EPS Conference on High Energy Physics,
Venice, Italy, 5-12 July 2017

Searching for massless Dark Photons at the LHC via Higgs production

based on :

S.Biswas, E.Gabrielli, M.Heikinheimo, BM, PRD 93 (2016) 093001

E.Gabrielli, M.Heikinheimo, BM, M.Raidal, PRD 90 (2014) 055032

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a few facts

- expected exp hints of fashionable theory solutions to SM puzzles are being late in showing up
- more and more crucial to look at signature-based BSM searches at the LHC ➜ boosts LHC discovery potential in a model-independent way
- Hidden/Dark (SM-uncharged) Sectors can provide new signatures not covered by present searches

Outline (Dark Photon → DP)

- Hidden Sectors with unbroken extra U(1) possibly solving Yukawa hierarchy + Dark Matter → predict massless DP's
- Higgs decays into massless DP's
- new Higgs signatures from DP's at colliders
- gg vs VBF at the LHC
- Outlook

Dark Photons (DP) from extra U(1)'s

- Hidden Sectors can contain light or massless gauge bosons mediating long-range forces between Dark particles
- DP's may have a relevant role in Cosmology and Astrophysics
- previous pheno studies mainly involving "massive" DP
- a massive DP interacts with SM matter via

"kinetic mixing" with SM hypercharge $U(1)_Y$ gauge boson :

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$ [U(1) gauge invariant]

mixing param.

4D interaction between field-strengths of two different U(1) allowed ➜

$$\mathcal{L}_{mix} = \chi B_{\mu\nu} C^{\mu\nu}$$

➜ a massive DP couples to SM particles with strength $-\chi e Q_{el}$

➜ quite a few exp bounds on that by now !

the massless Dark Photon case

if $U(1)_F$ unbroken no such constraints !

(on-shell DP's can be fully decoupled from SM sector at tree level)

(Holdom, PLB 166, 1986, 196)

massless DP's then interact with SM sector only through higher-dimensional (→ suppressed by $1/M^{D-4}$) interactions via messenger (if any) exchange !

→ potentially large DP couplings $\bar{\alpha}$ in the Hidden Sector (HS) allowed !

if produced in collisions :

→ stable + noninteracting

→ neutrino-like signature

(massless-DP Cosmology recently considered in Agrawal, Cyr-Racine, Randall, Scholtz, arXiv:1610.04611)

Explaining Yukawa hierarchy via HS and extra $U(1)_F$

- Hidden Sectors (HS) possibly explaining Flavor hierarchy + Dark Matter

Gabrielli, Raidal, arXiv:1310.1090

- Yukawa's are not fundamental constants but effective low-energy couplings (→ scalar messengers transfer radiatively *Flavor and Chiral Symm. Breaking* from HS fermions to SM fermions giving Yukawa couplings at one-loop)
- predict extra unbroken $U(1)_F$ → massless DP's
- for integer-$q_{(\text{dark fermions})}$ sequence :

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

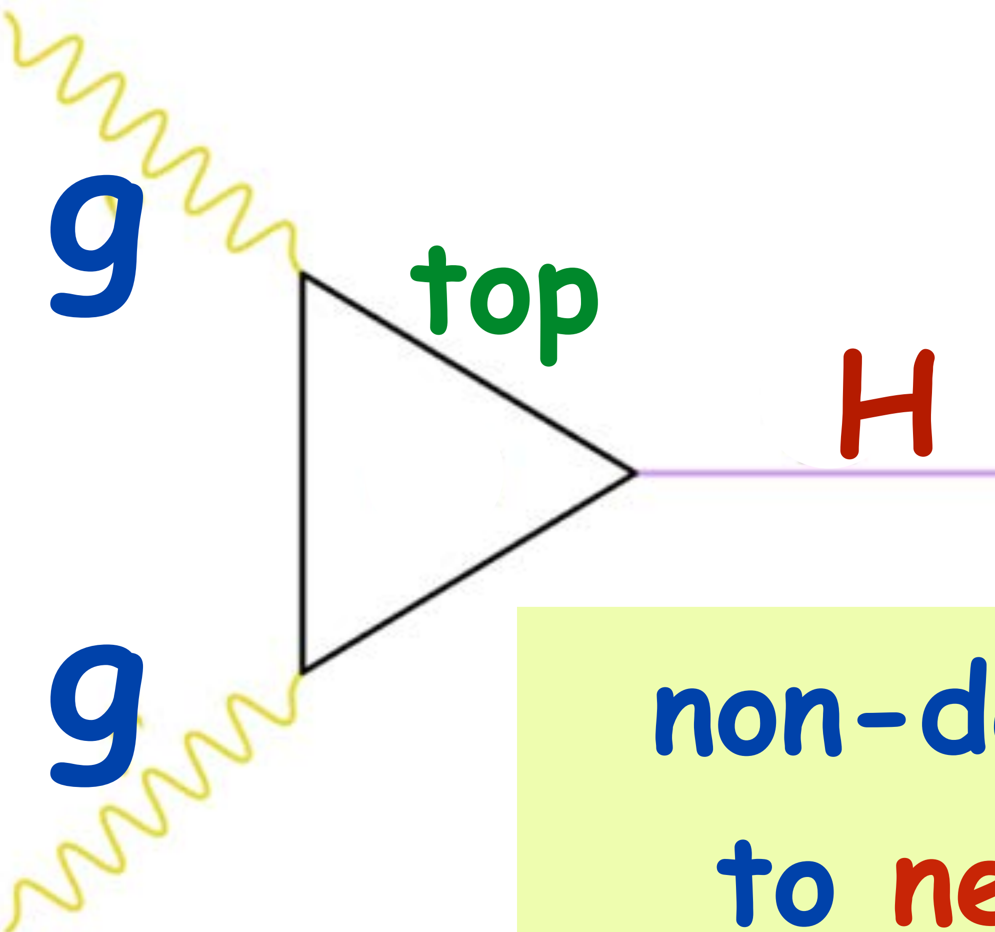
DP coupling

→ exponential hierarchy in $M_{(\text{Dark fermions})}$

→ exponential hierarchy in radiative $Y_{(\text{SM fermions})}$

- Dark fermions as dark-matter candidates

Higgs non-decoupling in SM !



$$\mathcal{A}_{gg\to H} \sim \frac{Y_{top}}{m_{top}} \to \frac{1}{v}$$

$$(m_{top} \to \infty)$$

non-decoupling can also apply to new heavy chiral states !

→ finite (potentially large) effects even from heavy BSM states !

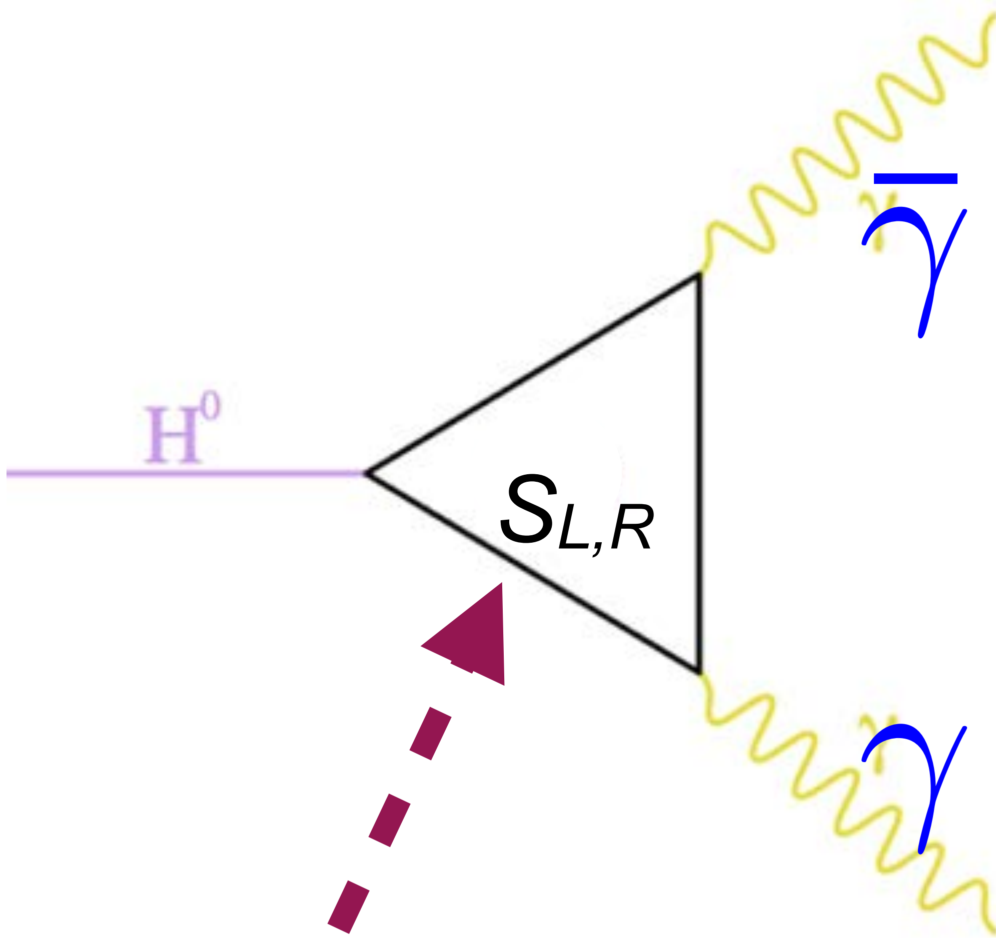
Higgs as a "source" of Dark Photons

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

mono-photon resonant signature

Gabrielli, Heikinheimo, BM, Raidal, arXiv:1405.5196 (PRD)

Dobrescu, hep-ph/0411004 (PRL)



massless (invisible) Dark Photon

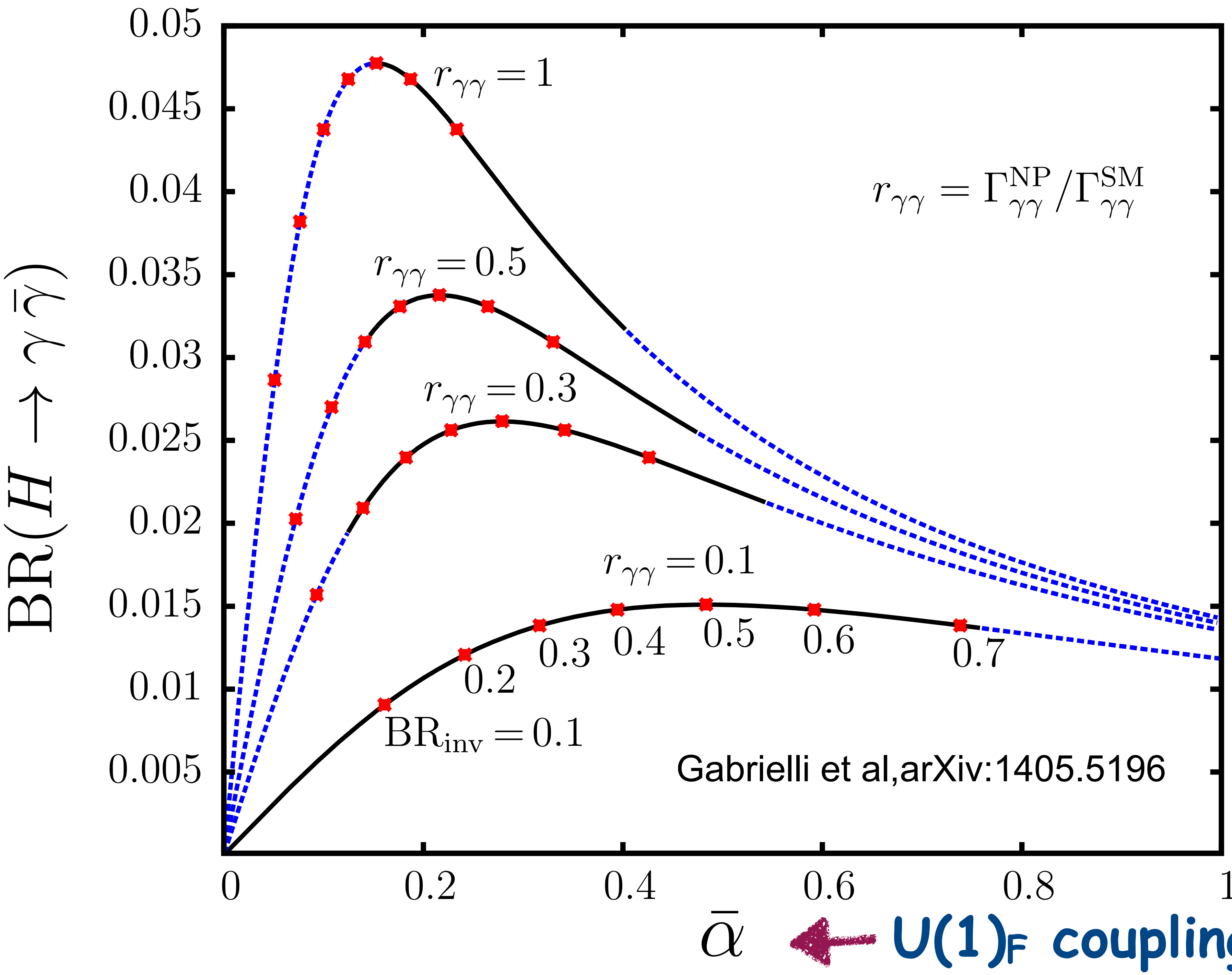
(mediating long-range $U(1)_F$ force between Dark particles)

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

H non-decoupling effects (just as in SM) possible:

$$\Gamma(H \to \gamma\bar{\gamma}) \sim \frac{1}{M^2_{Heavy}} \to \frac{1}{v^2}$$

$BR_H(\bar{\gamma}\gamma)$ prediction in minimal models



← U(1)$_F$ coupling

similar loop effects contribute to :

$$H \to \gamma\gamma$$

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

affects BR$_{inv}$:

(assuming NP does not affect H → gg, WW…)

solid lines corresponds to :

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

$$BR(H \to \gamma\bar{\gamma})$$

up to 5% !

new Higgs signature at colliders

resonant mono-photon signature at 8 TeV

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

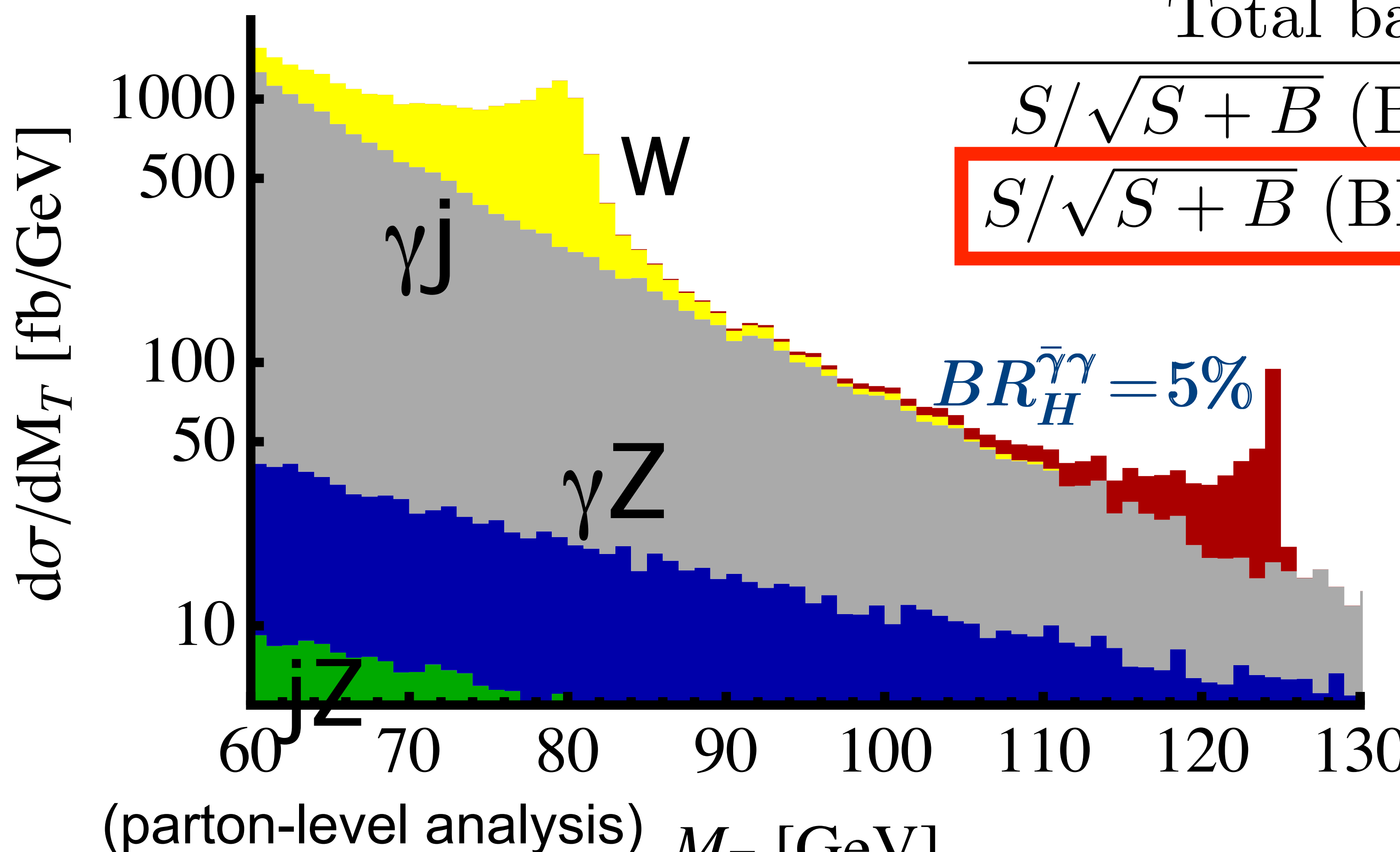
$E_{miss} \sim E_\gamma \sim m_H/2$

(A_1) 50 GeV $< p_T^\gamma <$ 63 GeV (A_2) 60 GeV $< p_T^\gamma <$ 63 GeV

σ (fb)	$\sigma \times A_1$	$\sigma \times A_2$
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

(8TeV/20fb^{-1})

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

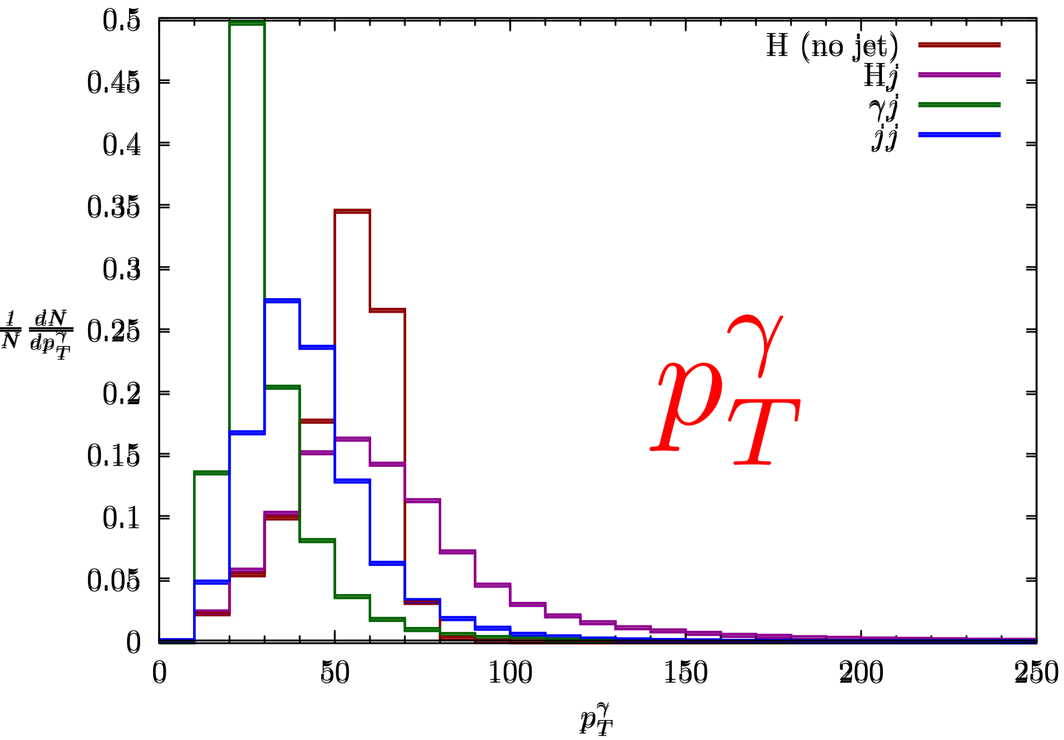


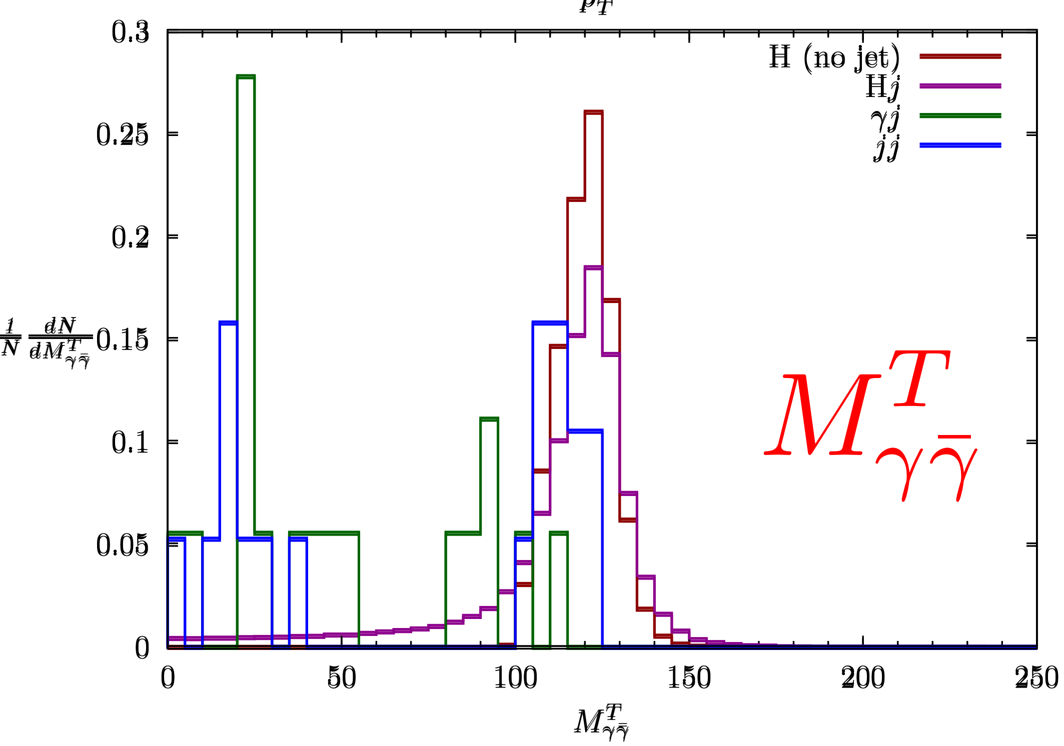
(parton-level analysis)

model-independent measurement of BR_{DP}!

resonant mono-photon signature at 14TeV

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





(includes parton-shower)

σ (fb)

	$\sigma \times A$ [8 TeV]	$\sigma \times A$ [14 TeV]
$H \to \gamma\bar{\gamma}$ $(\mathrm{BR}_{\gamma\bar{\gamma}} = 1\%)$	44	101
γj	63	202
new➔ $jj \to \gamma j$	59	432
$e \to \gamma$	55	93
$W(\to \ell\nu)\gamma$	58	123
$Z(\to \nu\nu)\gamma$	102	174
total background	337	1024

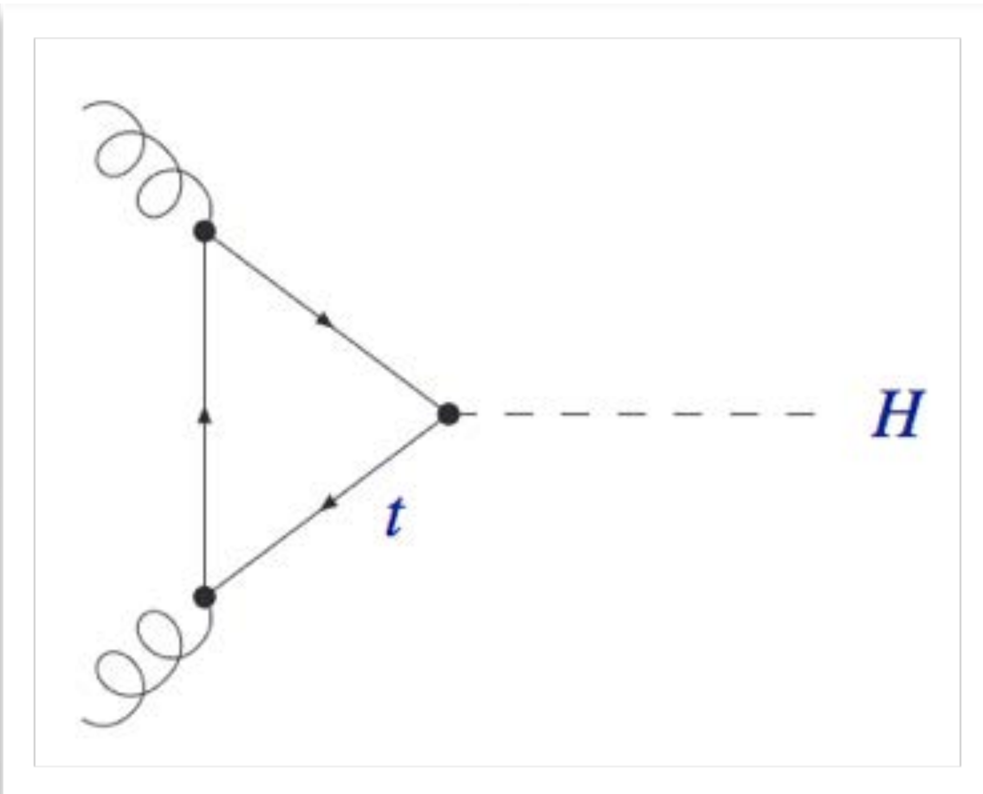
TABLE I: Cross section times acceptance A (in fb) for the gluon-fusion signal and backgrounds at 8 and 14 TeV, assuming $\mathrm{BR}_{\gamma\bar{\gamma}}$= 1%, with the selection $p_T^\gamma > 50$ GeV, $|\eta^\gamma| < 1.44$, $\not{E}_T > 50$ GeV, and 100 GeV $< M^T_{\gamma\bar{\gamma}} <$ 130 GeV.

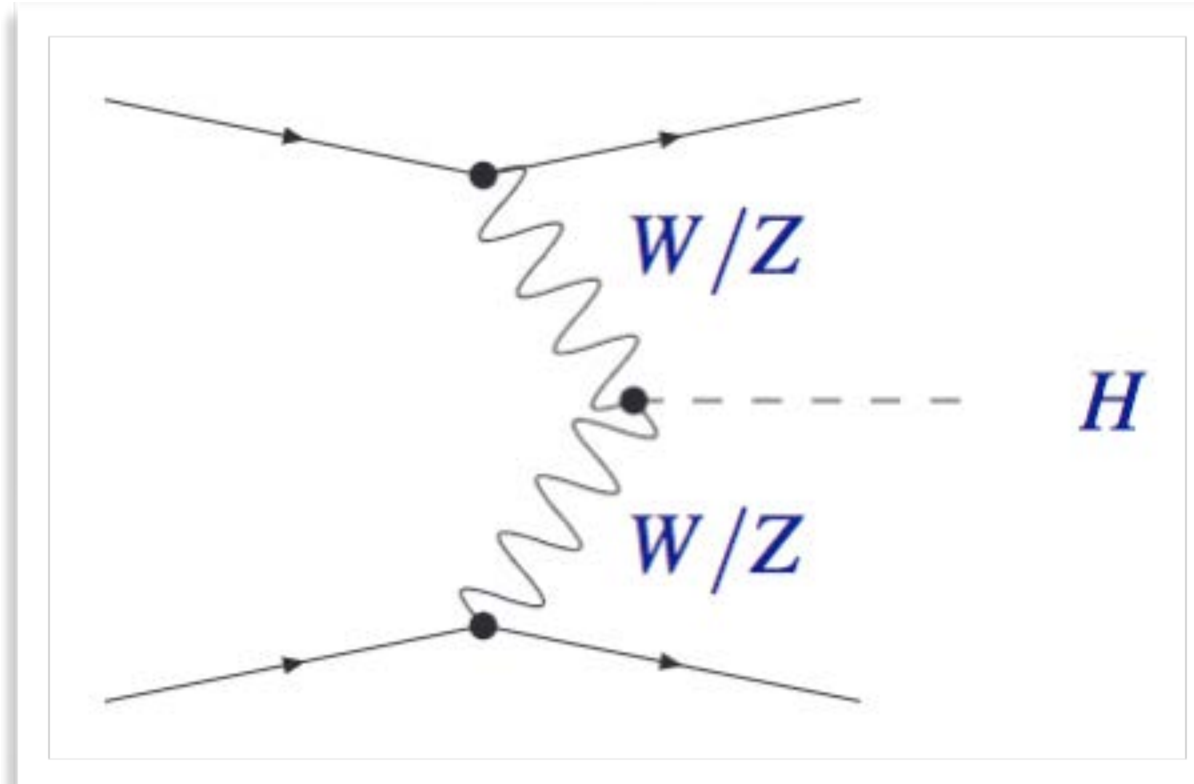
MadGraph5_aMC@NLO + PYTHIA (bckgr)
ALPGEN + PYTHIA (H signal)

γj **bckgr modeled on data at 8 TeV**
(CMS, arXiv:1507.00359 [hep-ex] (PLB))

Biswas, Gabrielli, Heikinheimo, BM, arXiv:1603.01377 (PRD)

gg fusion vs VBF





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

$p\gamma_T > 30$ GeV $|\eta\gamma| < 2.5$

$E_{Miss,T} > 30$GeV

$p_j > 20$ GeV and $|\eta| < 5.0$

$\eta_{j1} \times \eta_{j2} < 0$ and $|\eta_{j1} - \eta_{j2}| > 4.0$

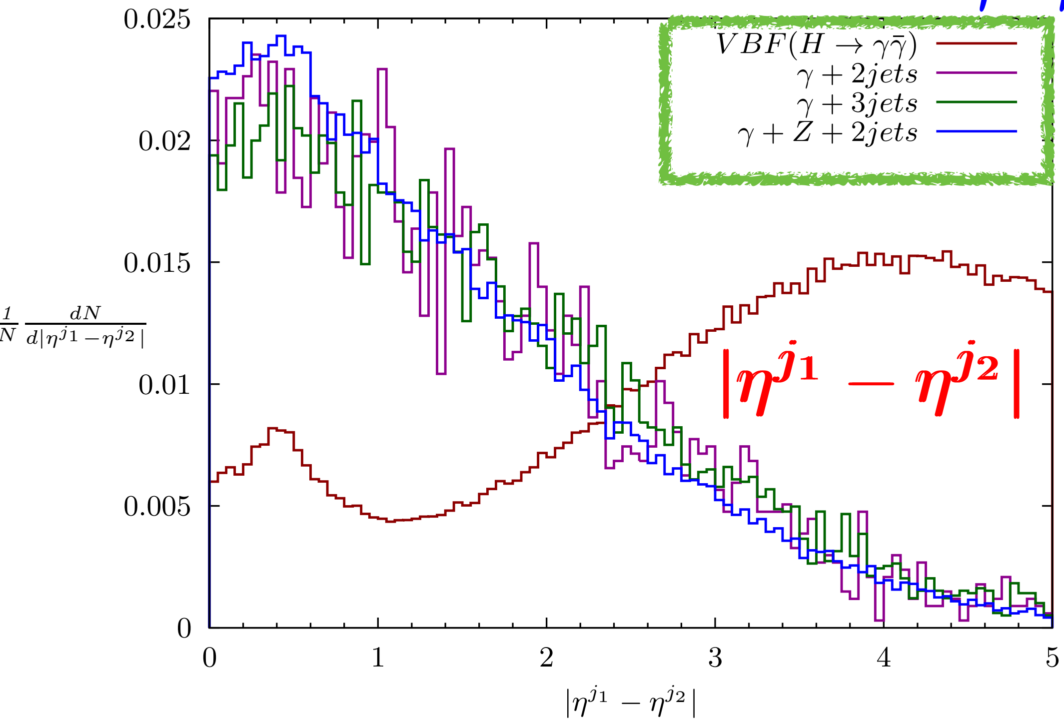
100 GeV $< M_T <$ 130 GeV

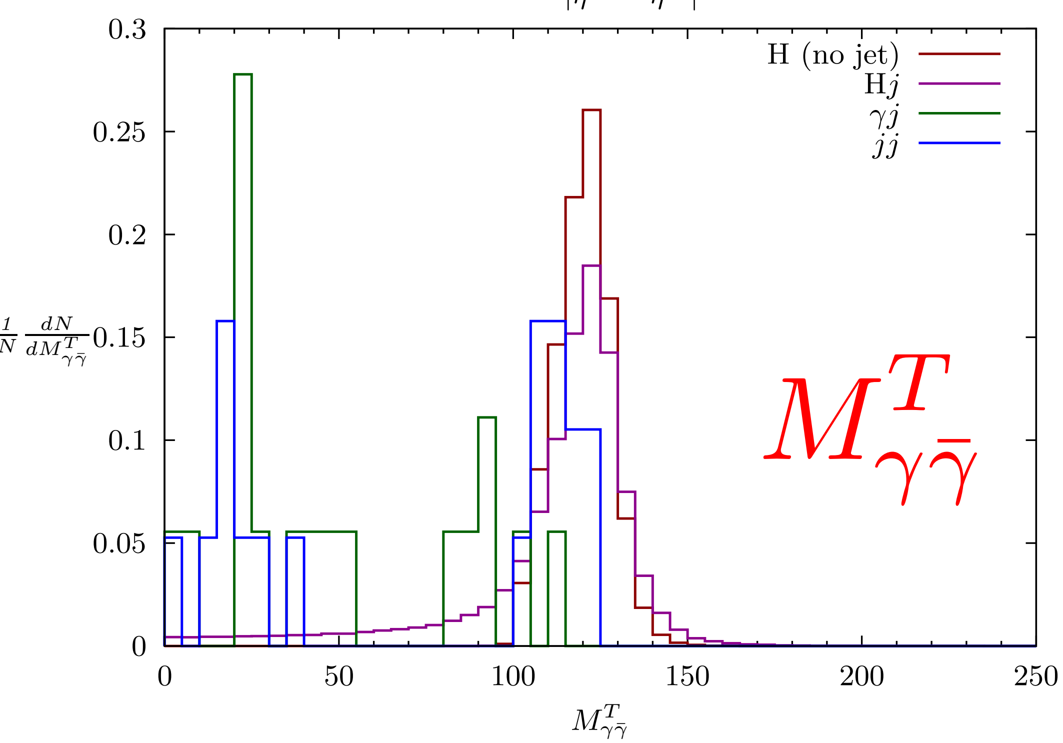
$\Delta\phi(j_i, E_{Miss,T}) > 1.5$

mono-photon signature in VBF at 14TeV

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

+ two extra forward jets !





reference BR_{DP}

$BR_{\gamma\bar{\gamma}}$=1%.

σ (fb)

Cuts *(sequential)*	Signal	γ+jets	$\gamma + Z$+jets	QCD multiijet
Basic cuts	17.7	266636	1211	72219
Rapidity cuts	8.8	8130	38.1	33022
$M^T_{\gamma\bar{\gamma}}$ cuts	5.0	574	6.5	3236

Cuts *(individual)*	Signal	γ+jets	$\gamma + Z$+jets	multijet	L=300 fb^{-1}
$y^* < 1.0$	2.67	84.2	1.84	758	1.6 σ
$\Delta\phi(j_i, \not{E}_T)$ >1.5	1.82	6.9	2.16	37	4.6 σ
both cuts	1.21	1.2	0.67	19	4.5 σ

MadGraph5_aMC@NLO + PYTHIA
ALPGEN + PYTHIA

Biswas, Gabrielli, Heikinheimo, BM, arXiv:1603.01377 (PRD)

model-independent bounds @ LHC 14 TeV

$gg \to H \to \bar{\gamma}\gamma$ **vs** $VV \to H \to \bar{\gamma}\gamma$

$\mathrm{BR}_{\gamma\bar{\gamma}}$ (%)	L= 100 fb^{-1}		L=300 fb^{-1}		L=3 ab^{-1}	
Significance	2σ	5σ	2σ	5σ	2σ	5σ
$\mathrm{BR}_{\gamma\bar{\gamma}}$(VBF)	0.76	1.9	0.43	1.1	0.14	0.34
$\mathrm{BR}_{\gamma\bar{\gamma}}$ (ggF)	0.064	0.16	0.037	0.092	0.012	0.029

gg fusion sensitive down to BR_{DP} ~ 10^{-4}-10^{-3}

(VBF ~10 times worse ...)

Biswas, Gabrielli, Heikinheimo, BM,
arXiv:1603.01377 (PRD)

Outlook

- massless DP's theoretically appealing

  (evading most of present exp bounds on massive DP's !)

- Higgs boson as the SM portal to DP's
  - new effective vertices for DP's from Hidden Sectors explaining Flavor Hierarchy + Dark Matter

- rich phenomenological implications @ LHC (and ee colliders)

  see also Biswas, Gabrielli, Heikinheimo, BM, arXiv:1503.05836 (JHEP) ; arXiv:1703.00402

- new class of FCNC signatures from top, b, c, s, tau, mu decays into a massless DP

  Gabrielli, BM, Raidal, Venturini, arXiv:1607.05928 (PRD)
  Fabbrichesi, Gabrielli, BM, arXiv:1705.03470 (PRL)
  Dobrescu, hep-ph/0411004 (PRL)
  - very distinctive → bounds expected to be limited just by statistics !

- implications for astro-part/cosmology (mostly yet to work out !)