LNF Autumn Institute II :
Testing the Standard Model at low and high energies
Frascati, 28 November 2017

focus on LHC, FCC, NA62

Searching for massless Dark Photons

based on :

M.Fabbrichesi, E.Gabrielli, BM, PRL 119 (2017) 031801

E.Gabrielli, BM, M. Raidal, E. Venturini, PRD 94 (2016) 115013

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

INFN Roma

Barbara Mele

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 → boosts discovery potential in a model-independent way
- Hidden/Dark (SM-uncharged) Sectors can provide new signatures not covered by present searches

four paths to advance in HEP today (ATLAS/CMS):

* by exploring the characteristics of the Higgs sector and confirming/spoiling the SM picture
  (primary relevance since the Higgs sector is so critical !)
* by searching for new heavy states coupled to the SM acting as a cut-off for the SM
  [possibly solving the naturalness issues and/or non-SM phenomena (dark matter, ...)]
* by exploring $\Lambda >> o(1\text{TeV})$ indirect effects through high-accuracy studies of SM x-sections/distributions and searches for rare processes (EFT parametrization)
* by looking for new DARK states (uncoupled to the SM at tree level) either in production or/and heavy-state (t,H...) decays (elusive signatures, maybe long-lived p.les)

four paths to advance in HEP today (ATLAS/CMS):

* Higgs
* new particles
* indirect effects
* Dark signals

* every single method is of fundamental importance to make progress !

Outline (Dark Photon → DP)

* what's peculiar to a massless DP's
* Hidden Sectors with unbroken extra U(1)
  → predicting massless DP's
* Higgs decays into massless DP's
* new Higgs signatures from DP's at colliders
* FCNC mediated by DP's
* massless DP's in kaon decays
* 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
- previous pheno studies mainly involving "massive" DP's
- 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 !

DP's may have a relevant role in Cosmology and Astrophysics

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

possible role in galaxy formation and dynamics:

- 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 Astro-particle Physics :

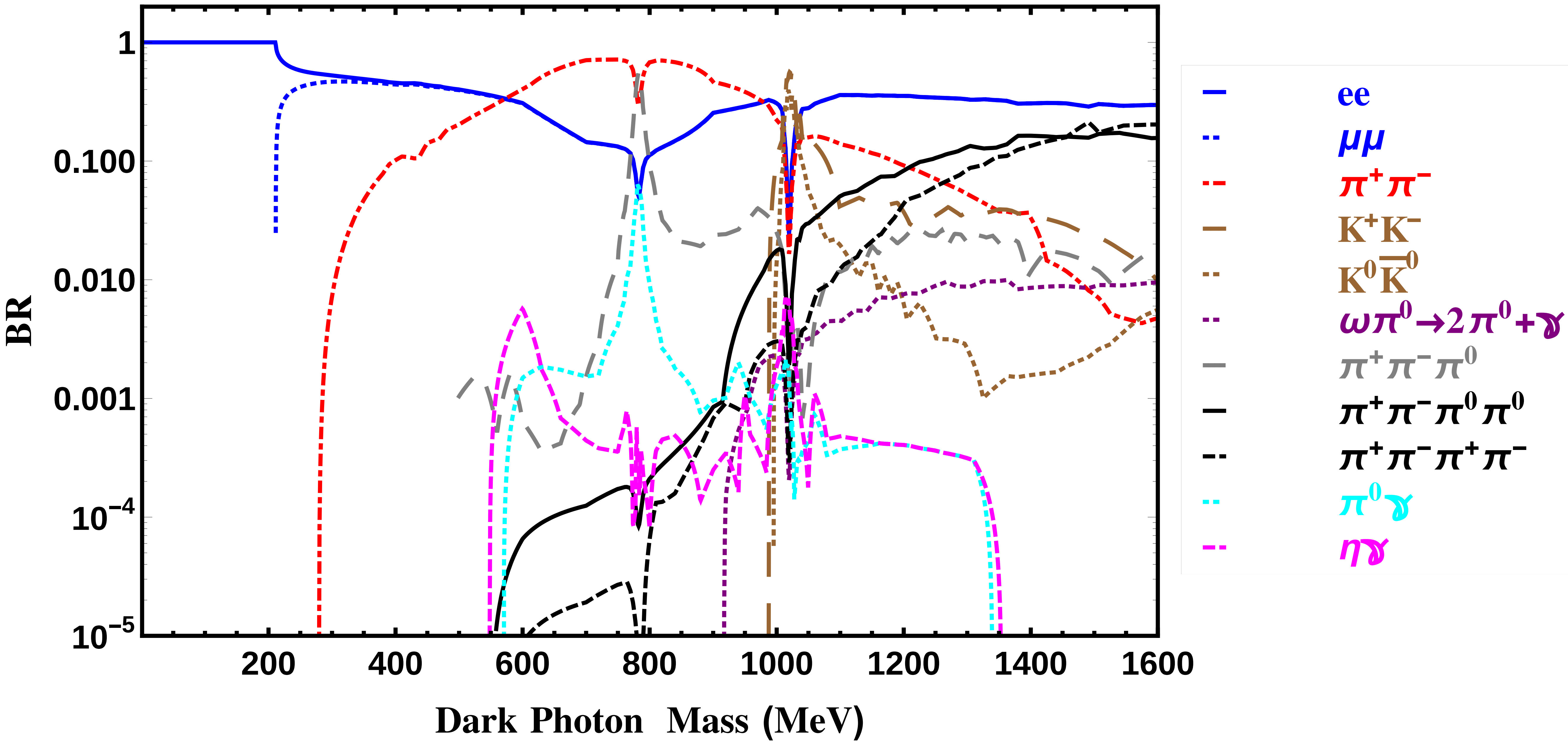
- may induce Sommerfeld enhancement of DM annihilation cross section
  (from PAMELA-Fermi-AMS2 positron anomaly) N.Arkani-Hamed, D.P. Finkbeiner, T.R. Slatyer, N.Weiner. PRD 79 (2009)
- may assist DM annihilations for the required magnitude making asymmetric DM scenarios viable

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

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

visible massive DP's decays

arXiv:1412.1485



strategies of massive-DP (A') searches

- **Bremsstrahlung:** $e^- Z \to e^- Z A'$,

  e- incident on a nuclear target (also $p\, Z \to p\, Z A'$)

- **Annihilation:** $e^+e^- \to \gamma A'$

  (favored for invisible A' decays)

- **Meson decays:** Dalitz decays, $\pi^0/\eta/\eta' \to \gamma A'$, and

  rare meson decays such as

  $K \to \pi A'$, $\varphi \to \eta A'$, and $D^* \to D^0 A'$,

  (A' mass reach limited by parent meson mass)

- **Drell-Yan:** $q\bar{q} \to A' \to l^+l^-$ (or h^+h^-)

strategies of massive DP detection

- Bump hunt in visible

  final-state invariant mass: $A' \to l^+l^-$ or $A' \to h^+h^-$

- Bump hunt in missing-mass

  in $e^+e^- \to \gamma A'$ or meson decay production channels

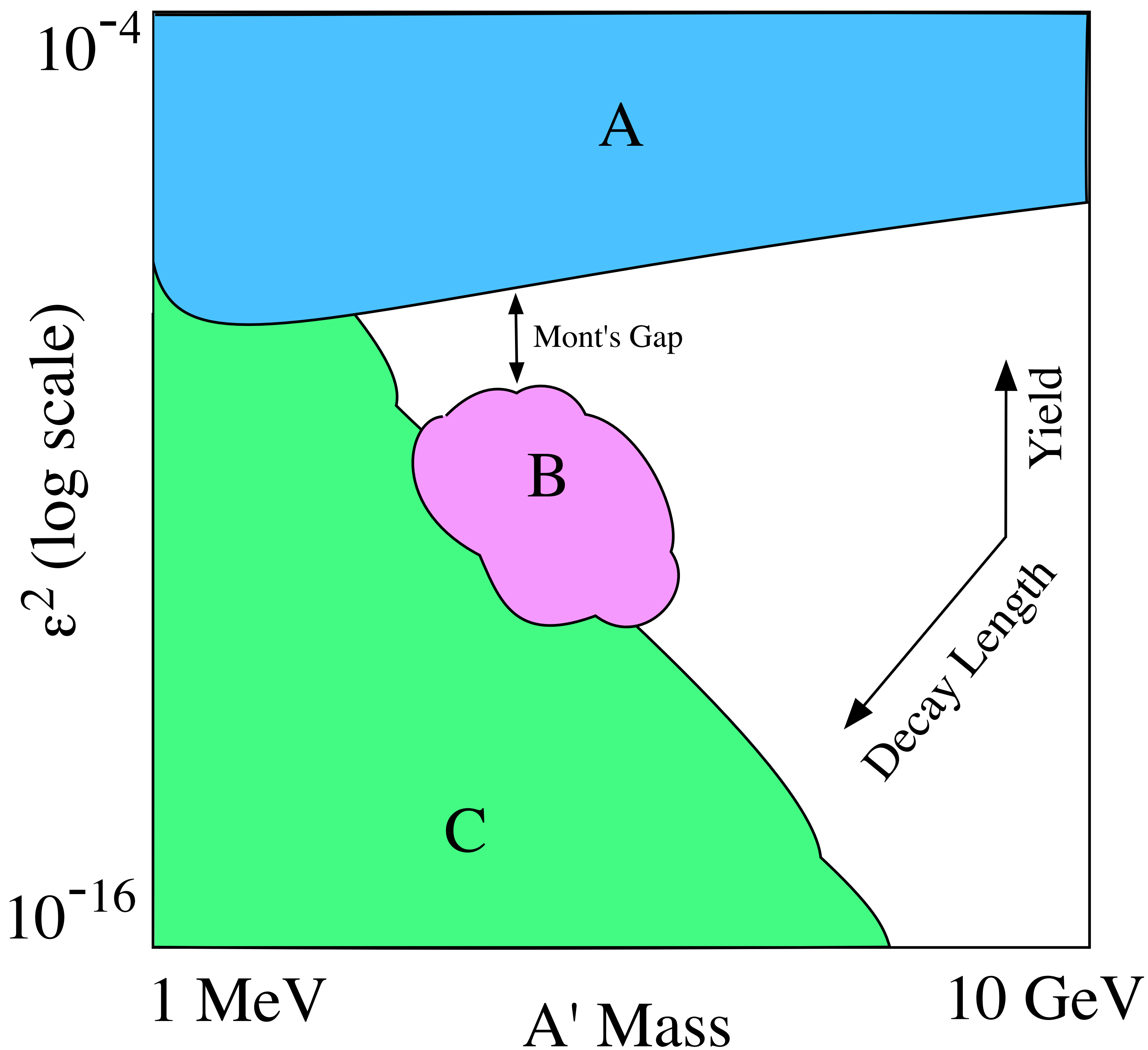
- Vertex detection in $A' \to l^+l^-$;

$$\mathcal{L}_{\text{kin.mix.}} = \frac{1}{2}\epsilon F^{\mu\nu}F'_{\mu\nu}$$

A' decay length scales with $1/(\varepsilon^2 m_{A'})$,

→ searches for displaced vertices in visible decay modes probe the very low-ε regions of parameter space.

A' search strategies vs (ε^2, $m_{A'}$)



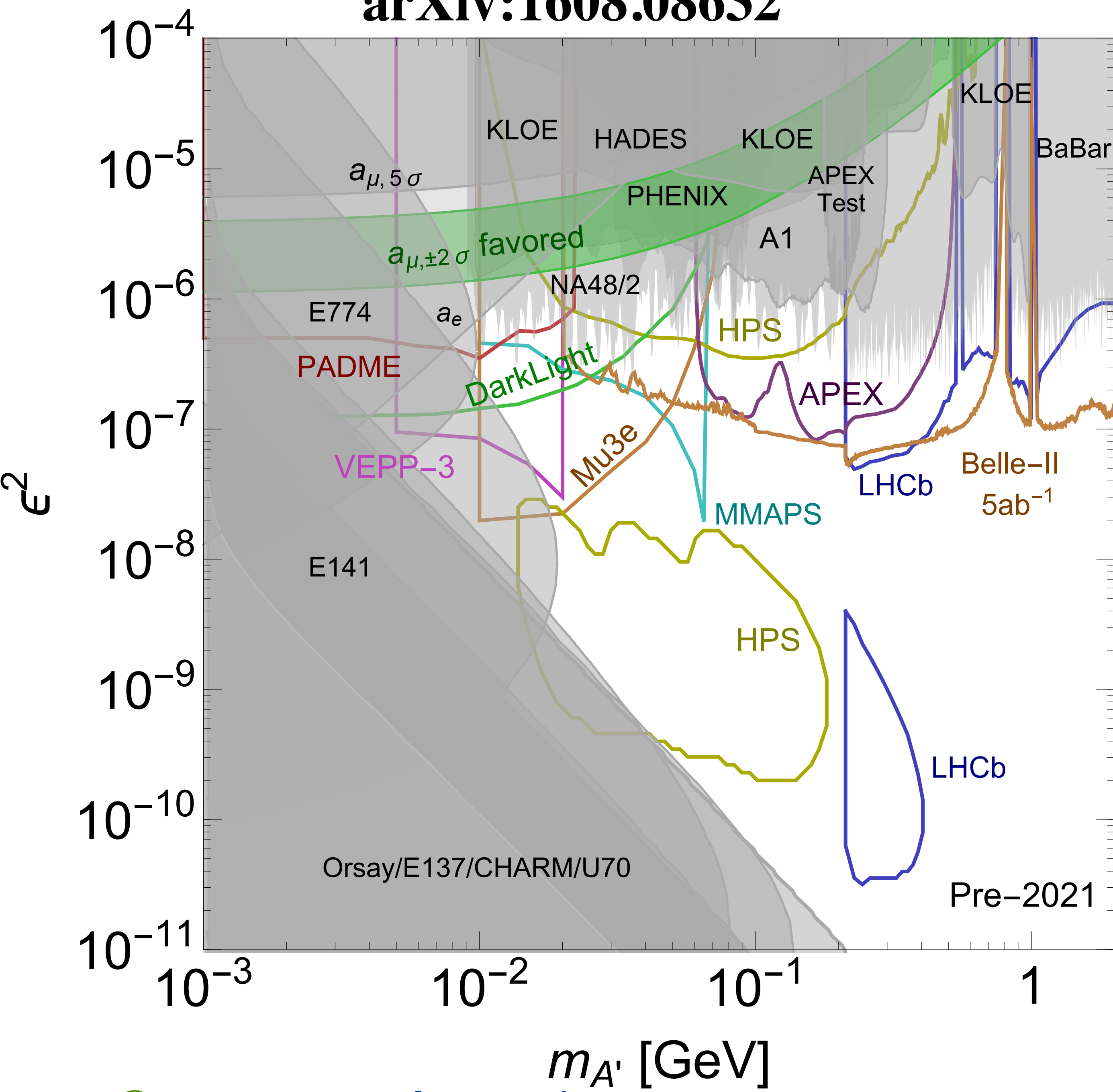
bump hunt
(visible/invisible)

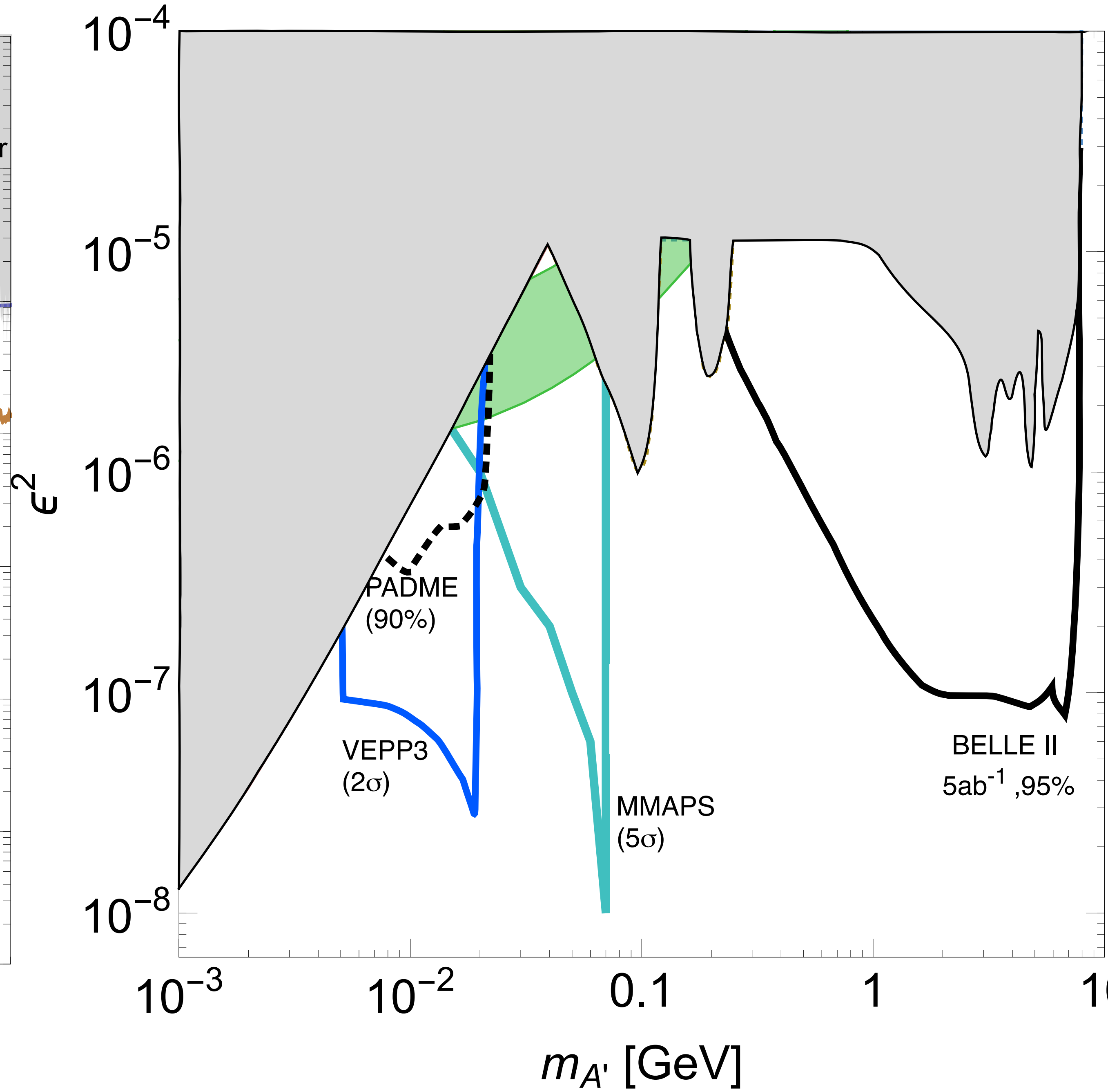
displaced vertex
(short decay length)

displaced vertex
(long decay length)

present constraints (gray dashed area)

arXiv:1608.08632





* visible decays
* invisible decays (significant BR to dark-sector)

many ongoing and proposed experiments !

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

what if dark photon mass vanishes ?

B. Holdom, *Phys. Lett.* **166B** (1986) 196

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

massive	massless
direct coupling to SM	**no** direct coupling to SM
$\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$	only higher dimensional operators
⬇	⬇
$g' q_f \bar{\psi}_i \gamma^\mu \psi_f A'_\mu$	$\frac{g}{\Lambda} \bar{\psi} \sigma^{\mu\nu} \psi \bar{F}_{\mu\nu}$

➡ massless DP's then interact with the 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 !

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

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

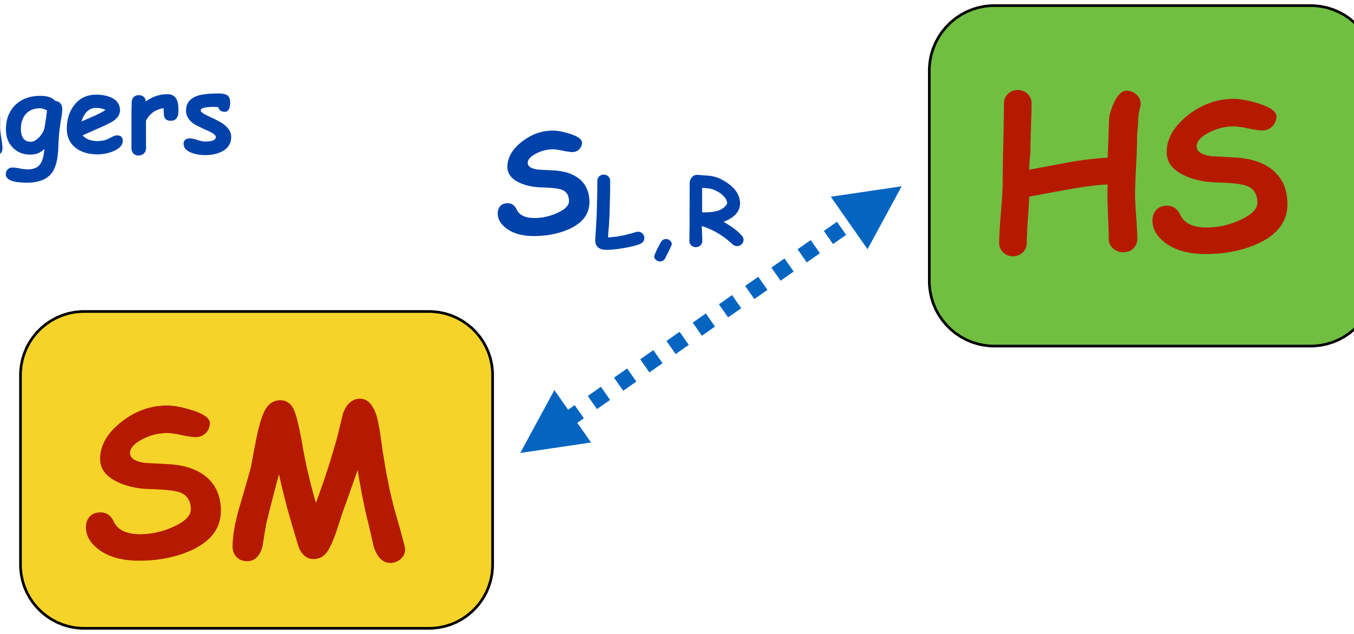
$$M_{D_f} \sim \exp\left(-\frac{\kappa}{q_{D_f}^2 \bar{\alpha}}\right)$$

DP coupling

- Dark fermions as dark-matter candidates

heavy scalar messengers $S_{L,R}$ sector

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



Messengers (Scalars)

Dark Sector (Fermions+ singlet 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

DP production mechanism ?

massless Dark Photon signature

if produced in collisions :

→ stable + noninteracting

→ neutrino-like signature

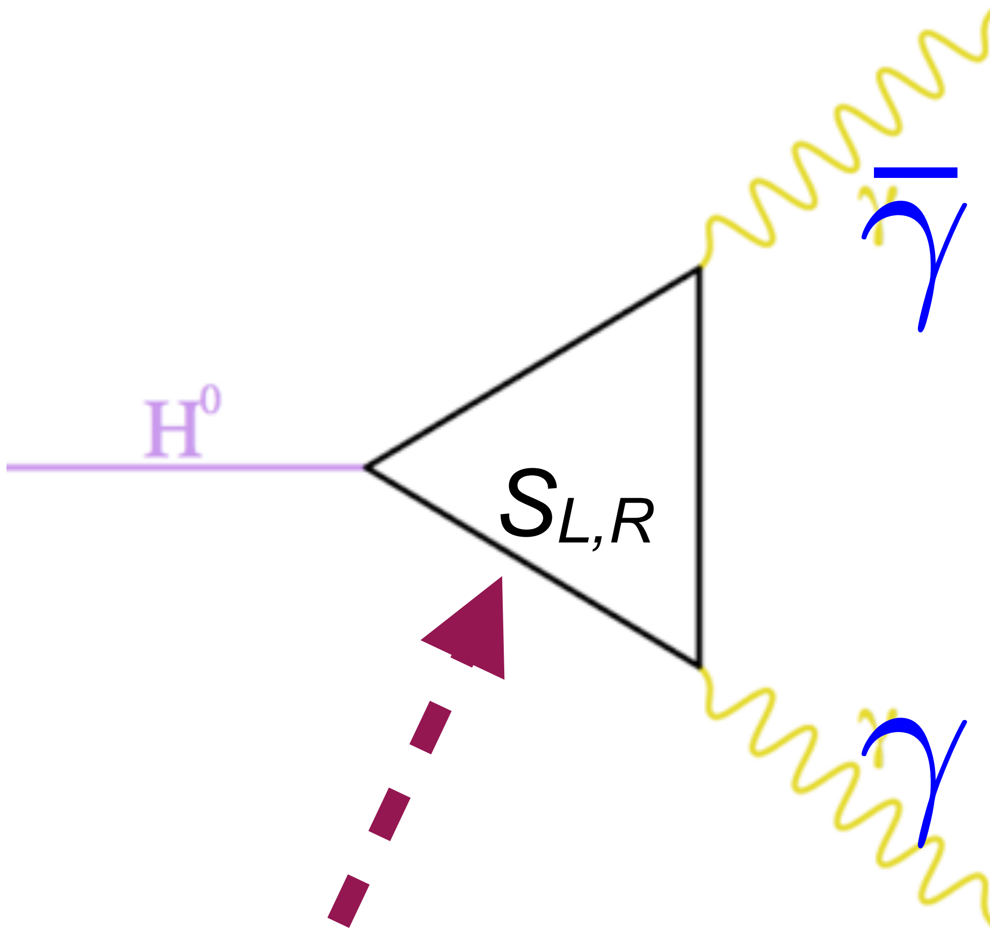
Higgs as a "source" of Dark Photons

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

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:

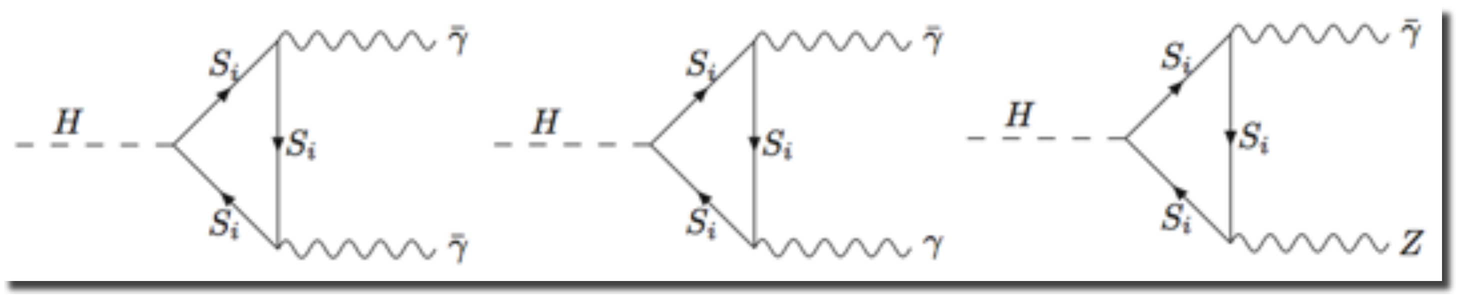
$$\Gamma(H \to \gamma\bar{\gamma}) \sim \frac{1}{M^2_{Heavy}} \to \frac{1}{v^2}$$

→ plenty of new signatures at colliders involving stable dark photons

exploration just started !

massless and invisible → ν-like

- in H decays : $H \to \gamma\bar{\gamma}$

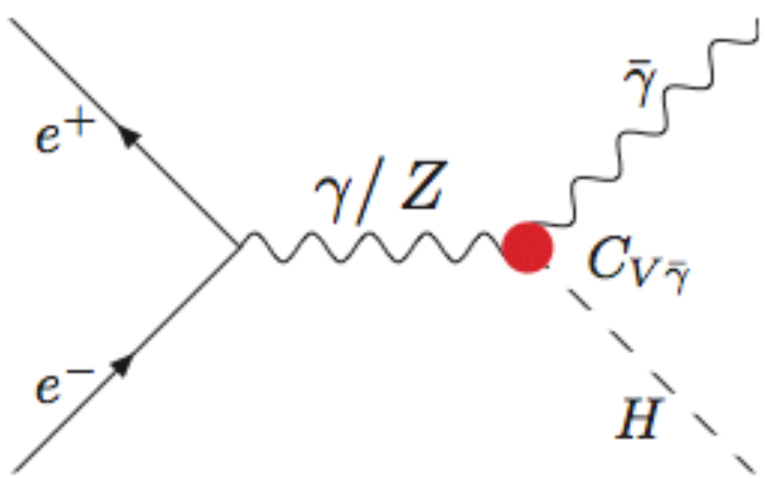


mono-photon resonant signature

Higgs non-decoupling effects (just as in SM) can enhance BR

Gabrielli, Heikinheimo, BM, Raidal, arXiv:1405.5196

- in H production



Higgs momentum balanced by a massless invisible system

Biswas, Gabrielli, Heikinheimo, BM, arXiv:1503.05836

resonant mono-photon signature at 8 TeV

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

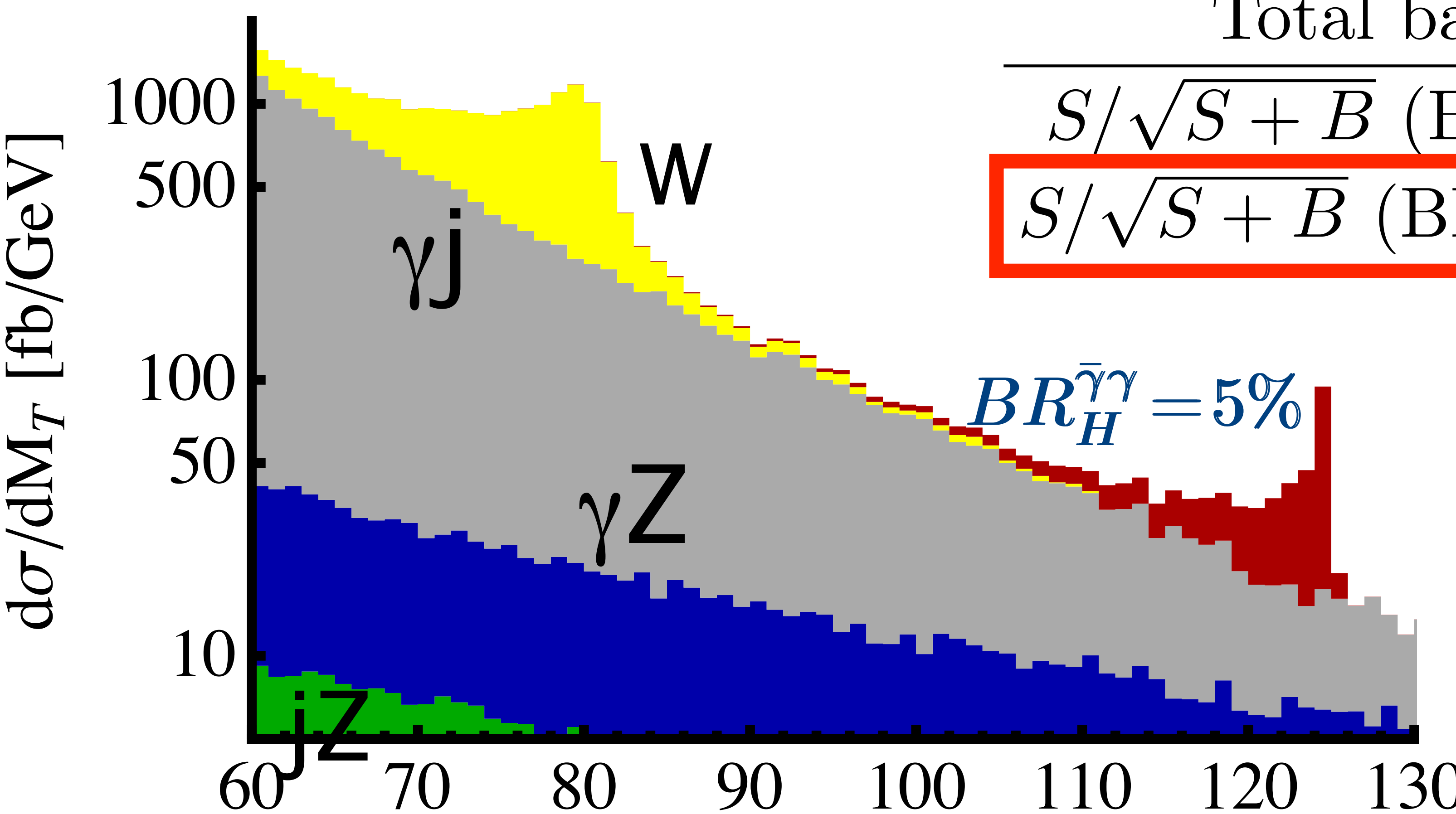
$E_{miss} \sim E_\gamma \sim m_H/2$

(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 $\boxed{\mathrm{BR}_{H\to\gamma\bar{\gamma}} = 1\%}$	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

($8\,\mathrm{TeV}/20\,\mathrm{fb}^{-1}$)

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

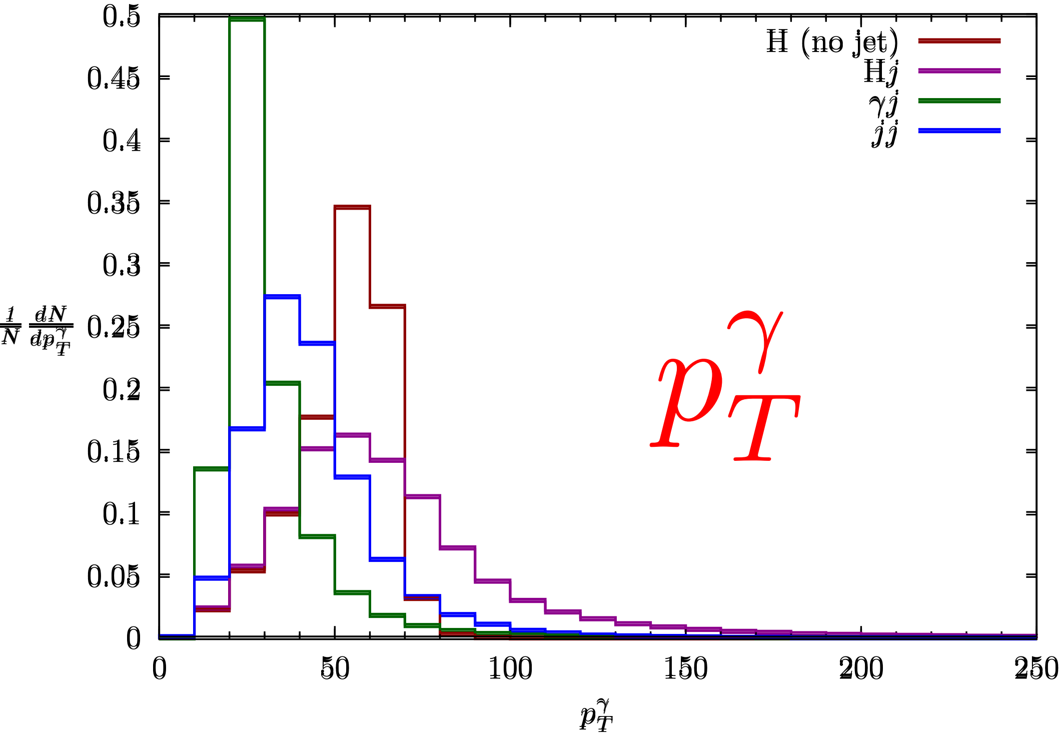


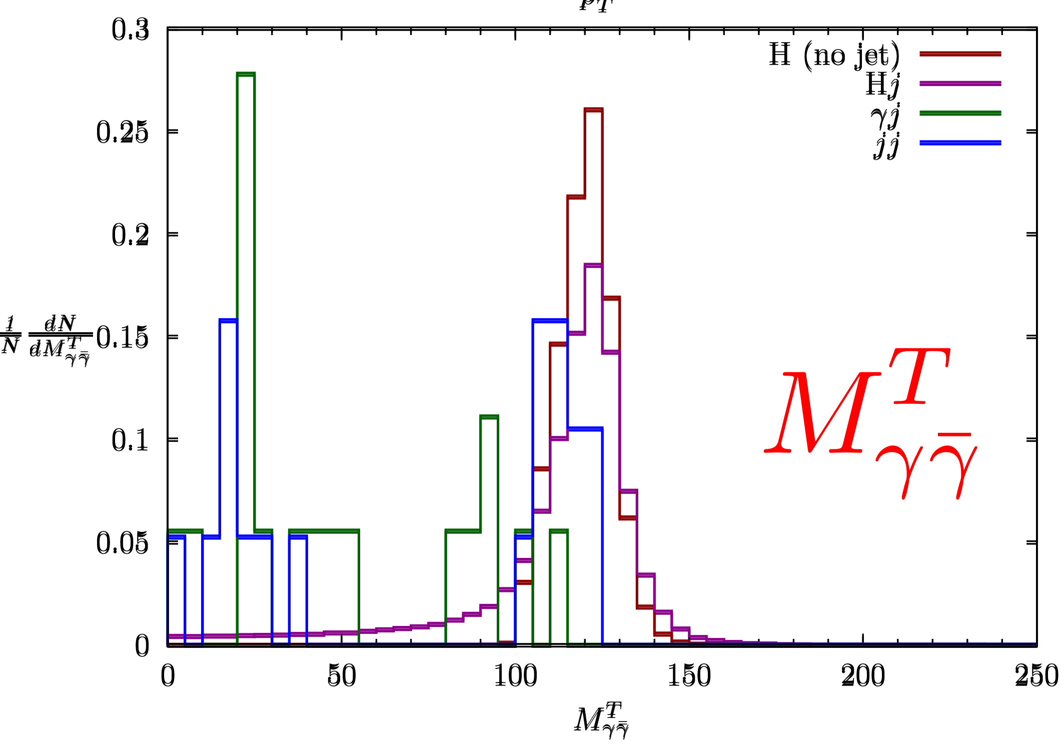
(parton-level analysis)

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]
$H \to \gamma\bar{\gamma}$ ($\mathrm{BR}_{\gamma\bar{\gamma}} = 1\%$)	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))

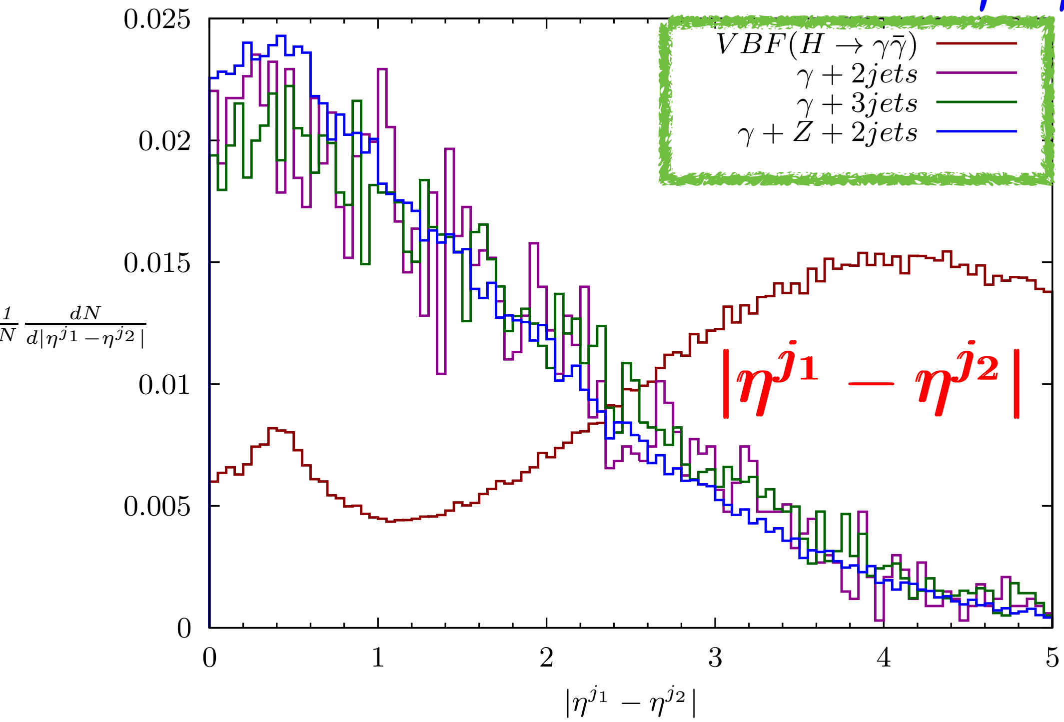
(includes parton-shower)

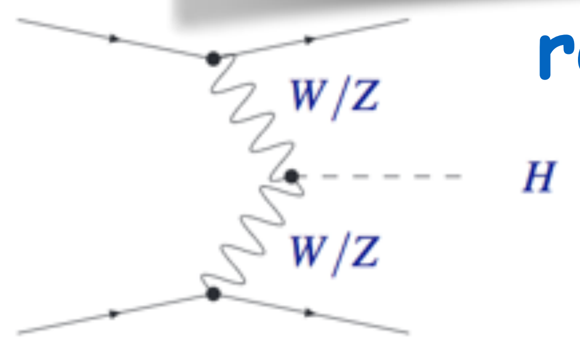
Biswas, Gabrielli, Heikinheimo, BM, arXiv:1603.01377 (PRD)

mono-photon signature in VBF at 14TeV

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

+ two extra forward jets !





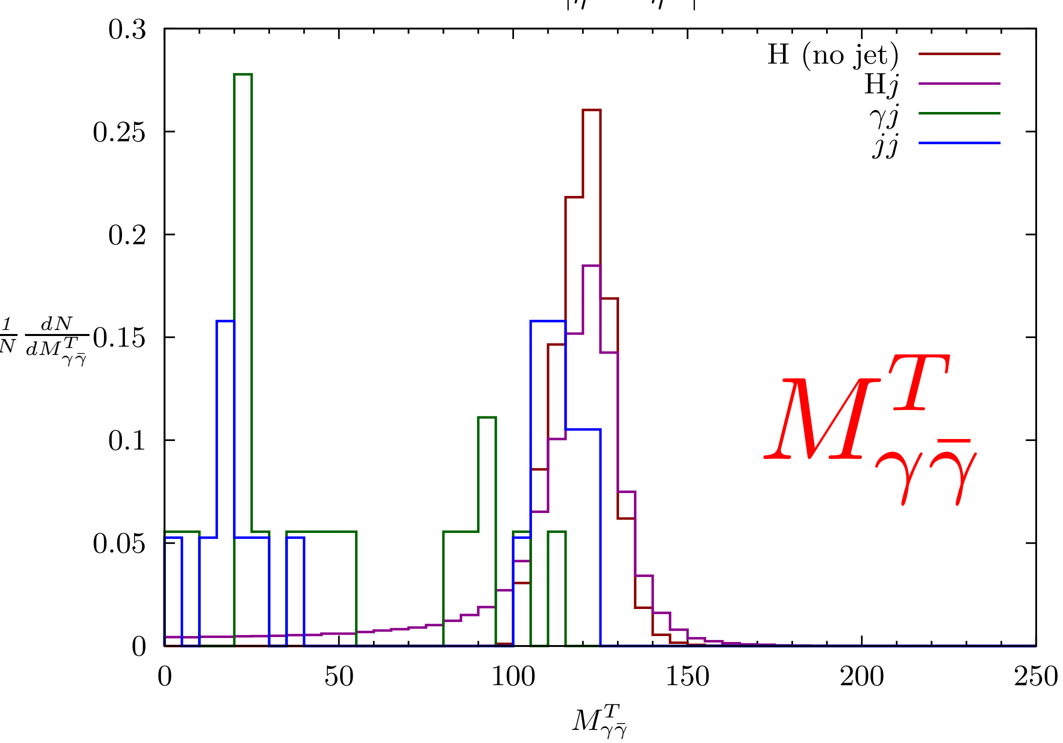
reference BR_{DP}

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

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

(including shower effects)

$$gg \to H \to \bar{\gamma}\gamma \quad \text{vs} \quad VV \to H \to \bar{\gamma}\gamma$$

$\mathrm{BR}_{\gamma\bar{\gamma}}$ (%)	$\mathrm{L}=100\,\mathrm{fb}^{-1}$		$\mathrm{L}=300\,\mathrm{fb}^{-1}$		$\mathrm{L}=3\,\mathrm{ab}^{-1}$	
Significance	2σ	5σ	2σ	5σ	2σ	5σ
$\mathrm{BR}_{\gamma\bar{\gamma}}(\mathrm{VBF})$	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

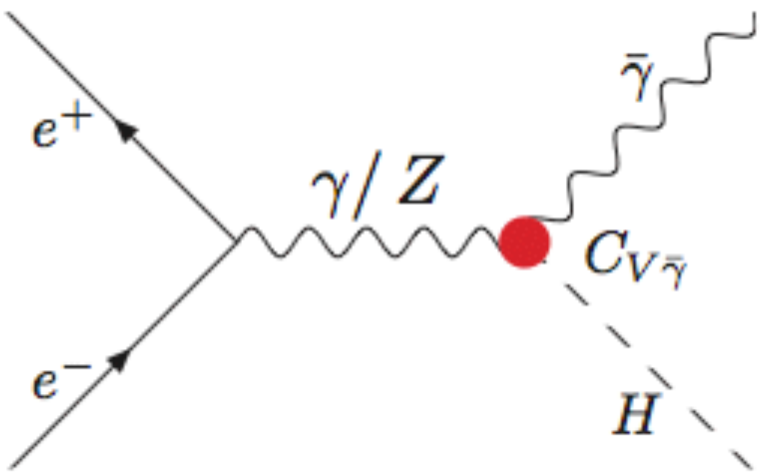
gg fusion sensitive down to $\mathrm{BR}_{DP} \sim 10^{-4}$-$10^{-3}$

(VBF ~10 times worse …)

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

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

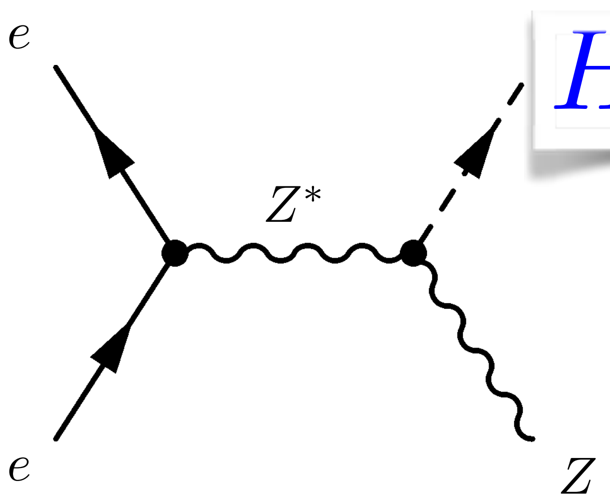
- **in H production :** $e^+e^- \to H\,\bar{\gamma} \to b\bar{b}\,\bar{\gamma}$



p_{Higgs} balanced by a massless invisible system

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

- **in H decays :**



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

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

(photon + E_{miss})

resonant signature

Biswas, Gabrielli, Heikinheimo, BM, arXiv:1703.00402 (PRD)

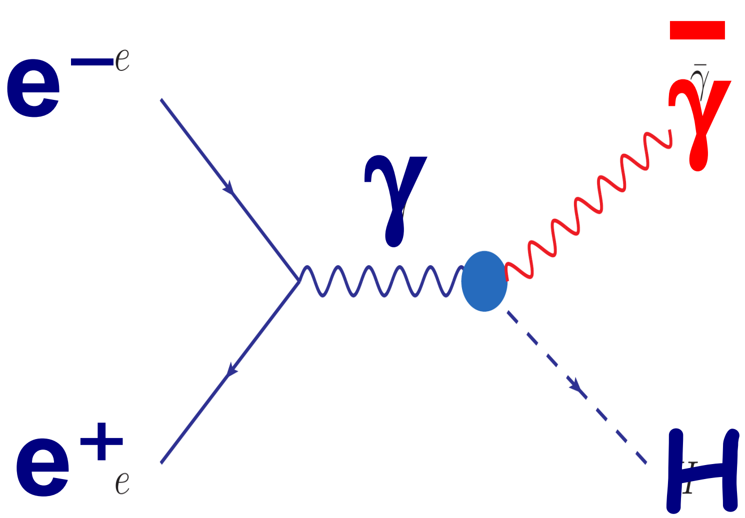
$$e^+e^- \to H\,\bar{\gamma} \to b\bar{b}\,\bar{\gamma}$$

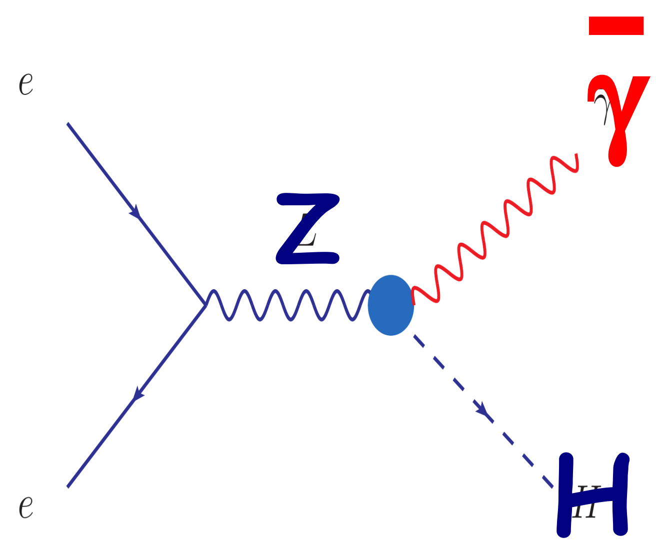
Model independent analysis:

DP field strength

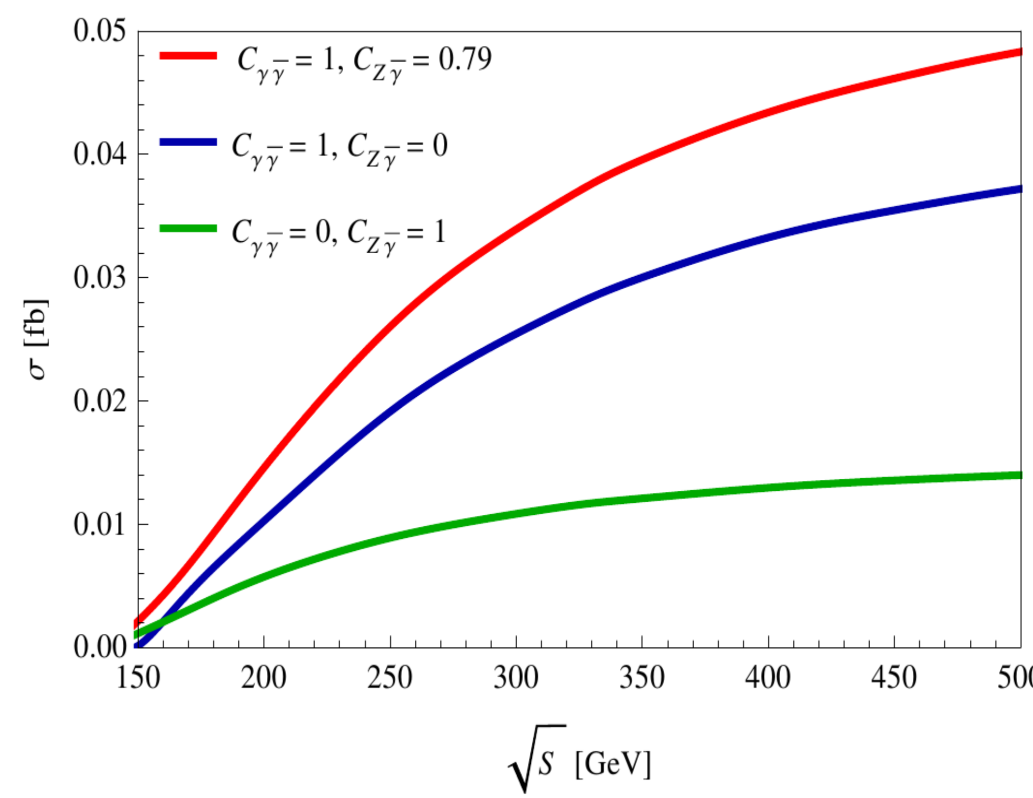
Effective Lagrangian parametrization

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





Total x-section



assuming mass degeneracy in Left and Right messeng

R=CZγ/Cγγ

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

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

Basic cuts
$$\left\{\begin{array}{ll} p_T^b > 20\ \mathrm{GeV}\,, & |\eta_b| < 2.5 \\ \Delta R(bb) > 0.4\,, & \not{E} > 40\ \mathrm{GeV} \end{array}\right.$$

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

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

Irreducible

$$\nu\bar{\nu}b\bar{b} \left\{\begin{array}{l} ZZ \to \nu\bar{\nu}b\bar{b} \\ ZH \to \nu\bar{\nu}b\bar{b} \\ \text{WW fusion} \to H\nu\bar{\nu} \end{array}\right.$$

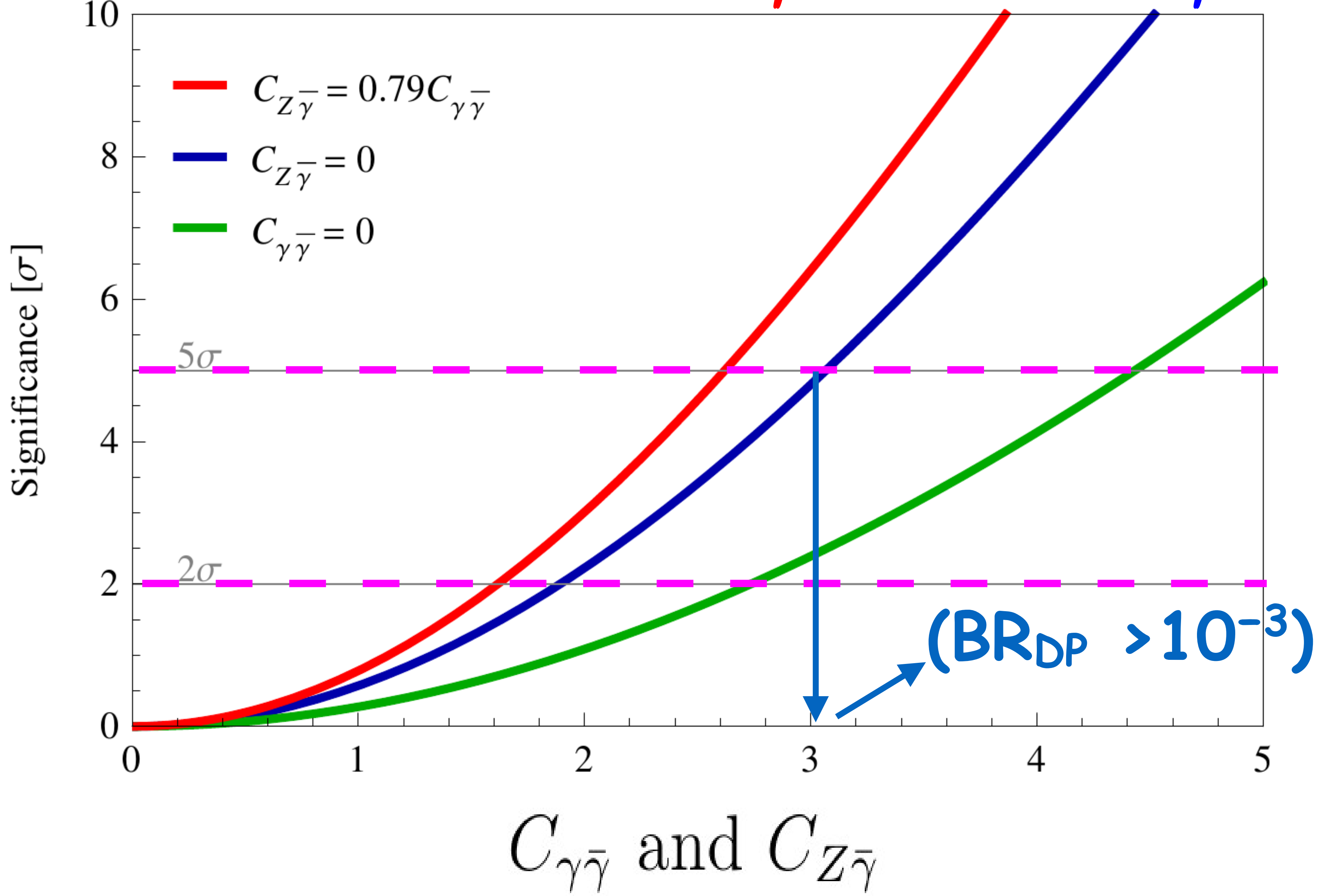
Reducible

$\nu\bar{\nu}q\bar{q}$ 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

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

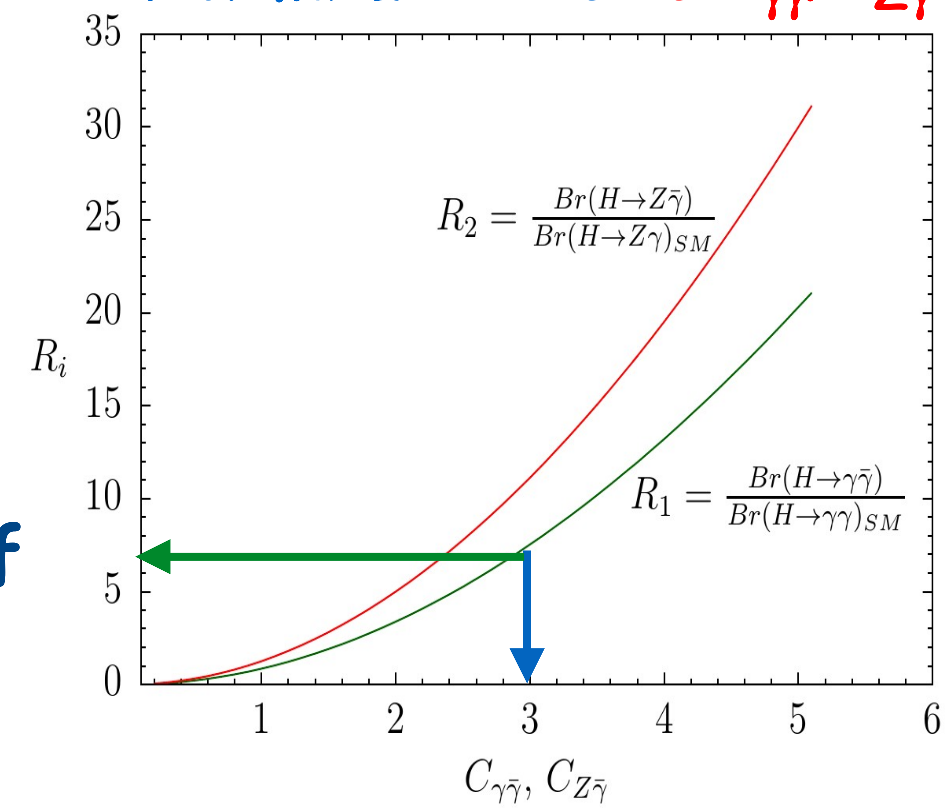


Significance for L=10ab-1

5σ

2σ

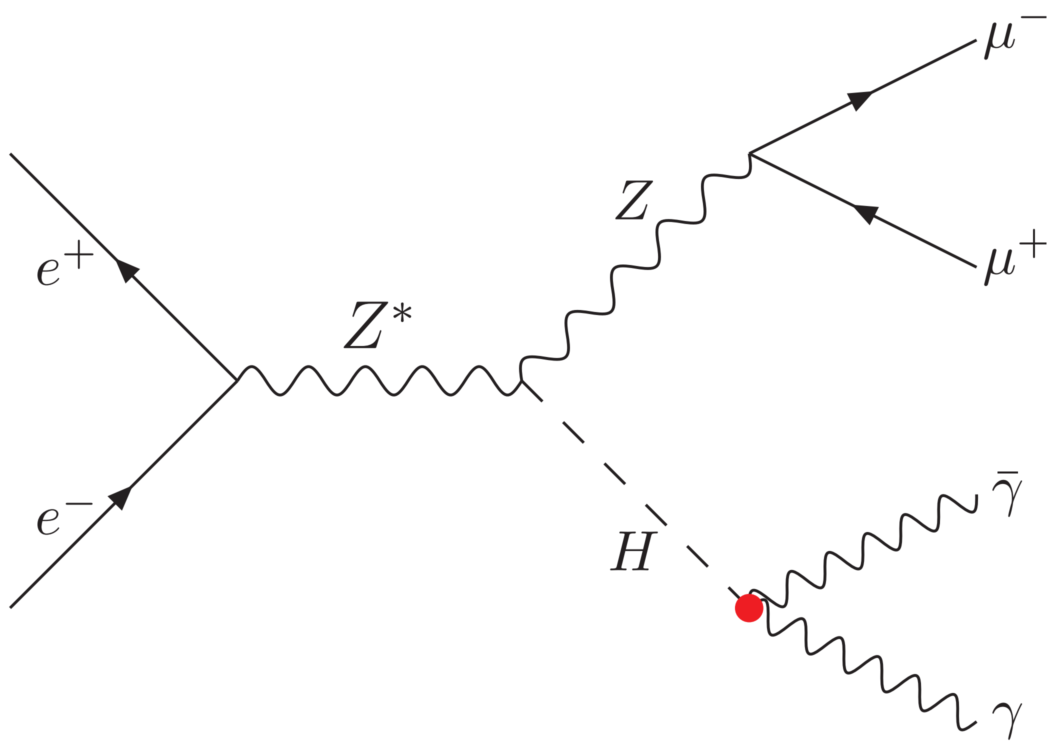
Normalized BRs vs $C_{\gamma\bar{\gamma}}/C_{Z\bar{\gamma}}$

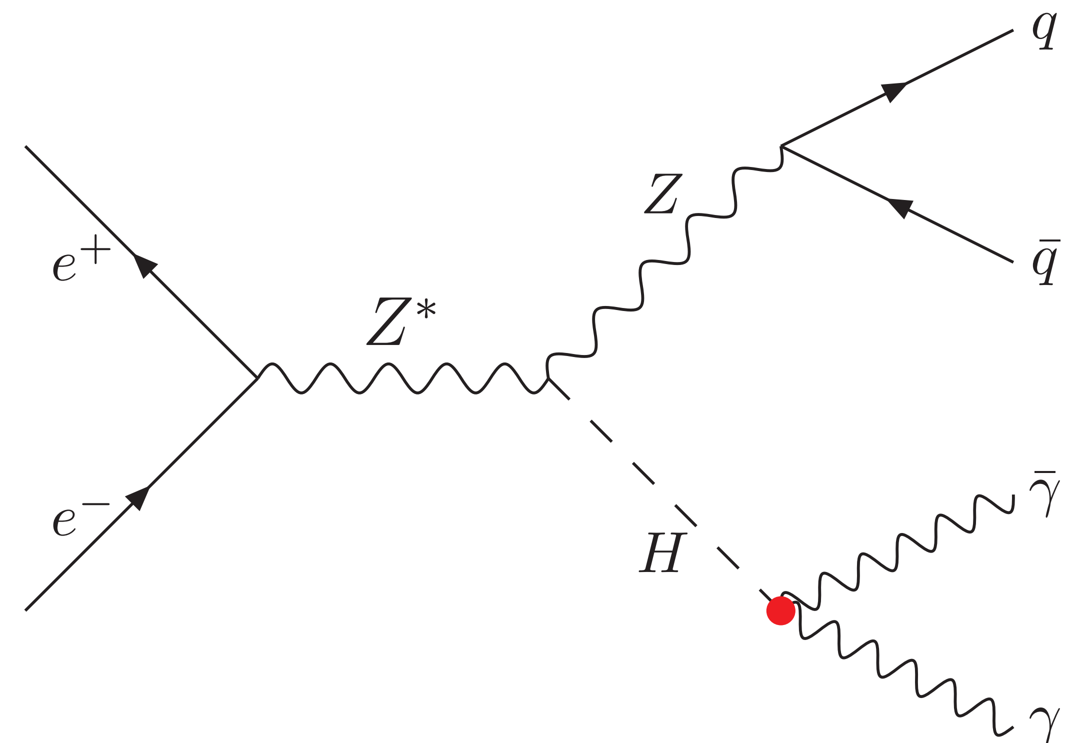


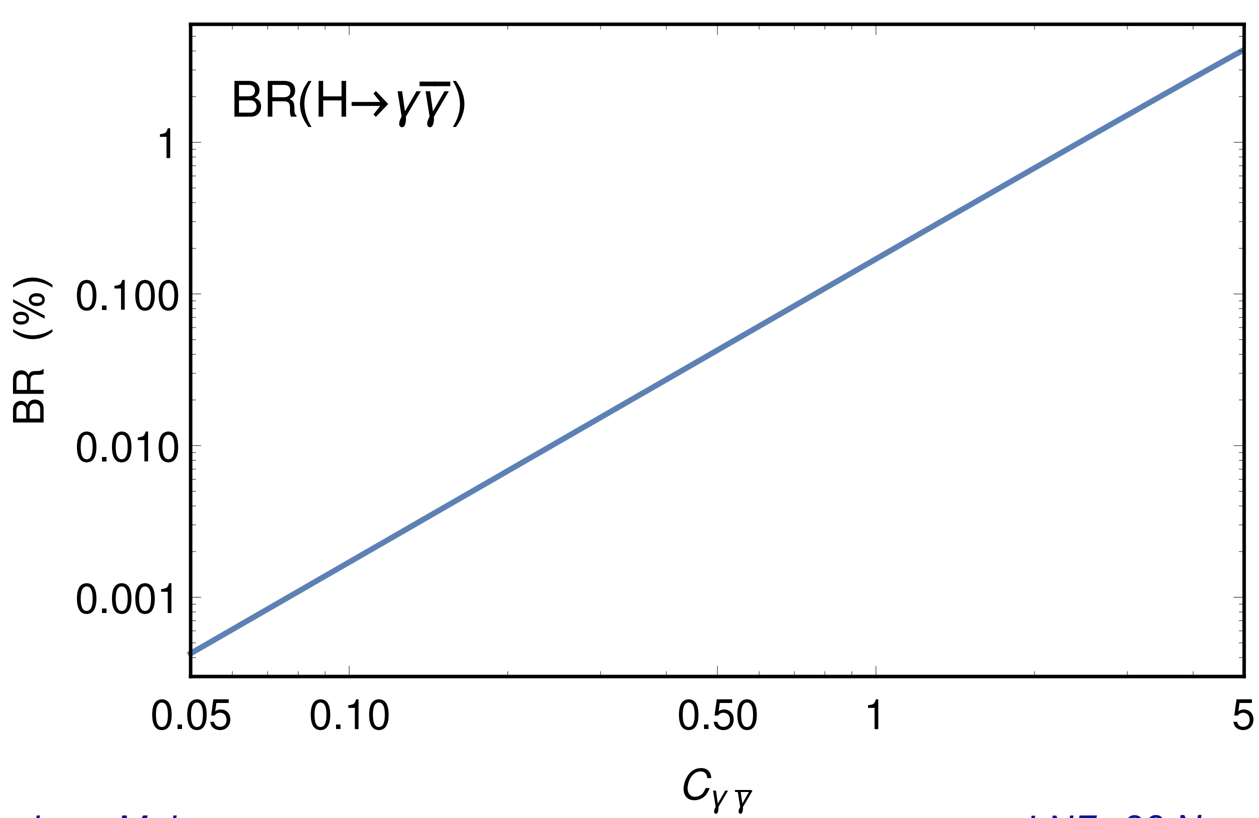
signif. = $S/\sqrt{S+B}$

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

$$e^+e^- \to ZH \to \mu^+\mu^- \; \gamma\bar{\gamma} \quad (q\bar{q} \;\; \gamma\bar{\gamma})$$



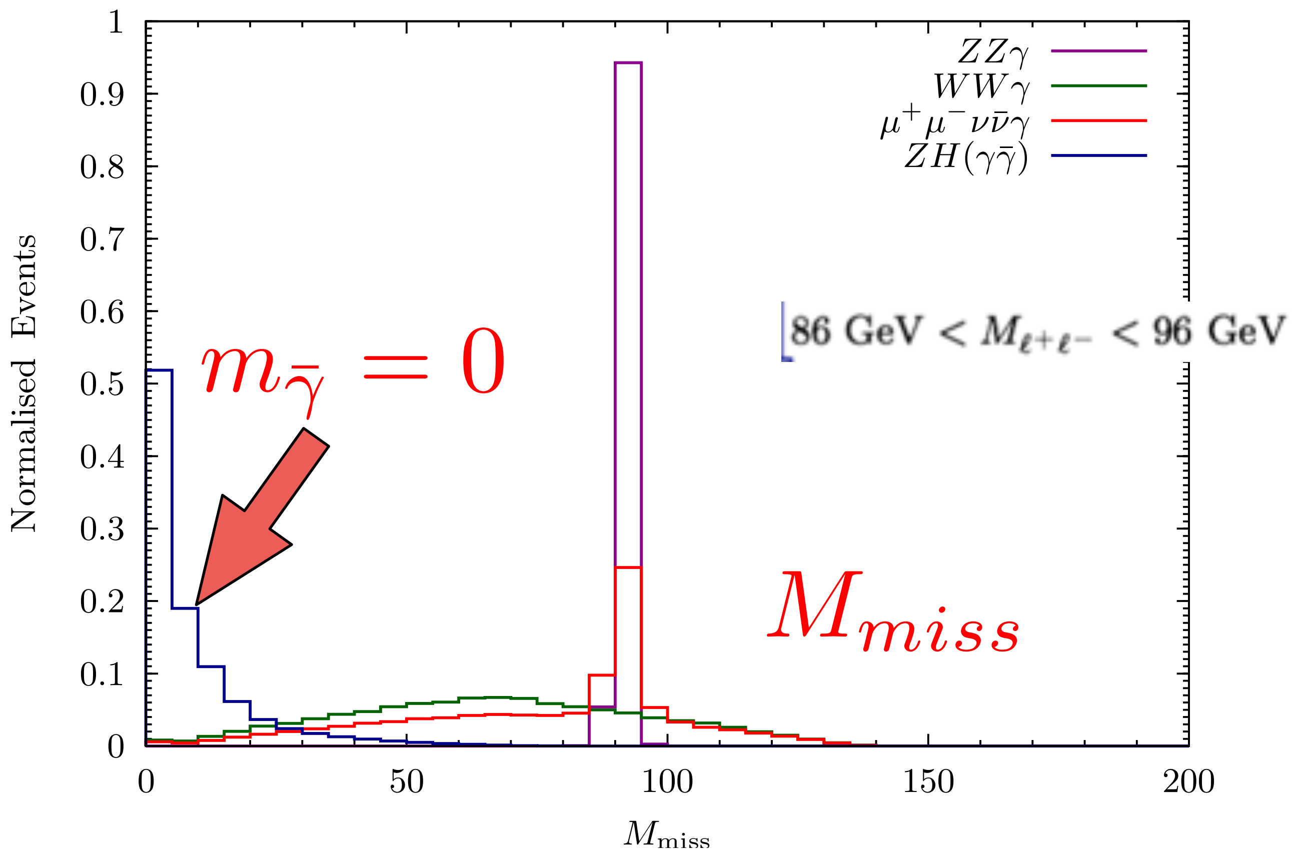


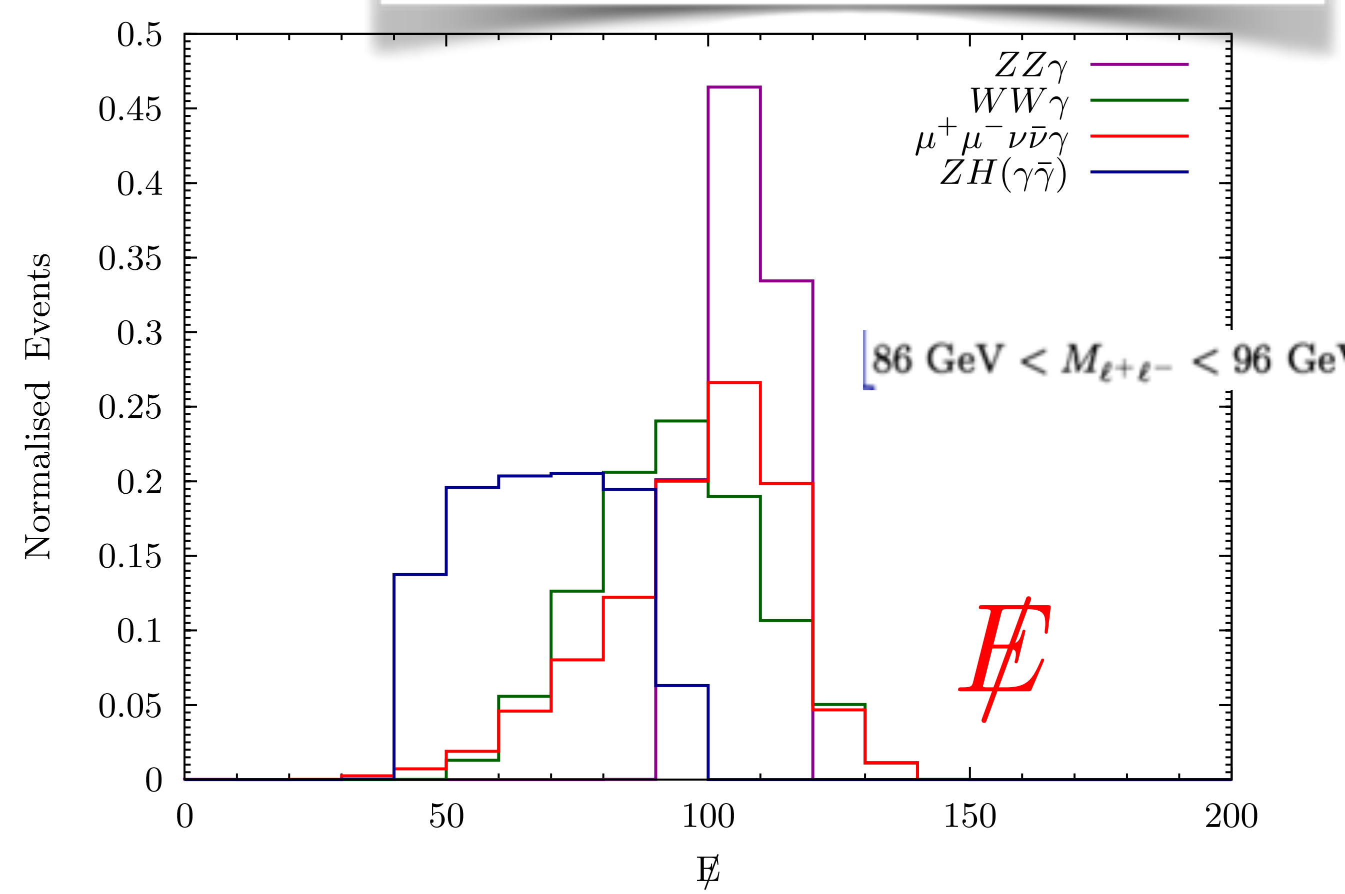


$$\Gamma(H \to \gamma\bar{\gamma}) \;=\; \frac{m_H^3 \alpha^2 |C_{\gamma\bar{\gamma}}|^2}{8\pi^3 v^2}$$

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

leptonic channel





Biswas, Gabrielli, Heikinheimo, BM, arXiv:1703.00402 (PRD)

simulation :

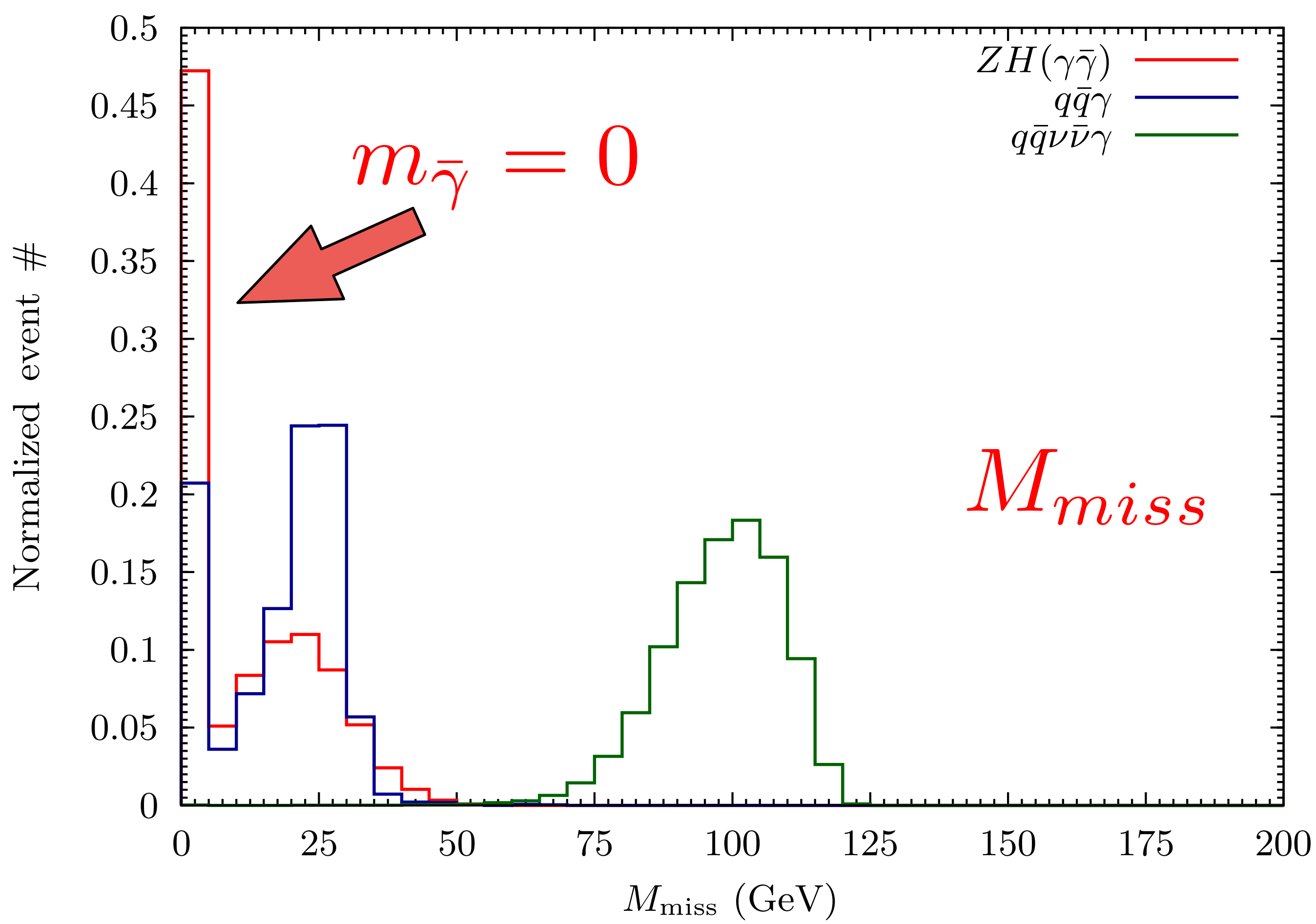
PYTHIA for signal and MadGraph+PYTHIA for backgrounds
ISR/FSR effects described by PYTHIA

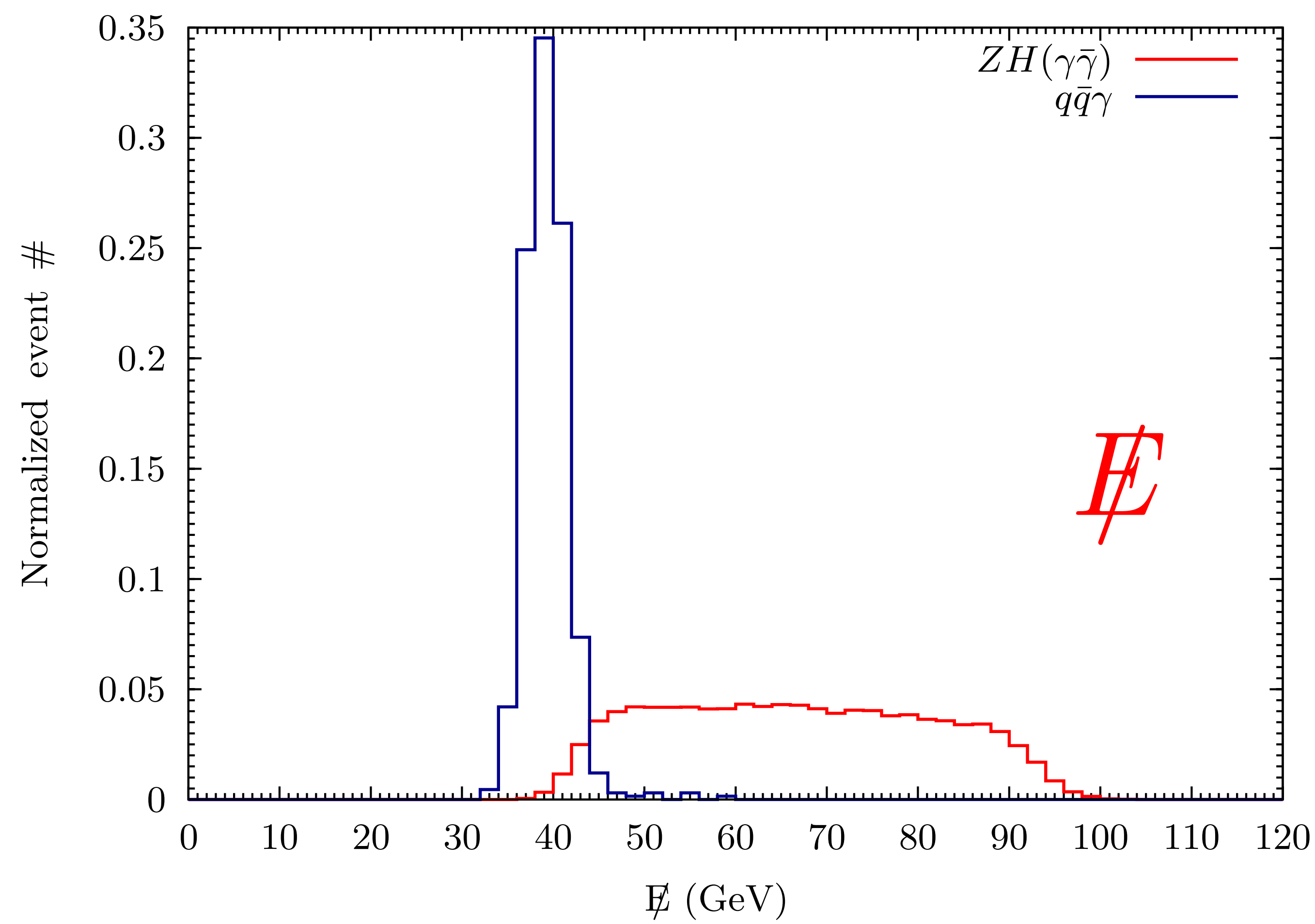
Finite detector resolutions for photon and muons according to ILD detector specifications in [arXiv:1605.00100]

hadronic channel

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

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





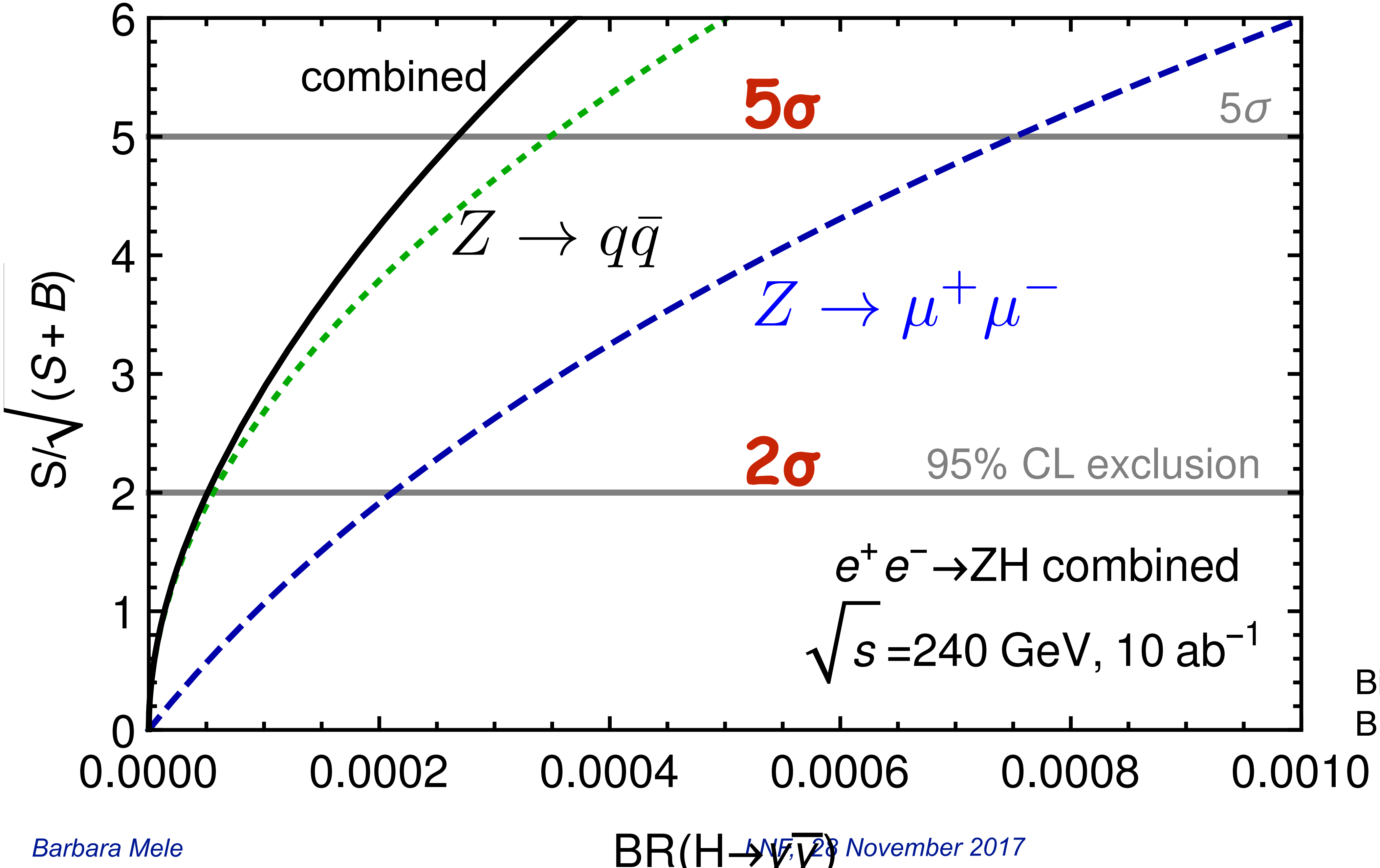
Biswas, Gabrielli, Heikinheimo, BM,
arXiv:1703.00402 (PRD)

$e^+e^- \to ZH \to \mu^+\mu^- \; \gamma\bar{\gamma} \quad (q\bar{q} \;\; \gamma\bar{\gamma})$

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

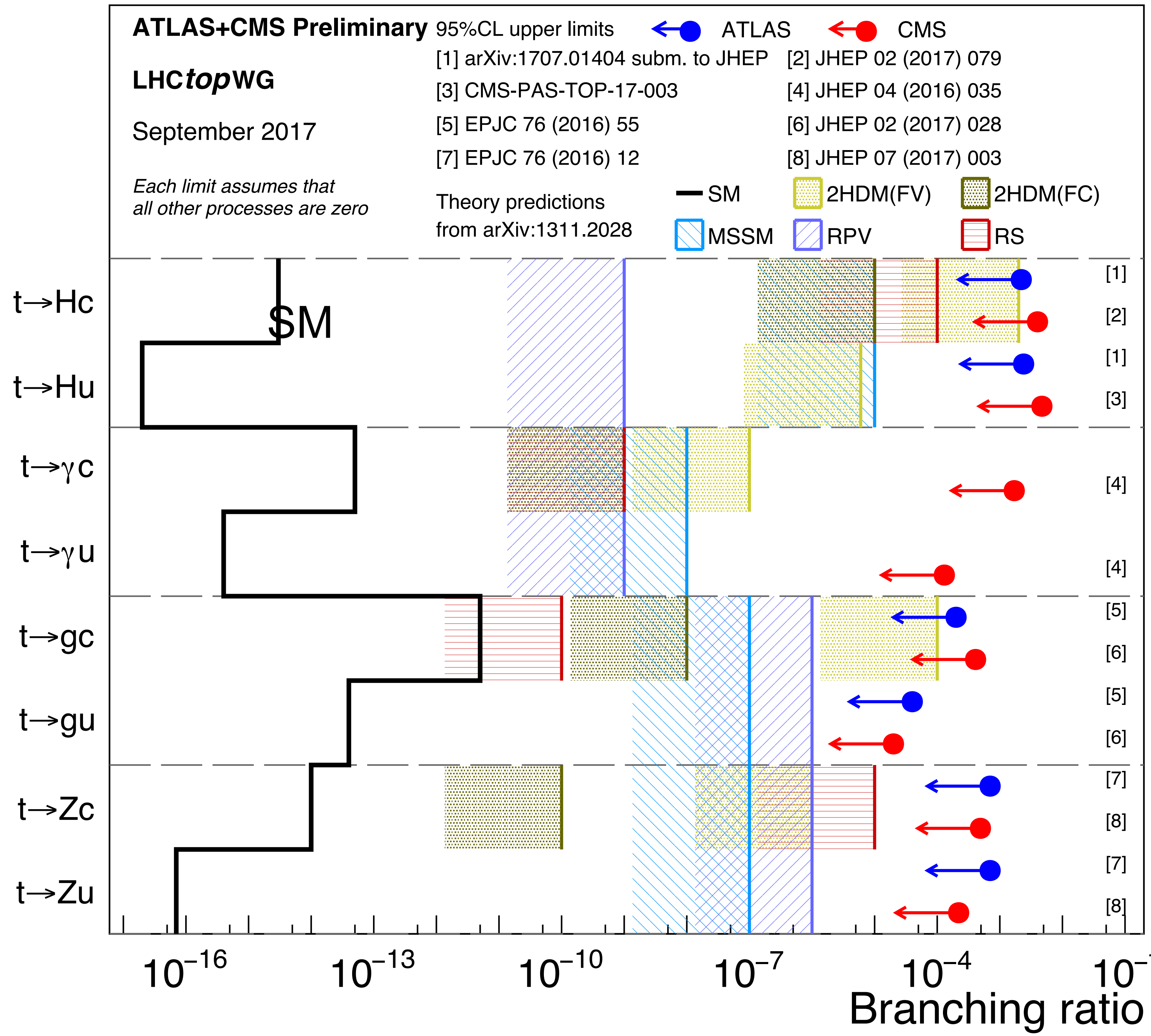
hadronic Z
most sensitive channel :

5σ sensitivity for
$BR_{DP} \sim 2\text{x}10^{-4}$!!!



Biswas, Gabrielli, Heikinheimo, BM, arXiv:1703.00402 (PRD)

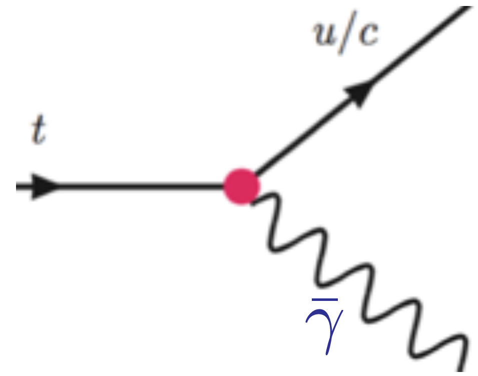
testing BSM via FCNC top interactions



* LHC more and more a top factory → great opportunity !
* order of magnitude improvement at HL-LHC
* huge gain at future colliders !

top FCNC's mediated by massless Dark Photons

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

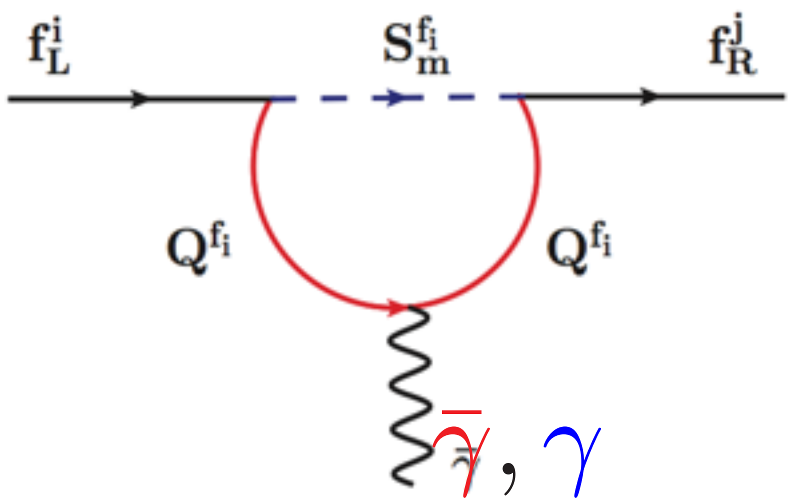


Gabrielli, BM, Raidal, Venturini, arXiv:1607.05928 (PRD)

also : $b \to s\,\bar{\gamma}$

vs $b \to s\,\gamma$

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



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):

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

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

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

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

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

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

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

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

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

Gabrielli, BM, Raidal, Venturini

→ new class of (very distinctive) FCNC signatures at ee colliders

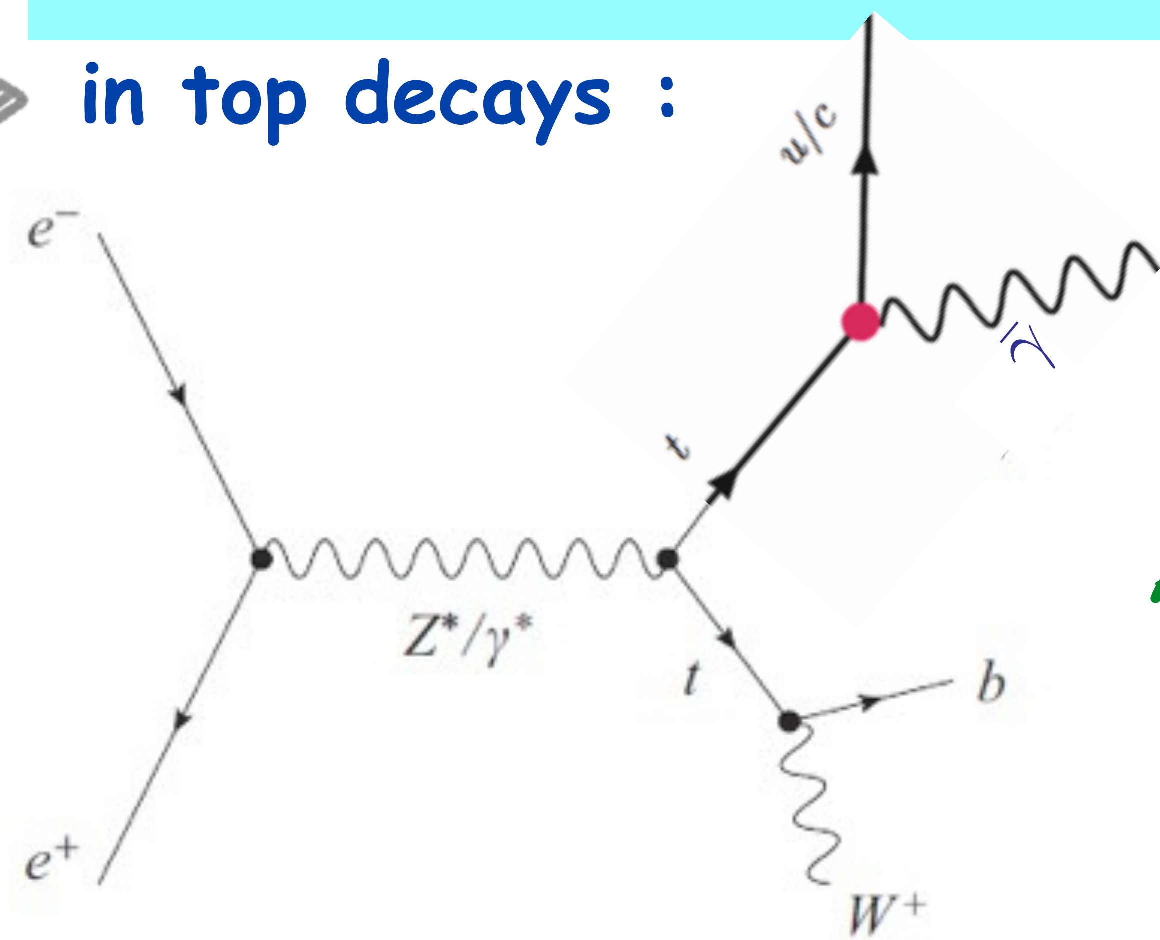
$$f \to f' \bar{\gamma}$$

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

Sensitivity is likely just statistics limited !

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 :



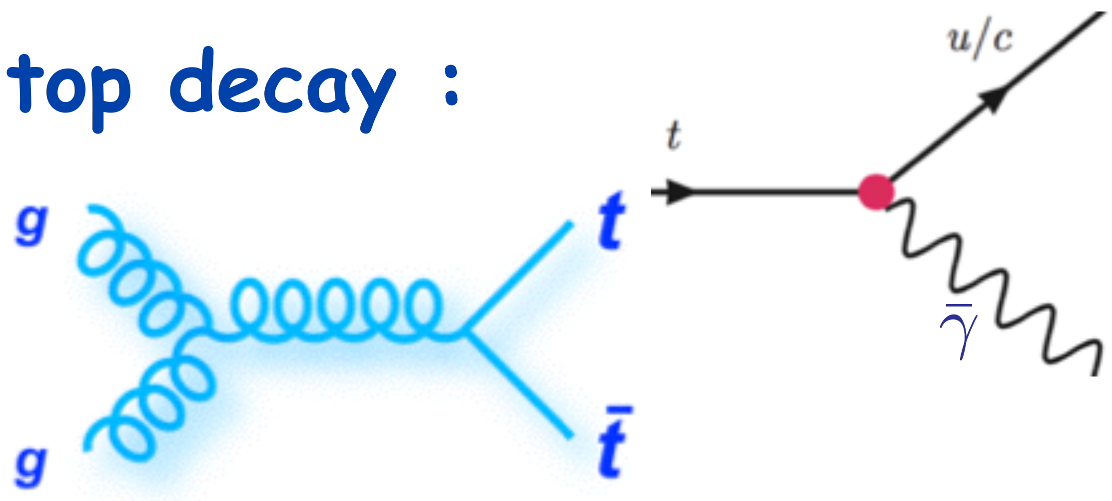
"top" + (mono-j + E_{miss})
resonant at m_{top}

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

Biswas, Gabrielli, BM, in progress

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

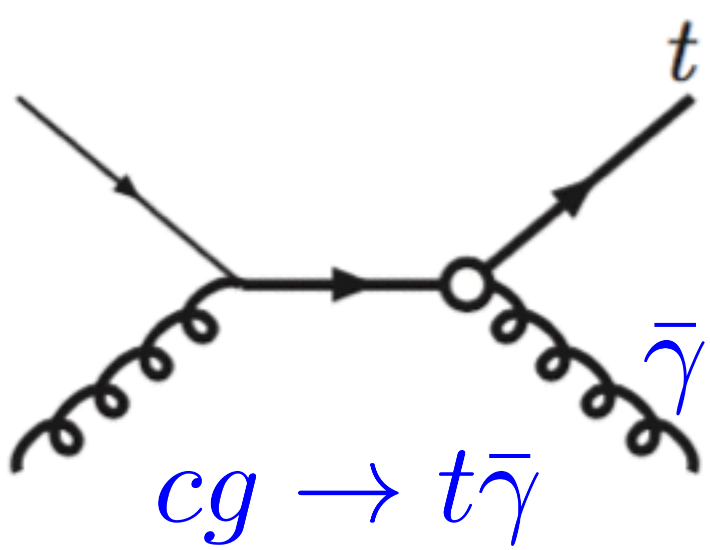
- in top decay :



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

[stop-like, for massless χ^0]

- in top production



"top" plus massless invisible system

signature in Kaon physics

Fabbrichesi, Gabrielli, BM, *Phys. Rev. Lett.* **119** (2017) 031801
[arXiv:1705.03470]

massless dark photon

unbroken U(1) symmetry

massless invisible system

$$\boxed{K^+ \to \pi^+ \pi^0 \bar{\gamma}}$$

($K^+ \to \pi^+ \bar{\gamma}$
forbidden by angular momentum conservation )

	spin 1 massless	spin 1 massive or axion-like scalar
$K^+ \to \pi^+ \pi^0 \bar{\gamma}$	✓	✓
$K^+ \to \pi^+ \bar{\gamma}$		✓

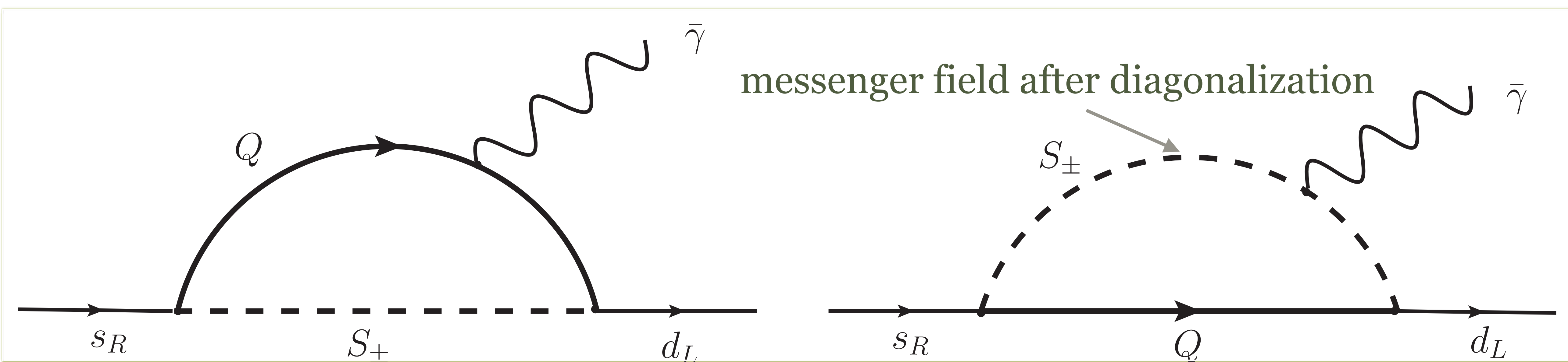
simplified model of dark sector

SM fermion

$$L \sim g_L(\bar{Q}_L q_R)S_R + g_R(\bar{Q}_R q_L)S_L$$

dark fermion

messenger



$$\boxed{\hat{Q} = (\bar{s}\,\sigma^{\mu\nu}\,d)\,\bar{F}_{\mu\nu}}$$

dipole operator (FCNC)

matrix element

$$\hat{M} \equiv \langle \bar{\gamma}\, \pi^+ \pi^0 | \, \mathcal{H}_{eff}^{\Delta S=1} \, | K^+ \rangle$$

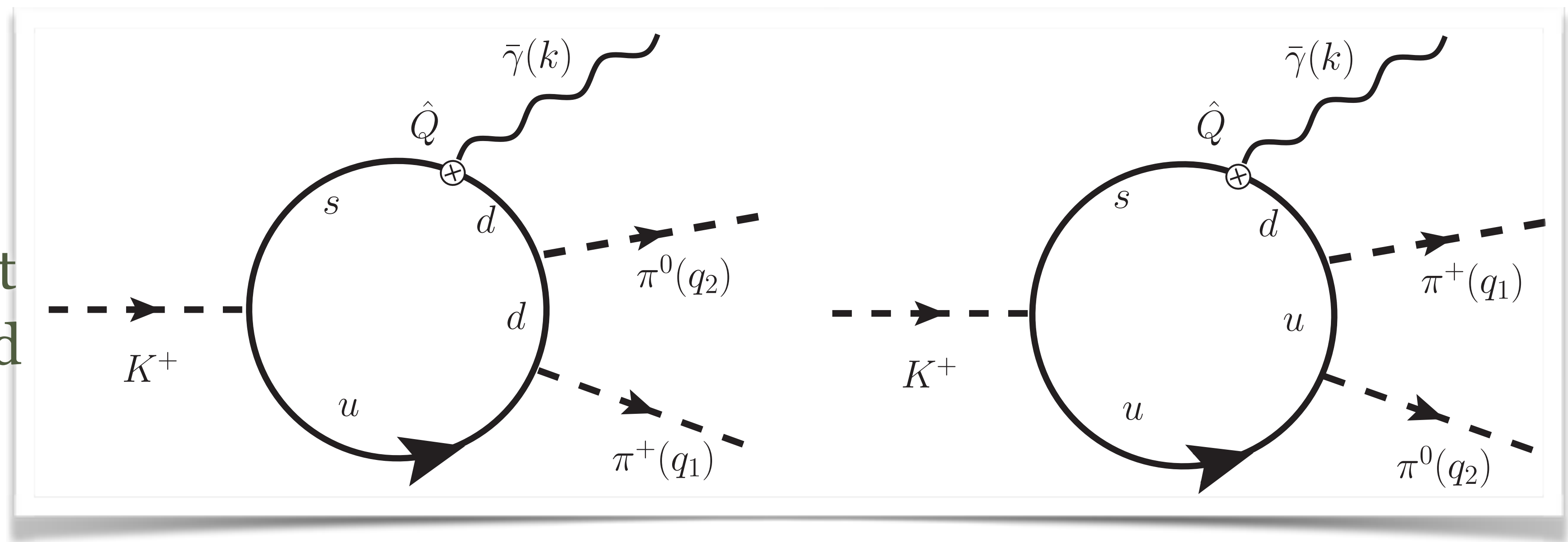
$$\mathcal{H}_{eff}^{\Delta S=1} = \frac{e_D}{64\,\pi^2} \frac{\xi}{\Lambda} \hat{Q}$$

$$\hat{Q} = (\bar{s}\,\sigma^{\mu\nu}\, d)\, \bar{F}_{\mu\nu}$$

matching scale ➜ mass of lightest-messenger and dark-fermion (assumed degenerate)

chiral quark model

(quarks are coupled to hadrons by an effective interaction so that matrix elements can be evaluated by loop diagrams)



$$\mathrm{BR}(K^+ \to \pi^+ \pi^0 \bar{\gamma}) \simeq 1.31\, \alpha_D\, \eta^2 \frac{\xi^2}{\Lambda^2}$$

RG

$$\alpha_D = e_D^2/4\pi$$

$$\xi = g_L g_R/2$$

constraints :

from extra contributions to K°K° mixing

$$\Delta M_K = 2\Re[\langle K^0|\mathcal{H}_{eff}^{\Delta S=2}|\bar{K}^0\rangle]$$

K^0- $\bar{K}^0$

$$\mathcal{H}_{eff}^{\Delta S=2} = \sum_i^5 C_i Q_i + \sum_{i=1}^3 \tilde{C}_i \tilde{Q}_i$$

NLO in RGE

$$\Delta M_K = 8.47 \times 10^{-13} \frac{\xi^2}{\Lambda^2}$$

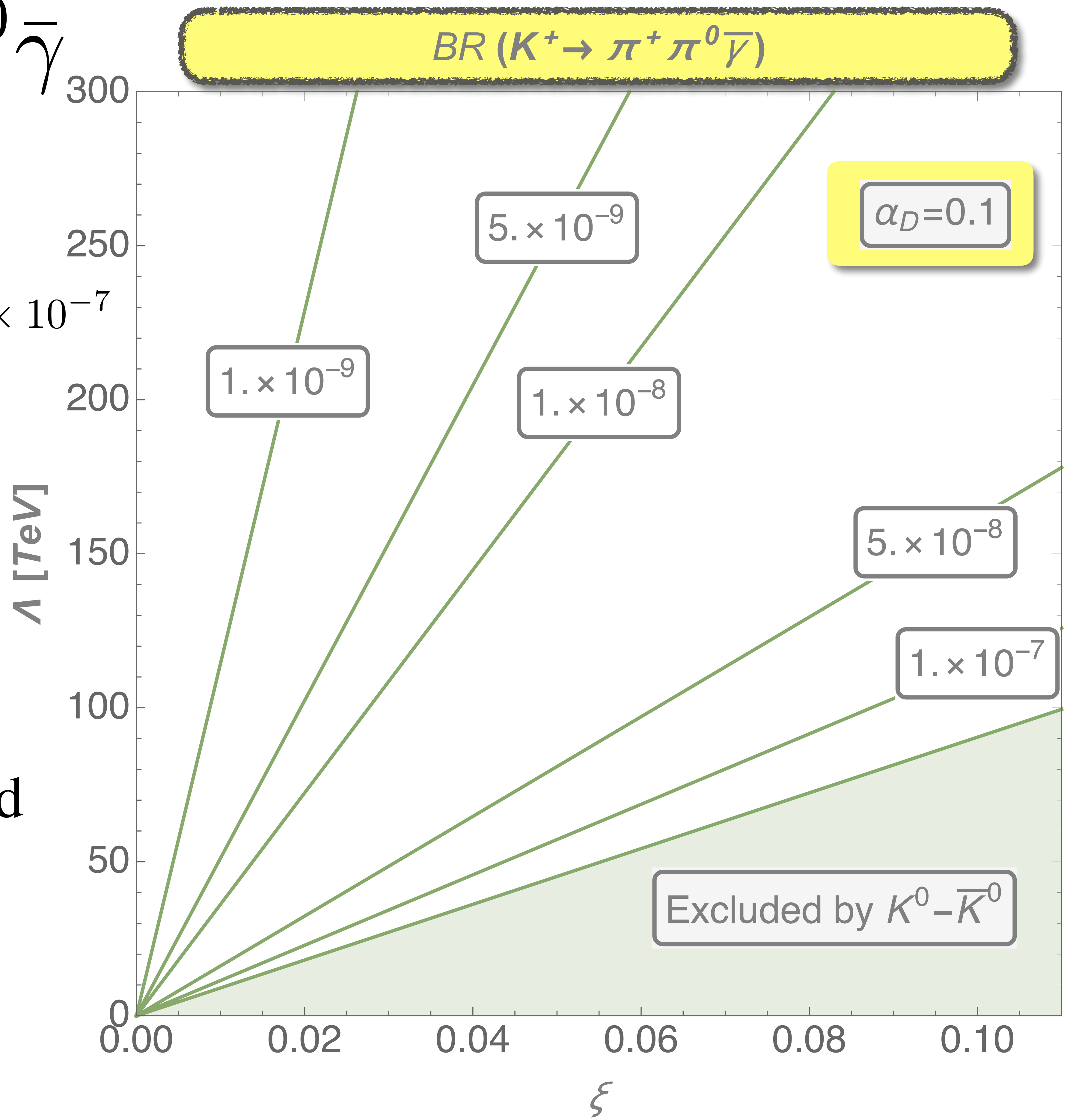
astrophysics

star cooling by emission of dark photons

$K^+ \to \pi^+\pi^0\bar{\gamma}$

BR contour

$$\mathrm{BR}(K^+ \to \pi^+\pi^0\bar{\gamma}) \lesssim 1.6 \times 10^{-7}$$



10^{13} K+ at NA62 soon with hermetic photon coverage and good missing-mass resolution (under consideration…)

1. TABLE I. In the first two rows, relevant operators are numbered according to the notation in [20,21]. The matrix elements $\langle K^0|Q_i|\bar{K}^0\rangle$ (in the vacuum insertion approximation for the renormalized operators Q_i at the low energy scale $\mu = 2$ GeV) are given in the third row multiplied by the respective bag factors $B_i(\mu)$ [21] evaluated at same scale, with $X_K(\mu) = (m_K/(m_d(\mu) + m_s(\mu)))^2$. The fourth row gives the Wilson coefficients at the matching scale (the common factor at the matching being $C^2 = \xi^2/(16\pi^2\Lambda^2)$ [9], where $\xi = g_L g_R/2$). Following [21], we take $m_d(\mu) = 7$ MeV, $m_s(\mu) = 125$ MeV, $m_K = 497$ MeV, $f_K = 160$ MeV, and $B_{1,2,3,4,5}(\mu) = 0.60, 0.66, 1.05, 1.03, 0.73$, respectively.

Q_1, $\tilde{Q}_1$	Q_2, $\tilde{Q}_2$	Q_3, $\tilde{Q}_3$	Q_4	Q_5
$\bar{d}^\alpha_L\gamma_\mu s^\alpha_L\bar{d}^\beta_L\gamma_\mu s^\beta_L, (L\leftrightarrow R)$	$\bar{d}^\alpha_R s^\alpha_L\bar{d}^\beta_R s^\beta_L, (L\leftrightarrow R)$	$\bar{d}^\alpha_R s^\beta_L\bar{d}^\beta_R s^\alpha_L, (L\leftrightarrow R)$	$\bar{d}^\alpha_R s^\alpha_L\bar{d}^\beta_L s^\beta_R$	$\bar{d}^\alpha_R s^\beta_L\bar{d}^\beta_L s^\alpha_R$
$1/3 m_K f_K^2 B_1(\mu)$	$-5/2 X_K m_K f_K^2 B_3(\mu)$	$1/24 X_K m_K f_K^2 B_3(\mu)$	$1/4 X_K m_K f_K^2 B_4(\mu)$	$1/12 X_K m_K f_K^2 B_5(\mu)$
$-1/24C^2$	0	$1/12C^2$	$1/6C^2$	$1/6C^2$

2.

$$\hat{M} = \frac{M(z_1, z_2)}{m_K^3}\varepsilon_{\mu\nu\rho\sigma}q_1^\nu q_2^\rho k^\sigma \varepsilon^\mu(k)$$

3.

main sources of uncertainty

- *—Chiral perturbation theory **higher order corrections***
- *—Chiral-quark-model **M-parameter** dependence*
- *—**RGE corrections***

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

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

  - very distinctive ➔ bounds expected to be limited just by statistics !

- look for $K^+ \to \pi^+ \pi^0 \bar{\gamma}$ at NA62 !

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