

Search for Dark photons at colliders

Emidio Gabrielli

University and INFN Trieste, Italy
NICPB, Tallinn, Estonia

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

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** $\leftrightarrow$ **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)

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 $\longrightarrow \hat{A}_1^\mu \quad \hat{A}_2^\mu$

$$e_1 J_\mu^{\mathbf{1}}(f_1) A_1^\mu + e_2 J_\mu^{\mathbf{2}}(f_2) A_2^\mu$$

we can identify $\mathbf{J}^{\mathbf{1}}$ with ordinary matter and $\mathbf{J}^{\mathbf{2}}$ 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

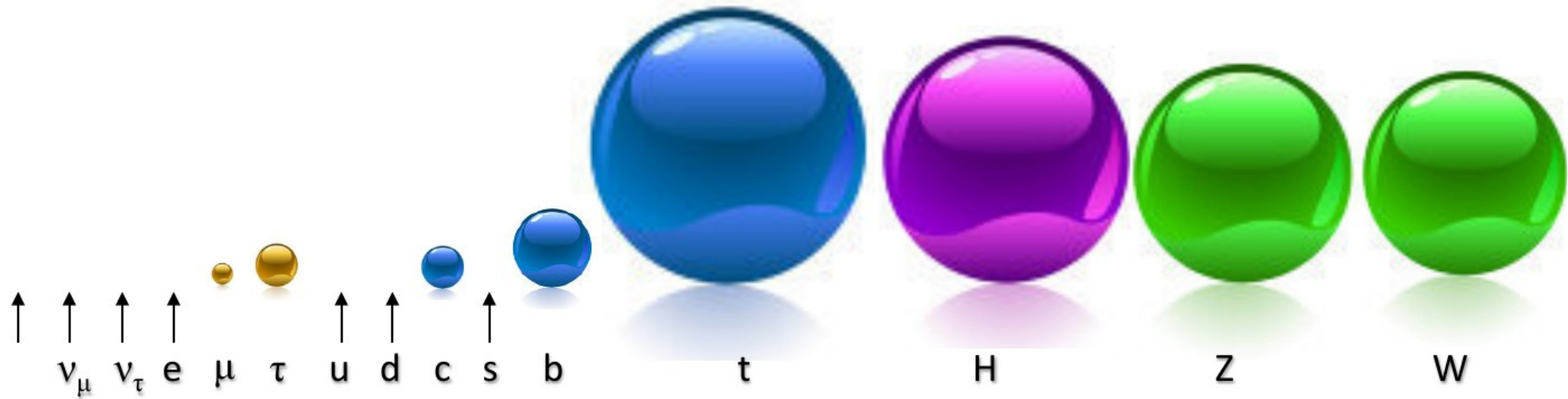
$\rightarrow$ dark photon couples also to ordinary matter $\rightarrow$ oscillations (for ultralight U(1))

Massive dark-photon scenarios more constrained !

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 $\sim 1/\Lambda \rightarrow$ Lee-Wick ghosts)
- **Dark Fermions get mass M_{Df} depending on their $U(1)_F$ charge q_{Df}**
- **Non-pert. solution**
EG, PRD 87 (2008)
EG, M. Raidal, PRD 89 (2014)
$$M_{Df} \sim \Lambda \exp\left(-\frac{\kappa}{q_{Df}^2 \bar{\alpha}}\right)$$

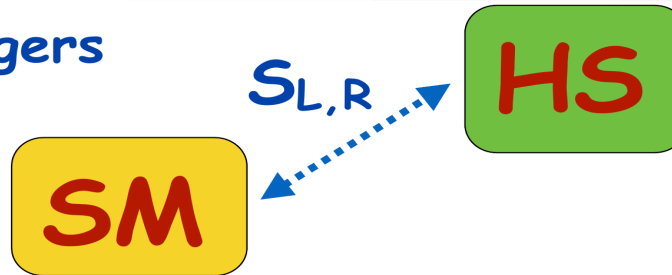
anom. dim. $\swarrow$
DP coupling $\swarrow$
- **Ex: exponential hierarchy in M_{Df} for integer $q_{Df}=1,2,3,\dots$**

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
 $M > 55 \text{ TeV}$
EW ones could be lighter

Flavor broken only
by q_{DF} charges →
Flavor universality of
messenger masses

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

Courtesy of B. Mele

Radiative Yukawa coupl.s follow M_{Df} hierarchy

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

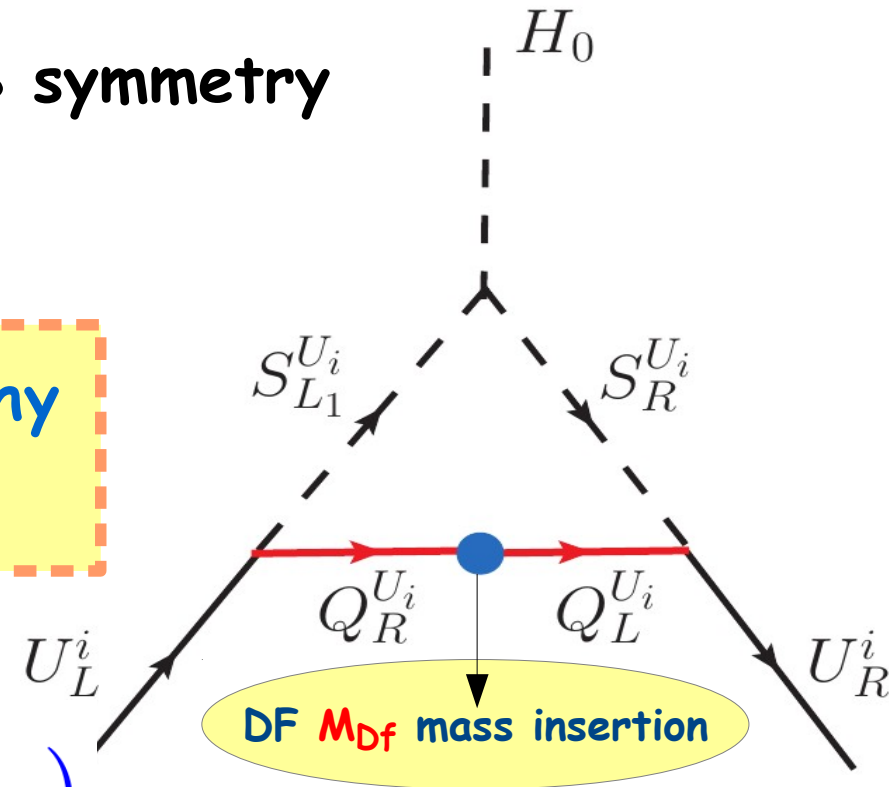
■ $Y_f = 0$ at tree-level $[(H \leftrightarrow -H)]$ SB symmetry

■ Y_f 's radiatively generated

■ Y_f 's same pattern of exp. hierarchy as Dark Fermion masses M_{Df}

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

Flavor $\longleftrightarrow$ Non-Universal q_{Df}



amazing matching with
observed spectrum for
 q_{Df} integers

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

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



$$M_{Q_i} > \frac{m_i}{L C_0(x_i)}$$

m_i = quark(i) masses

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

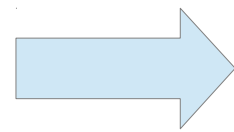
$$M_{Q_t} \gtrsim \left(\frac{55}{g_L g_R} \right) \text{TeV}$$



$$\bar{m} > M_{Qt} > 55 \text{ TeV}(1-\xi)$$

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

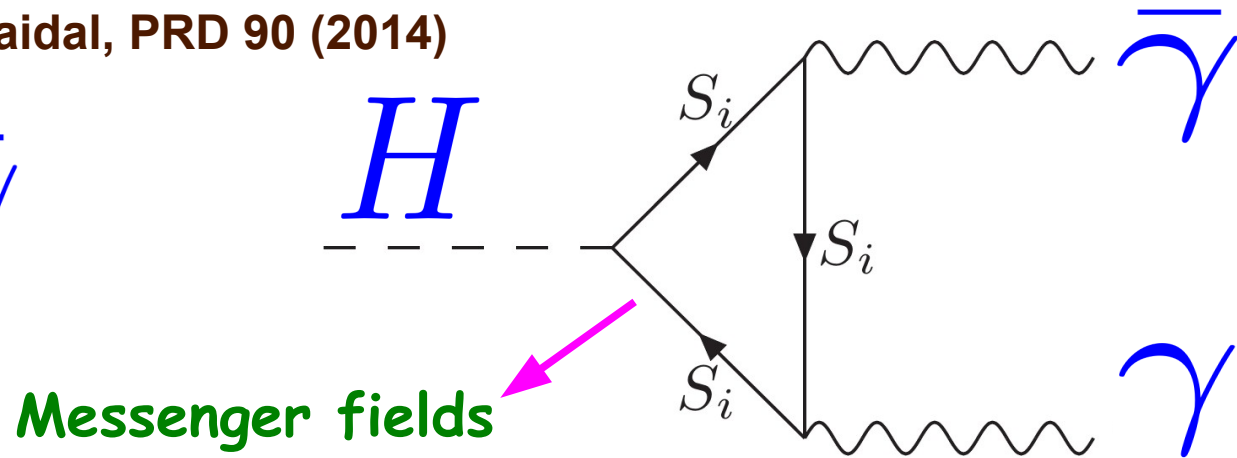
- **Dark Fermions** are the lightest massive dark particles all stable [due to conserved $U(1)_F$ charge]
potentially multi-DM candidates
- **DF** spectrum almost rescaled from SM-fermion spectrum [Dark Fermions associated to light SM fermions could be potentially very light]
- rich phenomenology at 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)

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



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

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

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

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 $U(1)_F$

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

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

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

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

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

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

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

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

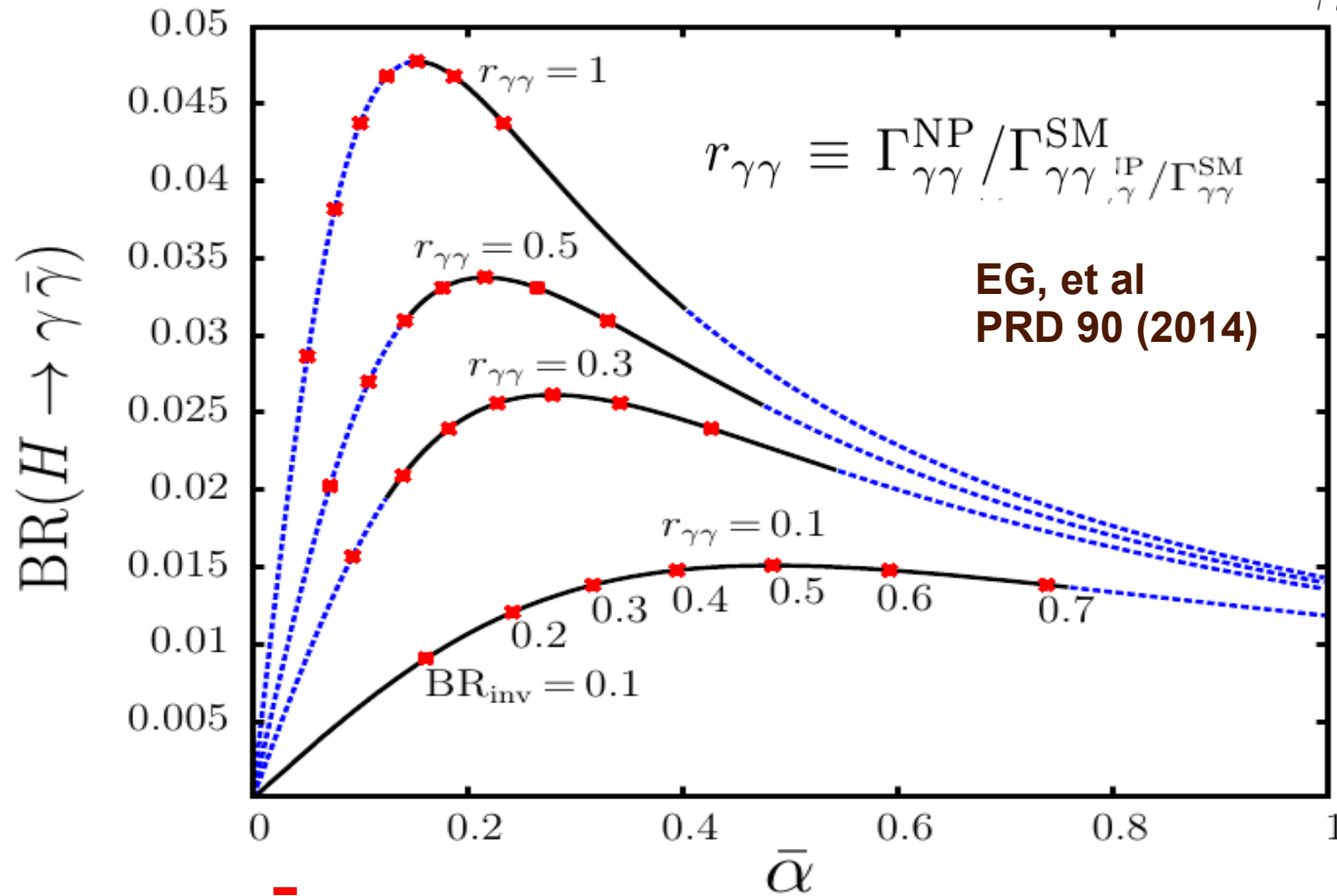
$$r_{\gamma\bar{\gamma}} = 2 r_{\gamma\gamma} \frac{R^2}{R_0^2} \left(\frac{\bar{\alpha}}{\alpha}\right), \quad r_{\bar{\gamma}\bar{\gamma}} = r_{\gamma\gamma} \frac{R_1^2}{R_0^2} \left(\frac{\bar{\alpha}}{\alpha}\right)^2$$

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

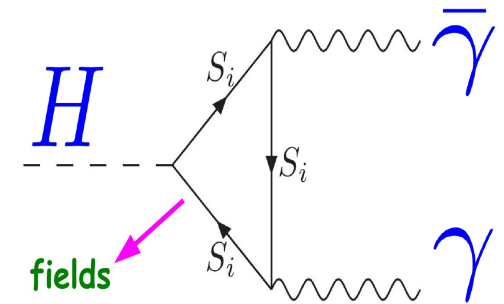
(simplified model 1 messenger only)

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

→ full lines



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



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

● Flavor scenario naturally predicts large BRs

Model independent analysis of $H \rightarrow \gamma\bar{\gamma}$ 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 as the transverse invariant mass of the $\gamma + \cancel{E}_T$ system

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

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

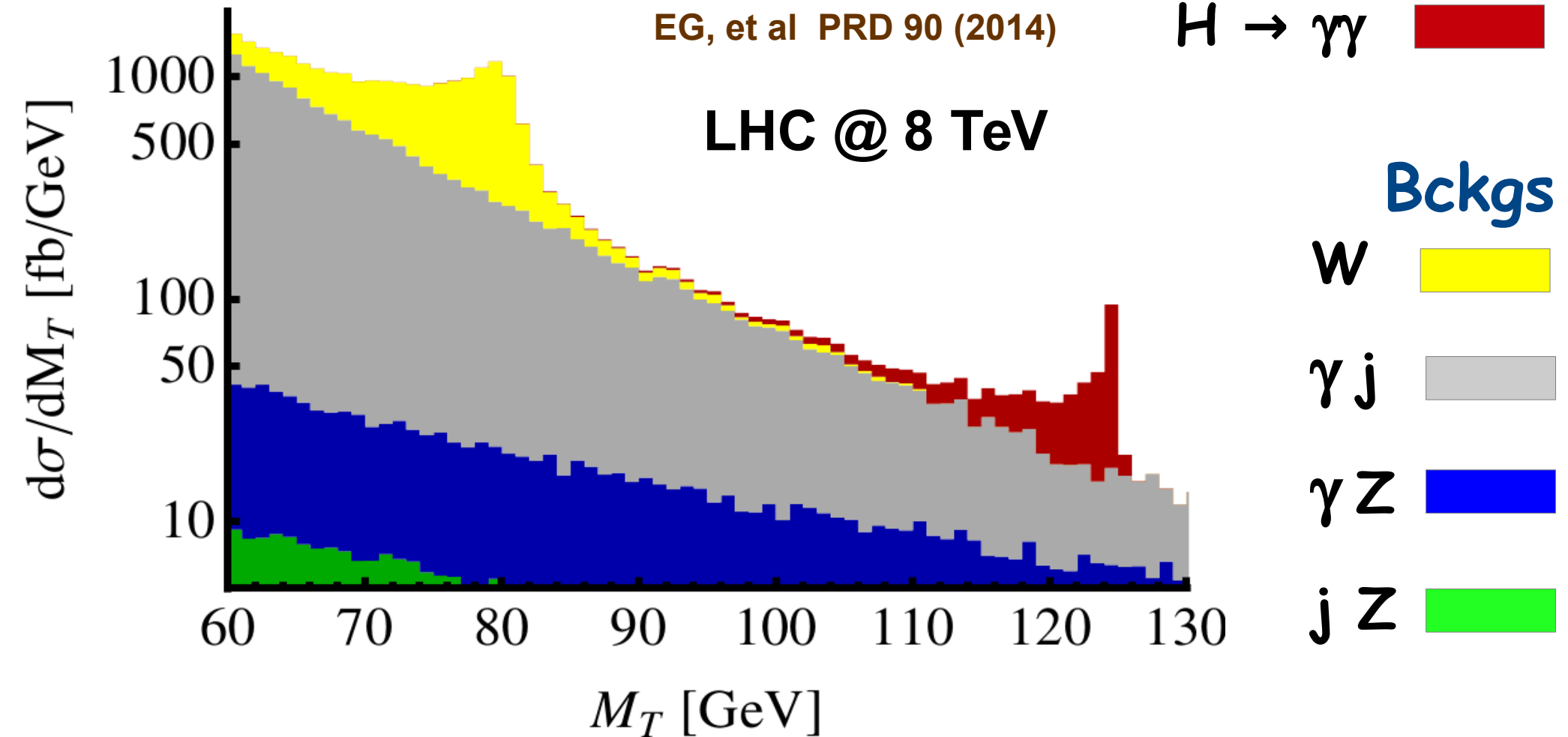
M_T distribution [fb/GeV]

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

EG, et al PRD 90 (2014)

$H \rightarrow \gamma\bar{\gamma}$ ■

Signal



■ M_T distribution peaked at original M_H mass

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

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

- 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.

Cross section X acceptance [fb] LHC @ 8 TeV

Bckgs

W 

γj 

γZ 

$j Z$ 

EG, et al PRD 90 (2014)

	$\sigma \times A_1$	$\sigma \times A_2$
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 $\text{BR}(H \rightarrow \gamma \bar{\gamma}) \sim 0.5 \%$ with 8 TeV data !
- Upgraded analysis at 14 TeV in progress (includes VBF + parton shower effects)

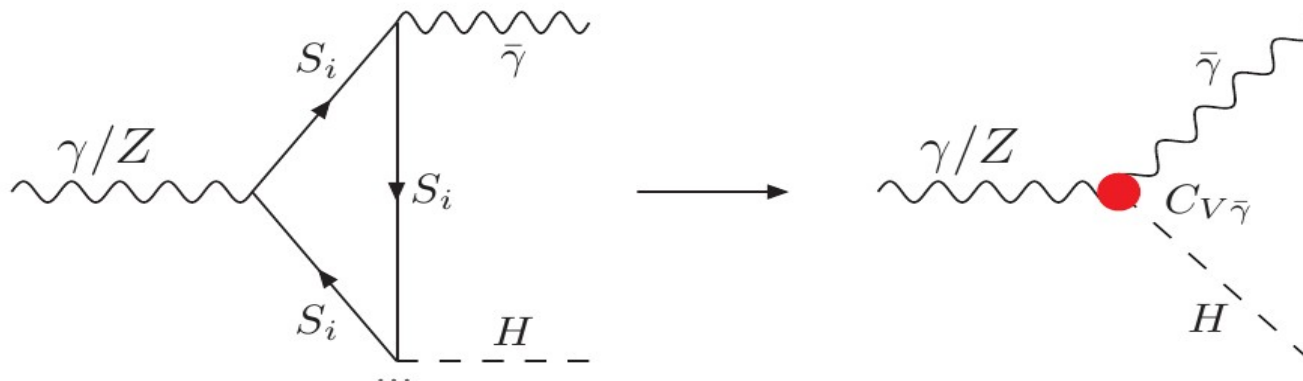
Implications of $H\bar{\gamma}$ and $HZ\bar{\gamma}$ at e^+e^- colliders

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



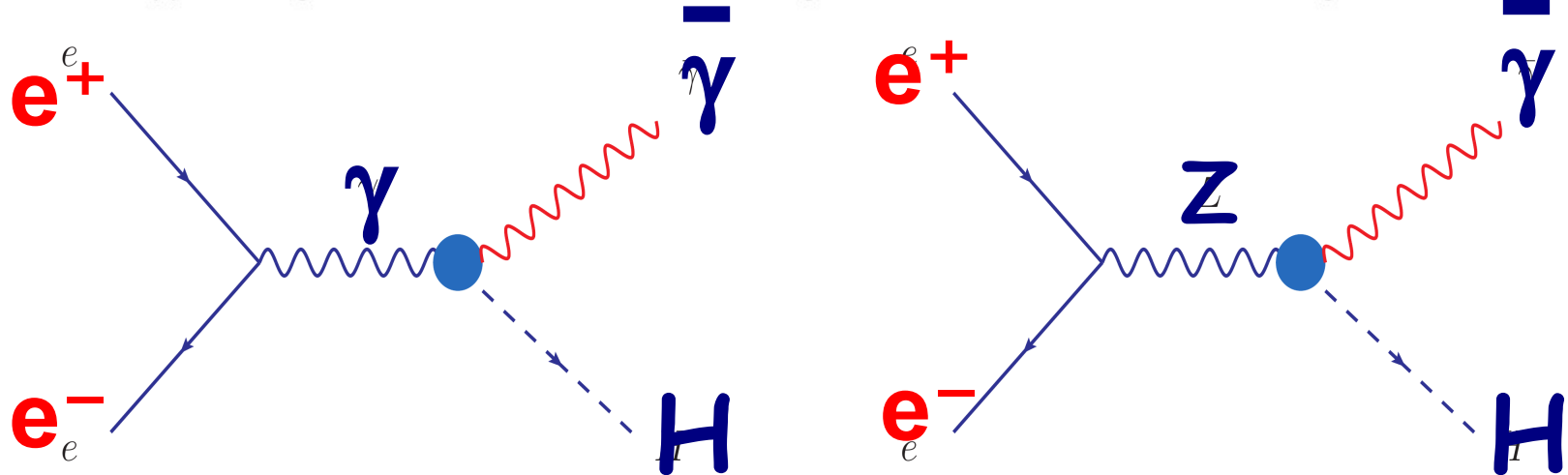
- Effective field theory approach adopted (valid for heavy messengers)
- Model independent analysis

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

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

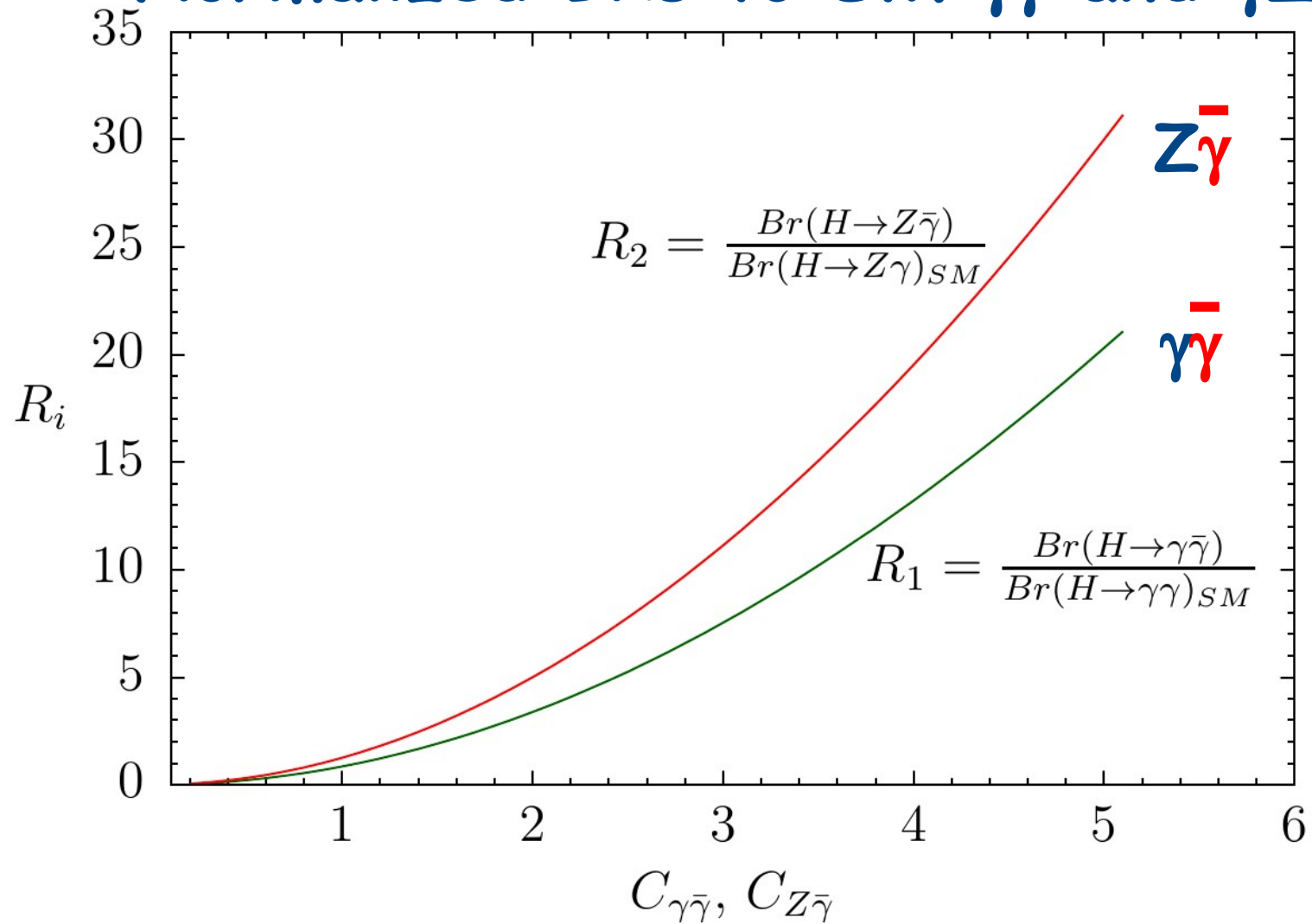
assuming mass degeneracy in Left and Right messengers

net result from a squark doublet →

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

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

Normalized BRs to SM $\gamma\gamma$ and γZ

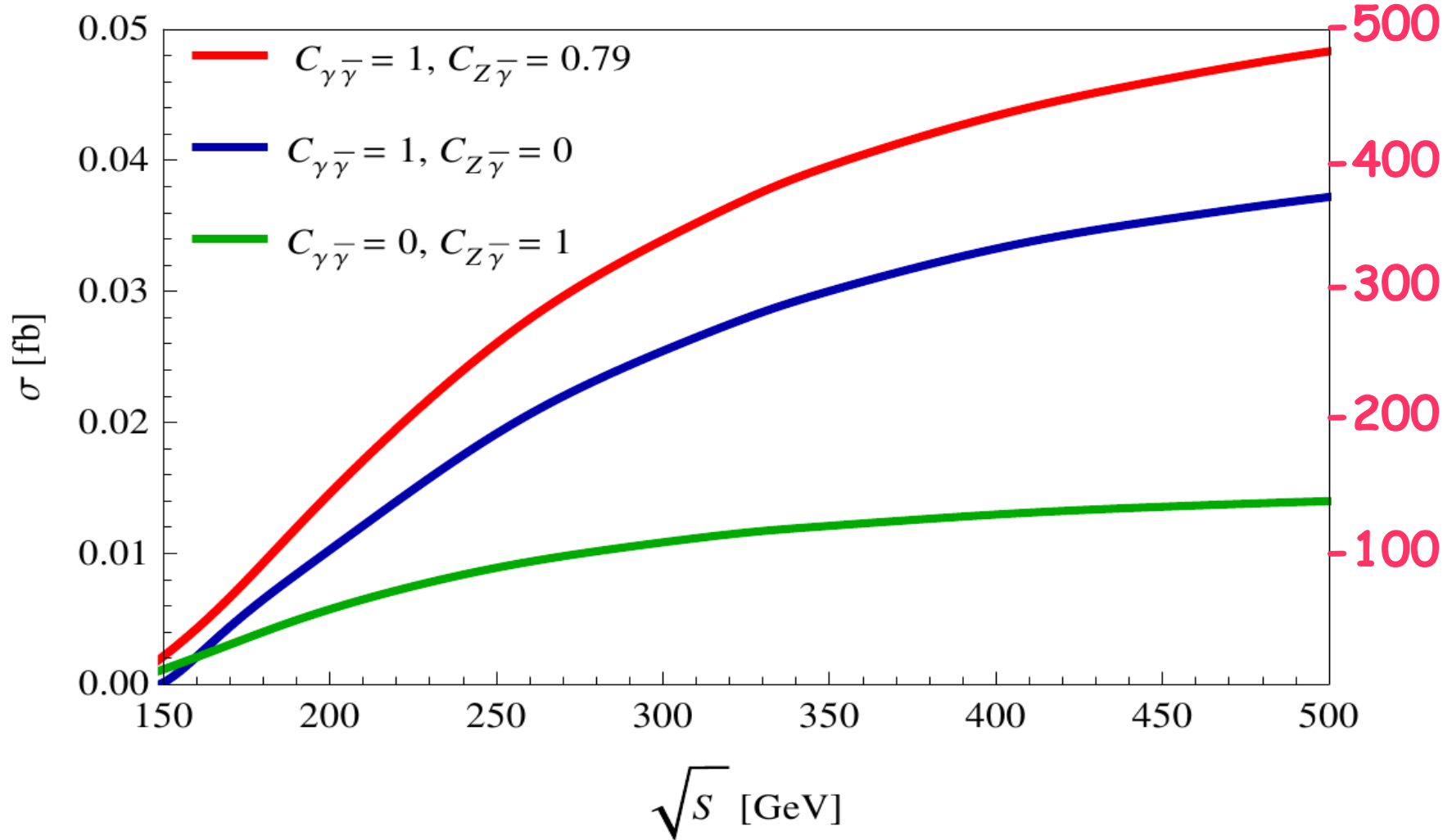


$$\Gamma(H \rightarrow \gamma\bar{\gamma}) = \frac{m_H^3}{64\pi\Lambda_{\gamma\bar{\gamma}}^2}, \quad 1/\Lambda_{\gamma\bar{\gamma}} = C_{\gamma\bar{\gamma}}/(\pi v)$$

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

Total cross section [fb]

**N. Events
for $L=10\text{ab}^{-1}$**



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

- signal $b\bar{b} + \cancel{E}$ $\longrightarrow$ Missing energy
- simulated signal with MADGRAPH using effective Lagrangian, then passed to PYTHIA for parton shower and initial state radiation

Basic cuts

$$\left\{ \begin{array}{l} p_T^b > 20 \text{ GeV} , \quad |\eta_b| < 2.5 \\ \Delta R(bb) > 0.4 , \quad \cancel{E} > 40 \text{ GeV} \\ \Delta R(bb) = \sqrt{\Delta\eta^2 + \Delta\phi^2} \end{array} \right.$$

- 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

$$b\bar{b} + \cancel{E}$$

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

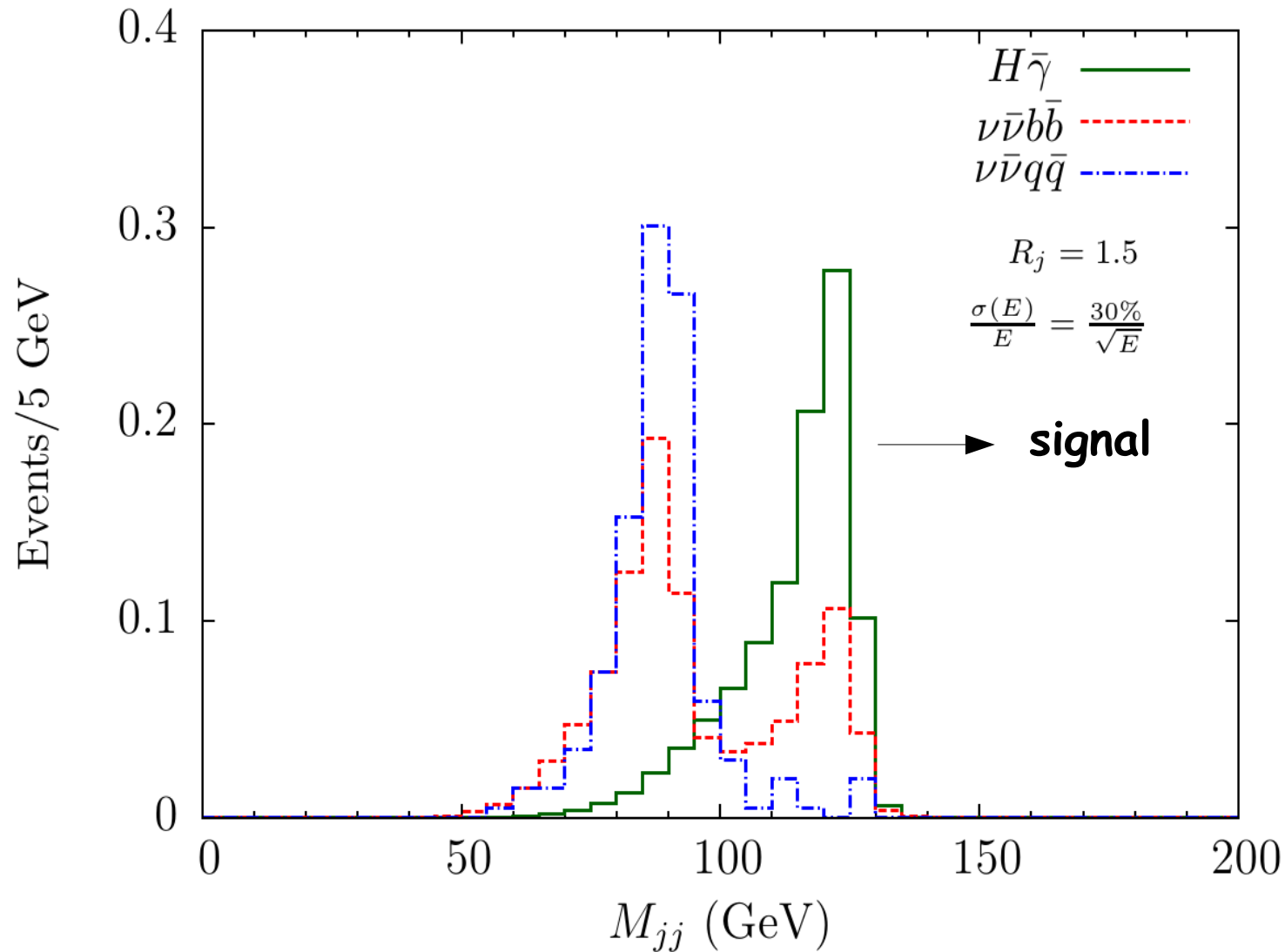
Two kinematical variables particularly efficient for separating signal from bckg

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

- $M_{\text{miss}} = \sqrt{\cancel{E}^2 - \cancel{p}^2}$ $\left\{ \begin{array}{l} \cancel{E} = \sqrt{s} - \sum E_{\text{visible}} \\ \cancel{p} = - \sum \mathbf{p}_{\text{visible}} \end{array} \right.$

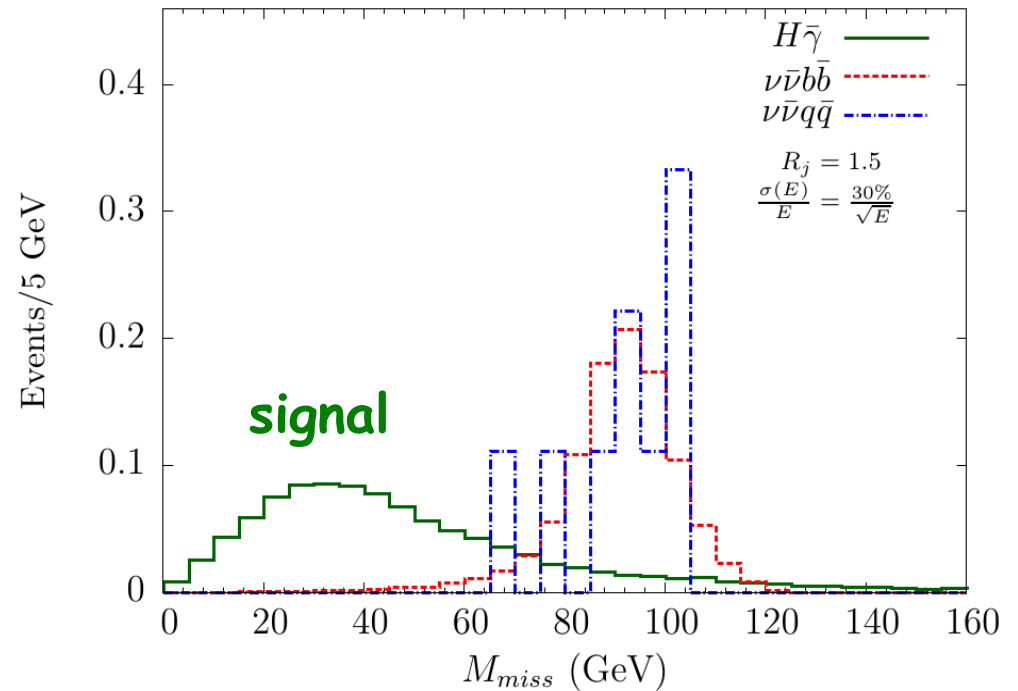
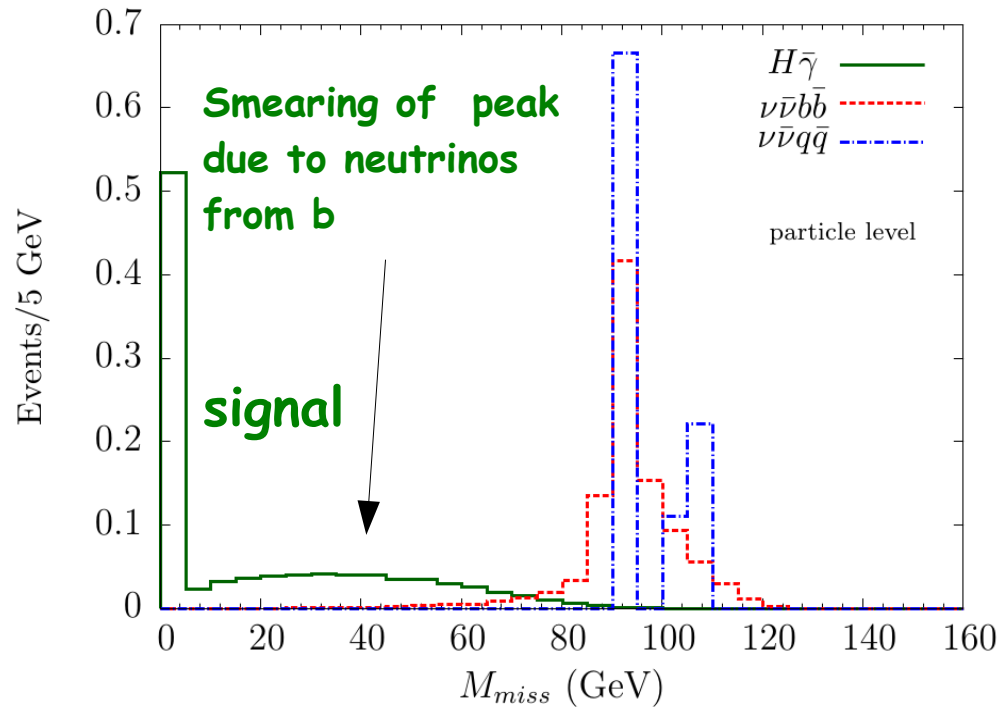
M_{miss} expected to approximatively vanish in the partonic description of $e^+e^- \rightarrow H \bar{\gamma}$

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

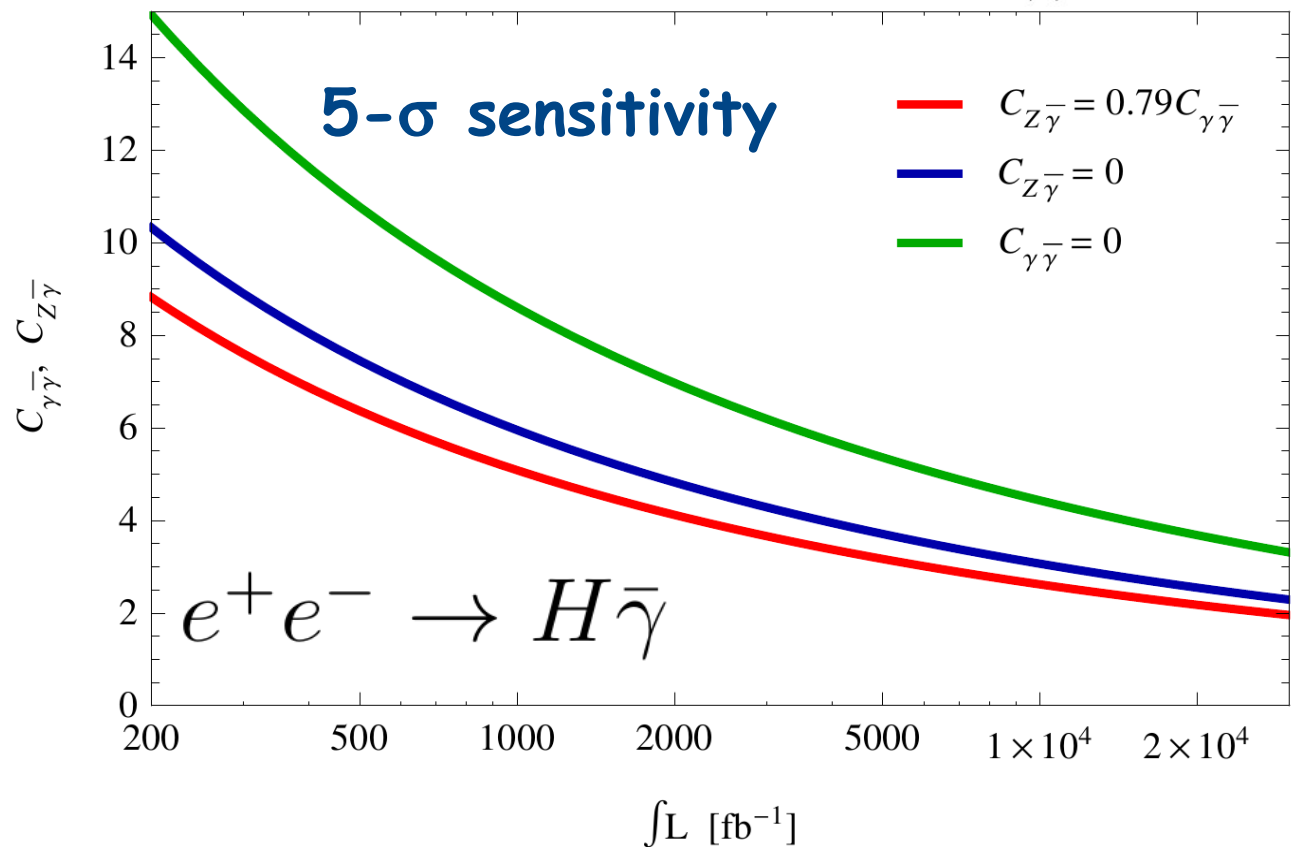
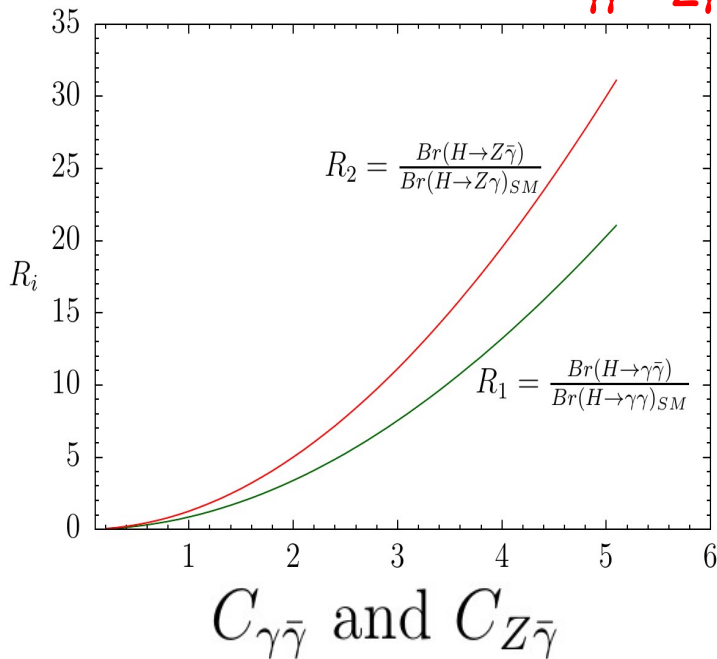
- Parton showering, jet reconstr., energy-resol. degrades M_{miss} spectrum of signal shifting the peak and smearing it
- suggests M_{jj} to be within 10% of peak value and $M_{\text{miss}} < 40 \text{ GeV} \rightarrow 40 \text{ GeV} < \cancel{E} < 100 \text{ GeV}$.

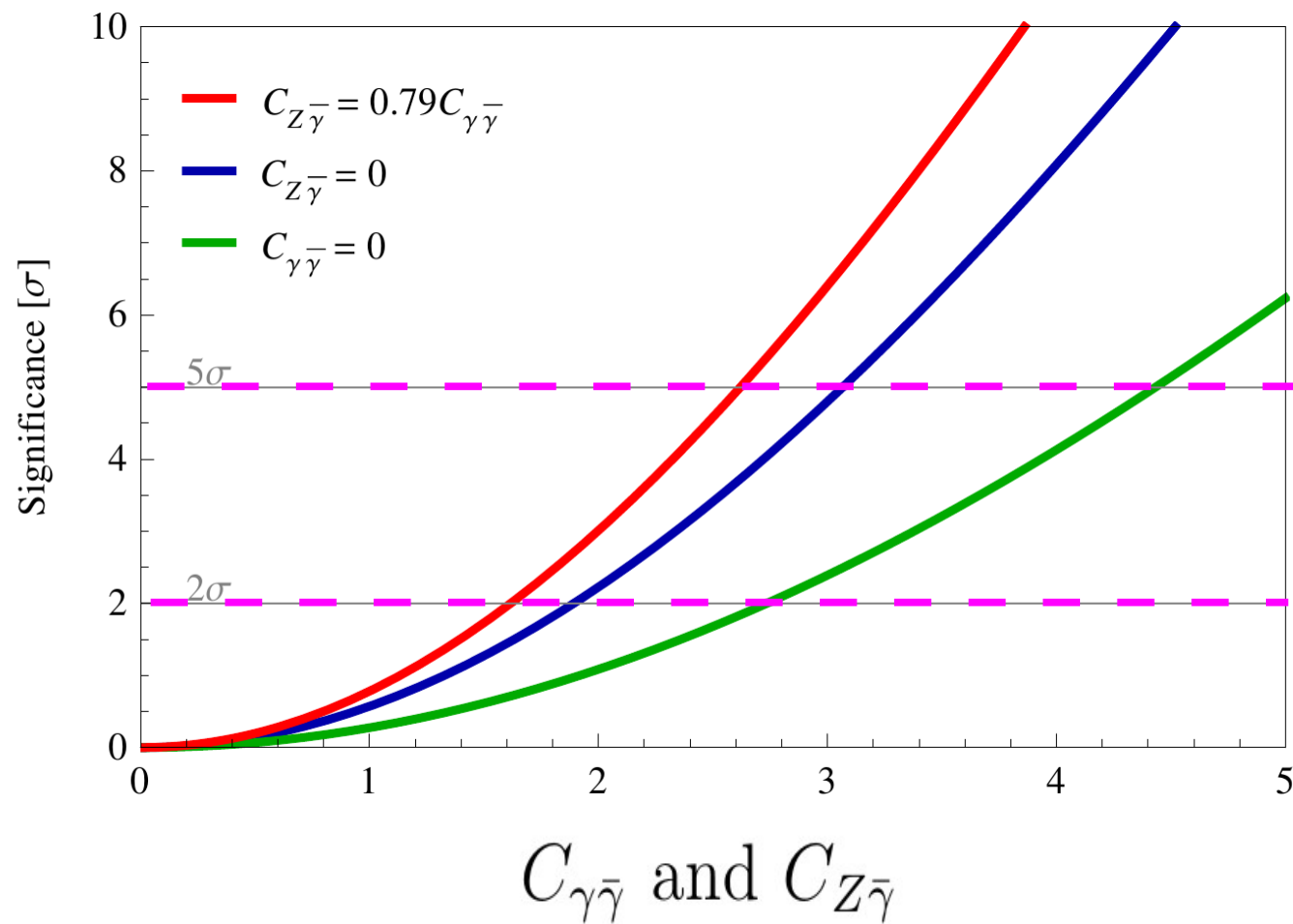
Results for $\sqrt{s} = 240$ GeV

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

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

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





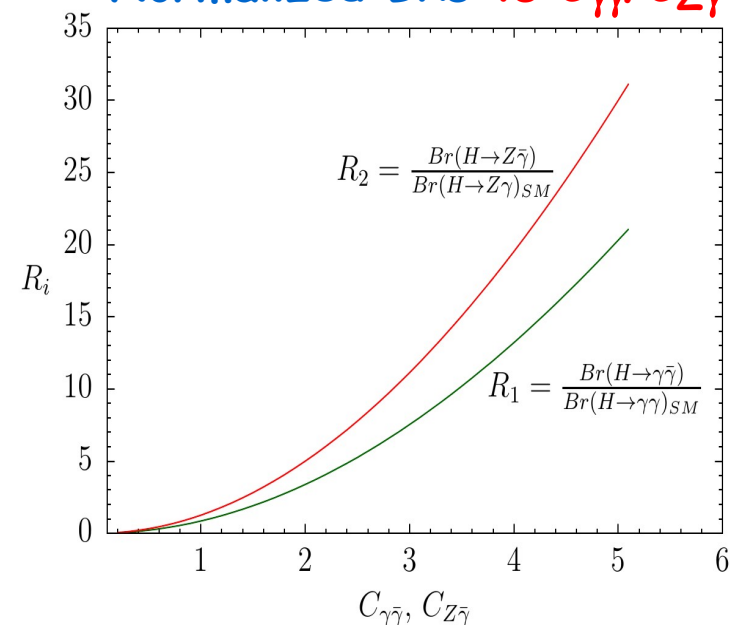
$$\text{sgnf} = S / \sqrt{S + B}$$

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

5 σ

2 σ

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



FCNC decays of SM fermions into dark photons

- The CKM can be generated in this framework
- This requires existence of FCNC currents at tree-level:

fermion(*i*)-darkfermion(*j*)-messenger(*j*) interactions $i \neq j$

- $f(i) \rightarrow f(j) \bar{\gamma}$ generated at one-loop
- Decoupling $\rightarrow$ characteristic scale $\sim$ messenger mass
- Potential new signatures for colliders

$$t \rightarrow c \bar{\gamma} \quad b \rightarrow s \bar{\gamma} \quad \tau \rightarrow \mu \bar{\gamma} \quad \mu \rightarrow e \bar{\gamma}$$

Work in preparation

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 indefinite metric, unitarity of S matrix 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

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

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

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

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

Outlook

- Hidden sector might have long distance interactions mediated by $U(1)_F$ gauge $\rightarrow$ 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
 - $\rightarrow$ search for $H \rightarrow \gamma\bar{\gamma}$, and $H \rightarrow Z\bar{\gamma}$
 - $\rightarrow$ potentially large rates due to non-decouplings
 - $\rightarrow$ new production mechanisms $pp \rightarrow H(\rightarrow bb) + \bar{\gamma}$

- e^+e^- collider implications: (beyond Higgs decays in $e^+e^- \rightarrow H Z$, with $H \rightarrow \gamma \bar{\gamma}$ and $H \rightarrow Z \bar{\gamma}$)
- $e^+e^- \rightarrow H(\rightarrow bb) + \bar{\gamma}$ 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
- New FCNC decay modes of SM fermions
 $t \rightarrow c \bar{\gamma}$ $b \rightarrow s \bar{\gamma}$ $\tau \rightarrow \mu \bar{\gamma}$ $\mu \rightarrow e \bar{\gamma}$
 $\rightarrow$ new signatures yet to be studied at colliders

Backup slides

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

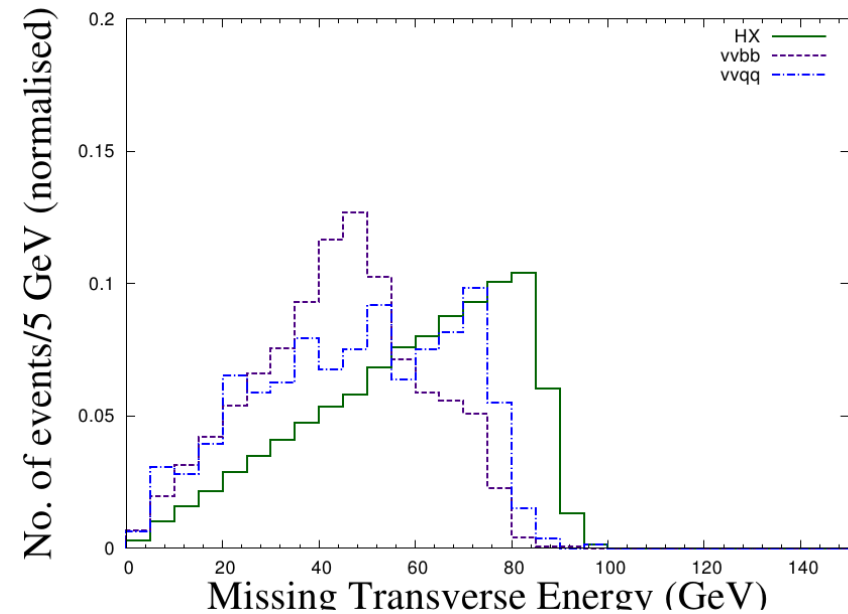
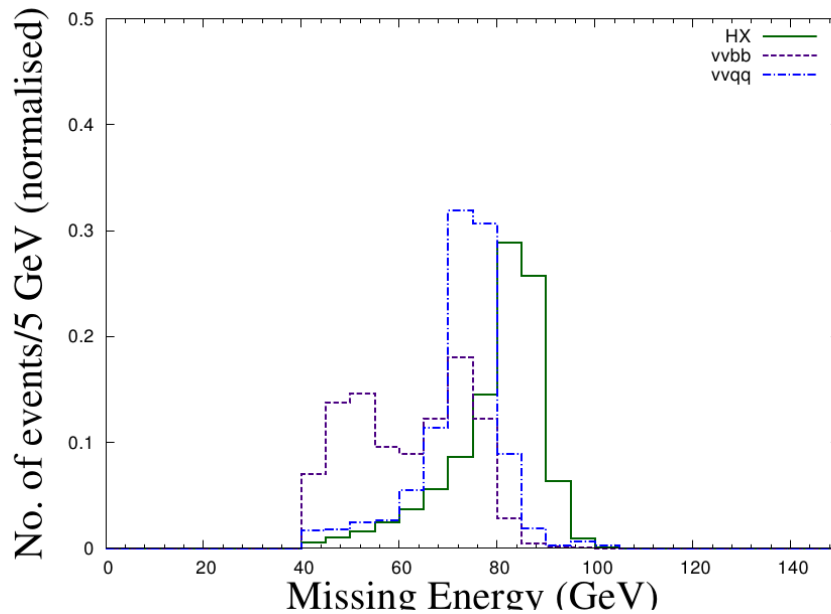
1. $pp \rightarrow \gamma j$, where large apparent $\cancel{E}_T$ is created by a combination of real $\cancel{E}_T$ from neutrinos in heavy quark decays and mismeasured jet energy.
2. $pp \rightarrow \gamma Z \rightarrow \gamma \nu \bar{\nu}$ (irreducible background);
3. $pp \rightarrow j Z \rightarrow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

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



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.