Autumn Institute - Challenges in collider physics

18 November 2016, LNF, Frascati, Italy

Massless Dark-Photon Phenomenology at Colliders

based on :

E.Gabrielli, BM, M. Raidal, E. Venturini, arXiv:1607.05928 (PRD)

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

S.Biswas, E.Gabrielli, M.Heikinheimo, BM, JHEP 1506 (2015) 102

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

E.Gabrielli, M.Raidal , PRD 89 (2014) 015008

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Frascati, 18 November 2016

Outline

- SM successful but not enough !
  importance of BSM signature-based searches at LHC
- massive and massless Dark Photons
- Hidden Sectors explaining Flavor hierarchy
  (Y_f's not fundamental constants but effective low-energy couplings)
  and predicting massless Dark Photons
- new Higgs signatures from Dark Photons at colliders
- FCNC's mediated by Dark Photons in heavy-flavour decays
- Outlook

everywhere in my slides:

Dark ↔ uncharged under SM

DP = **D**ark **P**hoton

Df = **D**ark **f**ermion

Hidden ↔ "not observed"

HS = **H**idden **S**ector

SM-Lagrangian criticalities

SM gauge group :

$SU(3)_{QCD} \times SU(2)_L \times U(1)_B$

spontaneusly broken
via Higgs mechanism

$\rightarrow \; SU(3)_{QCD} \times U(1)_{em}$

Higgs Lagrangian :

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi^\dagger \phi) \boxed{- \bar{\psi}_L \Gamma \psi_R \phi - \bar{\psi}_R \Gamma^\dagger \psi_L \phi^\dagger}$$

masses fix all Higgs interactions

$$V(\phi^\dagger \phi) = \boxed{-\mu^2 \phi^\dagger \phi} + \boxed{\frac{1}{2} \lambda (\phi^\dagger \phi)^2}$$

$$m_H^2 = 2\mu^2 = 2\lambda v^2$$

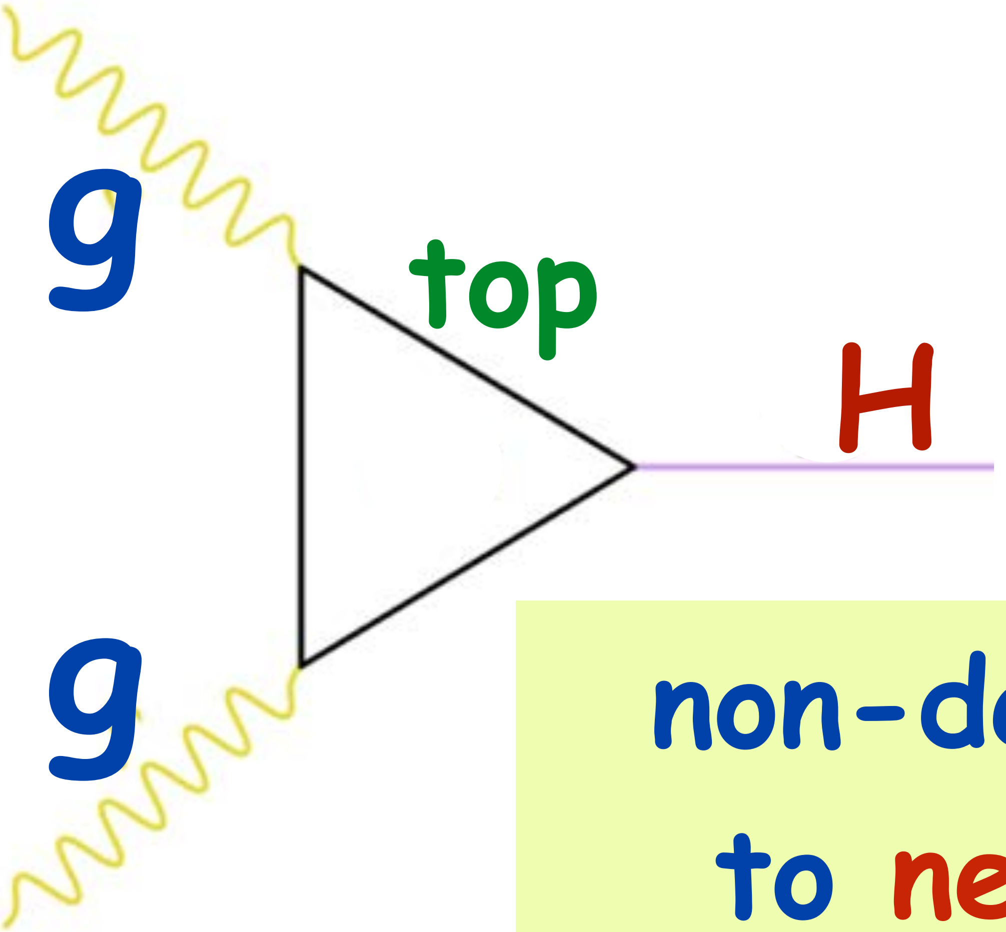
Higgs sector ➜ Criticalities

- Naturalness
- Flavor
- nature of EWPT

➜ Opportunities

- Higgs portal
- Non-decoupling
- extra scalars

Higgs non-decoupling !



$$A_{gg\to H} \sim \frac{Y_{top}}{m_{top}} \to \frac{1}{v}$$

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

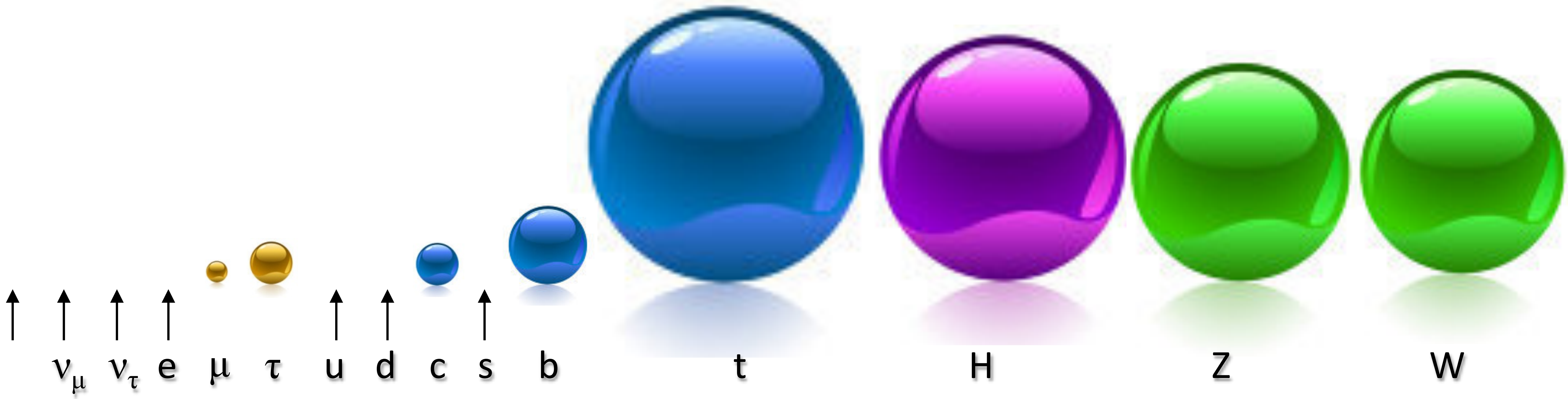
non-decoupling can also apply to new heavy chiral states !

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

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

origin of Flavor Symmetry Breaking ?

in general :

many proposed TH solutions to SM puzzles around, but …

presently no real EXP hint on how to enlarge SM to solve its issues

make BSM searches at colliders as inclusive as possible !

ingredients to optimize BSM searches at colliders

- highest collision cm energy and luminosity to produce heavy states with moderate production coupling

- highest ability to separate S from B, in particular in high-p_T tails and m(i,j) distributions (revealing scattering exchange of new states)

- highest ability to cover stealthy kinematical configurations (mass degeneracies, soft final objects …)

- exploiting as much as possible signature-based searches !

a most valuable activity in
BSM model building is suggesting
new kinds of signatures !
→ help pushing LHC discovery potential
in a model-independent way …

Hidden Sector models
can chart the way
in devising
new kinds of signatures
to look for !

FOCUS on Dark Photon (DP) from extra U(1)

- HS can contain light or massless gauge bosons (Dark Photons, DP) mediating long-range forces between Dark particles

- previous 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 $-\chi e Q_{el}$

Dark Photons

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)

in Cosmology :

- may solve the small-scale structure formation problems
- 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

  (from PAMELA-Fermi-AMS2 positron anomaly) N.Arkani-Hamed, D.P. Finkbeiner, T.R. Slatyer, N.Weiner. PRD 79 (2009)
- may assist DM annihilations for the required magnitude making asymmetric DM scenarios viable

  K.M. Zurek, Phys Rept. 537 (2014)

strong astrophysical and collider bounds on massive DP (Z')

let's turn to the massless-DP case …

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

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

(Holdom, PLB 166, 1986, 196)

massless DP will 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 in the Hidden Sector (HS) allowed !

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

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

Gabrielli, Raidal, arXiv:1310.1090

- HS containing N$_f$ heavy fermions (Dark Matter ?) charged under Dark unbroken U(1)$_F$ (➜ massless DP $\bar{\gamma}$)
- Chiral Simmetry spontaneously broken in HS via non-perturbative effects (higher-derivative in DP field ~ 1/Λ ➜ Lee-Wick ghosts)

Gabrielli arXiv:0712.2208

➜ Dark fermions (Df) get M$_{Df}$ mass depending on their U(1)$_F$ charge q$_{Df}$:

anom. dim.

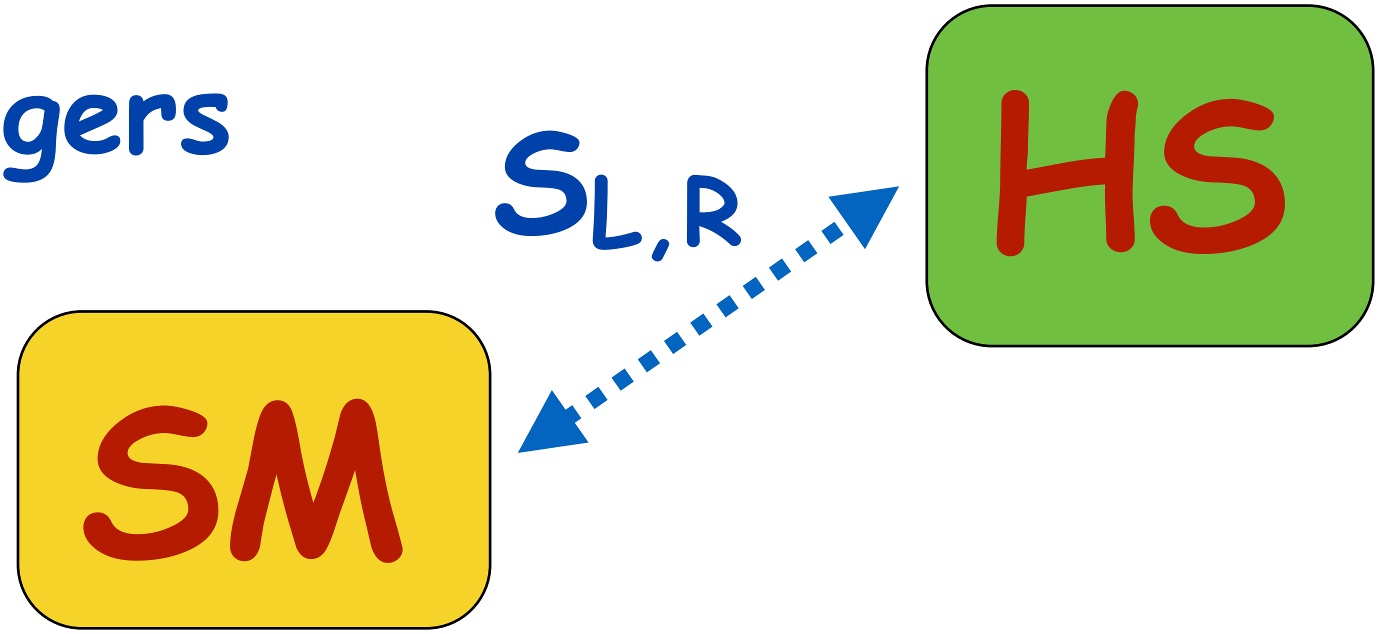
$$M_{D_f} \sim \exp(-\frac{\kappa}{q^2_{D_f}\bar{\alpha}})$$

DP coupling

- for integer-q$_{Df}$ sequence (q$_{Df}$=1, 2, 3, 4…)
  ➜ exponential hierarchy in M$_{Df}$

further ingredient: heavy scalar messengers $S_{L,R}$

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



Messengers (Scalars): $\hat{S}_L^{D_i}$, $\hat{S}_L^{U_i}$, $S_R^{D_i}$, $S_R^{U_i}$

Dark Sector (Fermions+ singlet Scalar): Q^{D_i}, Q^{U_i}, S_0

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

the scalar messengers

transfer radiatively

Flavor and Chiral Symm. Breaking

from HS fermions to SM fermions

generating

Yukawa couplings at one-loop !

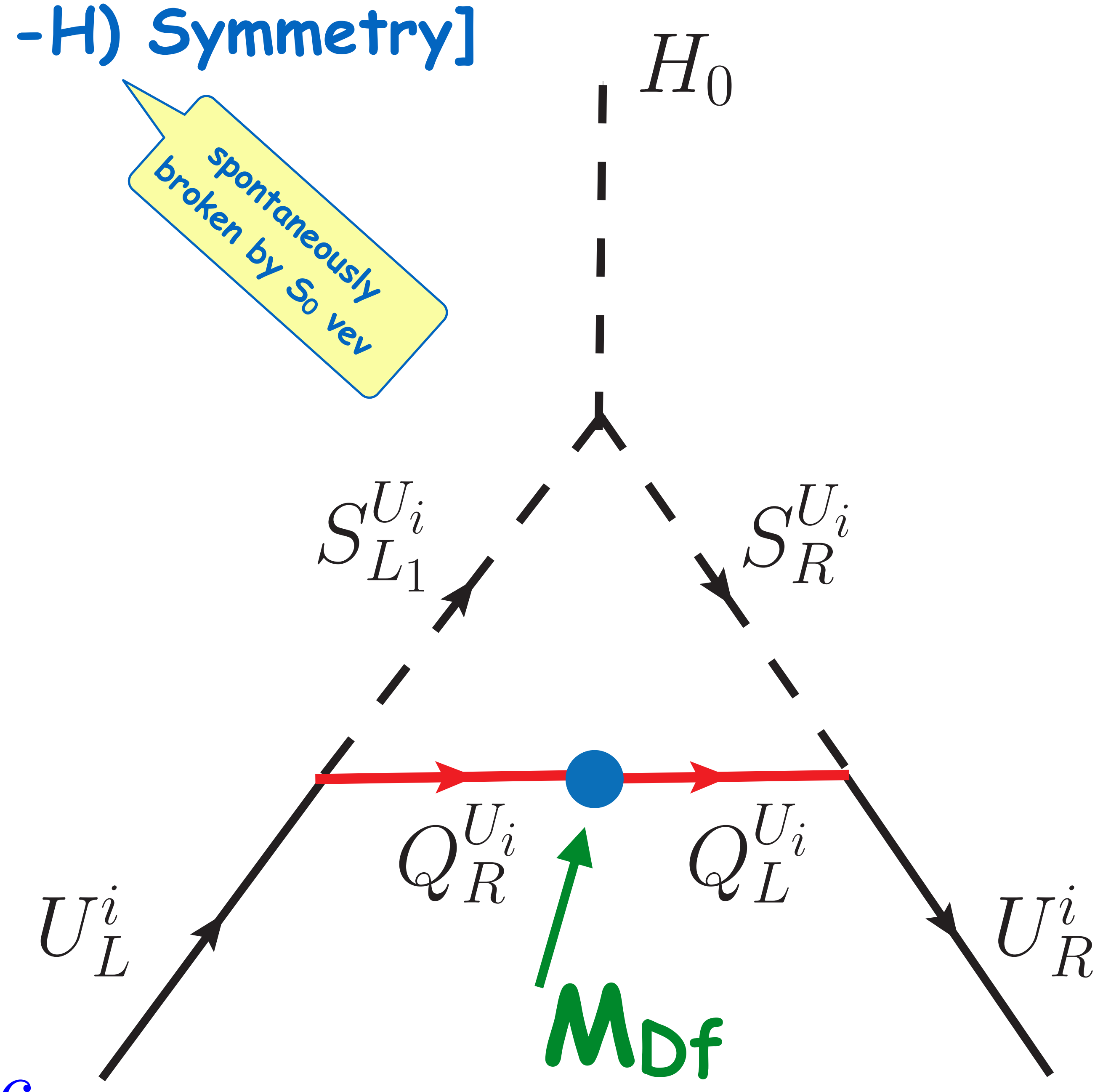
radiative Yukawa's follow M_{Df} hierarchy !!!

- $Y_f = 0$ at tree level [due to (H ↔ -H) Symmetry]
- Y_f's arise radiatively

(via loop-messenger exchange)
with same pattern
of exponential hierarchy of
Dark fermion (D_f) masses :

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

Flavor ⇔ **Non-Universal q_{Df}**


spontaneously broken by S_0 vev

example :

for $q_{D_e} = 4\,,\ q_{D_\mu} = 5\,,\ q_{D_\tau} = 6$

➜ given $m_e,\ m_\mu$ as input $\Rightarrow m_\tau \simeq 1.9\ \mathrm{GeV}$

(and, for Dirac ν's, $q_{D_{\nu_\tau}} = 3 \ \Rightarrow\ m_{\nu_\tau} \sim 5\ \mathrm{eV}$)

- Df are lightest Dark particles, potentially contributing to Dark Matter
- rich phenomenology at colliders if Df-mass scale accessible (yet to be explored…)

[colored-$S_{L,R}$ mass scale > 50 TeV] (vacuum stability)

FOCUS ON MASSLESS-DP PHENO

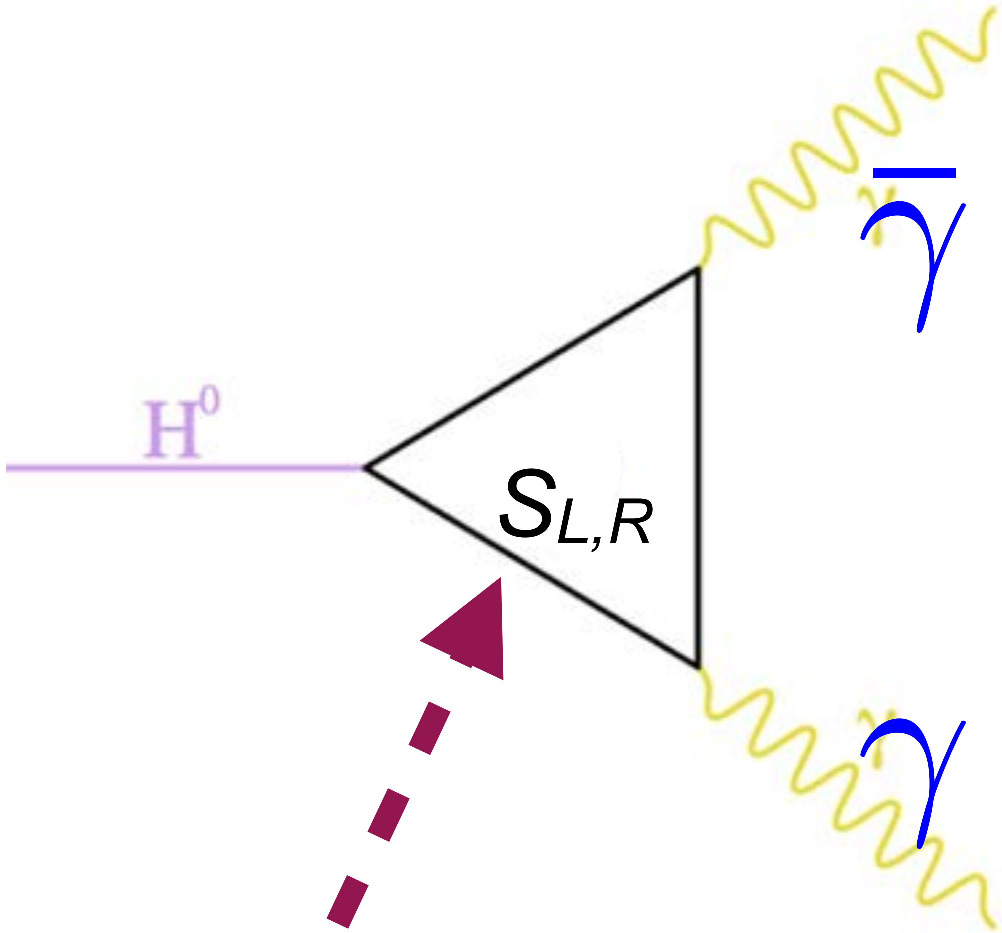
- shows up by a neutrino-like signature
- one straightforward (nontrivial) new signature in Higgs decays…

Higgs as a "source" of Dark Photons

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

mono-photon
resonant signature

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



massless (invisible)
Dark Photon

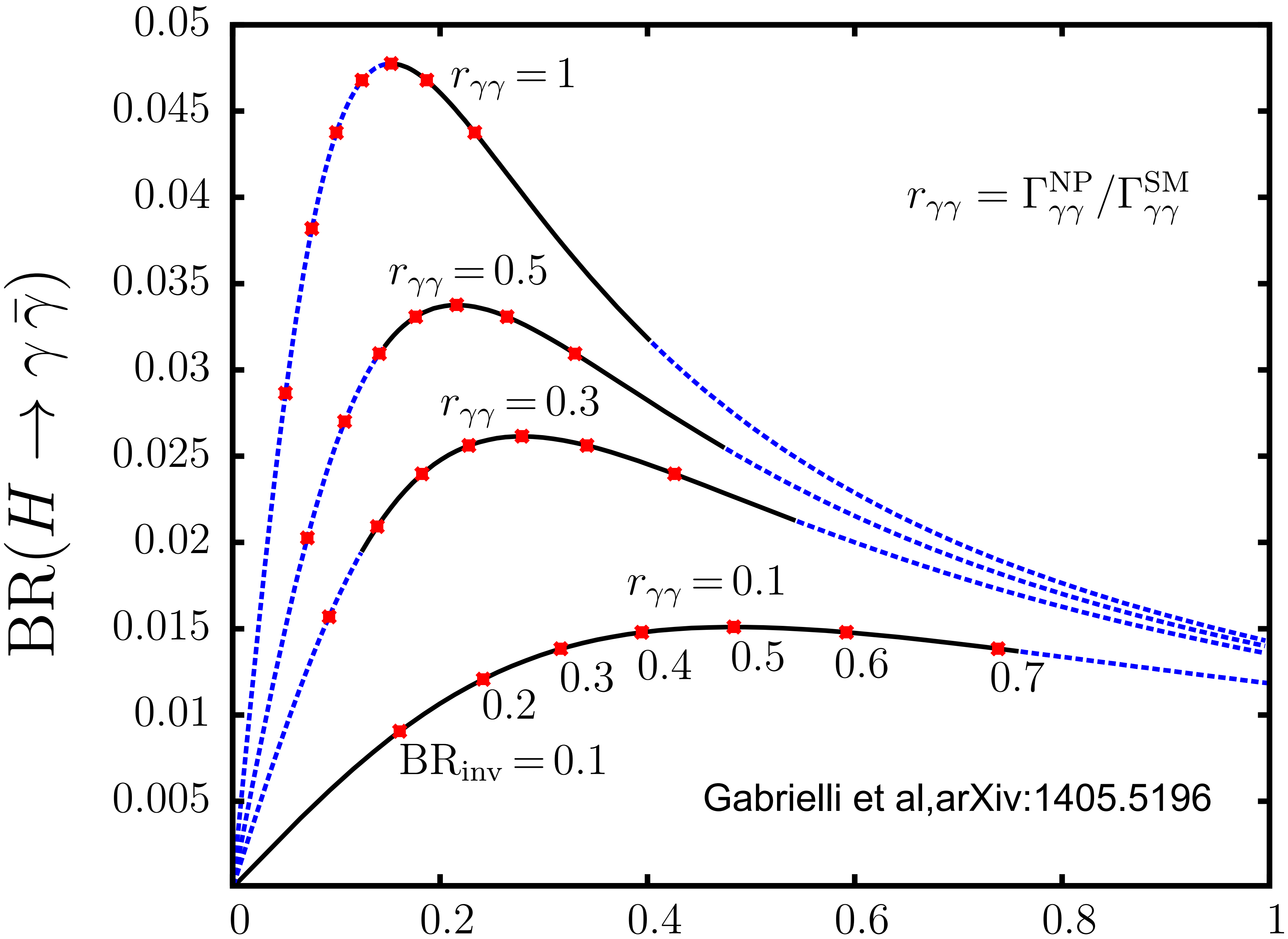
(mediating long-range
$U(1)_F$ force between
Dark particles)

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



similar loop effects contribute to :

$$H \to \gamma\gamma$$

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

affects $\mathrm{BR_{inv}}$:

$\bar{\alpha}$ ← **$\mathrm{U(1)_F}$ coupling**

solid lines corresponds to :

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

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

up to 5% !

resonant mono-photon signature at 8 TeV

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

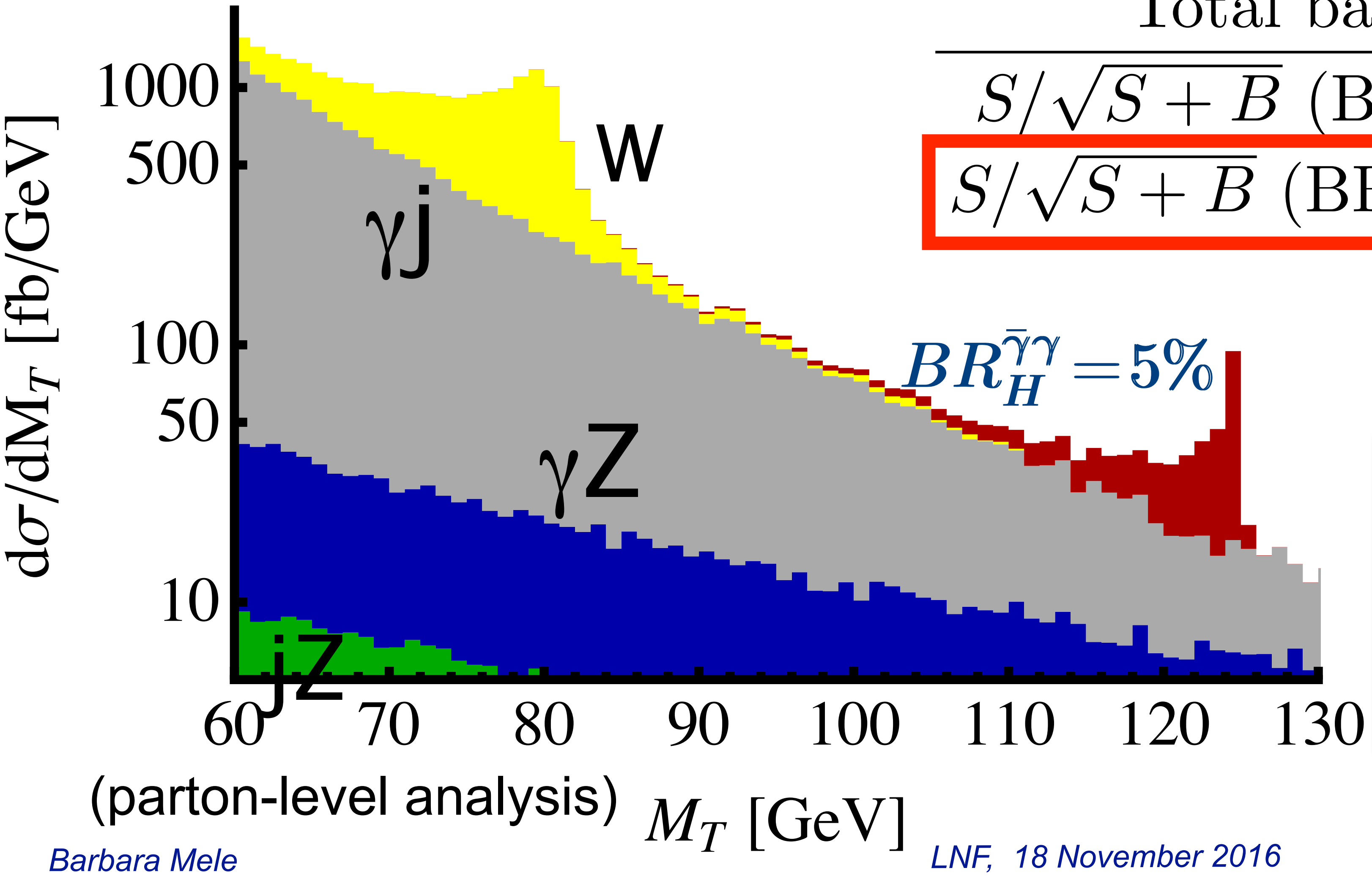
$E_{miss} \sim E_\gamma \sim m_H/2$

(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})

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

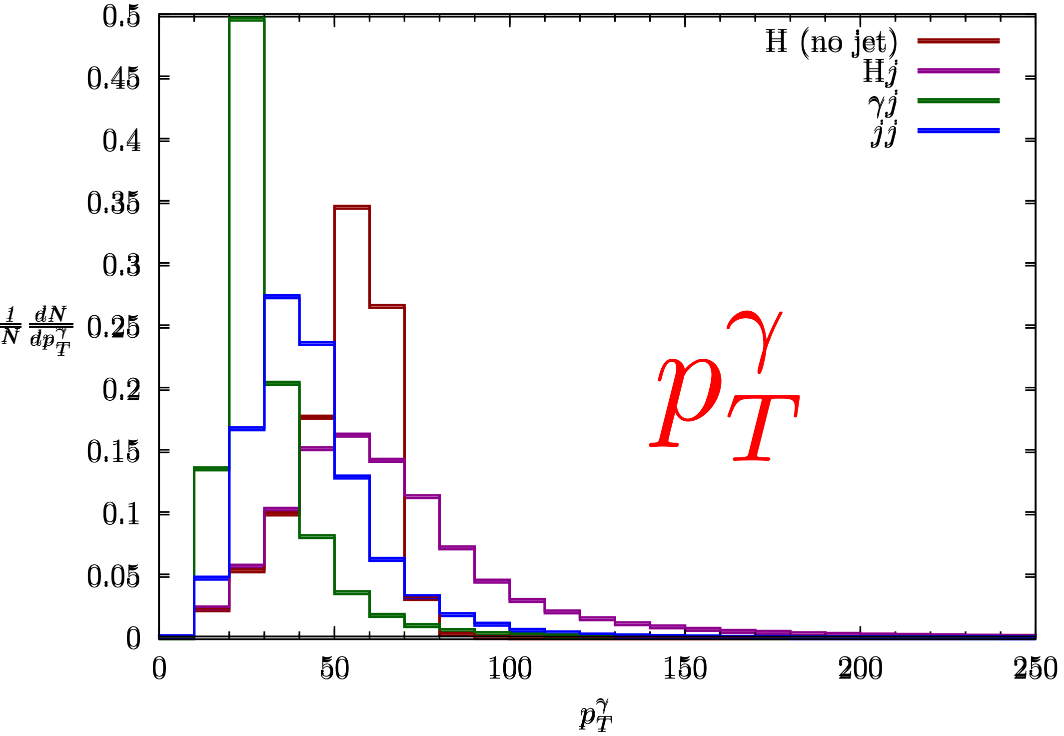


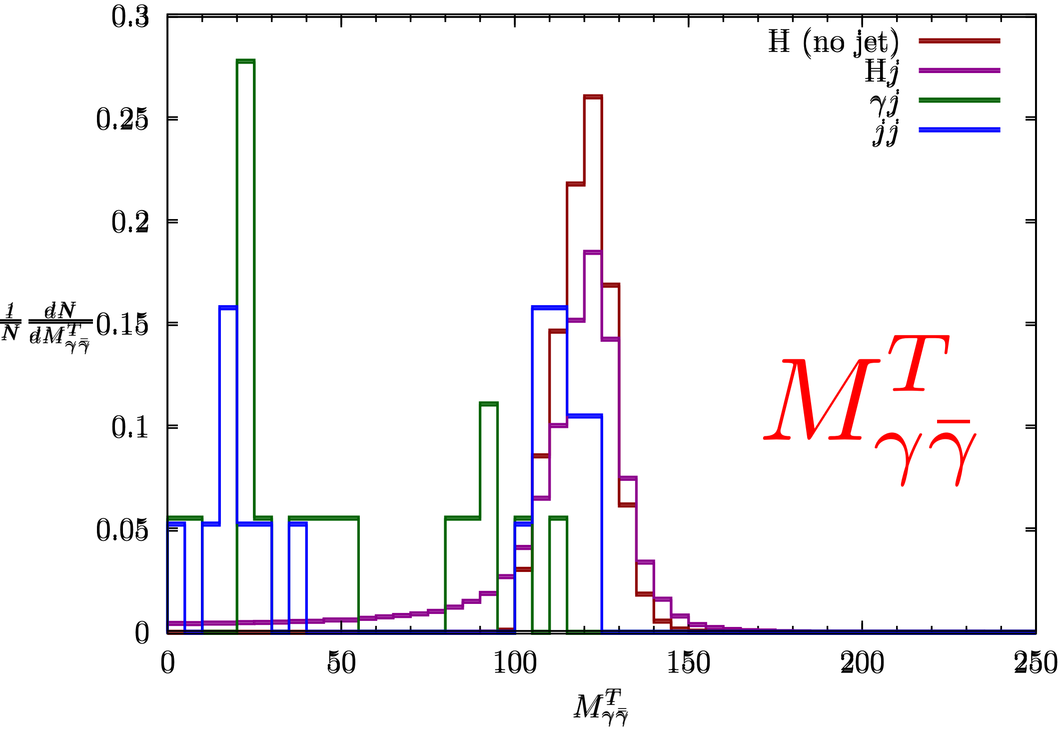
(parton-level analysis)

model-independent measurement of BR$_{DP}$!

resonant mono-photon signature at 14TeV

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





σ (fb)	$\sigma \times A$ [8 TeV]	$\sigma \times A$ [14 TeV]
$H \to \gamma\bar{\gamma}$ $\boxed{(\mathrm{BR}_{\gamma\bar{\gamma}} = 1\%)}$	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.

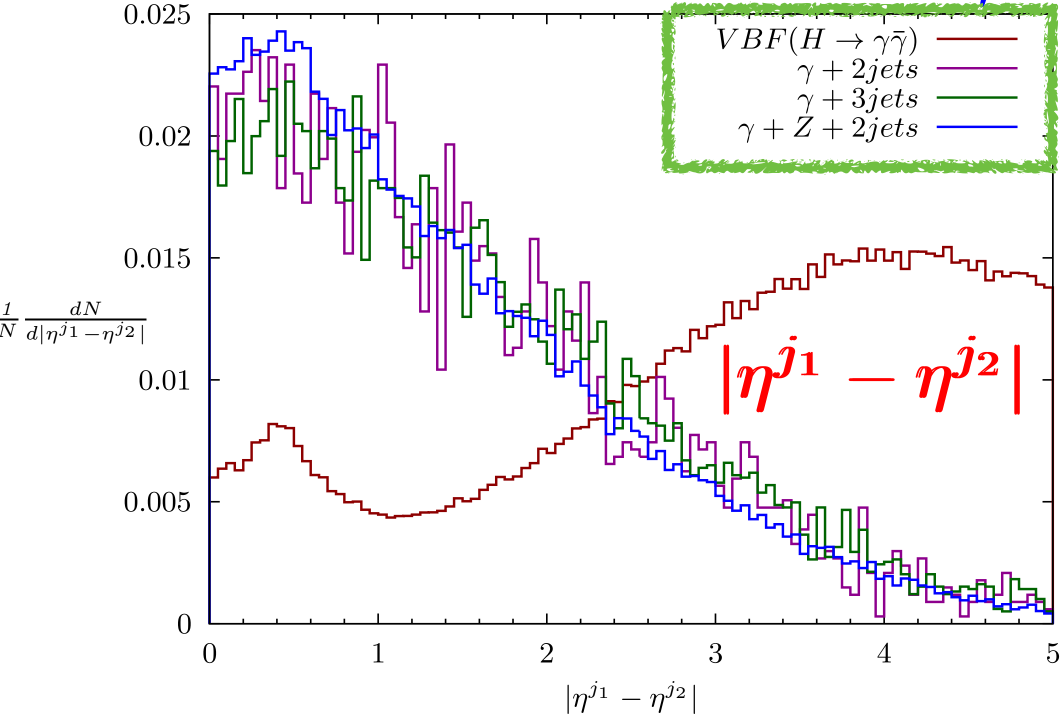
MadGraph5_aMC@NLO + PHYTIA (bckgr)
ALPGEN + PHYTIA (H signal)

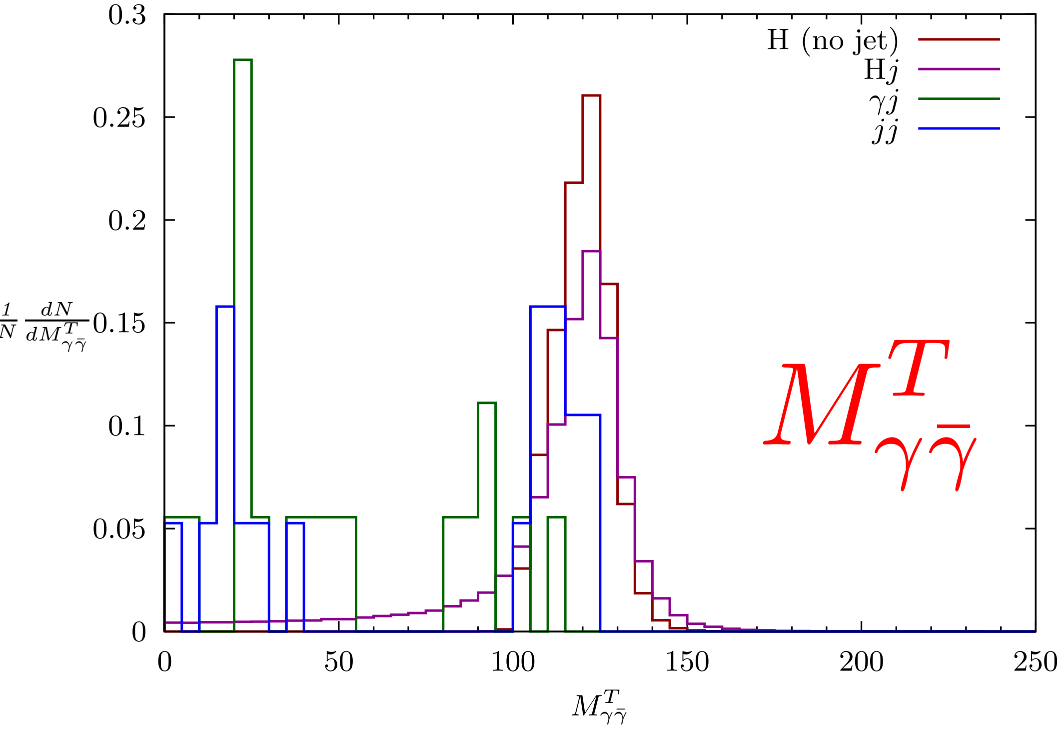
Biswas, Gabrielli, Heikinheimo, BM,
arXiv:1603.01377 (PRD)

mono-photon signature in VBF at 14TeV

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

two extra forward jets !





reference BR$_{DP}$

$\boxed{\mathrm{BR}_{\gamma\bar{\gamma}}=1\%.}$

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	$1.6\,\sigma$
$\Delta\phi(j_i, \not{E}_T) > 1.5$	1.82	6.9	2.16	37	$4.6\,\sigma$
both cuts	1.21	1.2	0.67	19	$4.5\,\sigma$

MadGraph5_aMC@NLO + PHYTIA
ALPGEN + PHYTIA

Discovery potential @ LHC 14 TeV

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

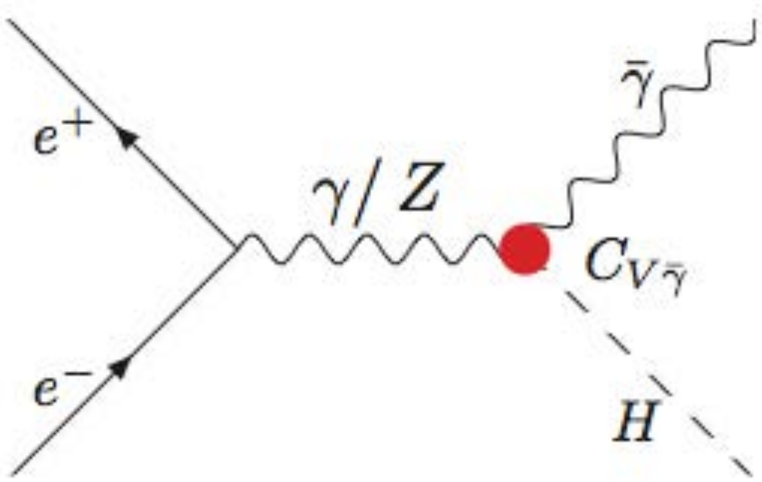
$\mathrm{BR}_{\gamma\bar{\gamma}}$ (%)	L=100 fb^{-1}		L=300 fb^{-1}		L=3 ab^{-1}	
Significance	3σ	5σ	3σ	5σ	3σ	5σ
$\mathrm{BR}_{\gamma\bar{\gamma}}(\mathrm{VBF})$	1.1	1.9	0.65	1.1	0.21	0.34
$\mathrm{BR}_{\gamma\bar{\gamma}}\,(ggF)$	0.096	0.16	0.055	0.092	0.017	0.029

gg fusion sensitive down to $\mathrm{BR}_{DP} \sim 10^{-4}$-$10^{-3}$

(VBF ~10 times worse …)

new Higgs signatures at e^+e^- colliders from stable dark photons

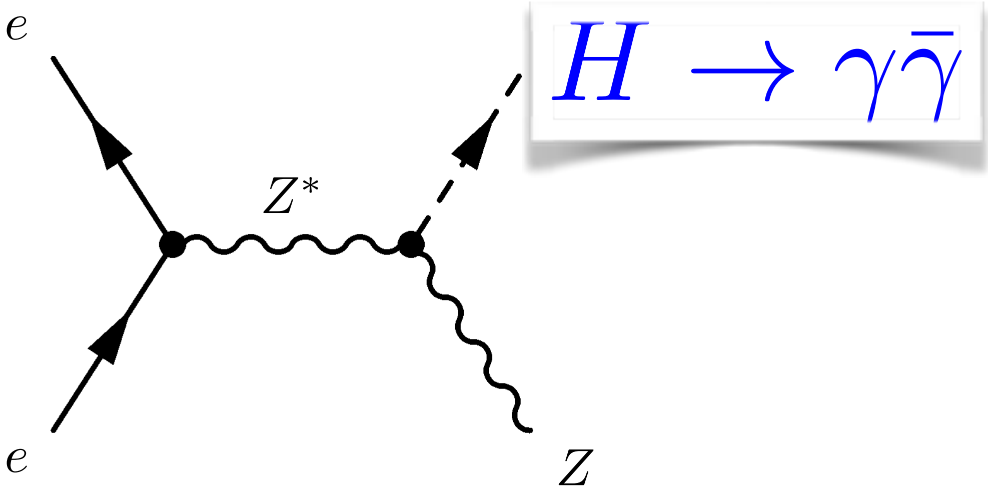
- **in H production :** $e^+e^- \to H\,\bar{\gamma} \to b\bar{b}\,\bar{\gamma}$



p_{Higgs} balanced by a massless invisible system

Biswas, Gabrielli, Heikinheimo, BM, arXiv:1503.05836 (JHEP)

- **in H decays :**



$$e^+e^- \to ZH \to Z\,\gamma\bar{\gamma}$$

(photon + E_{miss}) resonant signature

Biswas, Gabrielli, Heikinheimo, BM, in progress

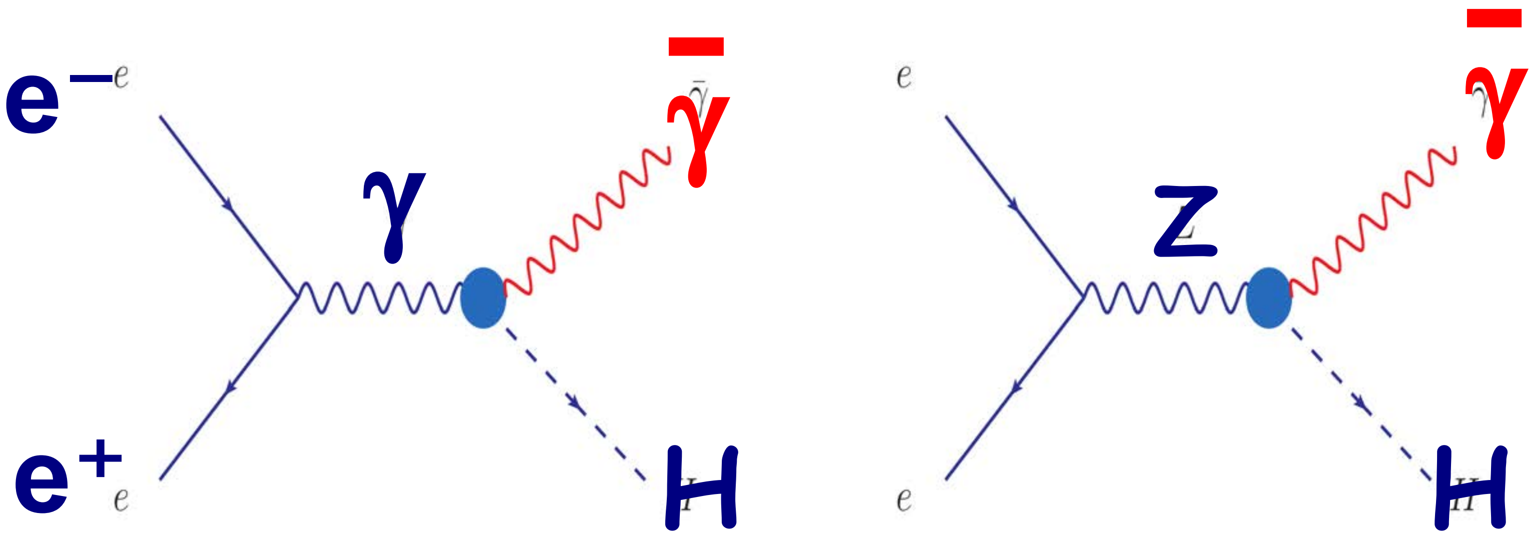
$e^+e^- \to H\,\bar{\gamma} \to b\bar{b}\,\bar{\gamma}$

Model independent analysis:

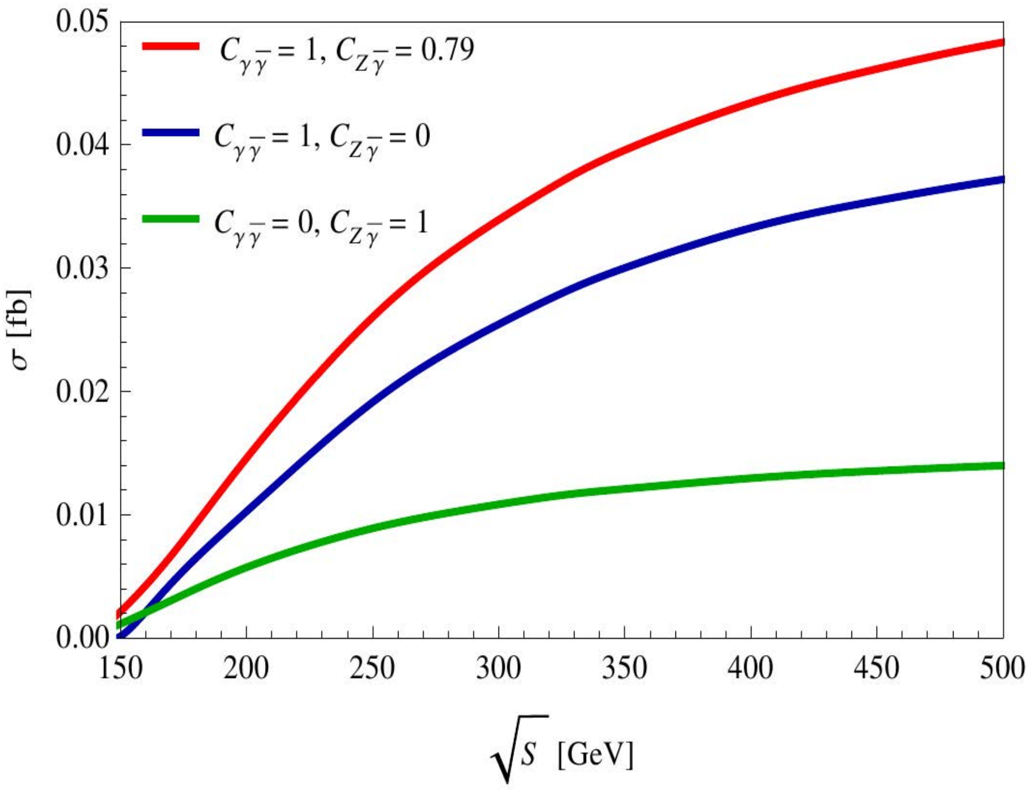
Effective Lagrangian parametrization

DP field strength

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



Total x-section



assuming mass degeneracy in Left and Right messeng

R=$C_{Z\gamma}/C_{\gamma\gamma}$

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

FCC-ee (~ ILC) : $\sqrt{S}$ = 240 GeV with $\int L \sim 10$ ab^{-1}

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

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

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

Irreducible

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

Reducible

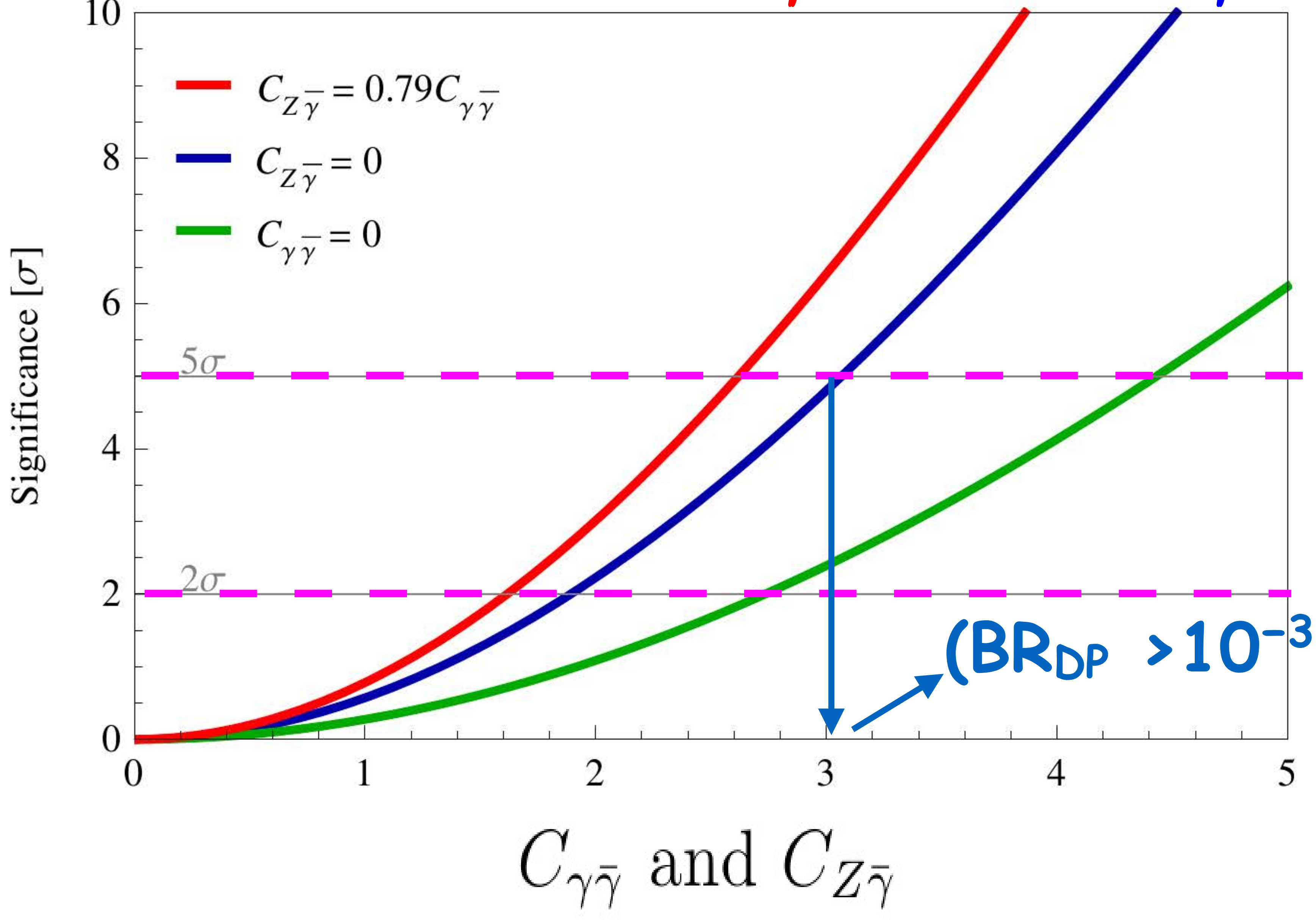
$\nu\bar{\nu}q\bar{q}$. Mostly from on-shell Z pairs

where two light jets are misidentified with two b-jets

we assume: b-tagging efficiency of 80%

fake b-jet rejection factor 1/100

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



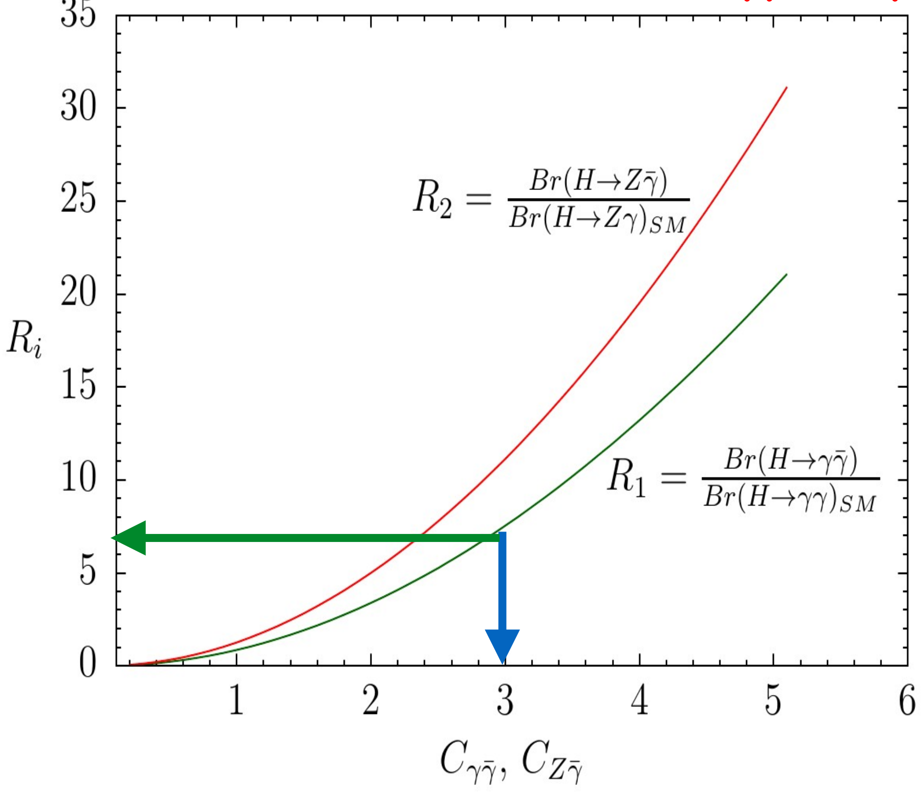
(BR_{DP} >10^{-3})

Significance for L=10ab-1

5σ

2σ

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

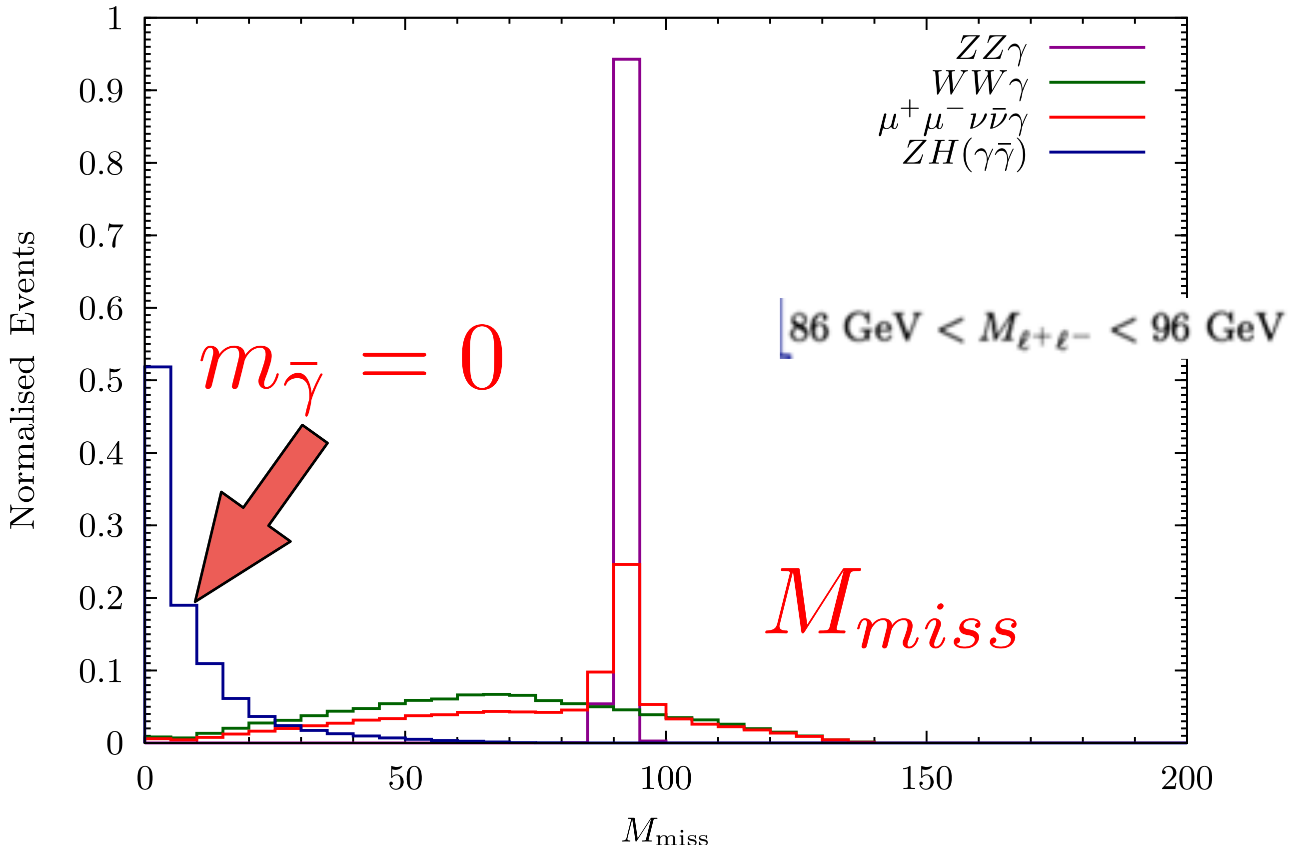


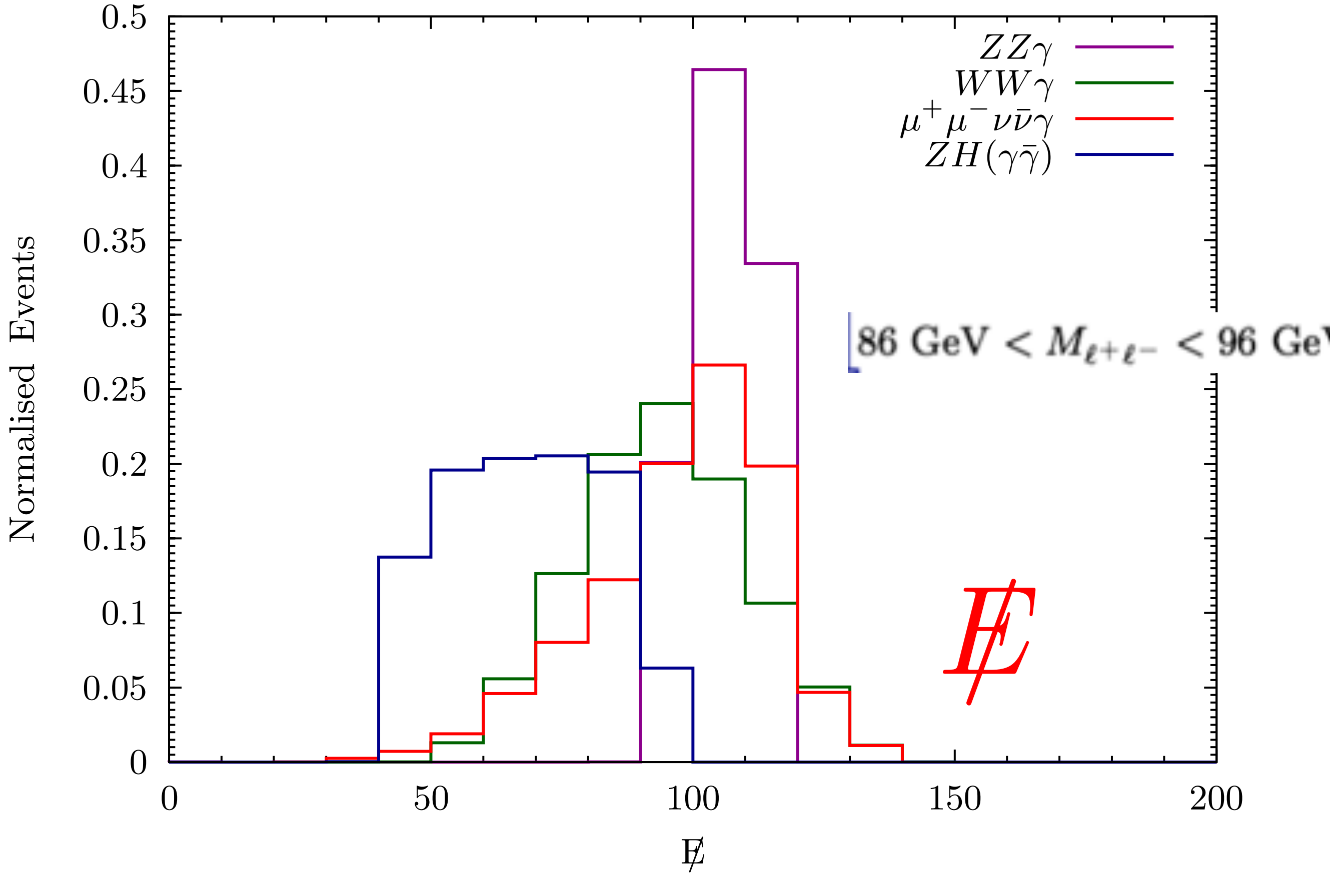
signif. = $S/\sqrt{S+B}$

5σ values of $C_{\gamma\bar{\gamma}}$ and $C_{Z\bar{\gamma}}$ in the natural range of predictions for the U(1)$_F$ Flavor model

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

Biswas, Gabrielli, Heikinheimo, BM
(preliminary)



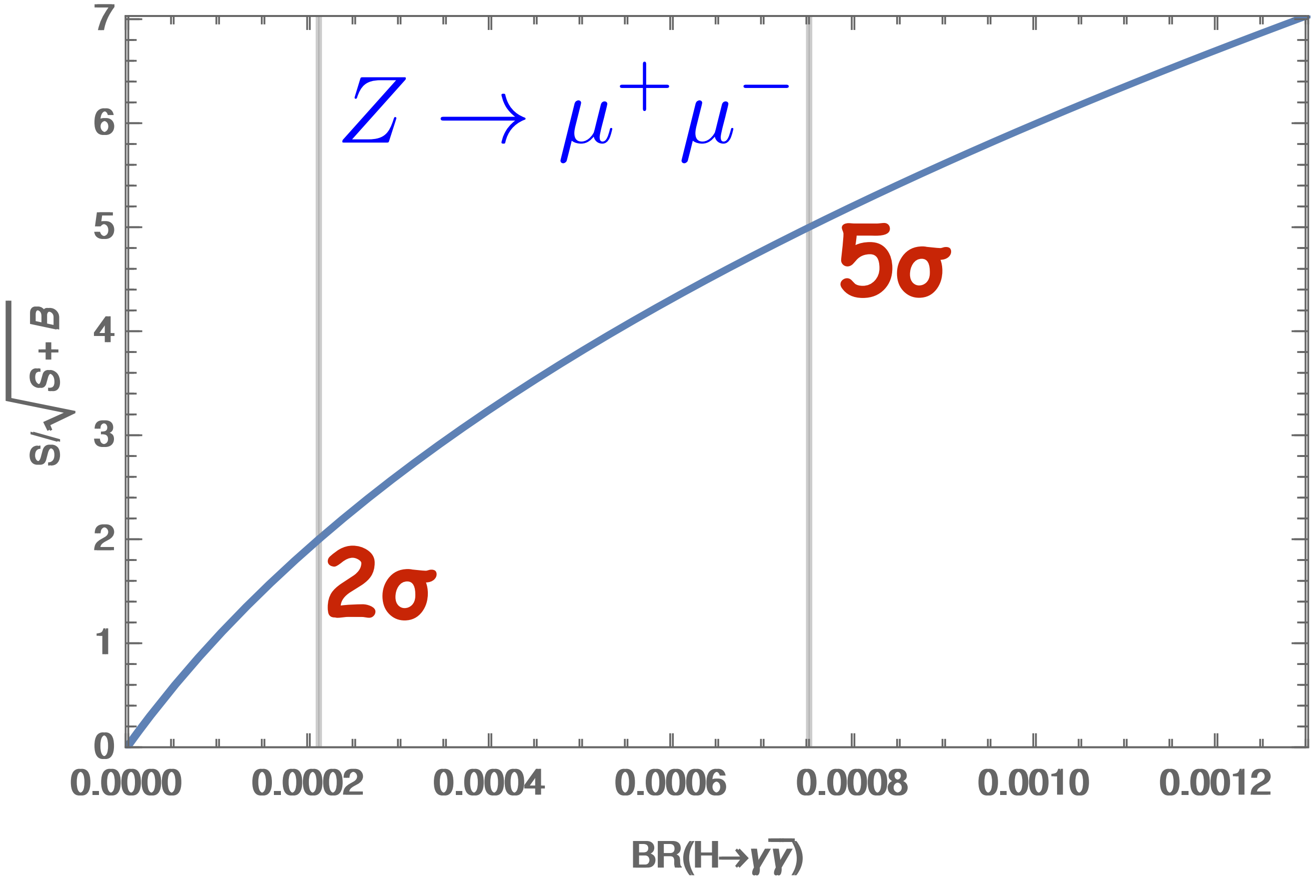


simulation :

PYTHIA for signal and MadGraph+PYTHIA for backgrounds

ISR/FSR effects described by PYTHIA

Finite detector resolutions for photon and muons according to ILD detector specifications in [arXiv:1605.00100]



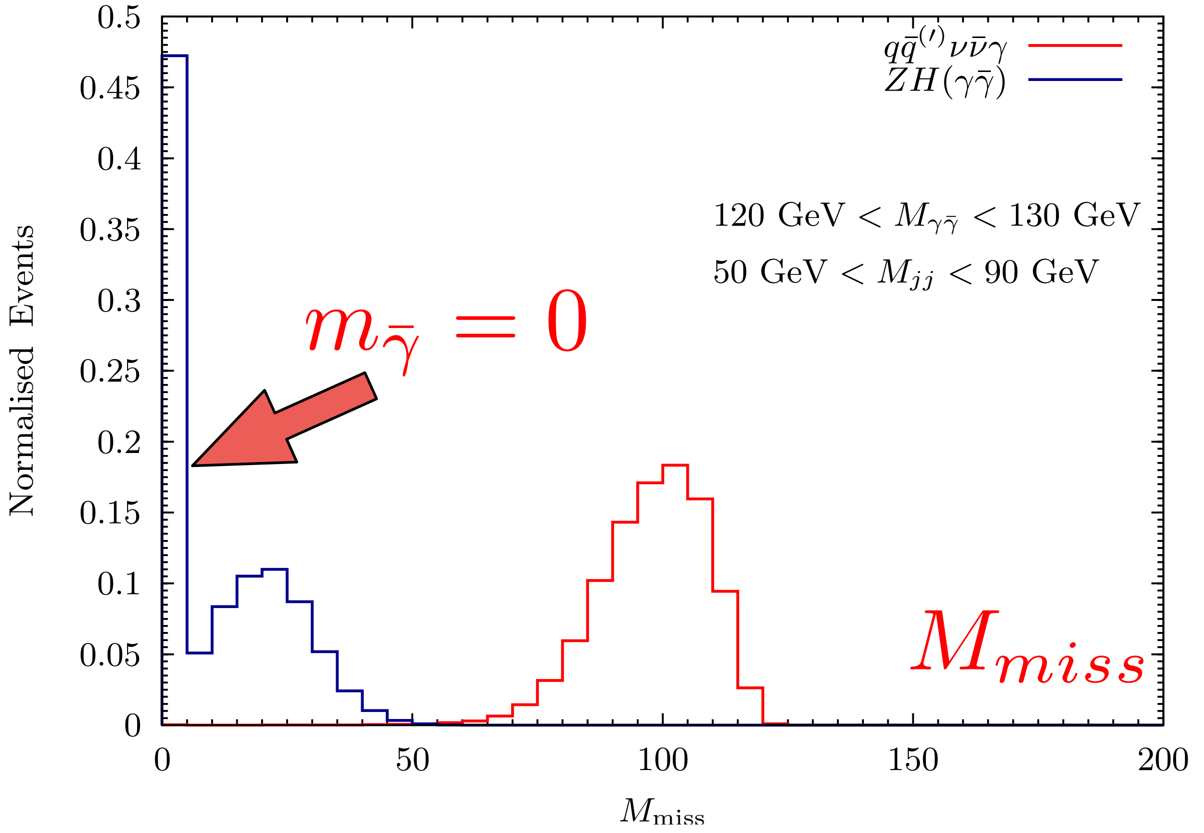
Biswas, Gabrielli, Heikinheimo, BM
(preliminary)

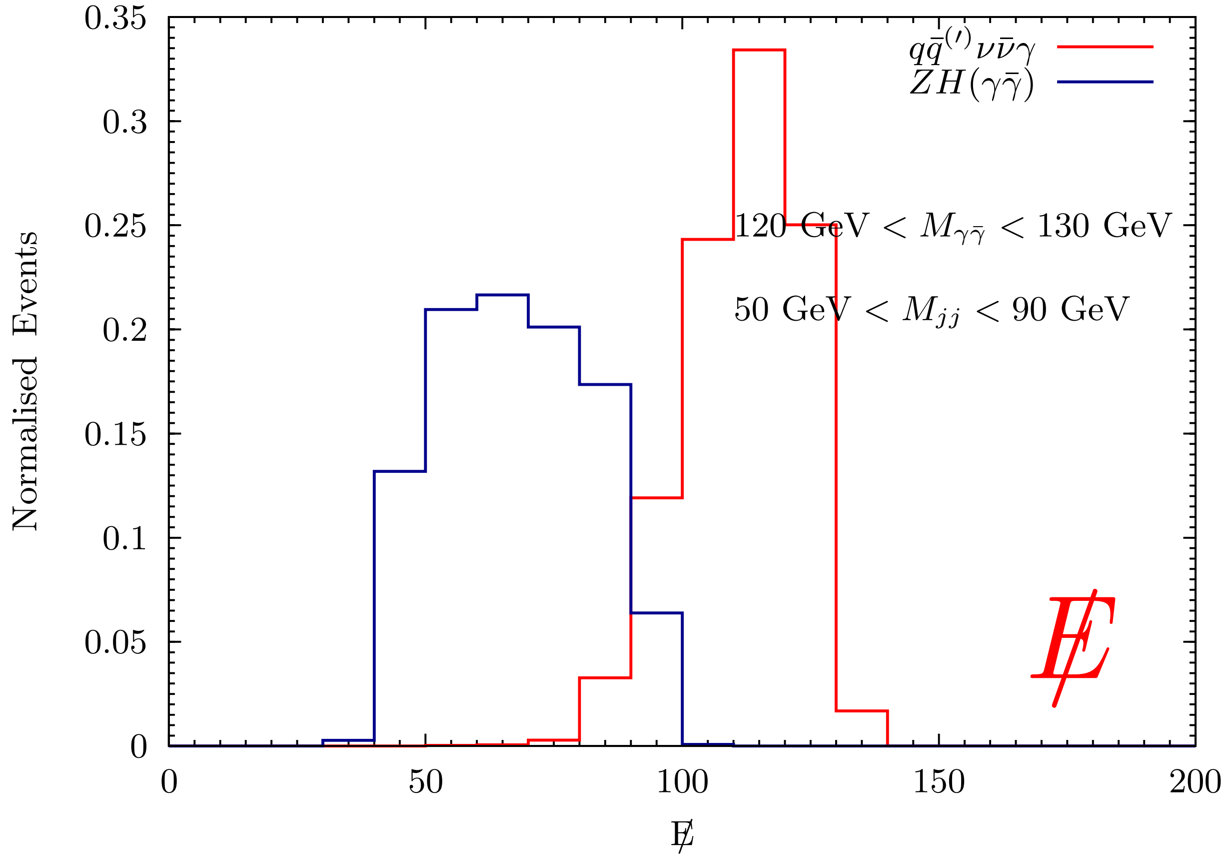
$\sqrt{S} = 240$ GeV $\int L \sim 10$ ab-1

leptonic and hadronic Z
show comparable potential :

5σ sensitivity for
$BR_{DP} \sim$ a few 10^{-4} !!!

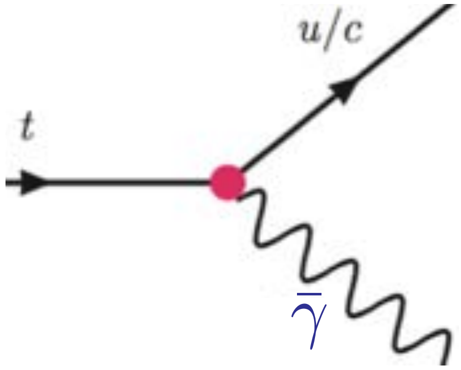
$$e^+e^- \to ZH \to qq\,\gamma\bar{\gamma}$$





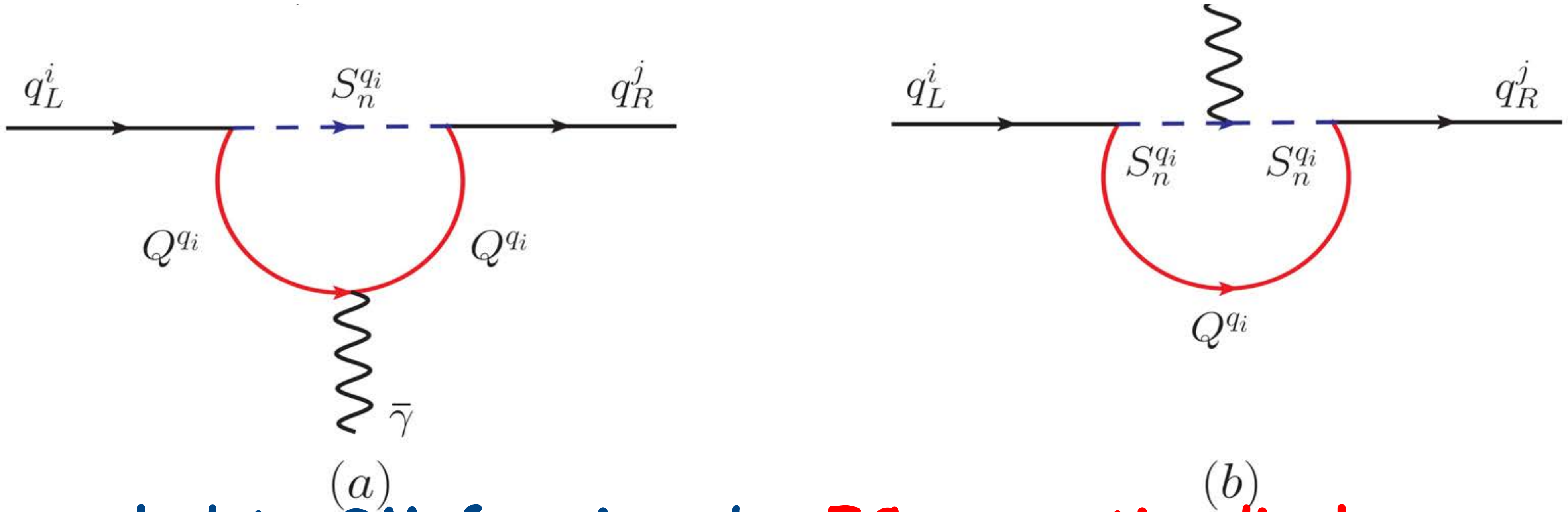
FCNC's mediated by Dark Photons

$t \to q\,\bar{\gamma}$



$b \to s\,\bar{\gamma}$ $\qquad$ $\ell \to \ell'\,\bar{\gamma}$

Gabrielli, BM, Raidal, Venturini
arXiv:1607.05928 (PRD)



- **DP coupled to SM fermions by FC magnetic-dipole operators**

$$\mathcal{L}_{\rm eff} = \sum_{q=U,D}\sum_{i,j=1}^{3}\left(\frac{1}{2(\Lambda_L^q)_{ij}}\left[\bar{q}_R^j(x)\sigma_{\mu\nu}\bar{F}^{\mu\nu}(x)q_L^i(x)\right] + \frac{1}{2(\Lambda_R^q)_{ij}}\left[\bar{q}_L^j(x)\sigma_{\mu\nu}\bar{F}^{\mu\nu}(x)q_R^i(x)\right]\right)$$

$\bar{\bar{F}}_{\mu\nu}$ = dark photon field strength

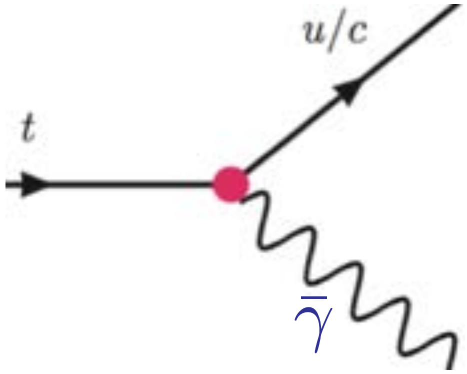
- suppressed by scales $\Lambda_{L,R}$ proportional to typical messenger mass scale

- Decay width $\quad \Gamma(q^i \to q^j\bar{\gamma}) \;=\; \dfrac{m_{q_i}^3}{16\pi^3}\left(\dfrac{1}{(\Lambda_L^q)_{ij}^2} + \dfrac{1}{(\Lambda_R^q)_{ij}^2}\right)$

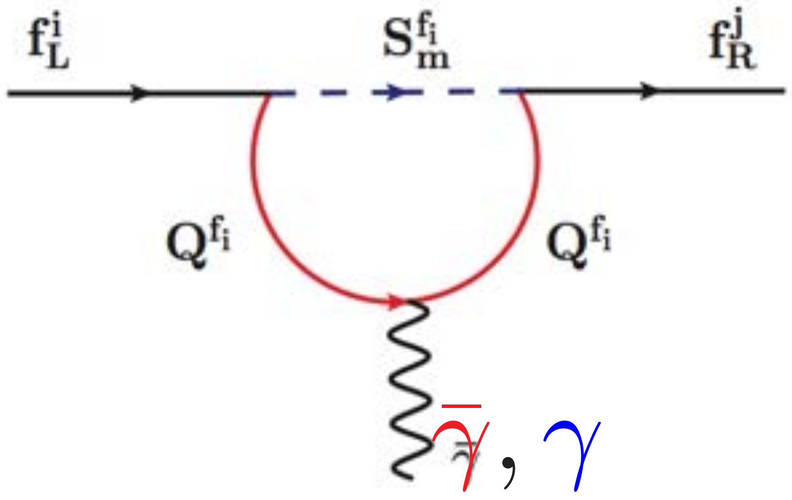
connection with FCNC's mediated by photons

$$t \to (c,u)\,\bar{\gamma}$$

$t \to q\,\bar{\gamma}$ versus $t \to q\,\gamma$



same for $b \to s\,\bar{\gamma}$
versus $b \to s\,\gamma$



new heavy states in loops contribute
with same flavor matrix (but different U(1) charges)
to FCNC decays into photon and dark photon

$$\mathrm{BR}(t \to (c,u)\,\bar{\gamma}) \;=\; \frac{\bar{\alpha}}{\alpha}\left(\frac{q_3^U\, f_2(x_3^U, \xi_U)}{e_U\, \bar{f}_2(x_3^U, \xi_U)}\right)^2 \mathrm{BR}(t \to (c,u)\,\gamma)$$

LHC (present bounds):

$$\mathrm{BR}^{\mathrm{exp}}(t \to u\,\gamma) \;<\; 1.3 \times 10^{-4}$$
$$\mathrm{BR}^{\mathrm{exp}}(t \to c\,\gamma) \;<\; 1.7 \times 10^{-3}$$

$$\Rightarrow$$

$$\mathrm{BR}^{(t \to u\gamma)}(t \to u\,\bar{\gamma}) \;<\; 1.8 \times 10^{-2}\left(\frac{\bar{\alpha}}{0.1}\right)$$
$$\mathrm{BR}^{(t \to c\gamma)}(t \to c\,\bar{\gamma}) \;<\; 2.3 \times 10^{-1}\left(\frac{\bar{\alpha}}{0.1}\right)$$

but … imposing vacuum-stability and dark-matter bounds
gives BR($t \to q\,\bar{\gamma}$) < 10^{-4}

further upper bounds from $f \to f'\gamma$ constraints

$$\mathrm{BR}^{\mathrm{exp}}(\bar{B} \to X_S\gamma) \;=\; (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$$

⇒

$$\mathrm{BR}^{(b\to s\gamma)}(b \to s\,\bar{\gamma}) \;<\; 8.5 \times 10^{-3}\left(\frac{\bar{\alpha}}{0.1}\right)$$

$$\mathrm{BR}(\tau^- \to e^-\gamma) \;<\; 3.3 \times 10^{-8}$$

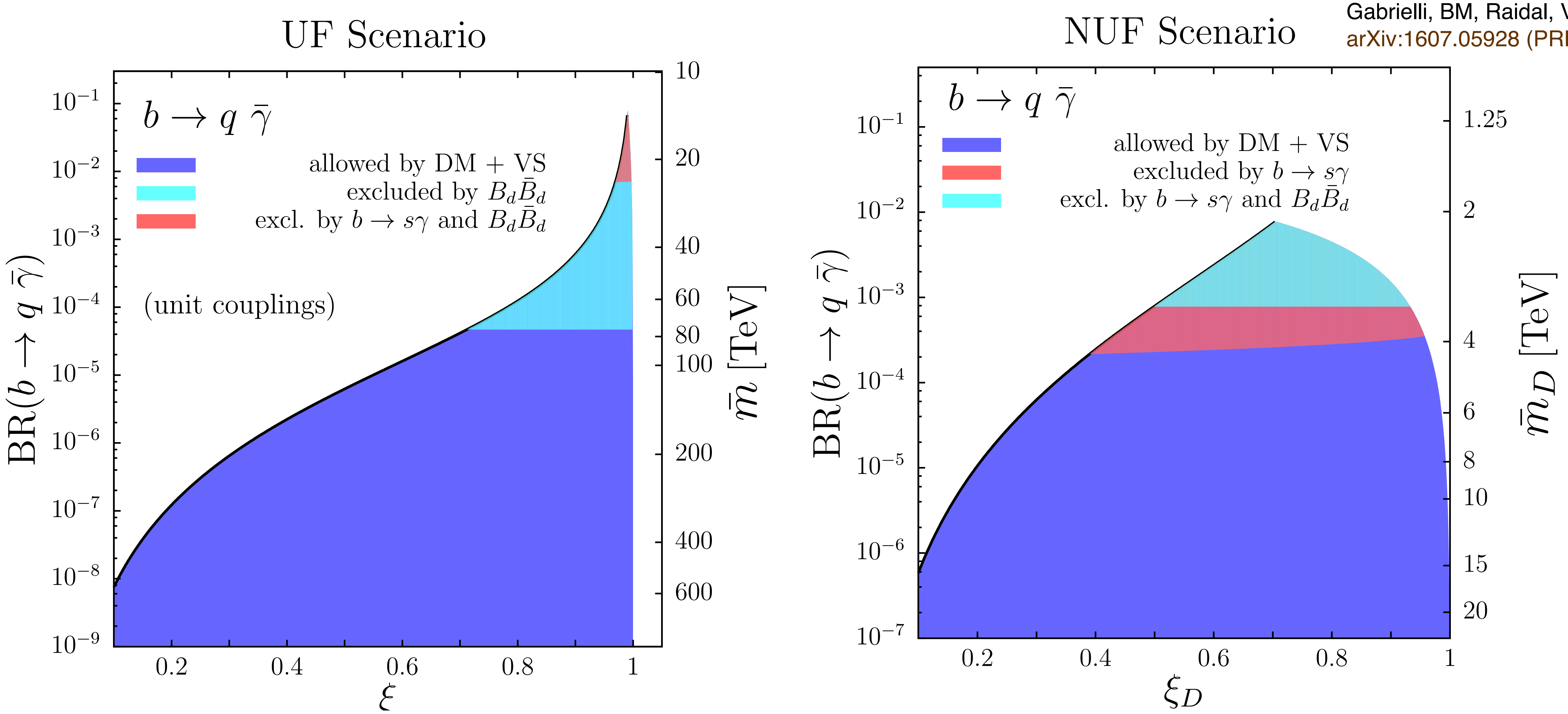
$$\mathrm{BR}(\tau^- \to \mu^-\gamma) \;<\; 4.4 \times 10^{-8}$$

⇒

$$\mathrm{BR}^{(\tau\to\mu\gamma)}(\tau \to \mu\,\bar{\gamma}) \;<\; 5.9 \times 10^{-6}\left(\frac{\bar{\alpha}}{0.1}\right)$$

$$\mathrm{BR}^{(\tau\to e\gamma)}(\tau \to e\,\bar{\gamma}) \;<\; 1.1 \times 10^{-5}\left(\frac{\bar{\alpha}}{0.1}\right)$$

U(1)$_F$-flavour model predictions for BR($b \to q\,\bar{\gamma}$)



Gabrielli, BM, Raidal, Venturini
arXiv:1607.05928 (PRD)

- **Large and possibly measurable BR's are allowed in most cases**
  - BR(t → q $\bar{\gamma}$) ~ 10^{-10} - 10^{-7}
  - BR(b → q $\bar{\gamma}$) ~ 10^{-5}-10^{-4}
  - BR(c → u $\bar{\gamma}$) ~ 10^{-8} - 10^{-4}
  - BR(τ → l $\bar{\gamma}$) ~ 10^{-10} - 10^{-6}
  - BR(μ → e $\bar{\gamma}$) ~ 10^{-10} - 10^{-6}

depending on various parameters and on flavor universality structure of messenger sector new class of (very distinctive) FCNC signatures at ee colliders

$$f \to f' \bar{\gamma}$$

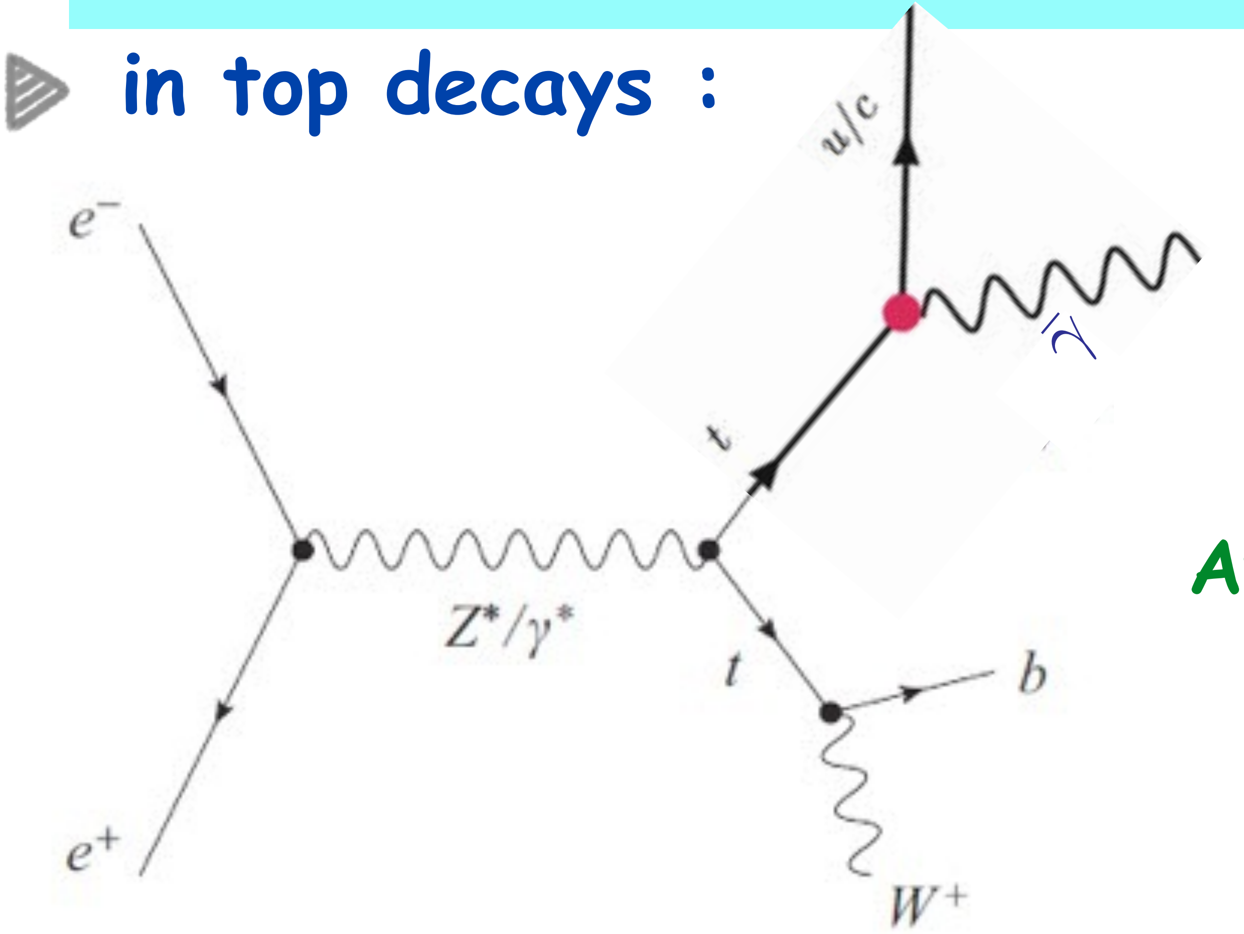
for light fermions : $E_{miss} \sim E_{f'} \sim E_f/2$

Sensitivity is likely just limited by statistics !

at FCC-ee →

10^6 top pairs ➜ $BR_{top} \sim 10^{-5}$
10^{11} b pairs ➜ $BR_b \sim 10^{-10}$
10^{10} tau pairs ➜ $BR_{tau} \sim 10^{-9}$

- in top decays :



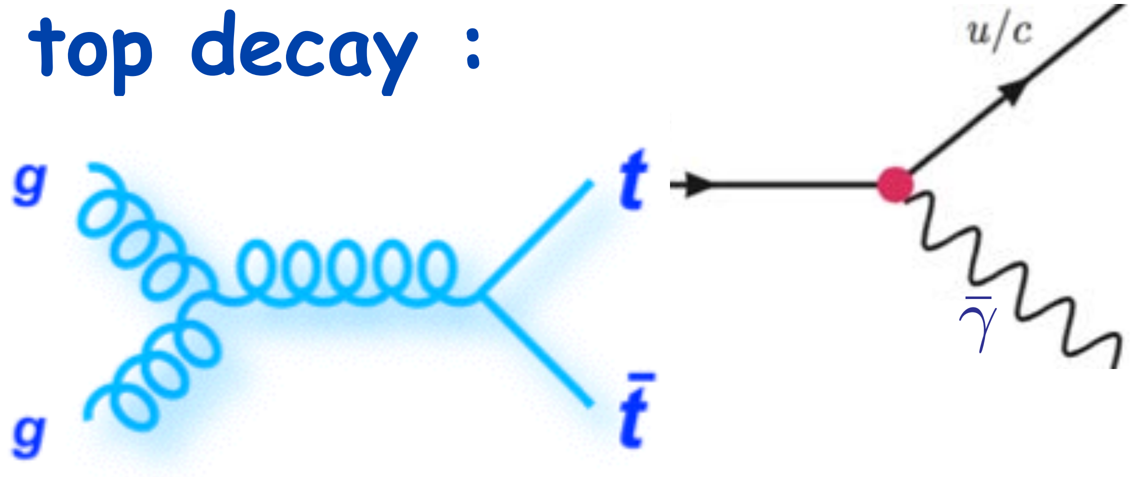
"top" + (mono-j + E_{miss})
resonant at m_{top}

At tt threshold : ~ large monochr. E_{miss}
$E_{miss} \sim E_q \sim m_{top}/2$

Biswas, Gabrielli, BM, in progress

→ at LHC new FCNC signatures in BOTH top decay AND top production

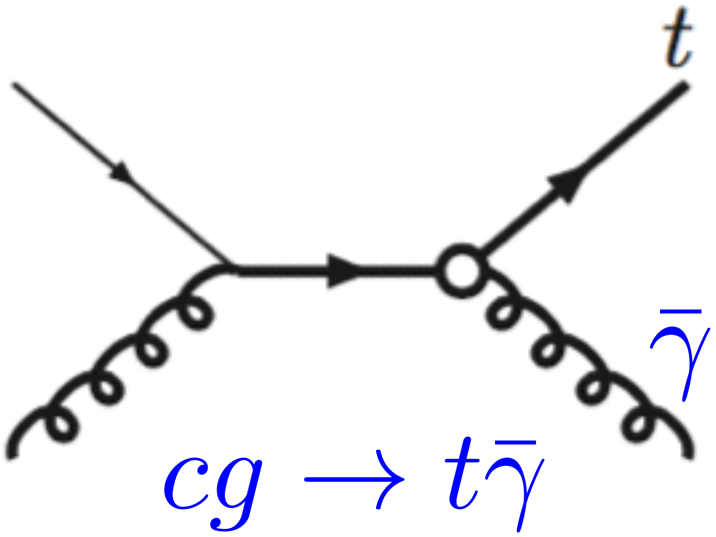
- in top decay :



"top" + (mono-j + E^T_{miss}) resonant at m_{top}

[stop-like, for massless χ^0]

- in top production :



"top" plus **massless** invisible system

in ATLAS,arXiv:1410.5404
and CMS-PAS-EXO-16-040
no constraint on M_{inv}

Outlook

- Hidden Sectors fruitful (and theoretically-consistent) way to parametrise our ignorance about what is missing in SM
  - useful also for devising new kinds of exp. signatures to boost LHC potential for BSM discovery
- massless Dark Photon theoretically appealing (evading most of present experimental bounds on massive DP !)
- Higgs boson can be the SM portal to DP's : new effective vertices involving DP can appear from HS explaining Flavor Hierarchy (or possibly other BSM …)
- new class of FCNC signatures from top, b, c, tau, mu decays into a massless dark photon
  - very distinctive → bounds expected to be mostly limited by statistics !
- rich phenomenological implications @ LHC and ee colliders
- potential implications for astroparticle/cosmology yet to work out !