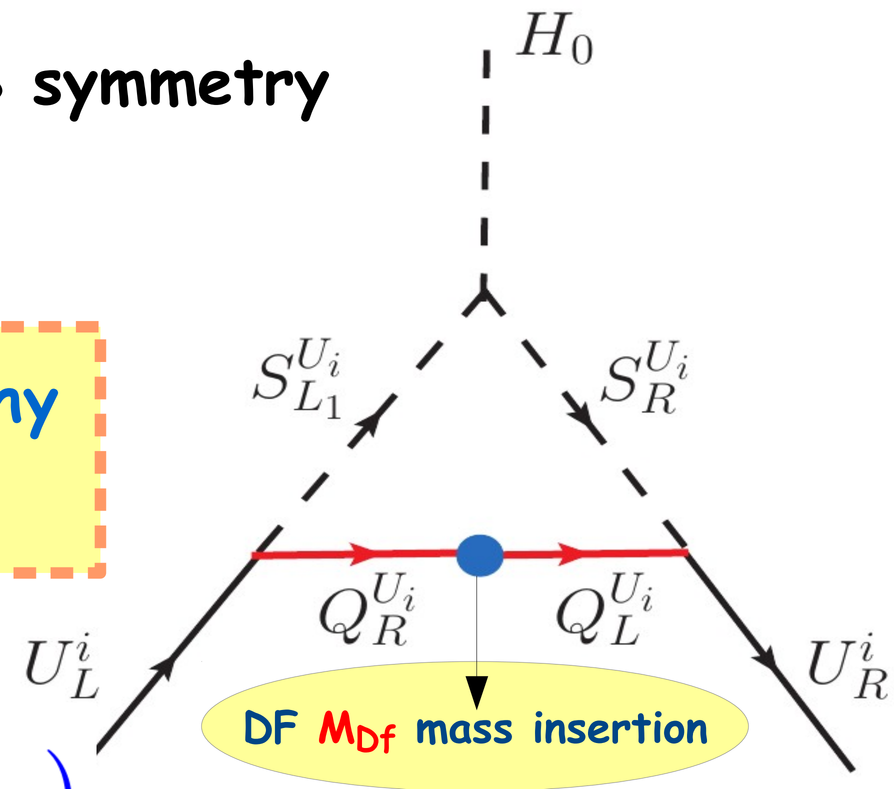
Courtesy of B. Mele

Barbara Mele Milano, 12 February 2015 29

Radiative Yukawa coupl.s follow M_{Df} hierarachy

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

- $Y_f = 0$ at tree-level [(H ↔ -H] SB symmetry
- Y_f's radiatively generated
- Y_f's same pattern of exp. hierarchy as Dark Fermion masses M_{Df}



$$Y_f \sim M_{D_f} \sim \exp(-\frac{\kappa}{q^2_{D_f}\bar{\alpha}})$$

Flavor ⇔ **Non-Universal q_{Df}**

amazing matching with observed spectrum for q_{Df} integers

- Dark Fermions are the lightest massive dark particles all stable [due to conserved $U(1)_F$ charge] potentially multi-DM candidates

- DF spectrum almost rescaled from SM-fermion spectrum [Dark Fermions associated to light SM fermions could be potentially very light]

- rich phenomenology at colliders [exploration just started]

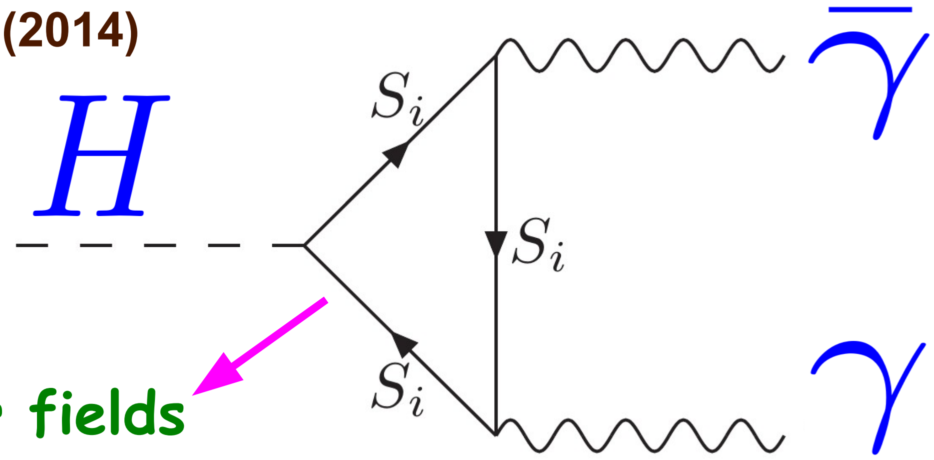
- in the meantime:

  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)

$$H \to \gamma\bar{\gamma}$$



- Effective coupling has same structure as H → γ γ

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

→ model independent parametrization

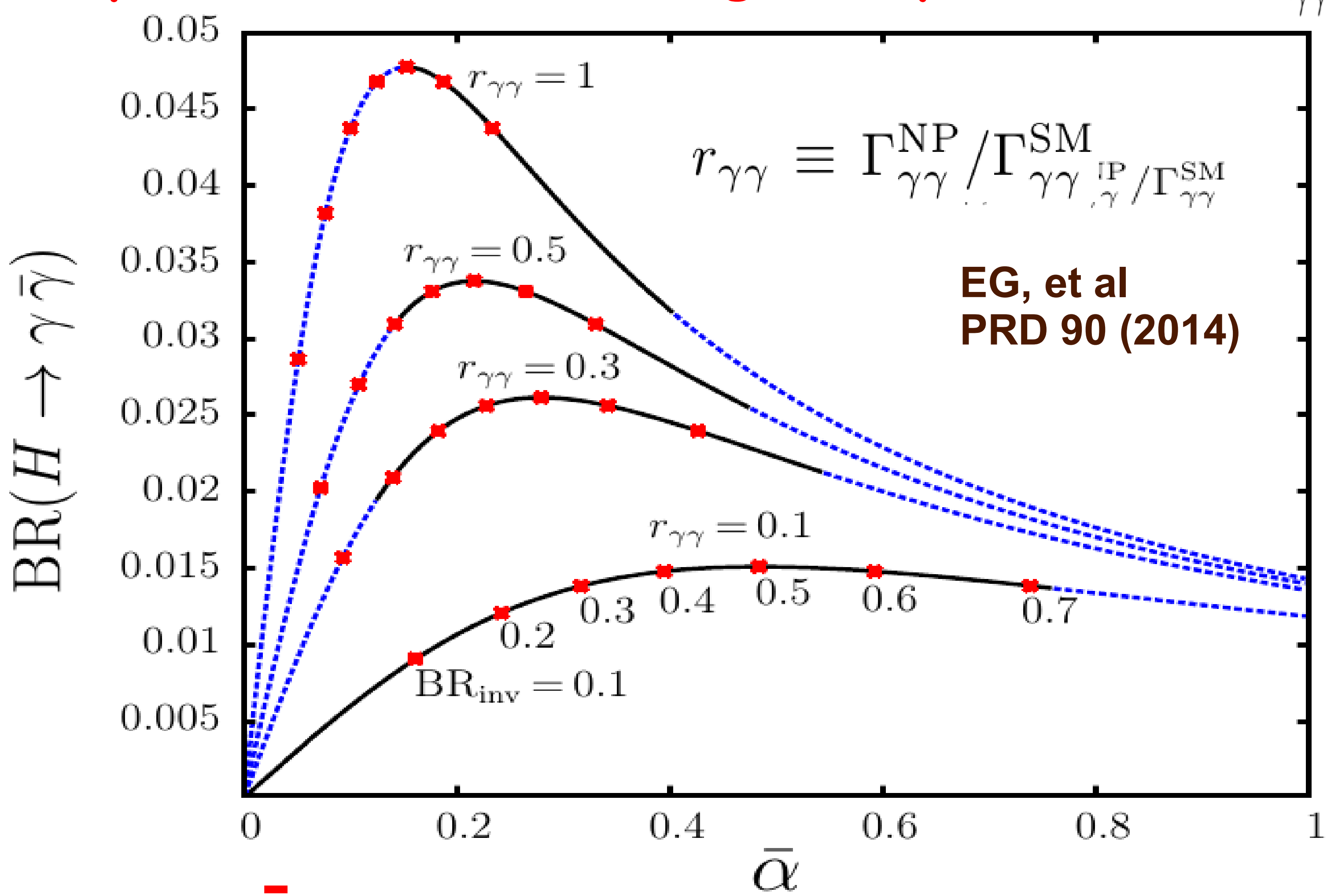
- non-decoupling effect → $\Lambda_{\gamma\bar{\gamma}}$ ~ Higgs vev
- DP coupling ($\bar{\alpha}$) could be large (allowed if DP is massless)
- Potentially large rates expected !

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

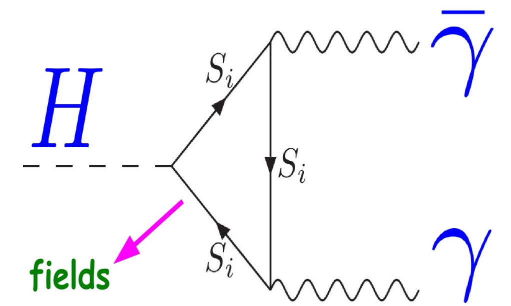
(simplified model 1 messenger only)

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

→ full lines



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



- BR($H \to \gamma\bar{\gamma}$) can be as large as 5% consistently with all LHC constraints
- Flavor scenario naturally predicts large BRs

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

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

$$pp \to \gamma + \not{E}_T$$

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

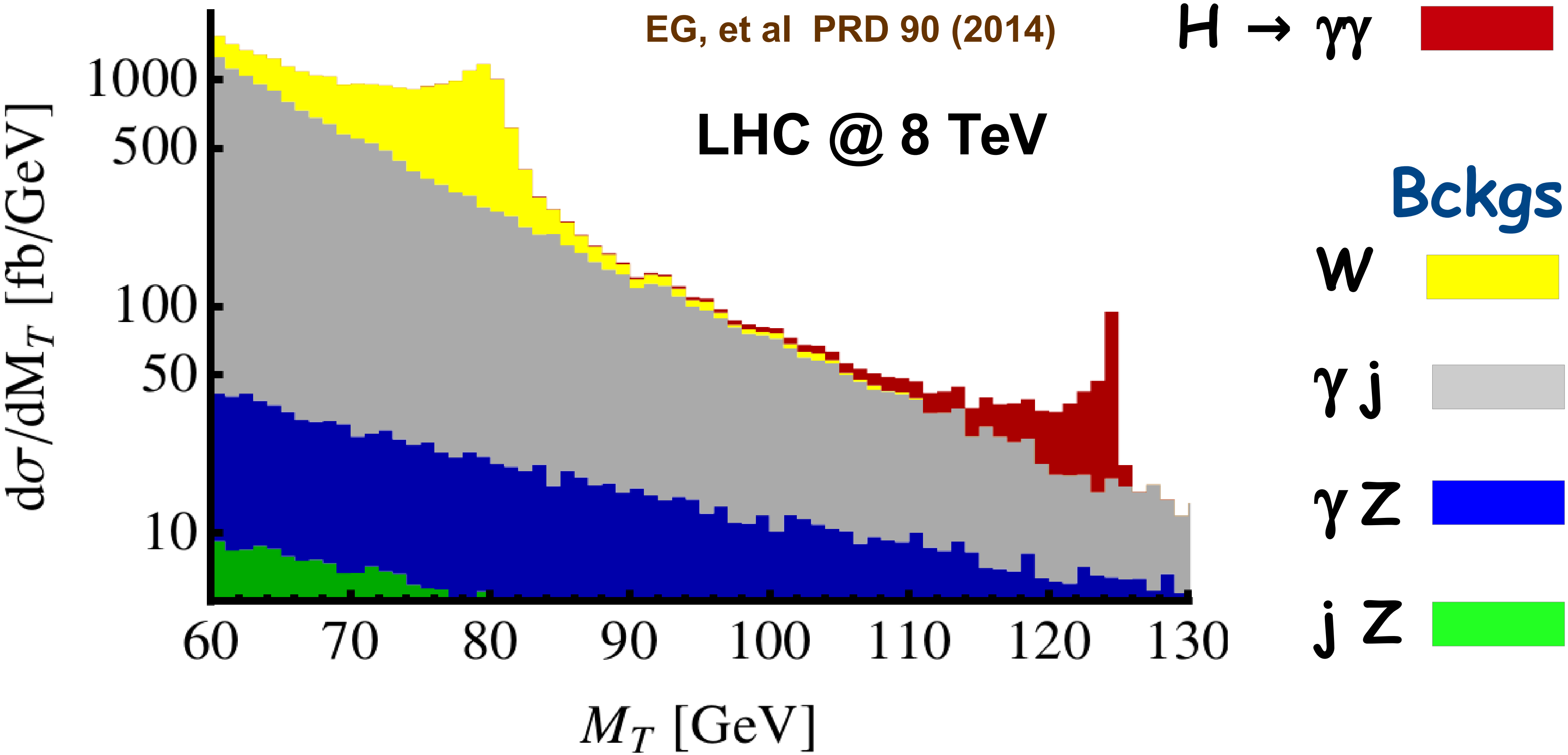
- In the Lab frame one can define the variable M_T as the transverse invariant mass of the $\gamma + \not{E}_T$ system

$$M_T = \sqrt{2 p_T^\gamma \not{E}_T (1 - \cos\Delta\phi)}$$

where $\Delta\phi$ is the azimuthal distance between the P_T^γ photon momentum and the missing transverse momentum $\not{E}_T$

M_T distribution [fb/GeV]

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



- M_T distribution peaked at original M_H mass
- P_T^{γ} distribution exhibits similar structure at $M_H/2$

Event selection for $\gamma + \not{E}_T$

- One isolated photon with $50 \text{ GeV} < p_T^\gamma < 63 \text{ GeV}$ and $|\eta^\gamma| < 1.44$.
- Missing transverse momentum with $\not{E}_T > 50 \text{ GeV}$.
- Transverse mass in $100 \text{ GeV} < M_T < 126 \text{ GeV}$.
- No isolated jets or leptons.

Cross section X acceptance [fb] LHC @ 8 TeV

Bckgs

W

γ j

γ Z

j Z

EG, et al PRD 90 (2014)

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

acceptance include previous cuts and:

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

- significance $S/\sqrt{S+B}$ corresponds to L=20 fb^{-1}
- 5 x sigma sensitivity on BR($H \to \gamma\bar{\gamma}$) ~ 0.5 % with LHC data @ 8 TeV . Upgraded analysis at 13 TeV in progress

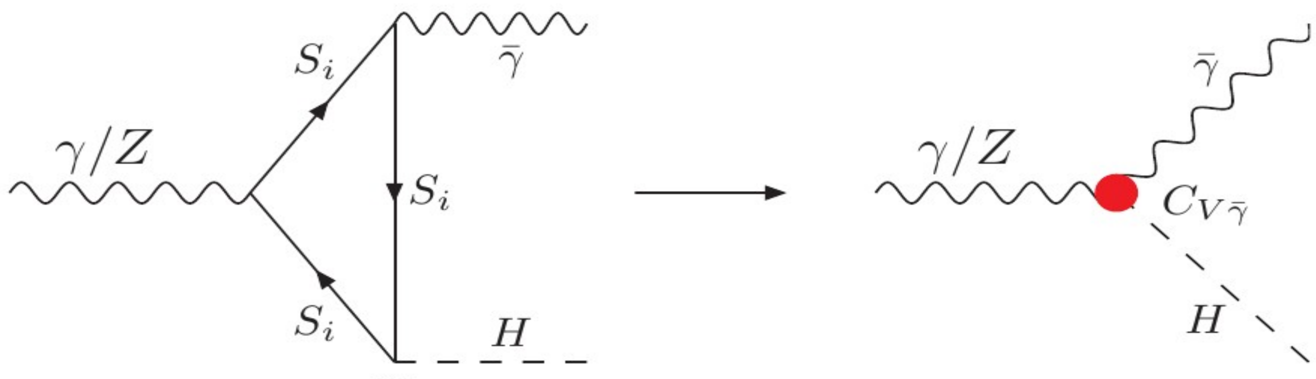
Implications of $H\gamma\bar{\gamma}$ and $Hz\bar{\gamma}$ at e+e- colliders

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

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

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

- we look at Higgs decay in $H \to b\bar{b}$ (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

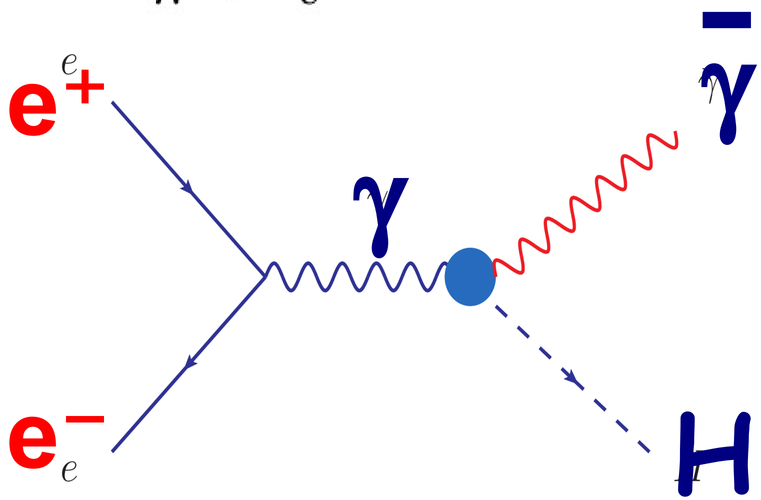
$$e^+e^- \to H\bar{\gamma} \to b\bar{b}\bar{\gamma}$$

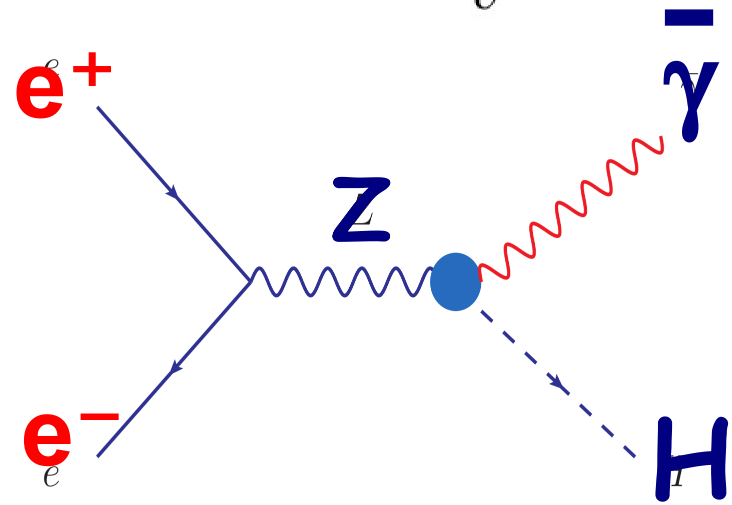
Model independent analysis:

DP field strength

Effective Lagrangian parametrization

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

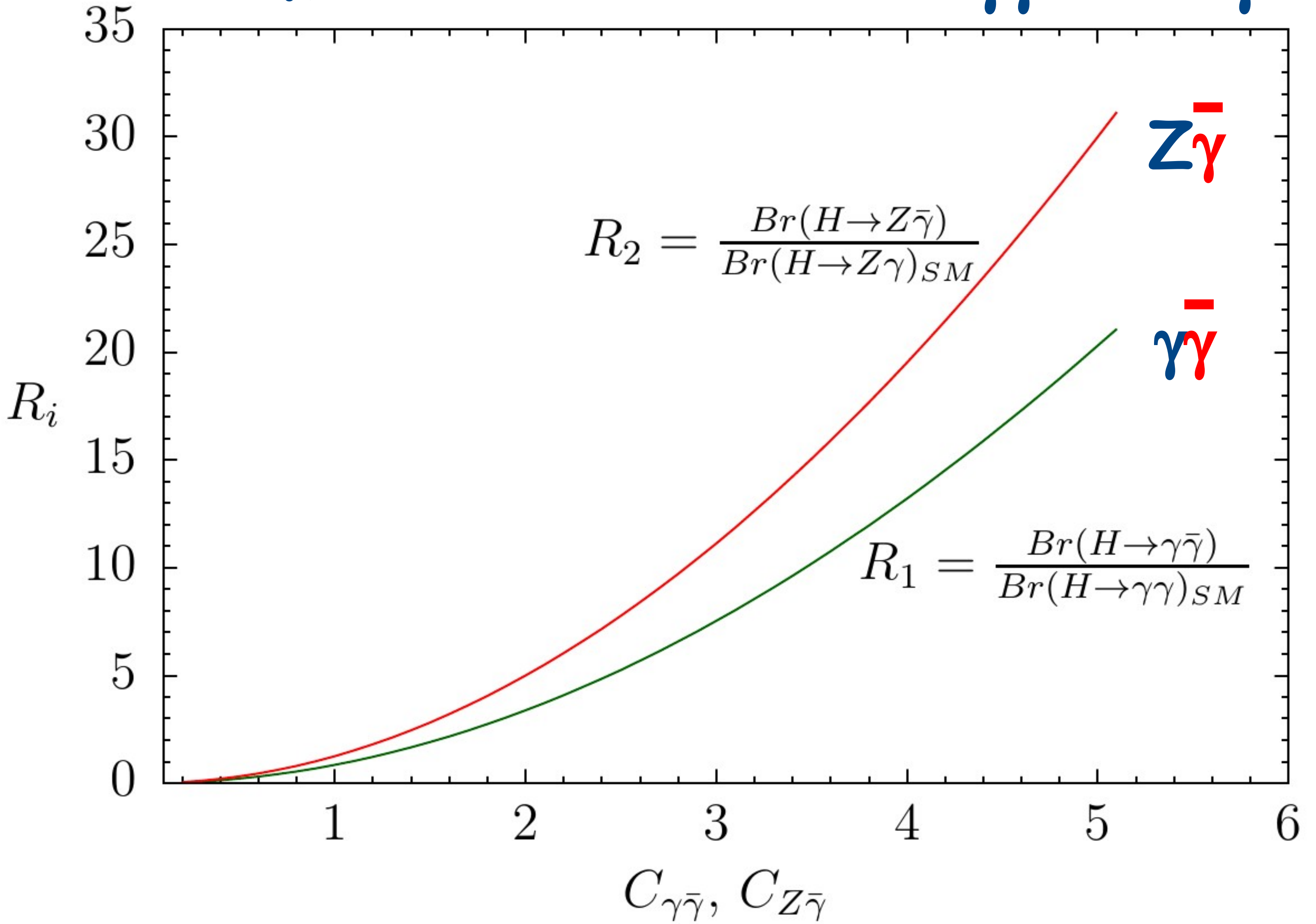




assuming mass degeneracy in Left and Right messengers → $C_{Z\bar{\gamma}} = C_{\gamma\bar{\gamma}} \, R_{Z\gamma}$

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

Normalized BRs to SM γγ and γZ

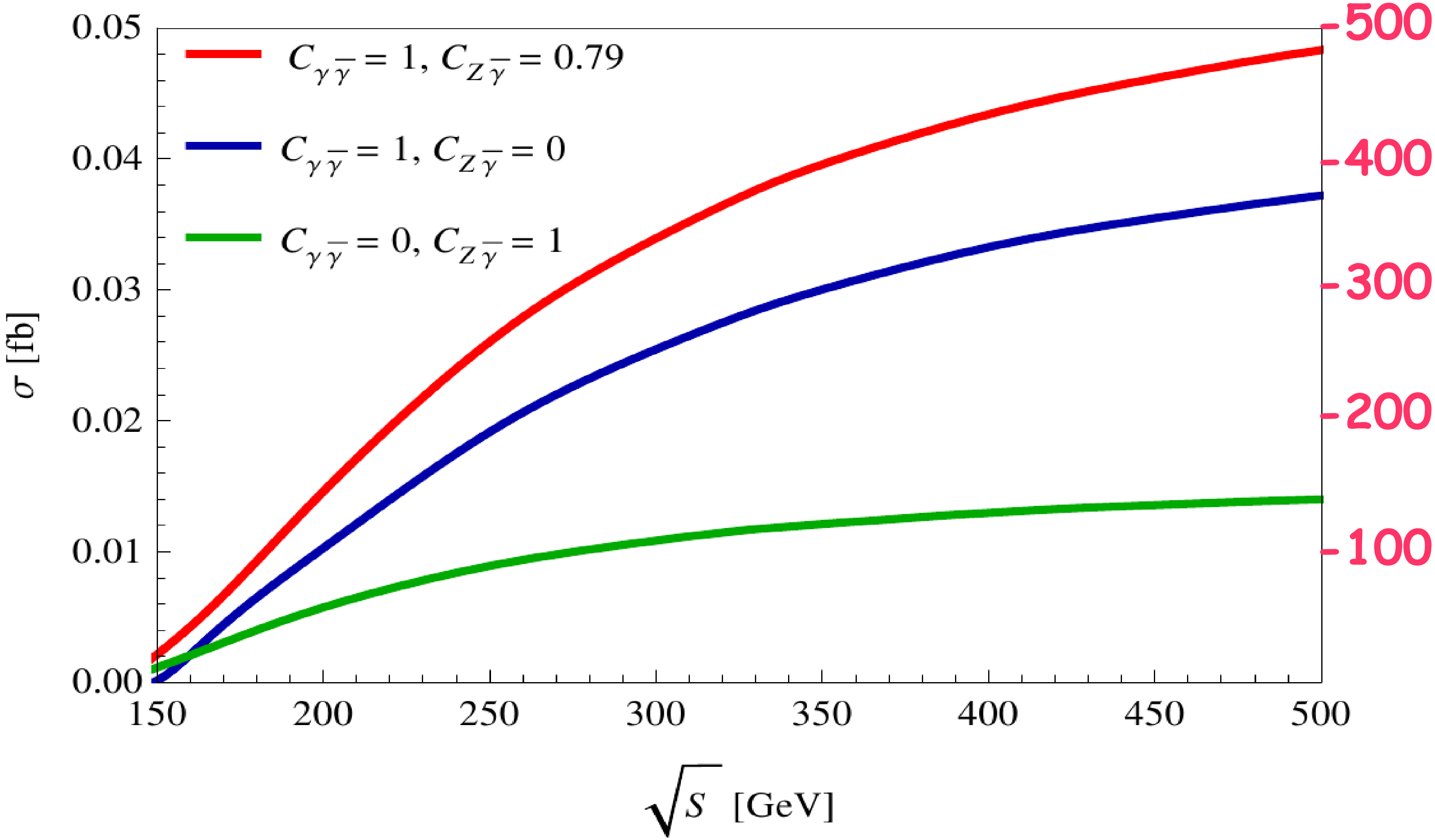


$$\Gamma(H \to \gamma\bar{\gamma}) = \frac{m_H^3}{64\pi\Lambda_{\gamma\bar{\gamma}}^2}, \qquad 1/\Lambda_{\gamma\bar{\gamma}} = C_{\gamma\bar{\gamma}}/(\pi v)$$

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

Total cross section [fb]

N. Events for L=10ab^{-1}



S/B analysis for e+e- → H $\bar{\gamma}$ $\sqrt{s}$ =240 GeV

- signal $b\bar{b}$ + $\not{E}$ ⟶ Missing energy
- simulated signal with MADGRAPH using effective Lagrangian, then passed to PYTHIA for parton shower and initial state radiation

Basic cuts

$$\begin{cases} p_T^b > 20 \text{ GeV}, & |\eta_b| < 2.5 \\ \Delta R(bb) > 0.4, & \not{E} > 40 \text{ GeV} \end{cases}$$

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

- after showering and hadronization we reconstruct jets and b-jets according to the PYTHIA jet-cone algorithm assuming R_j = 1.5 (optimizes mass reconstruction)

Main backgrounds for $b\bar{b} + \not{E}$

Irreducible

$$\nu\bar{\nu}b\bar{b} \begin{cases} ZZ \rightarrow \nu\bar{\nu}b\bar{b} \\ ZH \rightarrow \nu\bar{\nu}b\bar{b} \\ \text{WW fusion} \rightarrow H\nu\bar{\nu} \end{cases}$$

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

Two kinematical variables particularly efficient for separating signal from bckg

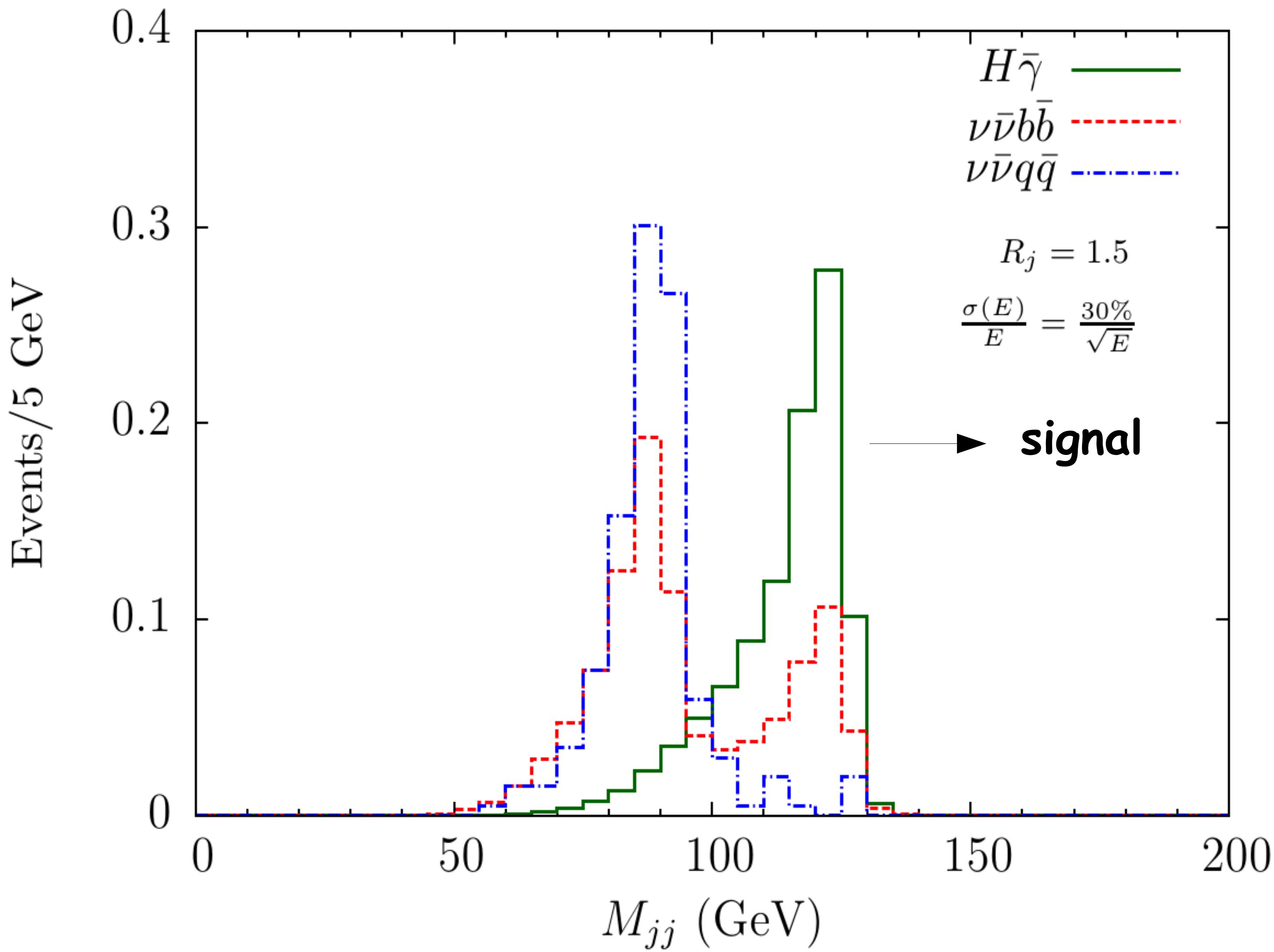
- M_{jj} = invariant mass of the two jets with higher transverse momentum P_T (after showering) (directly connected to b-pair invariant mass)

- $$M_{\text{miss}} = \sqrt{\not{E}^2 - \not{\mathbf{p}}^2}$$

$$\begin{cases} \not{E} = \sqrt{s} - \sum \mathrm{E}_{visible} \\ \not{\mathbf{p}} = -\sum \mathbf{p}_{visible} \end{cases}$$

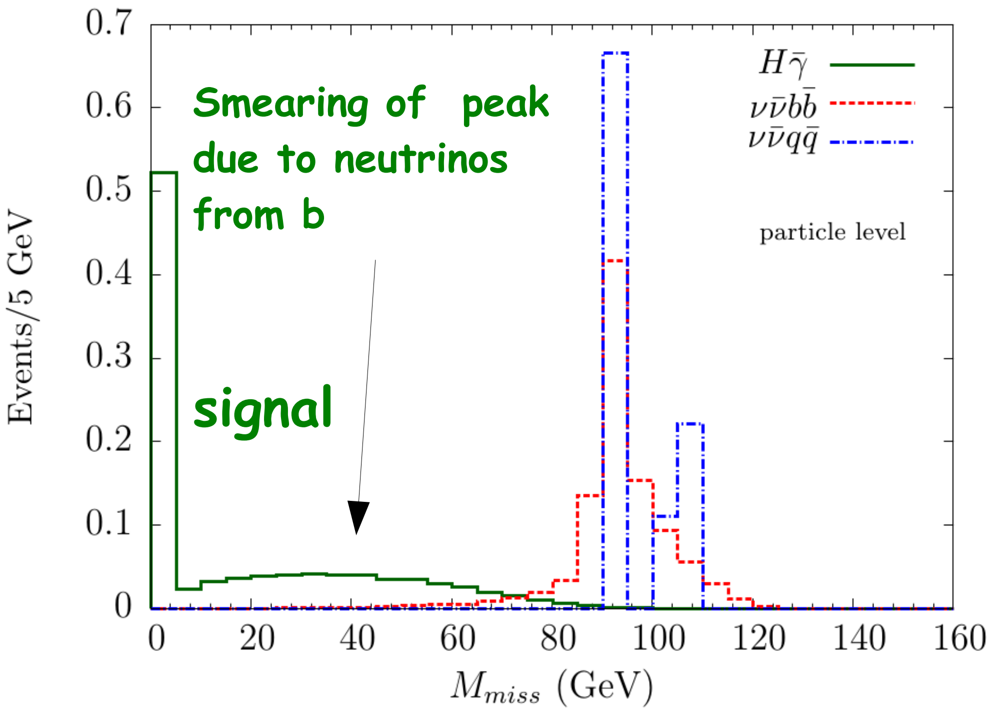
M_{miss} expected to approximatively vanish in the partonic description of $e^+e^- \to H \bar{\gamma}$

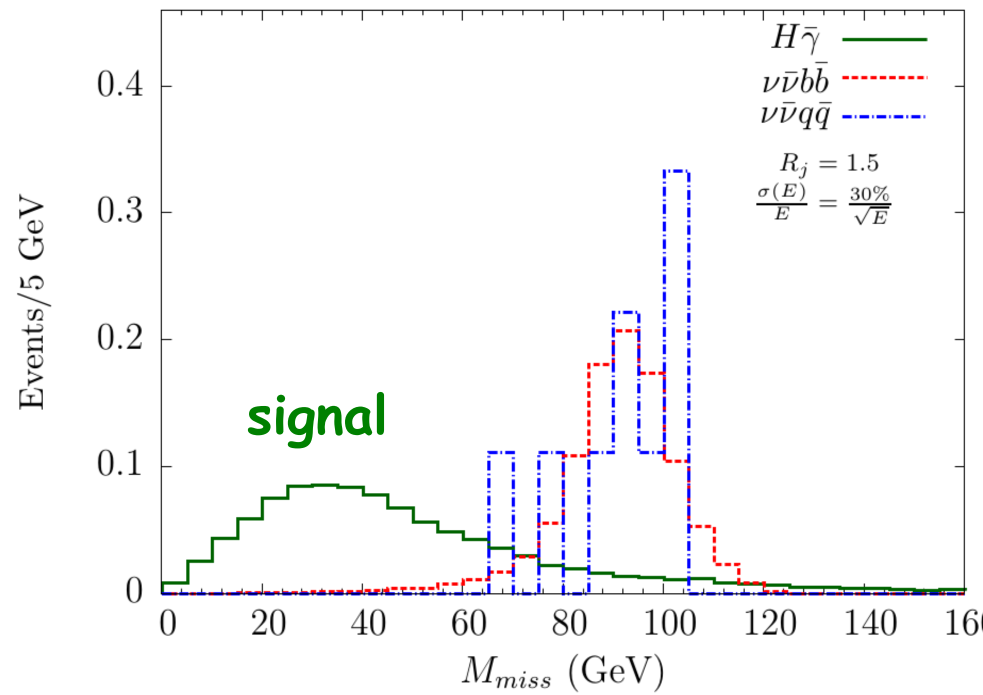
M_{jj} distributions (all normalized to 1)



We also account for finite detector resolution by applying the jet-energy smearing $\sigma(E)/E = 30\%/\sqrt{E}$.

M_{miss} distributions (all normalized to 1)





parton level **after PYTHIA**

- Parton showering, jet reconstr., energy-resol. degrades M_{miss} spectrum of signal shifting the peak and smearing it

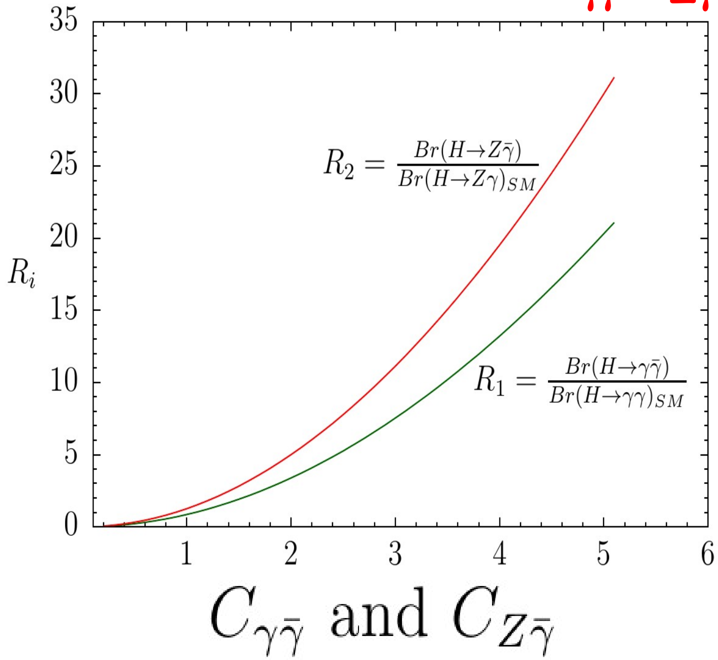
- suggests M_{jj} to be within 10% of peak value and M_{miss} < 40 GeV → $40\ \mathrm{GeV} < \not{E} < 100\ \mathrm{GeV}.$

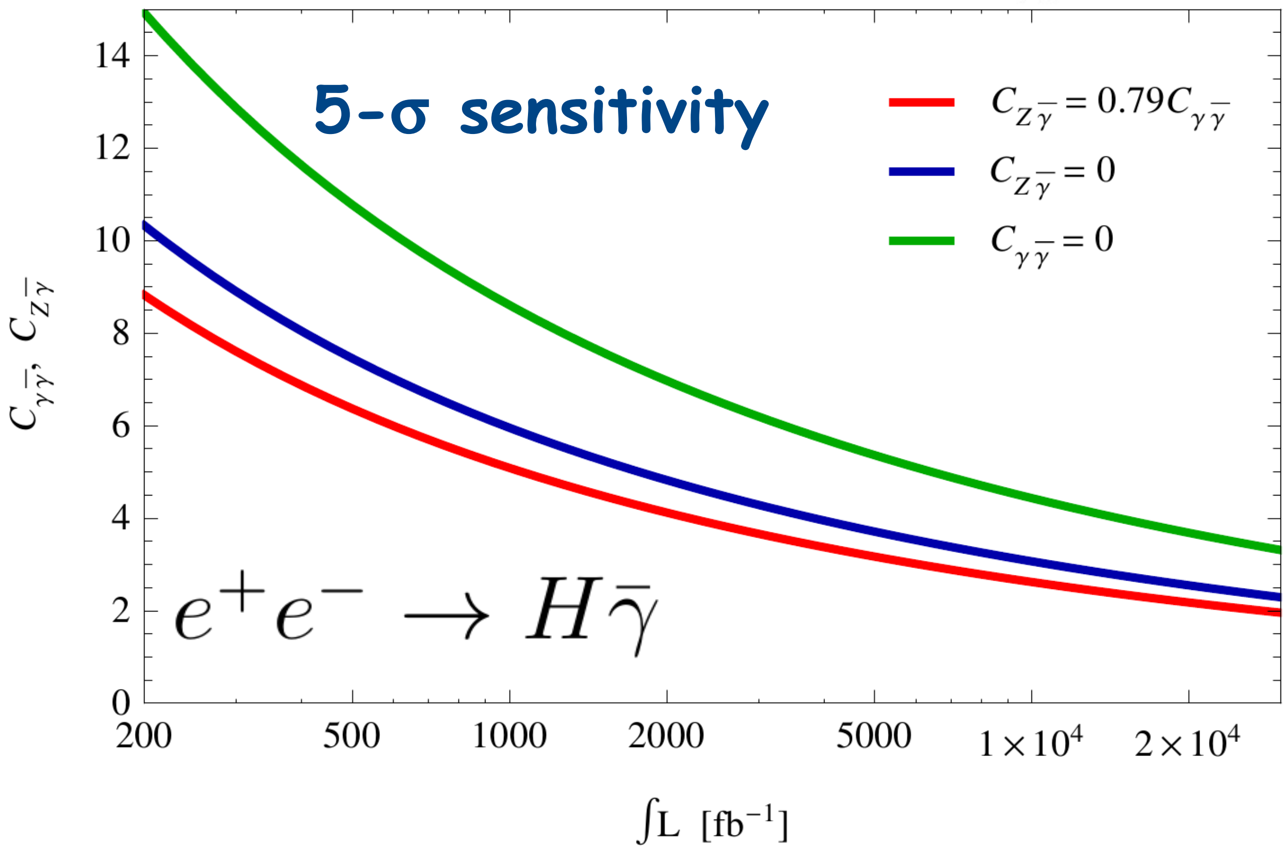
Results for $\sqrt{s}$ =240 GeV

Process	Cross section (fb)	Acceptance after cuts (%)
$H\bar{\gamma}$ $(C_{Z\bar{\gamma}} = 0)$	$10.1 \times 10^{-3}\ C^2_{\gamma\bar{\gamma}}$	17.3
$H\bar{\gamma}$ $(C_{\gamma\bar{\gamma}} = 0)$	$4.8 \times 10^{-3}\ C^2_{Z\bar{\gamma}}$	17.3
$H\bar{\gamma}$ $(C_{Z\bar{\gamma}} = 0.79\ C_{\gamma\bar{\gamma}})$	$13.8 \times 10^{-3}\ C^2_{\gamma\bar{\gamma}}$	17.3
SM $\nu\bar{\nu}b\bar{b}$	115.	0.08

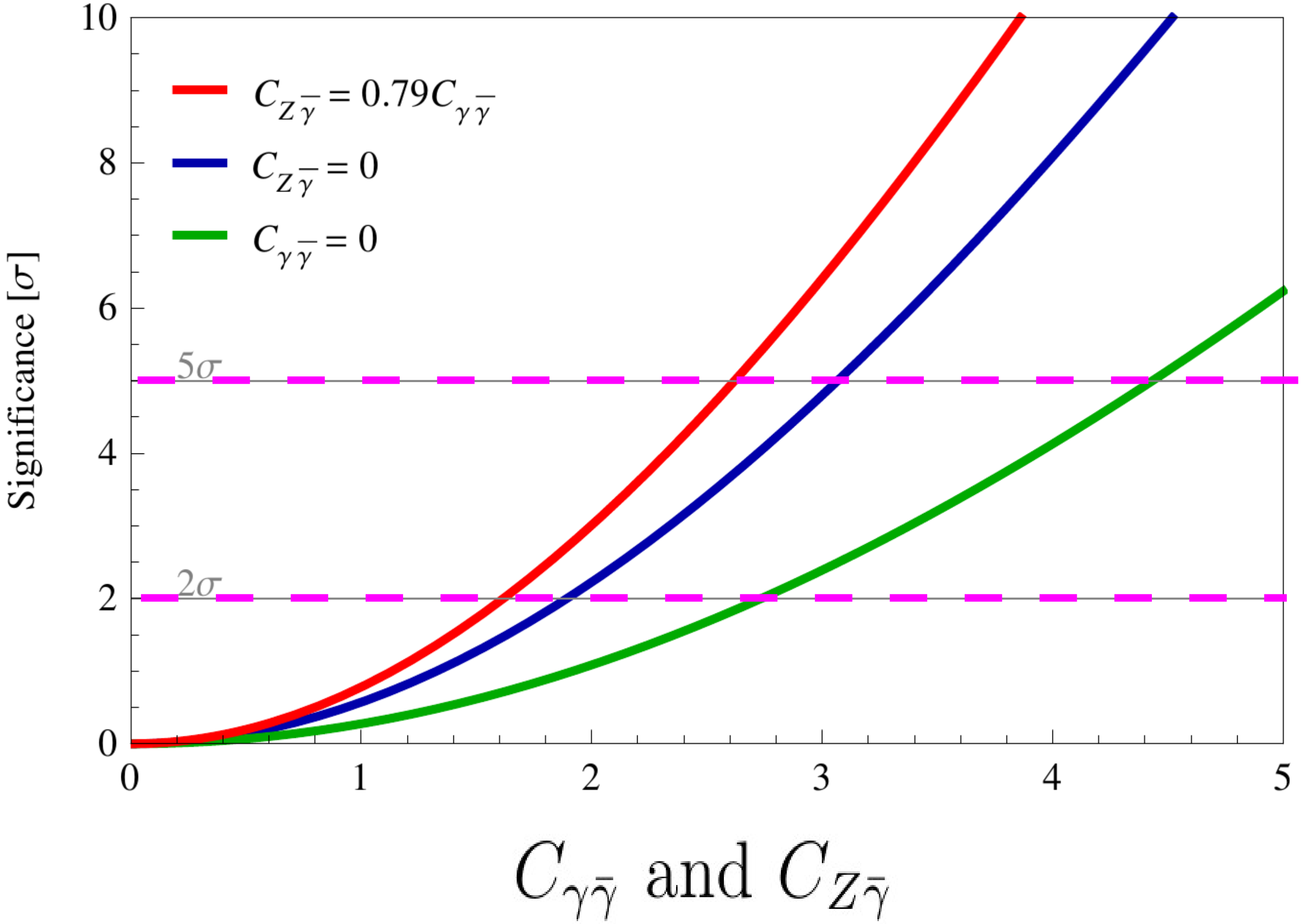
signal acceptance insensitive to relative contribution of $C_{\gamma\bar{\gamma}}$ and $C_{Z\bar{\gamma}}$

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





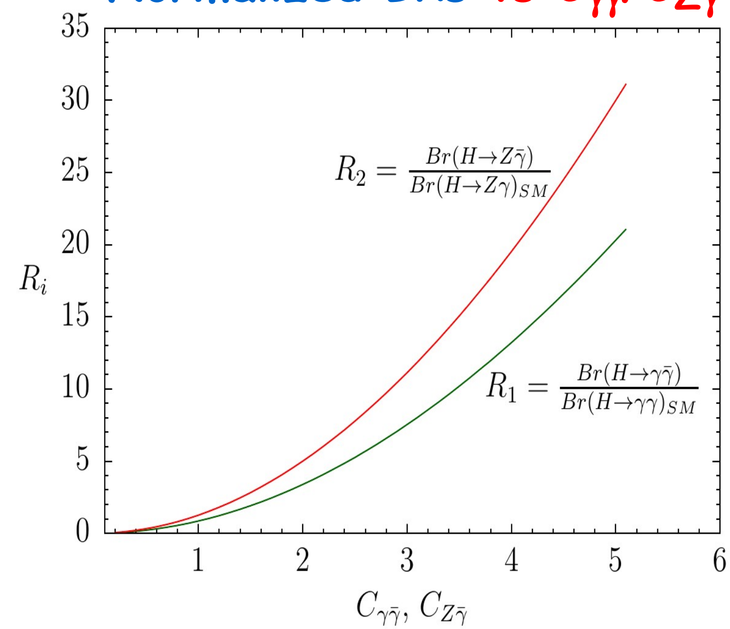
Significance for L=10ab-1



5σ

2σ

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



sgnf = $S/\sqrt{S+B}$

Outlook

- Hidden sector might have long distance interactions mediated by $U(1)_F$ gauge → Dark Photon predicted
- Higgs boson can be the SM portal to Dark Photons
- New effective vertices can appear: $HZ\bar{\gamma}$ and $H\gamma\bar{\gamma}$
- Rich phenomen. implications @ LHC expected
  - → search for $H \to \gamma\bar{\gamma}$, and $H \to Z\bar{\gamma}$
  - → potentially large rates due to non-decouplings
  - → new production mechanisms $pp \to H(\to bb) + \bar{\gamma}$

- e+e- collider implications: (beyond Higgs decays in e+e- → H Z , with H → $\gamma\bar{\gamma}$ and H → $Z\bar{\gamma}$)

- e+e- → H(→bb) + $\bar{\gamma}$ allows good sensitivity on $HZ\bar{\gamma}$ and $H\gamma\bar{\gamma}$ effective couplings

- Yet to work out how much e+e- can extend LHC potential in the discovery of Dark Photon searches

Backup slides

Backgrounds for pp → H → $\gamma\bar{\gamma}$

1. $pp \to \gamma j$, where large apparent $\not{E}_T$ is created by a combination of real $\not{E}_T$ from neutrinos in heavy quark decays and mismeasured jet energy.

2. $pp \to \gamma Z \to \gamma \nu \bar{\nu}$ (irreducible background);

3. $pp \to jZ \to j\nu\bar{\nu}$, where the jet is misidentified as a photon;

4. $pp \to W \to e\nu$, where the electron (positron) is misidentified as a photon;

5. $pp \to \gamma W \to \gamma \ell \nu$, where the lepton is missed;

6. $pp \to \gamma\gamma$, where one of the photons is missed.

Background analysis for pp $\rightarrow$ H $\rightarrow \gamma\bar{\gamma}$

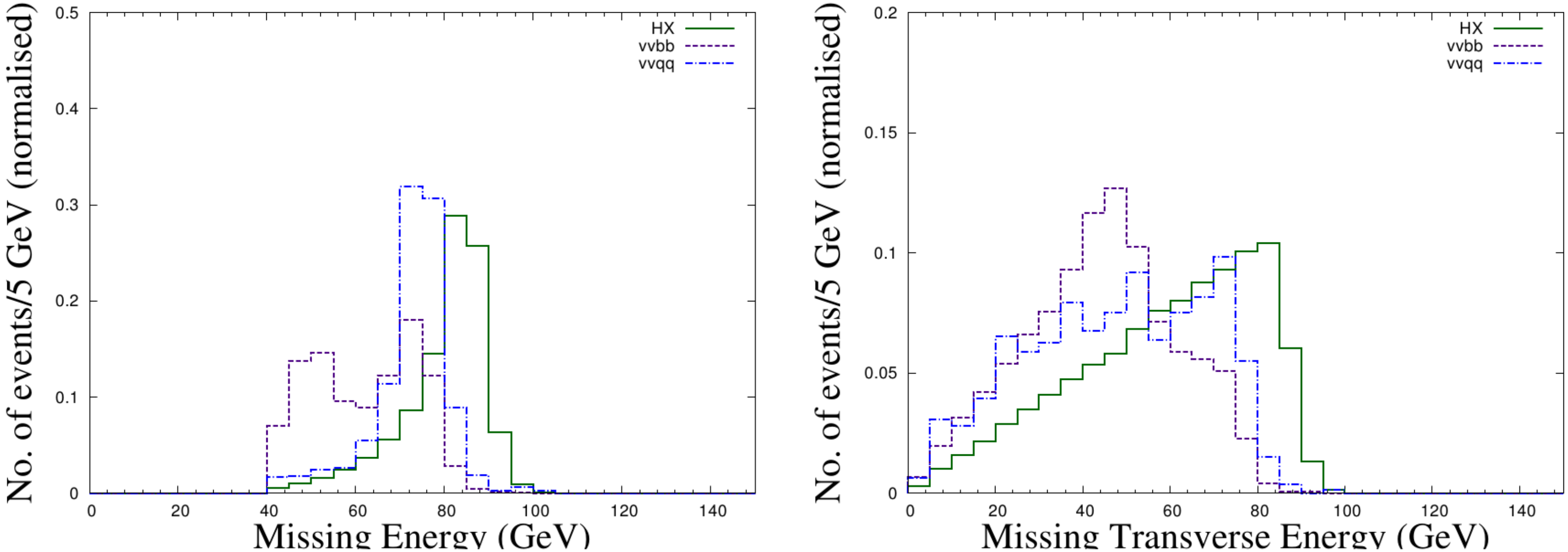
- $pp \rightarrow \gamma j$ is expected to be the dominant background → difficult to estimate without detailed information about the detector performance

- 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

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

- 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

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



A comparison of the missing energy ($\not{E}$) and the missing transverse energy ($\not{E}_T$) 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 $\not{E}$ (and $\not{E}_T$) 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.