Sapienza Università di Roma, 22 October 2018

Looking for massless Dark Photons at colliders

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based on :

M.Fabbrichesi, E.Gabrielli, BM, PRL 120 (2018) 171803

S.Biswas, E.Gabrielli, M.Heikinheimo, BM, PRD 96 (2017) 055012

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

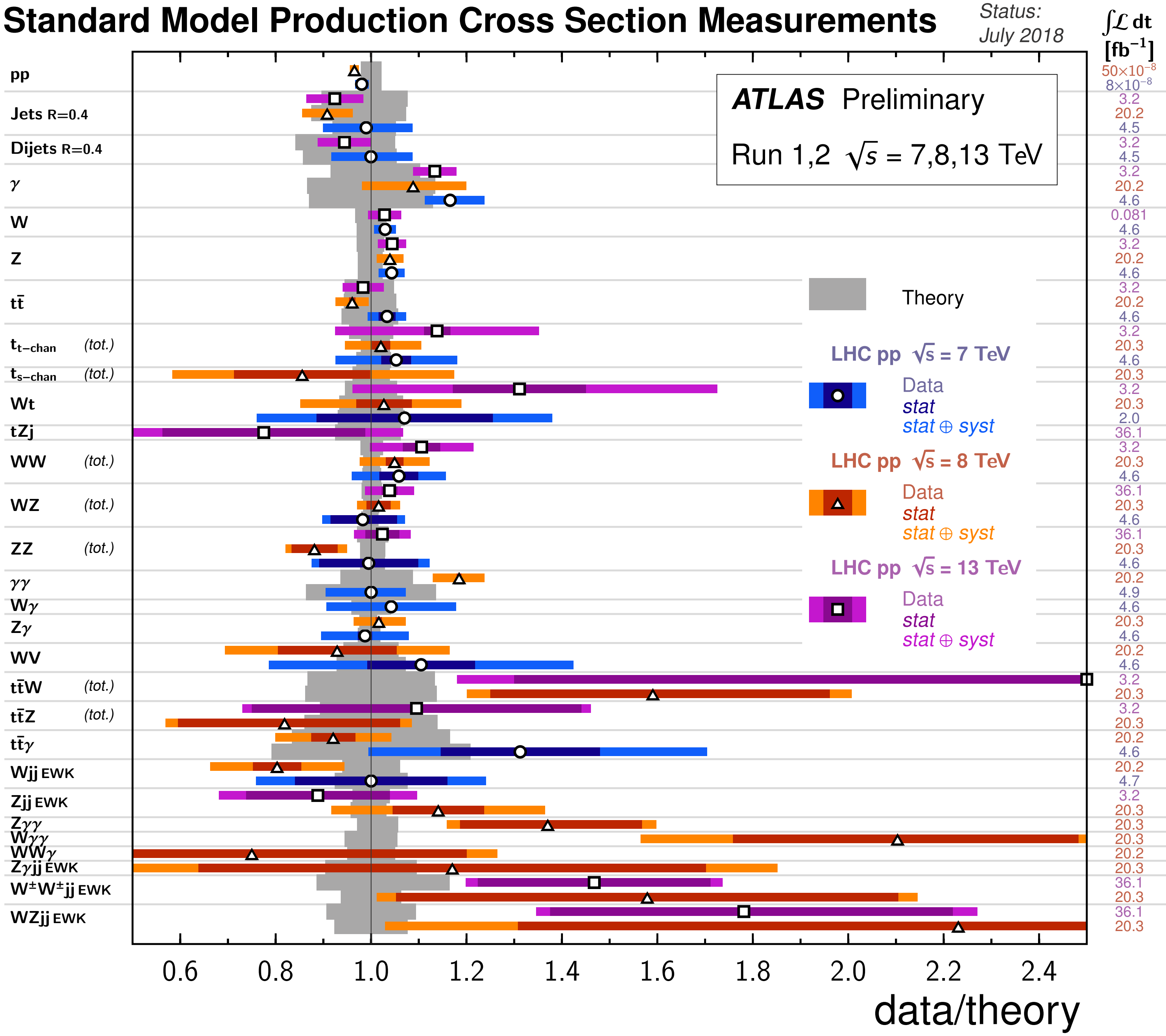
E.Gabrielli, M.Heikinheimo, BM, M.Raidal, PRD 90 (2014) 055032

Theory vision in HEP today (a)

ABC to decipher bulk of LHC physics

well known → Standard Model Lagrangian

- LHC exps controls SM x-sections at unexpected level !
- they challenge theorists' capability to make precision predictions
- notwithstanding extremely harsh backgrounds !



Theory vision in HEP today (b)

huge (but quite hazy!) expectations for new BSM phenomena !

- two kinds of issues with the SM :

  - existence of "external" phenomena :

    (quantum ?) Gravity + empirical evidences :

    - Dark Matter
    - Barion asymmetry
    - neutrino masses
    - . . .

  - "internal" poor consistency :

    mainly connected to the EWSB/Higgs sector

what's so tricky about the Higgs

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

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

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

- the only "fundamental" scalar particle (microscopic interpretation ?)
- not protected by symmetries (the less constrained SM sector):
  - naturalness problem : $m_H \sim g \times \Lambda_{\rm cutoff}$
- many different couplings all fixed by masses (?)
  - proliferation of parameters historically leads to breakdown in TH models
- fermion masses/Yukawa's hierarchy (?)
  - have neutrinos a special role ?!!!
- λ determines shape and evolution of Higgs potential → cosmology !

four major paths to advance in HEP at colliders:

- by exploring the characteristics of the Higgs sector and confirming (or 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 theory
  [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 elusive signatures (e.g. DARK states, uncoupled to the SM at tree level) either in production or/and heavy-state (t,H…) decays (may be 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 !

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

* Higgs

* new particles

* indirect effects

seminar focus → * "Dark signals"

Outline (Dark Photon → DP)

- what's peculiar to massless DP's
- Hidden Sectors with unbroken extra U(1)

→ → → → massless DP's pheno :

  - 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 and in Z^0 decays
- Outlook

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

- Hidden Sectors can contain light or massless gauge bosons mediating NEW long-range forces between Dark particles
- present 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 :

mixing param.

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

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

➜ DP's couple to SM particles like a photons but with strength $-\epsilon\, e\, Q_{el}$

➜ 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)

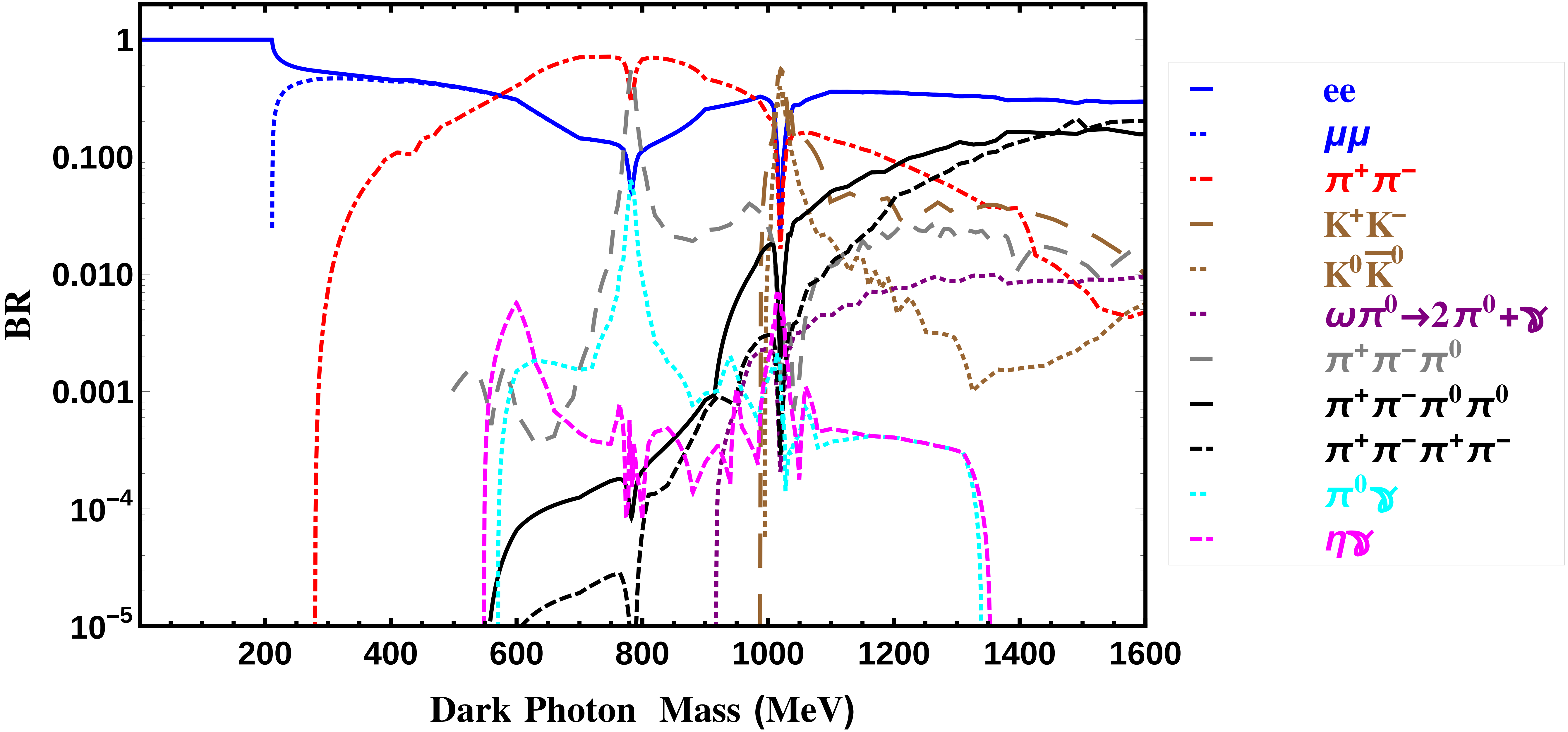
- may assist DM annihilations for the required magnitude making asymmetric DM scenarios viable

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

many astrophysical and collider bounds on massive DP (Z’) !

visible massive DP's decays

arXiv:1412.1485



strategies for massive-DP (A') searches

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

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

- **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

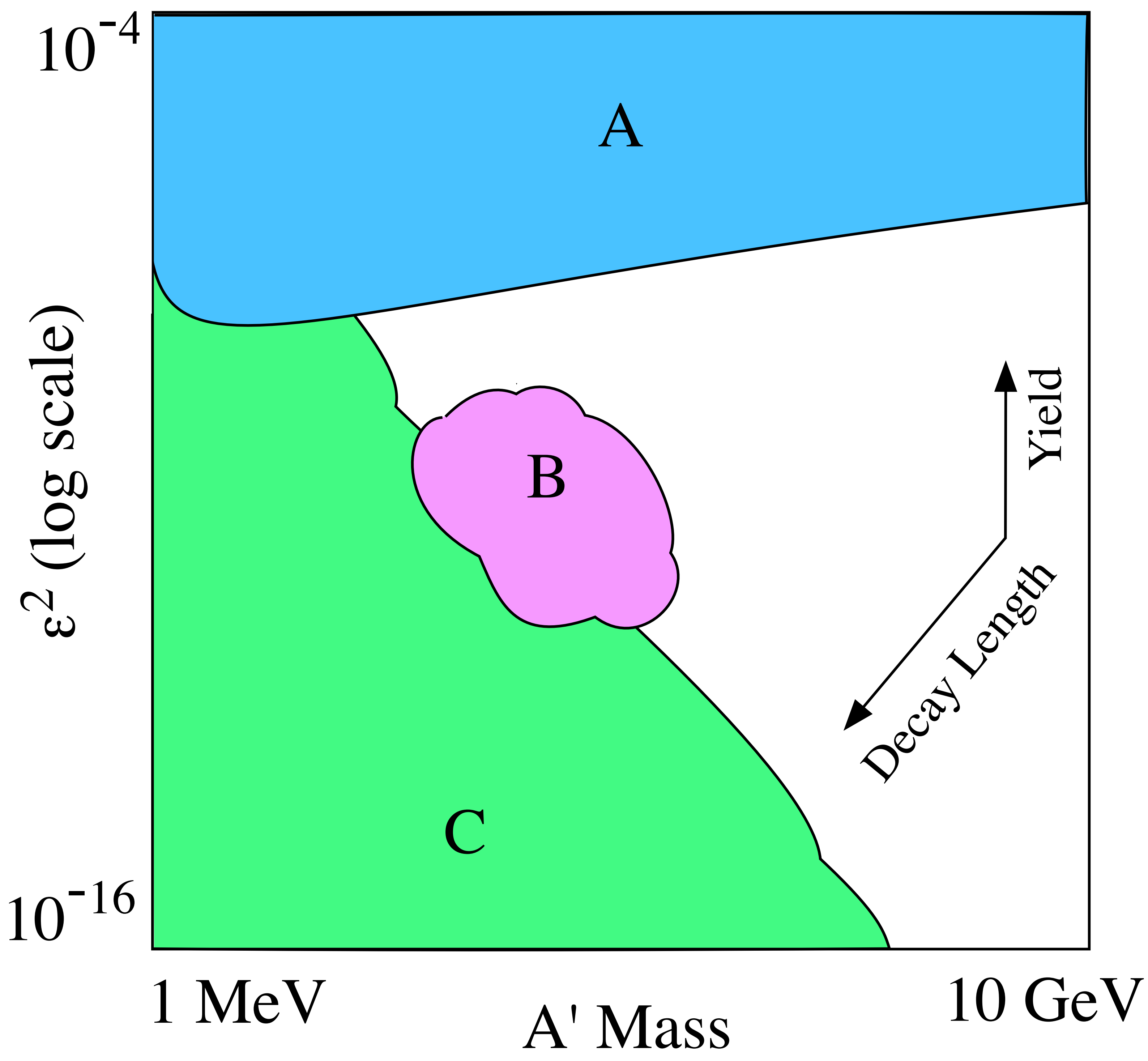
- Vertex detection in $A' \to l^+l^-$;

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

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, $m_{A'}$)



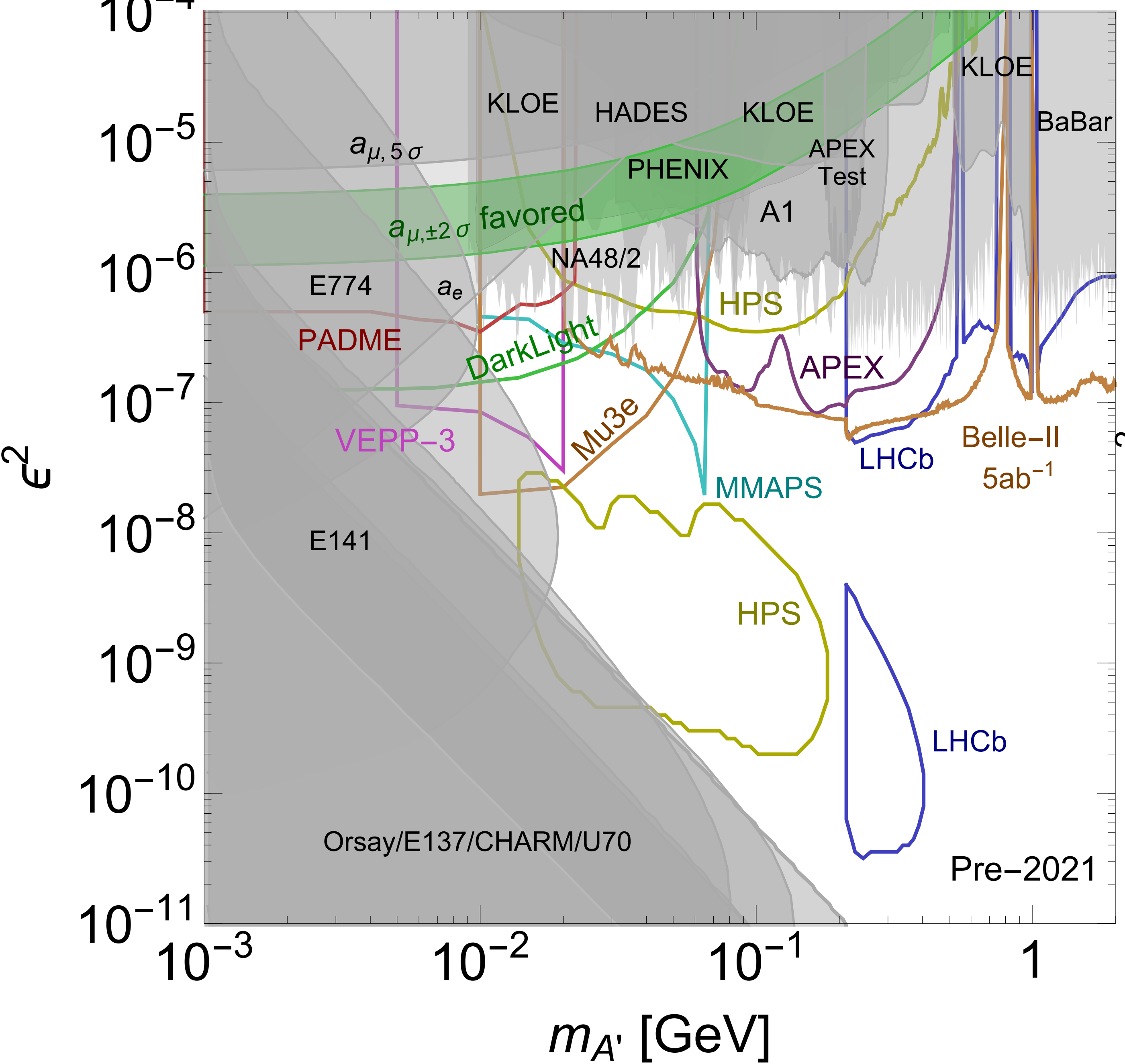
bump hunt
(visible/invisible)

displaced vertex
(short decay length)

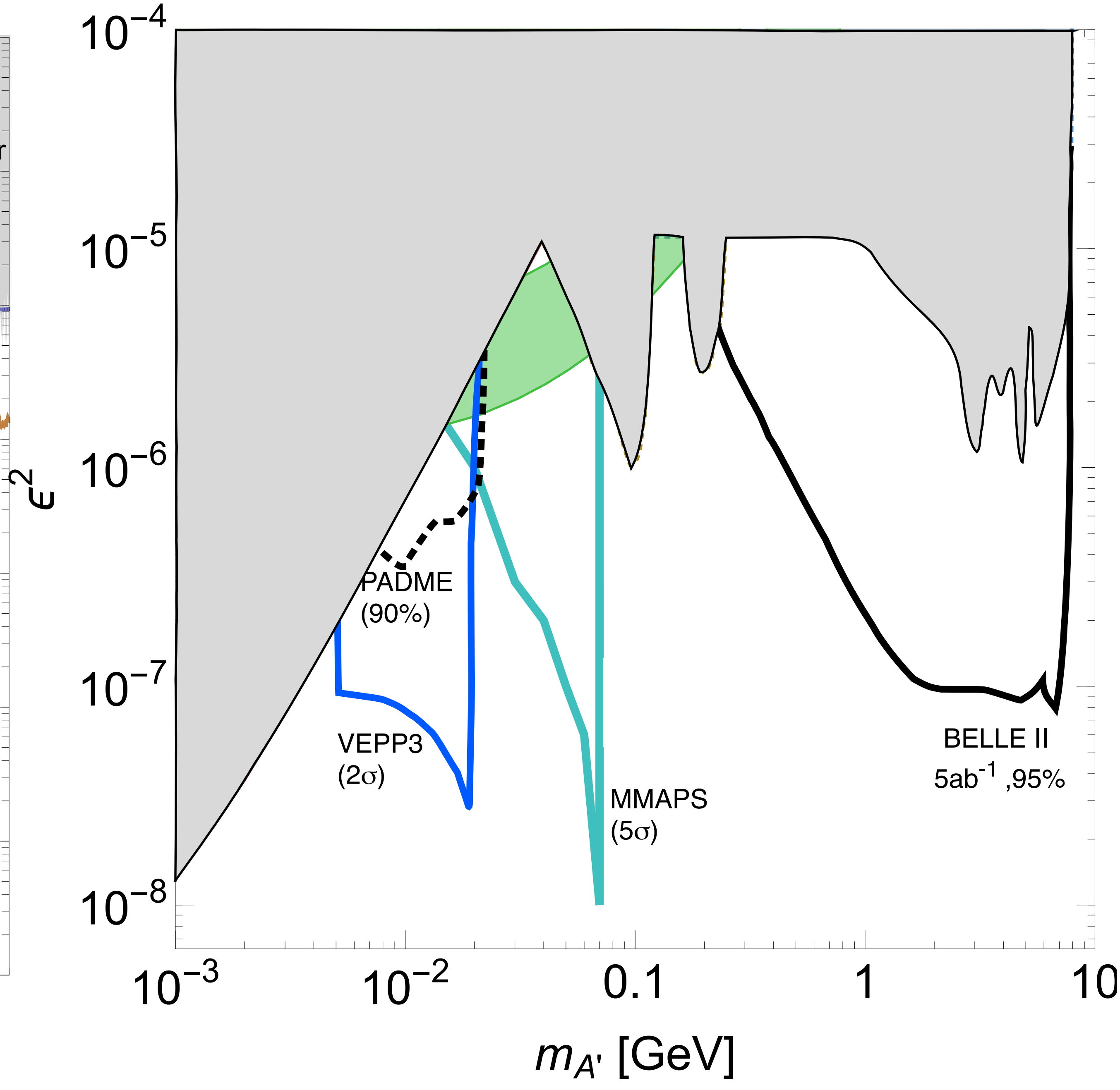
displaced vertex
(long decay length)

present constraints (gray dashed area)

arXiv:1608.08632



- **visible decays**



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

many ongoing and proposed experiments !

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

massless DP

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

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

what if dark-photon mass vanishes ?

massive DP

direct coupling to SM

$$\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

$$g' q_f \bar{\psi}_i \gamma^\mu \psi_f A'_\mu$$

massless DP

no direct coupling to SM

only
higher dimensional
operators

$$\frac{g}{\Lambda} \bar{\psi}\, \sigma^{\mu\nu} \psi\, \bar{F}_{\mu\nu}$$

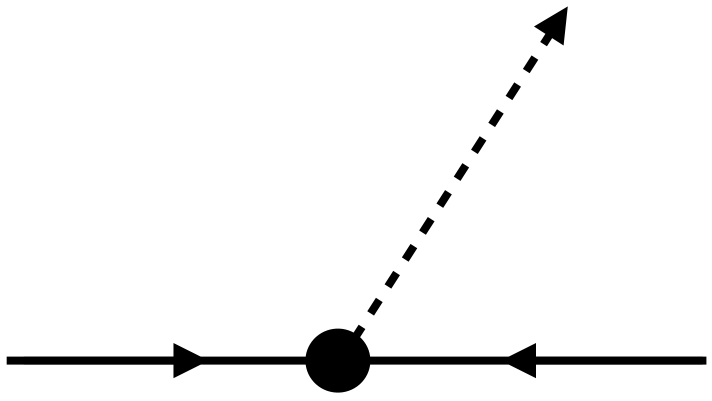
massless DP's can interact with the SM sector only through higher-dimensional (➜ suppressed by $1/M^{D-4}$) interactions via messenger (if any) exchange !

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

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

massless-Dark-Photon signatures :

when produced in collisions :



→ stable + noninteracting

→ neutrino-like signature

a template model for
massless dark-photons

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

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

Gabrielli, Raidal, arXiv:1310.1090, PRD

- 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)
- introducing extra unbroken $U(1)_F$ → massless DP's
- for integer-q(dark fermions) sequence :
  → exponential hierarchy in M(Dark fermions)
  → exponential hierarchy in radiative Y(SM fermions) !!

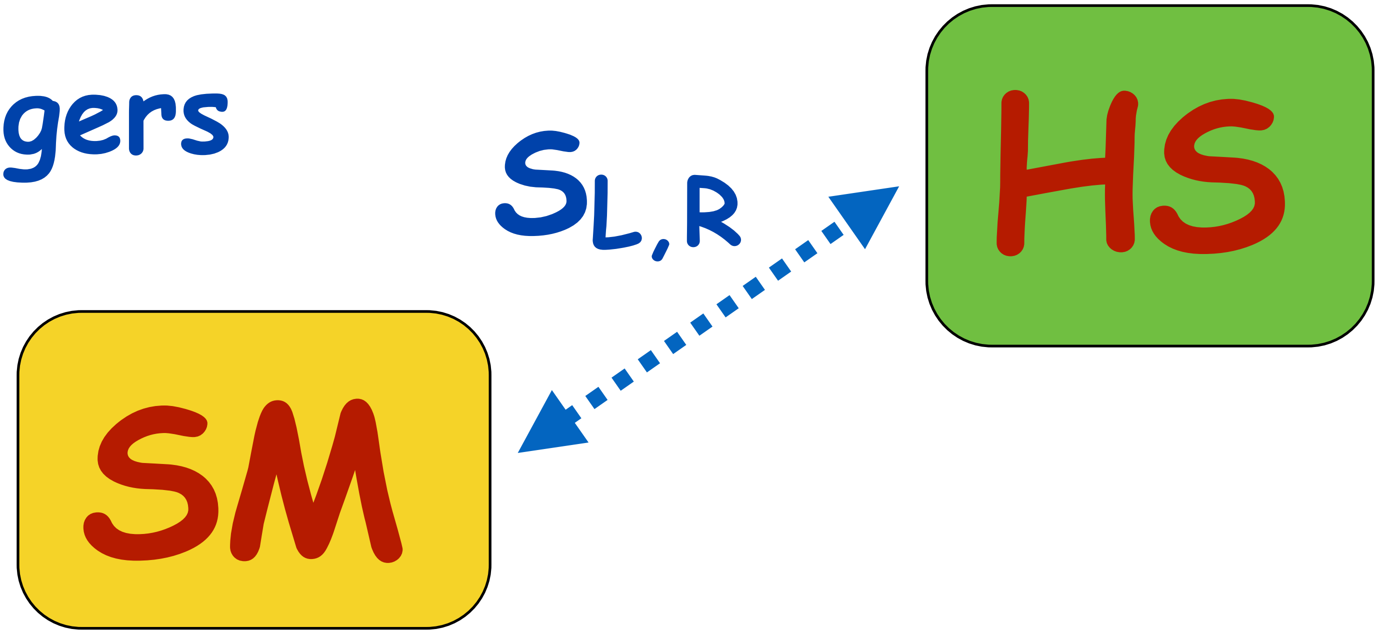
$$M_{D_f} \sim \exp\left(-\frac{\kappa}{q^2_{D_f}\bar{\alpha}}\right)$$

↑ 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


$S_{L,R}$

HS

SM

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

massless-Dark-Photon production mechanisms at colliders

different prod. channels ...

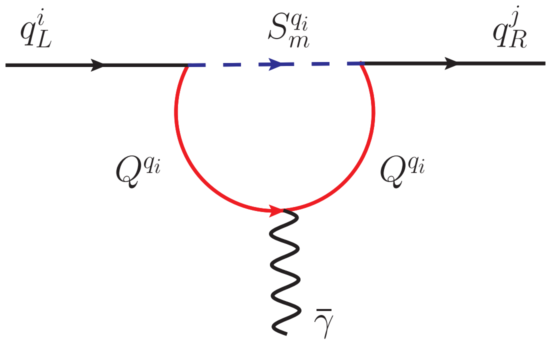
→ plenty of new signatures !

- via Higgs bosons

➡ see following...

Dobrescu, hep-ph/0411004 (PRL)
Gabrielli,Heikinheimo, BM, Raidal, arXiv:1405.5196 (PRD)
Biswas, Gabrielli, Heikinheimo, BM, arXiv:1603.01377 (PRD)

- via FCNC mediated by DP's



➡ new class of FCNC signatures from top, b, c, s, tau, mu decays $f \to f' \bar{\gamma}$

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

(very distinctive → exp bounds expected to be just limited by statistics in ee collisions !)

Dobrescu, hep-ph/0411004 (PRL)
Gabrielli, BM, Raidal, Venturini, arXiv:1607.05928 (PRD)
Fabbrichesi, Gabrielli, BM, arXiv: 1705.03470 (PRL)

- via Z bosons (evading Landau-Yang theorem)

$$Z \to \gamma\bar{\gamma}$$

Fabbrichesi, Gabrielli, BM, arXiv: 1712.05412 (PRL)

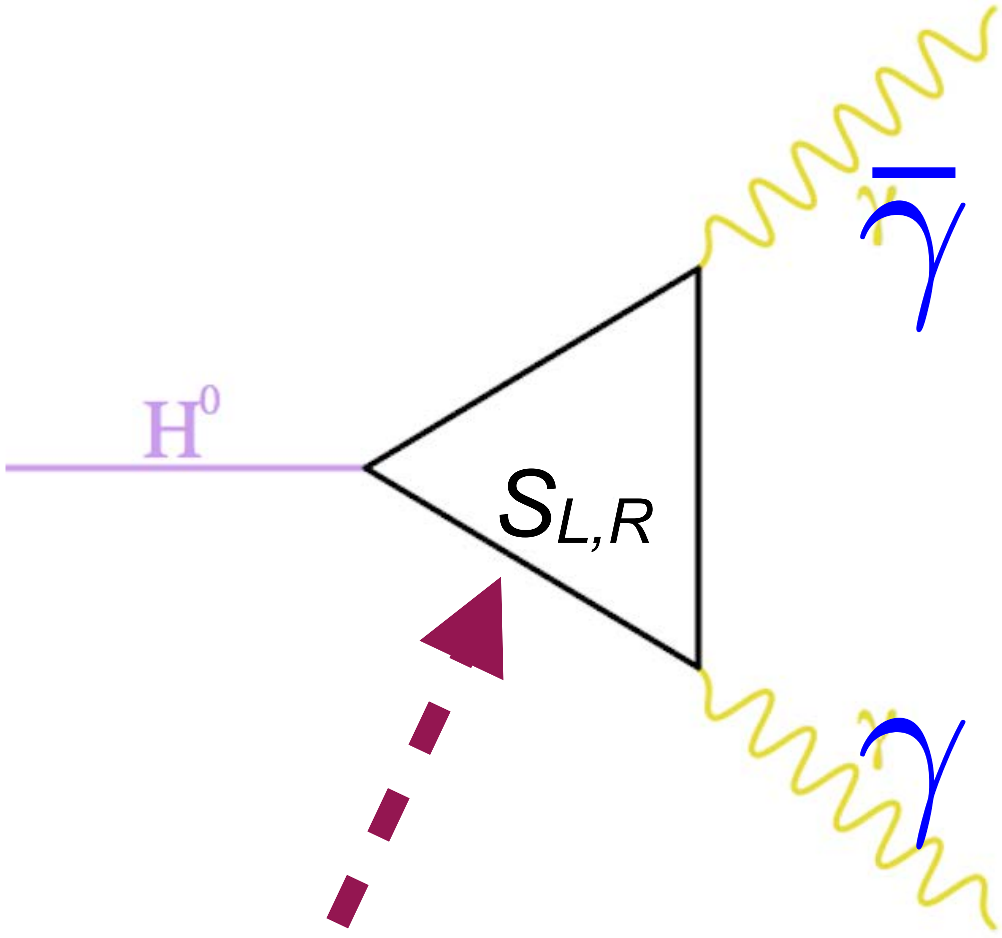
- ...

Higgs as a “source” of Dark Photons

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

mono-photon
resonant signature

Dobrescu, hep-ph/0411004 (PRL)
Gabrielli,Heikinheimo, BM, Raidal, arXiv:1405.5196 (PRD)
Biswas, Gabrielli, Heikinheimo, BM, arXiv:1603.01377 (PRD)



massless (invisible)
Dark Photon

$H \to \bar{\gamma}\bar{\gamma}$ contributing to Γ_H^{inv}

Higgs non-decoupling effects
can enhance BR up to a few % !

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

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

resonant mono-photon signature at 8 TeV

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

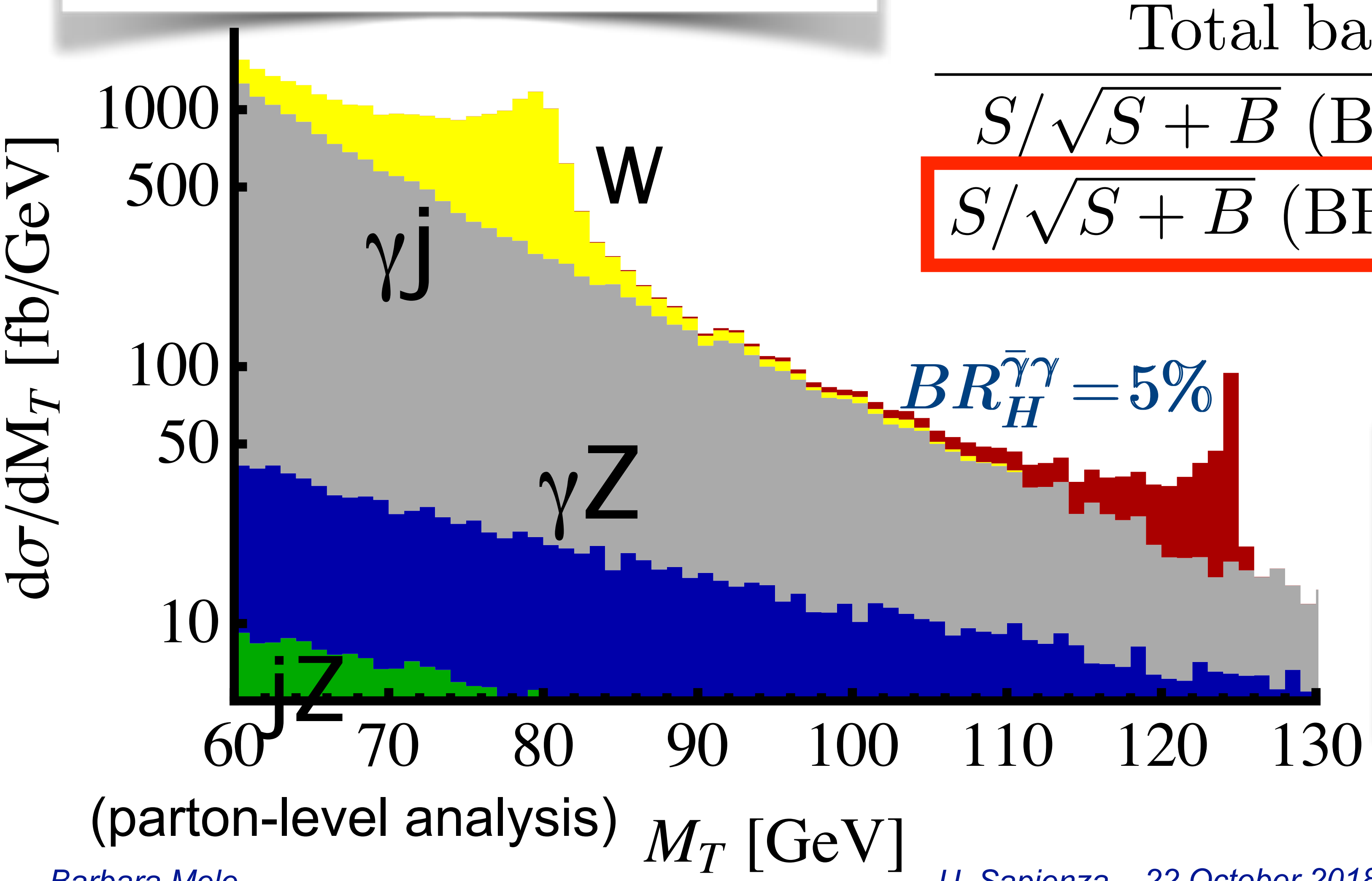
$$gg \to H \to \bar{\gamma}\gamma$$

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

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

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)



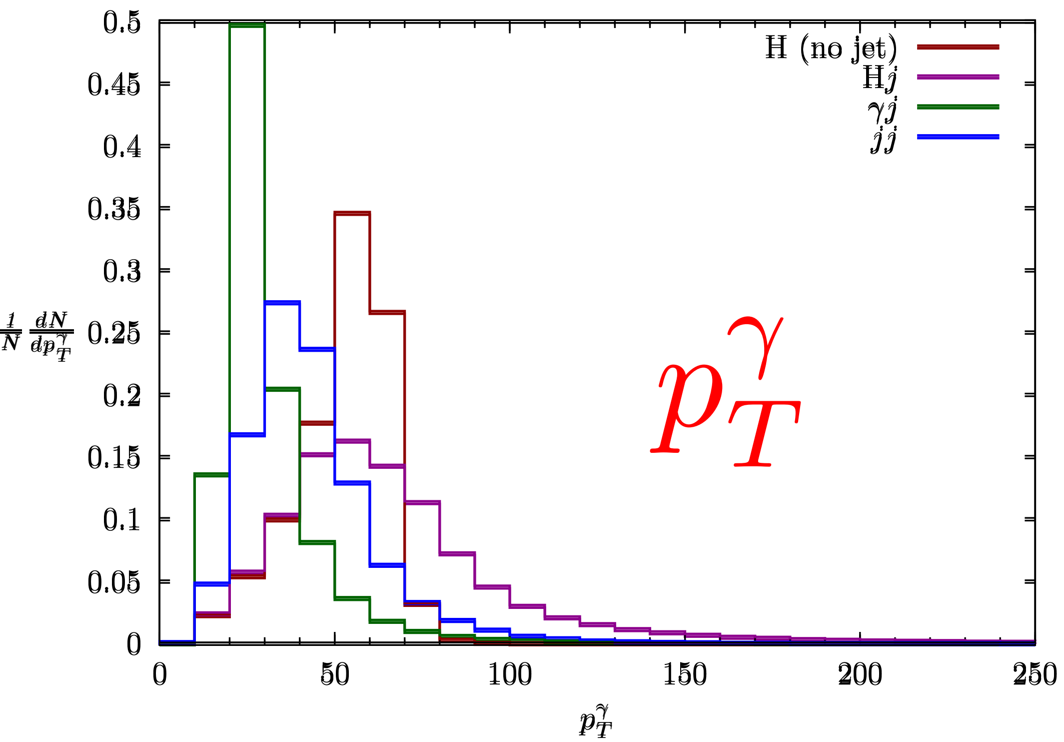
(parton-level analysis)

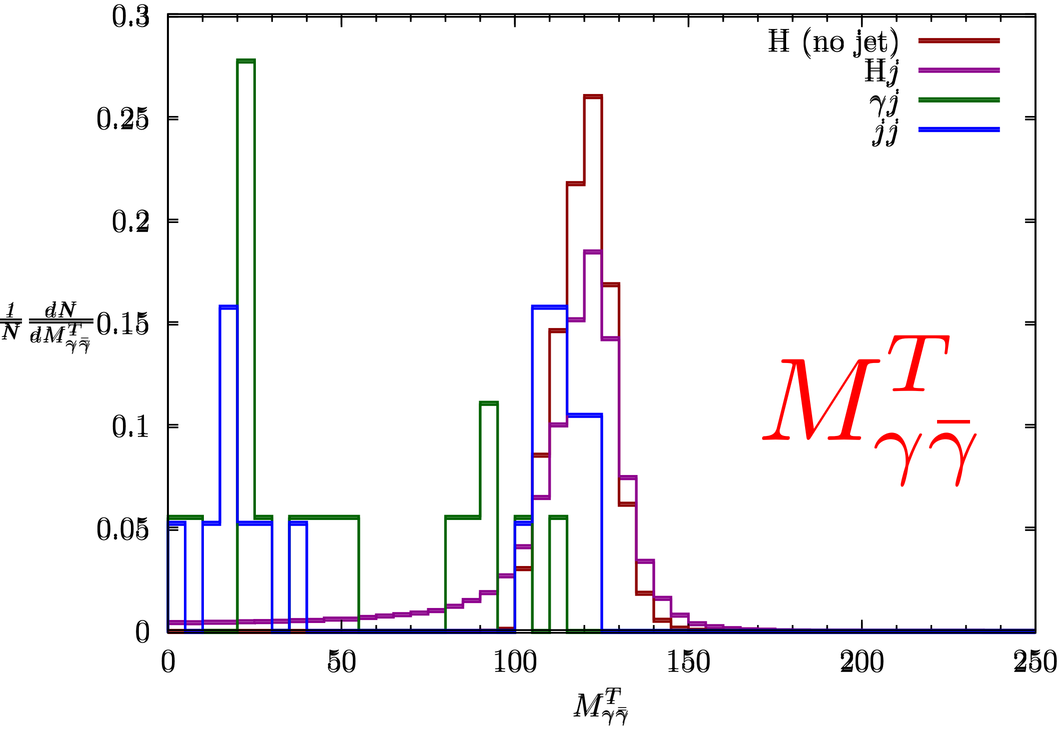
model-independent measurement of BR_{DP}!

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

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))

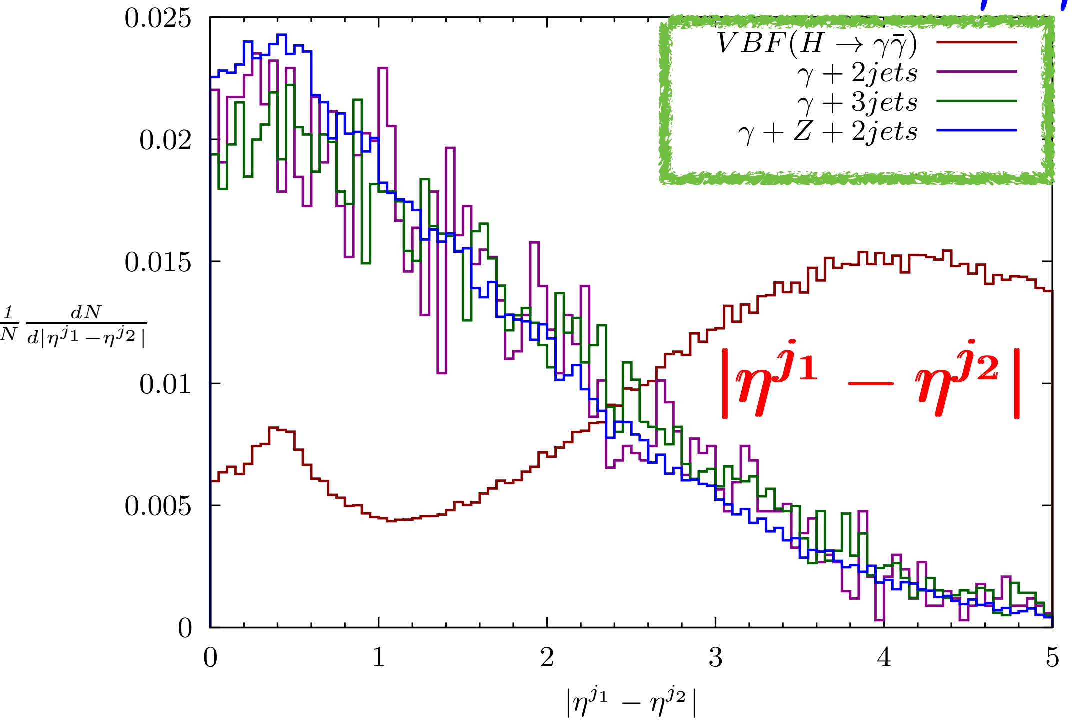
(includes parton-shower)

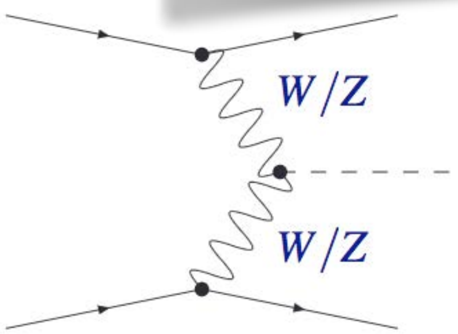
Biswas, Gabrielli, Heikinheimo, BM,
arXiv:1603.01377 (PRD)

mono-photon signature in VBF at 14TeV

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

+ two extra forward jets !





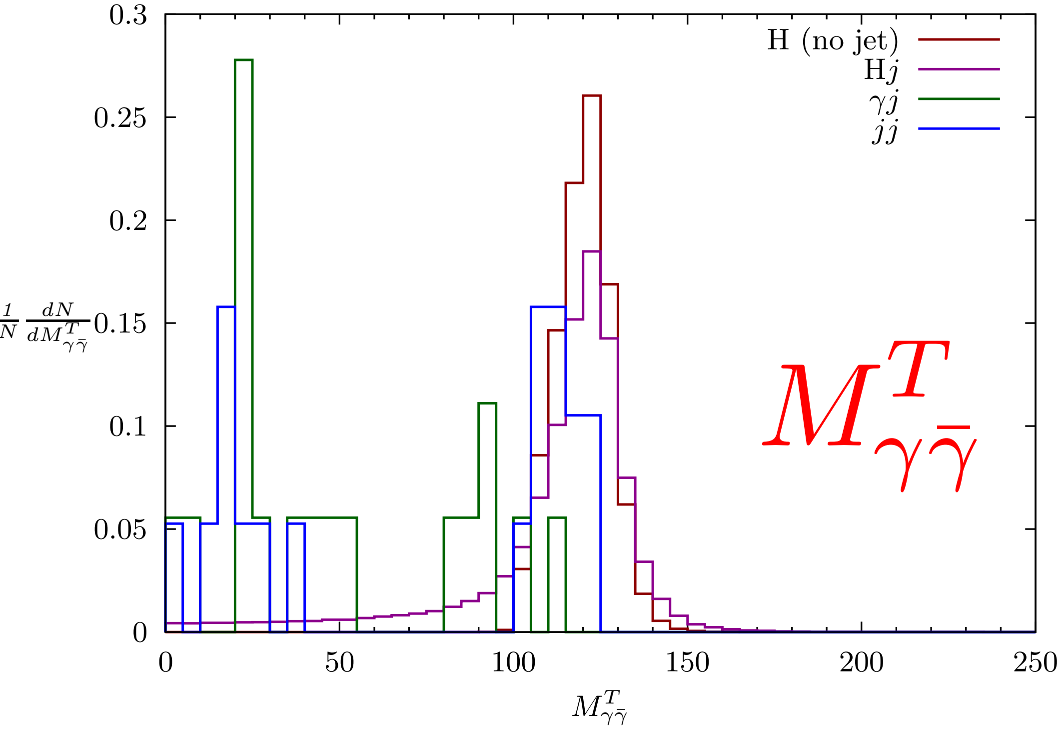
reference $\mathrm{BR_{DP}}$

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

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 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)

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

(γj-bckgr modelling critical !)

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

gg fusion sensitive down to $BR_{DP} \sim 10^{-4}$–10^{-3}

(VBF ~10 times worse …)

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

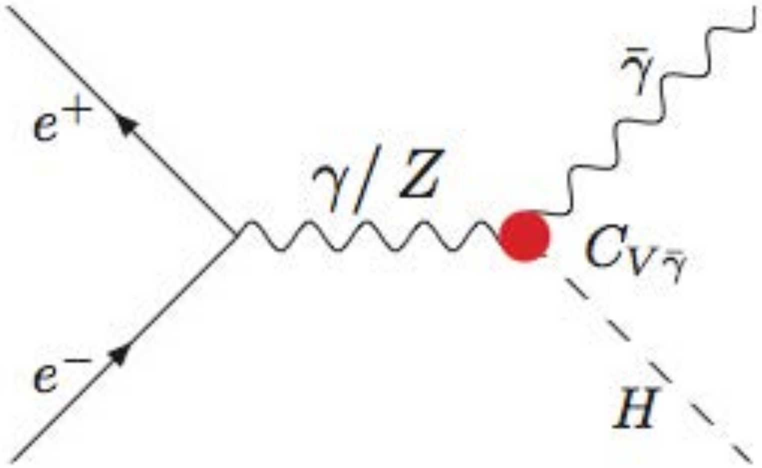
int. luminosity	3 ab^{-1}@14 TeV		15 ab^{-1}@27 TeV	
significance	2σ	5σ	2σ	5σ
CMS inspired	0.012	0.030	0.0052	0.013
jet veto in $\lvert\eta^j\rvert < 4.5$	0.020	0.051	0.021	0.053

- **alternative strategy to suppress the QCD background, which grows rapidly with the collision energy**

new Higgs signatures @ e^+e^- colliders from invisible dark photons

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

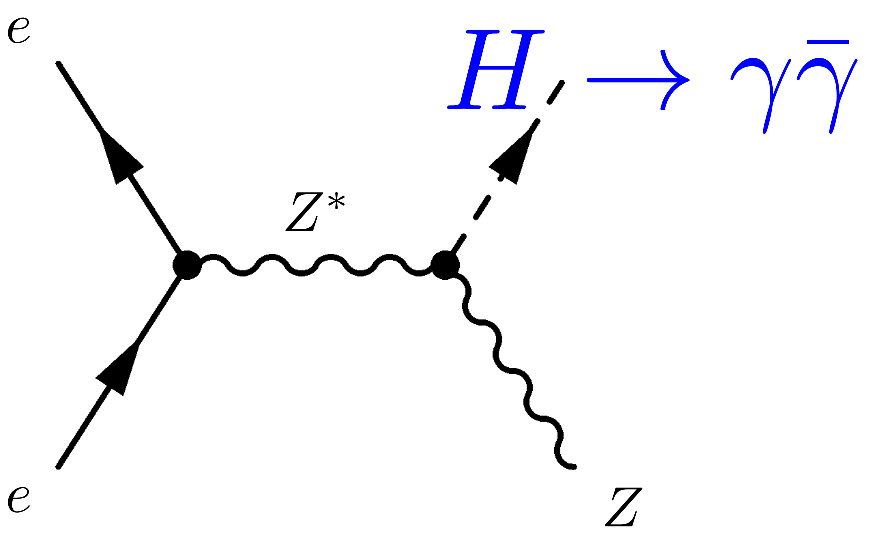
p_{Higgs} balanced by a massless invisible system



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

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

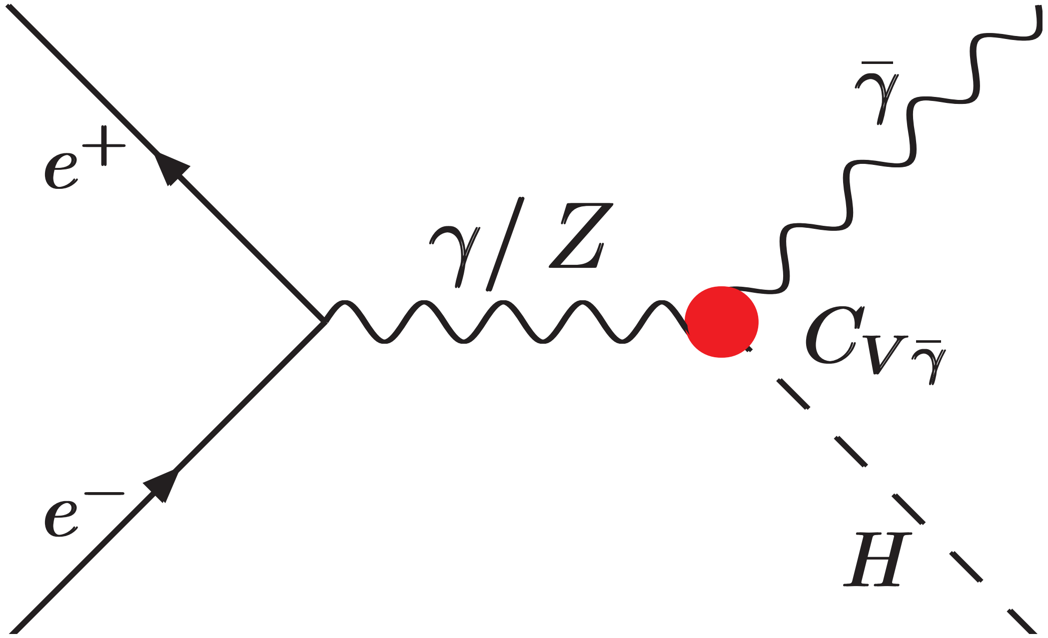
(photon + E_{miss}) resonant signature



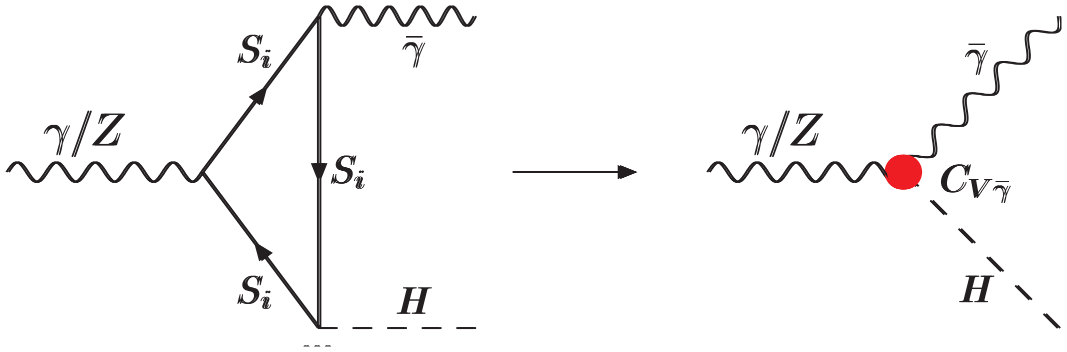
Biswas, Gabrielli, Heikinheimo, BM,
arXiv:1703.00402 (PRD)

Higgs + DP associate production

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



- new signature in e+e- collisions → Higgs recoiling from a massless invisible system



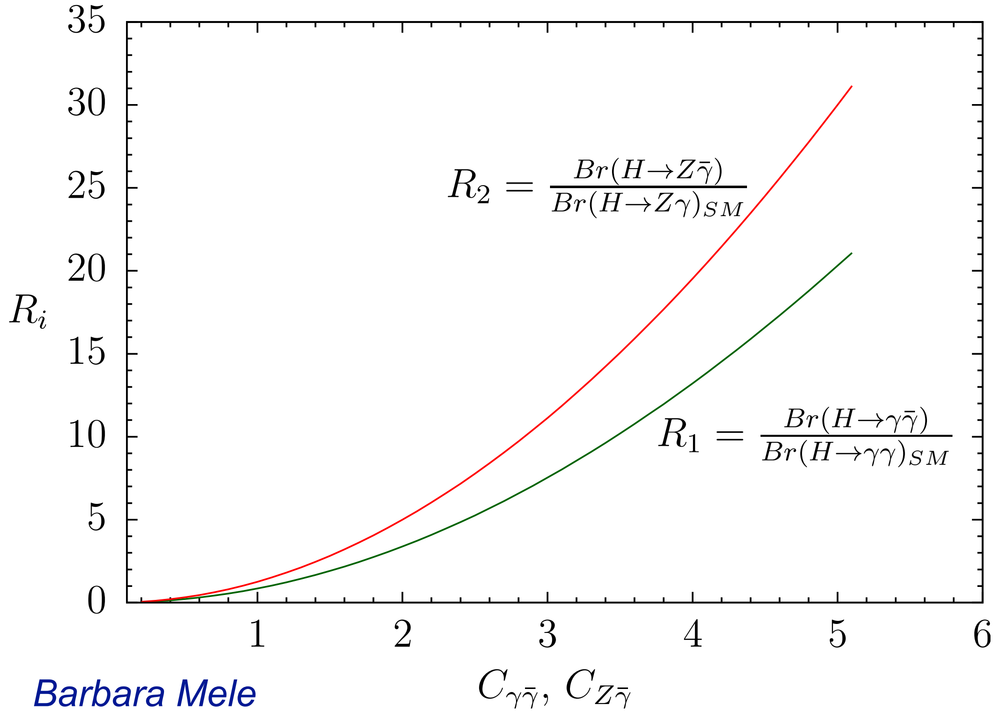
- model-independent analysis

  Effective-Lagrangian parametrization

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

DP field strength

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



$$\frac{BR(H\to\bar{\gamma}\gamma,\ \bar{\gamma}Z)}{BR(H\to\gamma\gamma,\ \gamma Z)_{SM}} \quad \text{vs} \quad C_{ij}$$

$e^+e^- \to H\,\bar{\gamma}$: total x-section

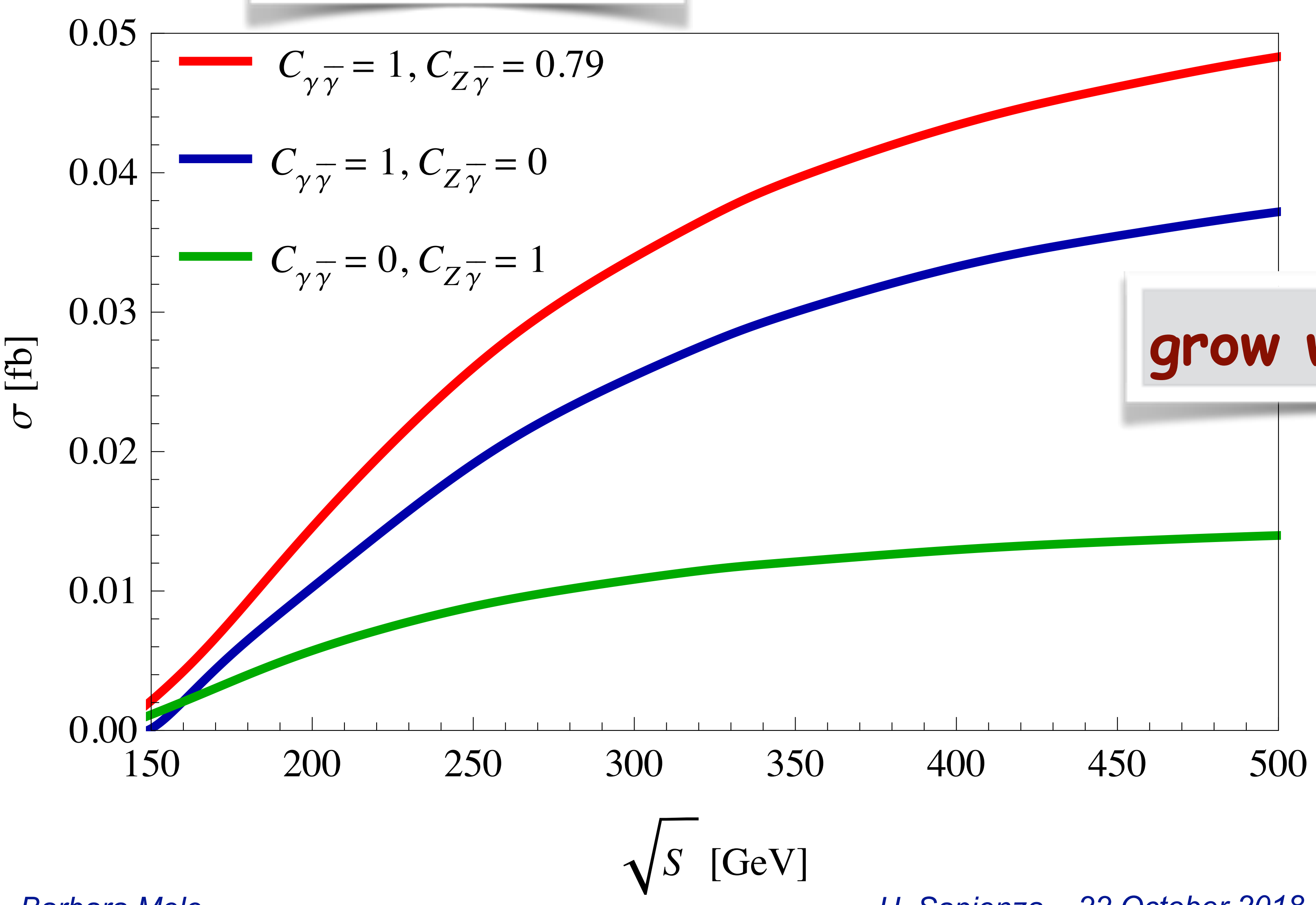
$$\mathcal{L}_{\rm DP_H} = \frac{\alpha}{\pi}\Big(\frac{C_{\gamma\bar{\gamma}}}{v}\gamma^{\mu\nu}\bar{\gamma}_{\mu\nu}H + \frac{C_{Z\bar{\gamma}}}{v}Z^{\mu\nu}\bar{\gamma}_{\mu\nu}H + \frac{C_{\bar{\gamma}\bar{\gamma}}}{v}\bar{\gamma}^{\mu\nu}\bar{\gamma}_{\mu\nu}H\Big)$$

- **three benchmarks for C_{ij} choice**

typical of vertices induced by scalar messengers in the fundamental $SU(2)_L \times SU(3)_C$ representation

(squark doublet with L/R degeneracy)

$$C_{Z\bar{\gamma}}/C_{\gamma\bar{\gamma}} \simeq 0.79$$



55 ab,

43 ab,

grow with √S from dim-5 operators

15 ab

√S~1TeV

could be ~10 times larger than that for C_{ij} >1…

S vs B at $\sqrt{S} = 240$ GeV & $\int L \sim 10\ \mathrm{ab}^{-1}$

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

large rates, moderate bckgrs

- signature ➜ two b jets + (massless) missing E/p

MadGraph5_aMC@NLO (Eff.Lag. in FeynRules)
+ PYTHIA for showering and hadronization ;
b-jets via jet-cone (R_j=1.5); E_j smearing ➜ $\sigma(E)/E = 30\%/\sqrt{E}$
b-tag. eff.~80% ; light-jet rejection ~ 100

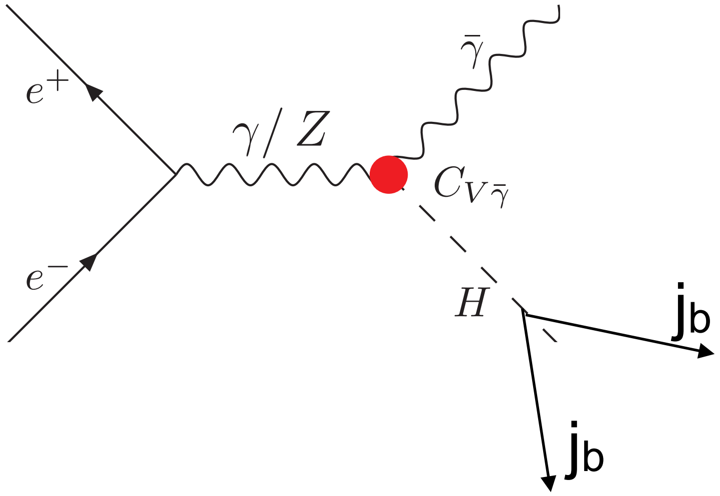
- main backgrounds :

$$ZZ \to \nu\bar{\nu}b\bar{b} \quad \nu\bar{\nu}q\bar{q}$$
$$ZH \to \nu\bar{\nu}b\bar{b}$$
$$H\nu\bar{\nu} \quad \text{(VBF)}$$

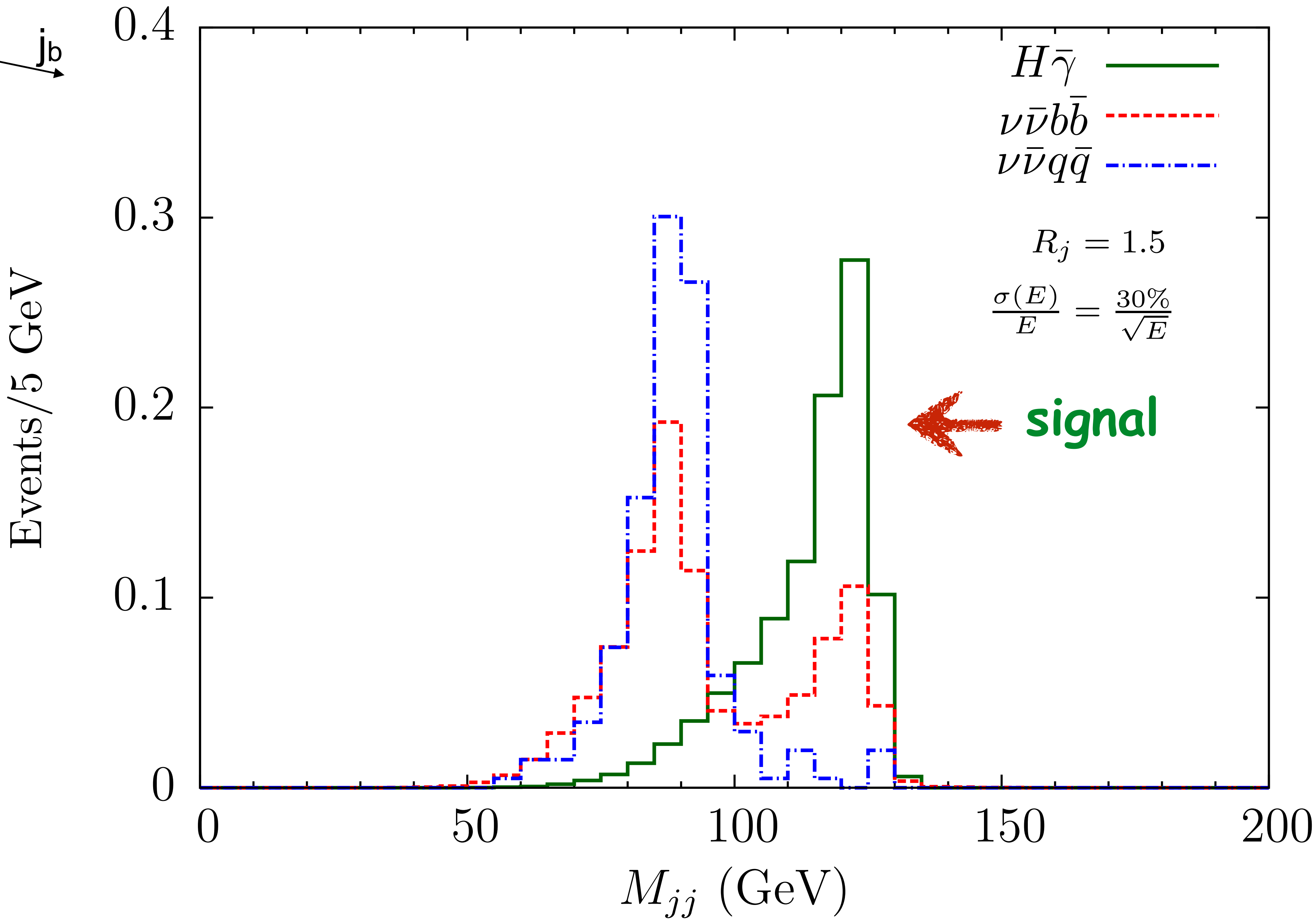
Basic cuts
$$\begin{cases} p_T^b > 20\ \text{GeV}\ , & |\eta_b| < 2.5 \\ \Delta R(bb) > 0.4\ , & \not{E} > 40\ \text{GeV} \end{cases}$$

- two particularly efficient observables for separating S from B

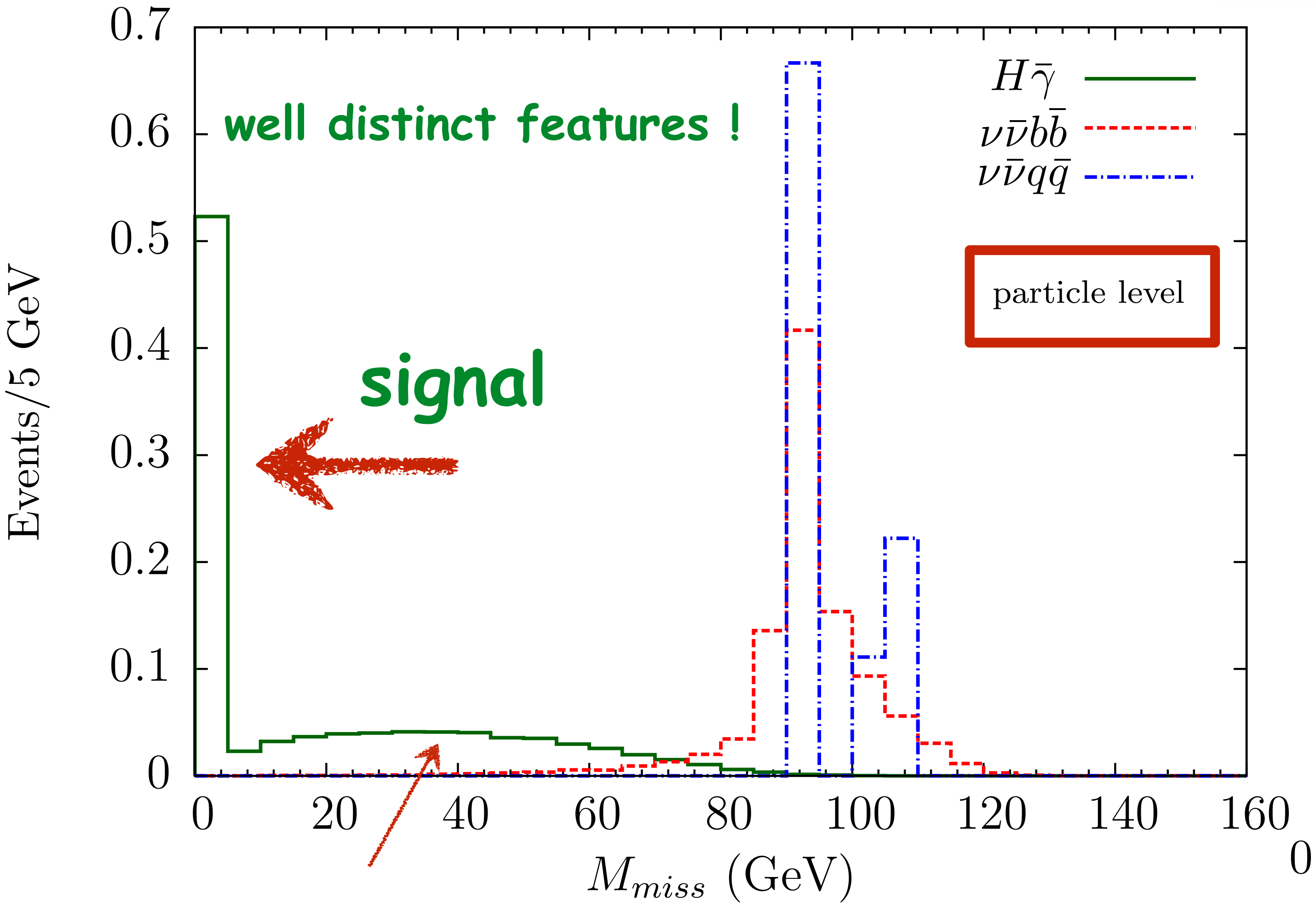
(normalized) M_{jj} distributions



jj ➜ two jets with largest p_T



(norm.) M_{miss} distrib.s before and after Pythia



well distinct features !

signal

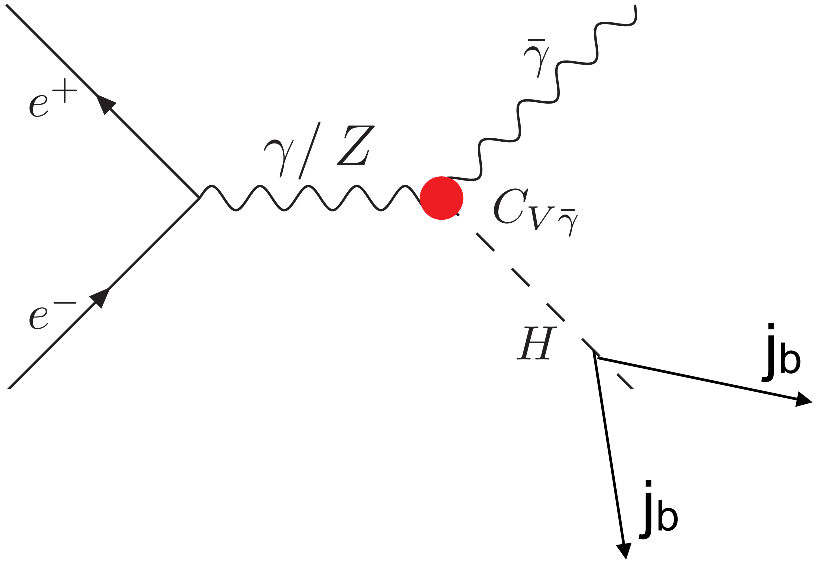
$$M_{\rm miss} = \sqrt{\not{E}^2 - \not{\mathbf{p}}^2}$$

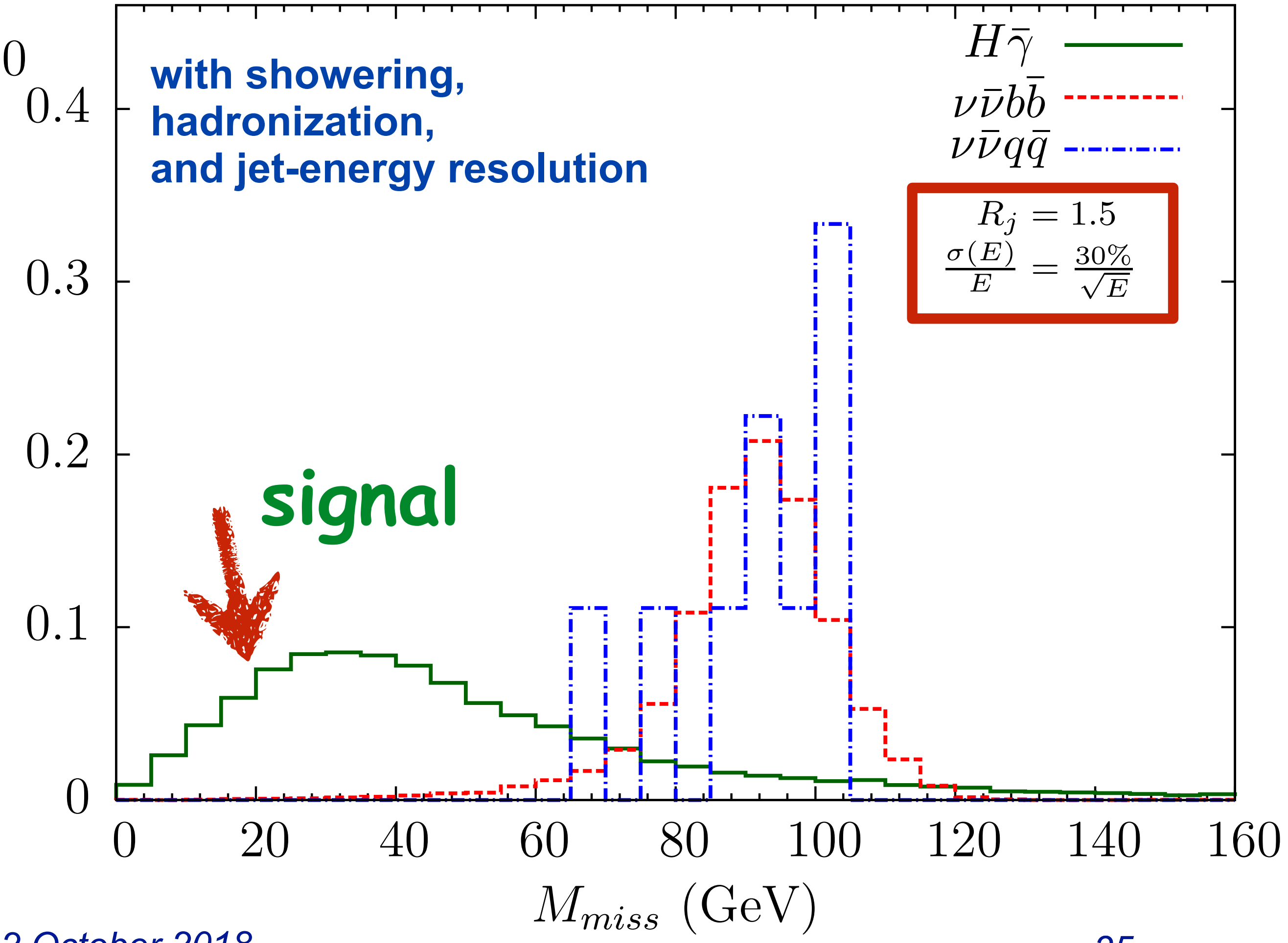
$$\not{E} = \sqrt{s} - \sum \mathrm{E}_{visible}$$

$$\not{\mathbf{p}} = - \sum \mathbf{p}_{visible}$$

includes lower-E particles escaping jet reconstruct.

due to finite acceptance





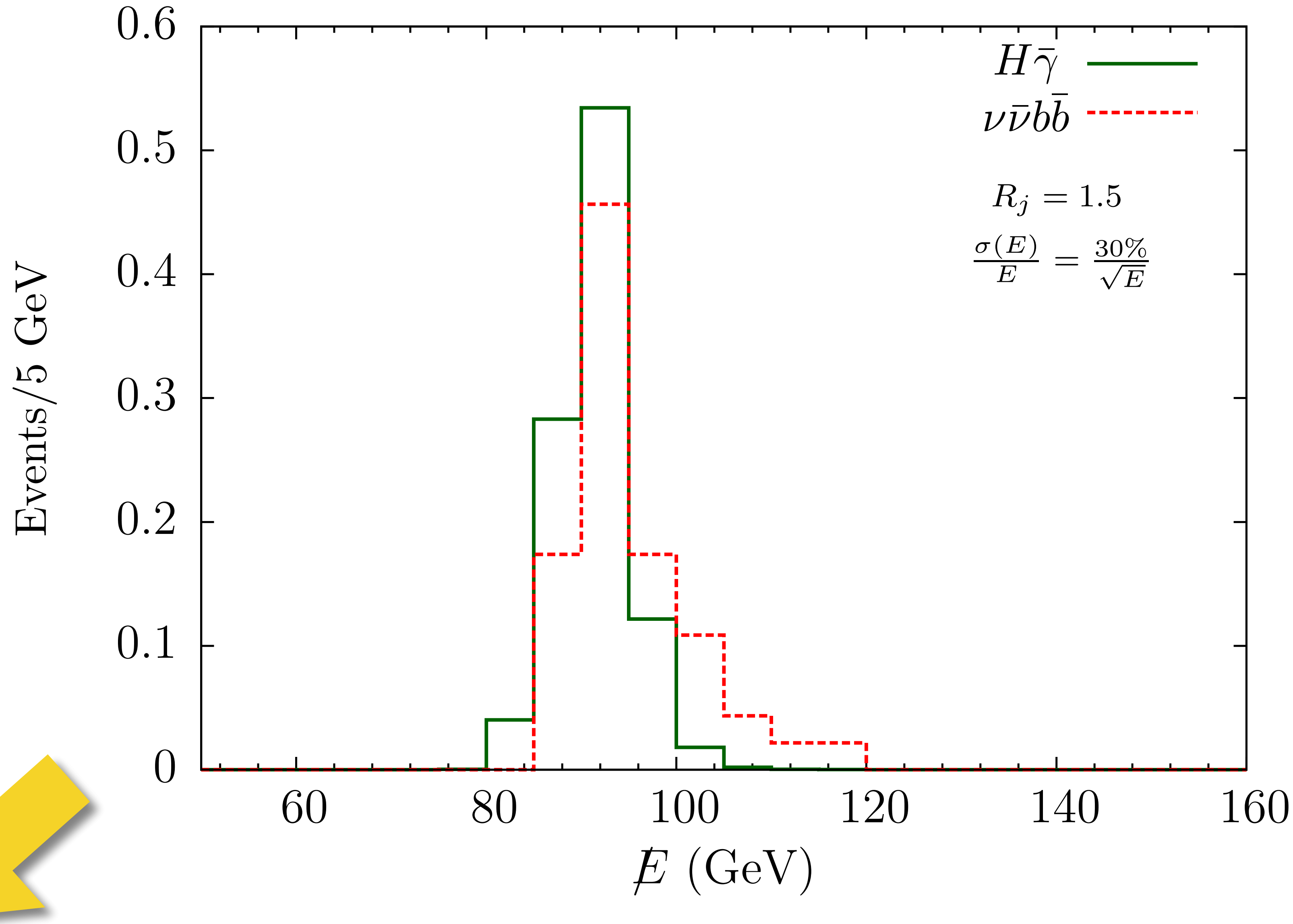
with showering, hadronization, and jet-energy resolution

signal

optimizing S/B via M_{jj} and M_{miss} cuts

impose
M_{jj} within 10%
from M_{jj}^H **(peak)**

impose
M_{miss} < 40GeV
➜ kills $\nu\bar{\nu}q\bar{q}$



impose $\not{E} < 100$ GeV

* final acceptance ➜ **17%** for $e^+e^- \to H\bar{\gamma} \to b\bar{b}\bar{\gamma}$

0.08% for $\nu\bar{\nu}b\bar{b}$

~ indipendently from C_{ij}

signal significance at $\sqrt{S}$ = 240 GeV & $\int L$ ~ 10 ab^{-1}

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

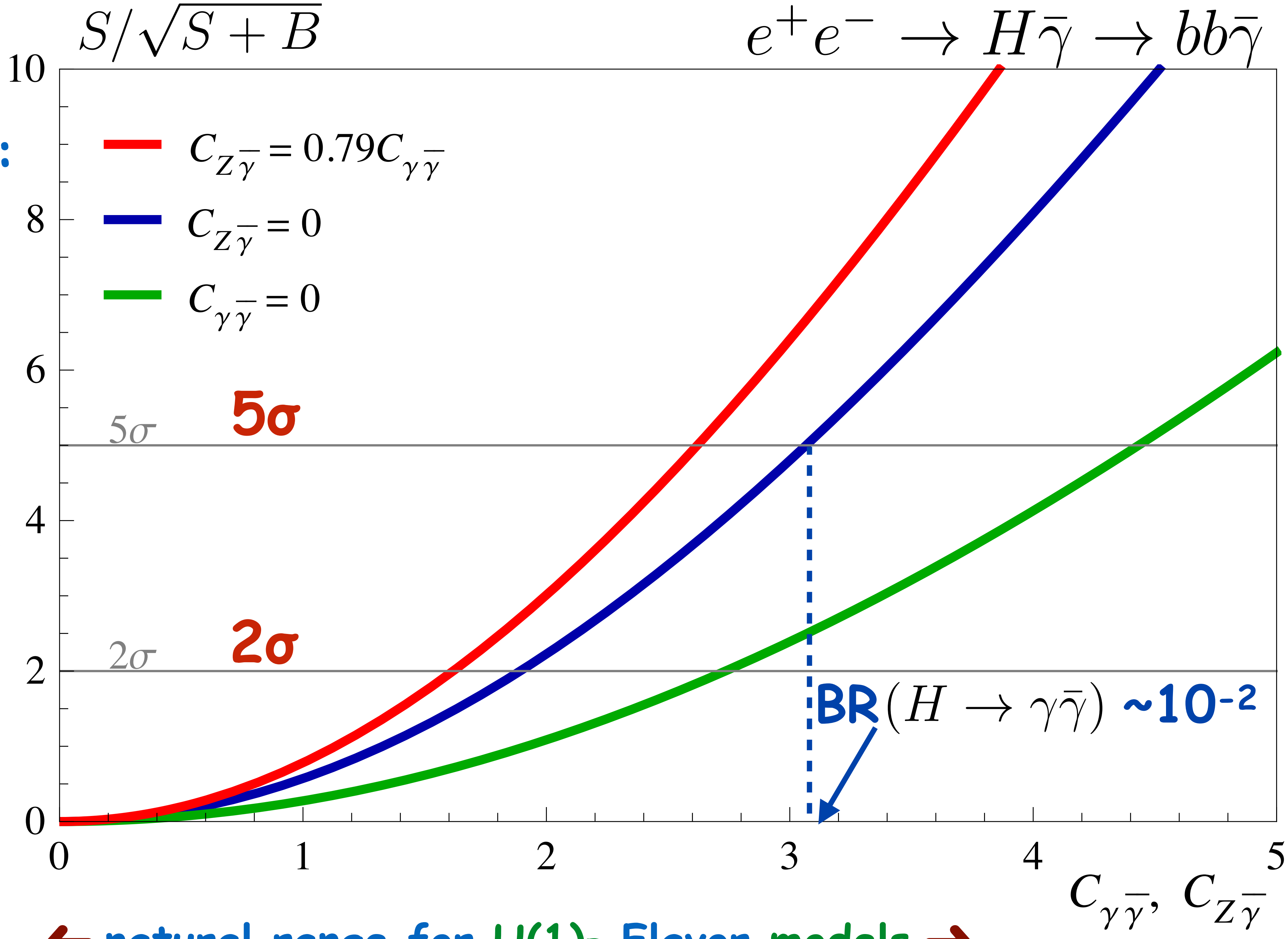
for $C_{Z\bar{\gamma}} = 0$,

- **excludes** couplings giving :

$$\mathrm{BR}(H \to \gamma\bar{\gamma}) \gtrsim 3\ \mathrm{BR}(H \to \gamma\gamma)$$

- **discovers** couplings giving :

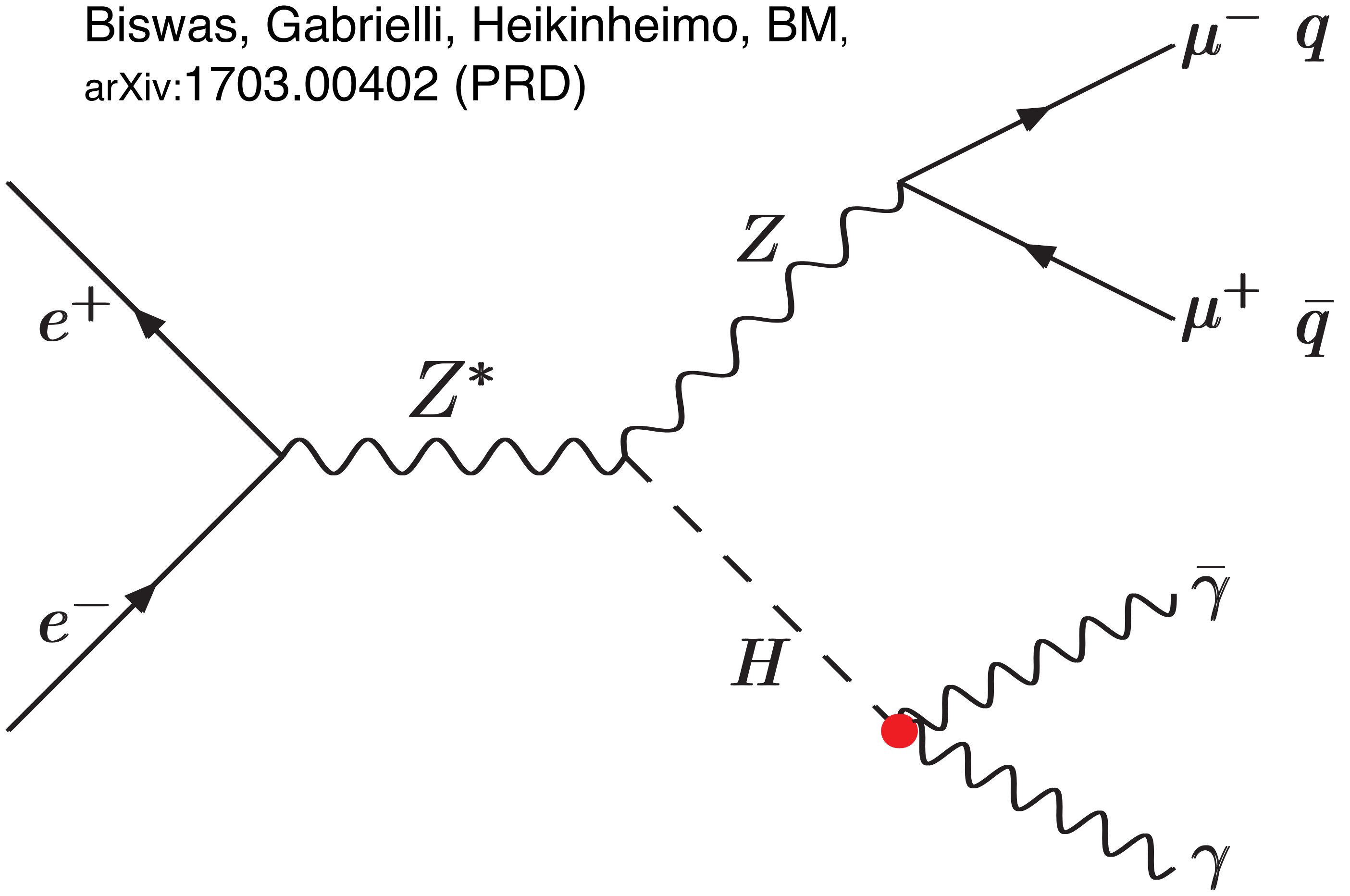
$$\mathrm{BR}(H \to \gamma\bar{\gamma}) \gtrsim 10^{-2}$$



← natural range for U(1)$_F$ Flavor models →

$e^+e^- \to ZH \to \mu^+\mu^-\gamma\bar{\gamma},\ q\bar{q}\,\gamma\bar{\gamma}$ @FCC-ee

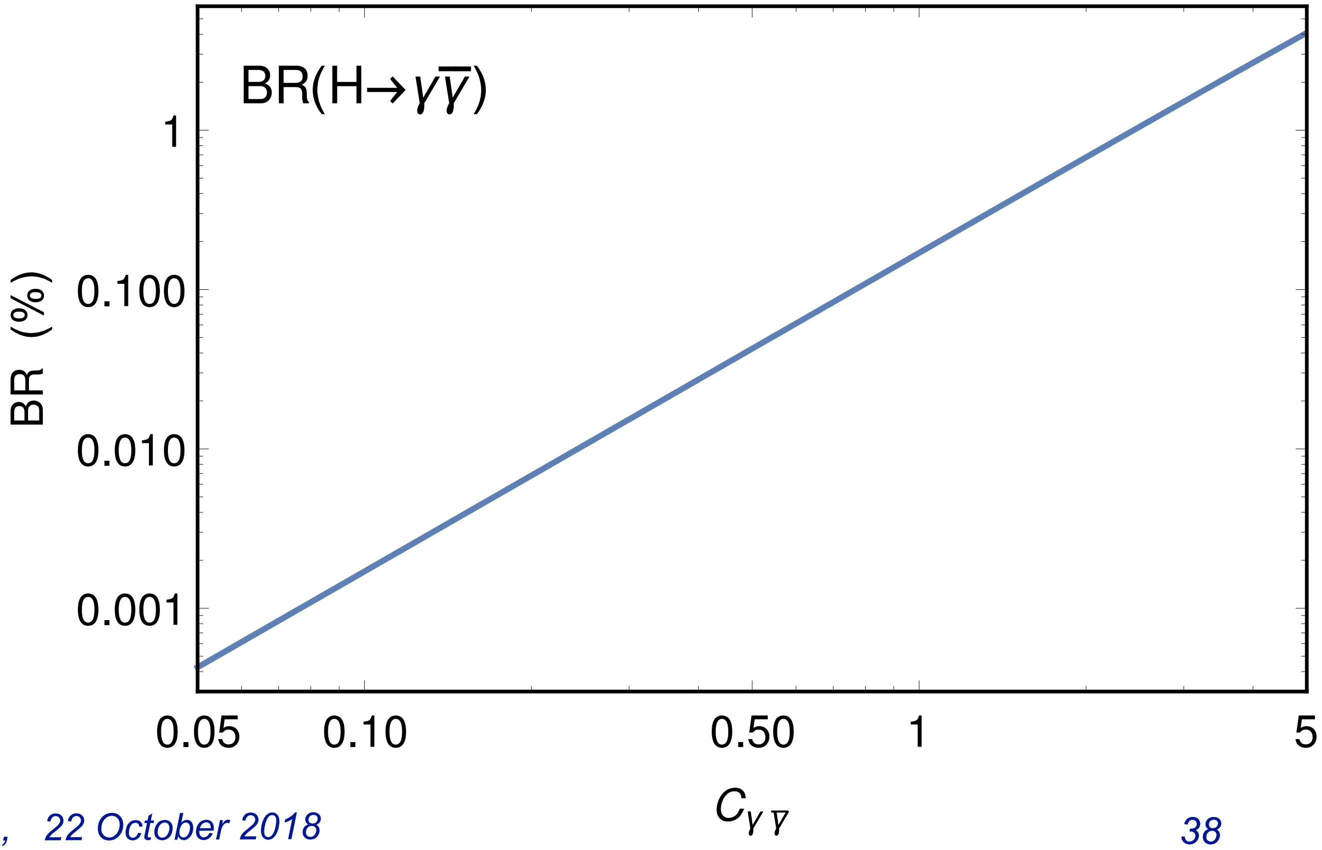
Biswas, Gabrielli, Heikinheimo, BM,
arXiv:1703.00402 (PRD)



- **signature:**
  a massless invisible p.le
  + a photon
  resonating at m_H plus
  a mu/jet pair resonating
  at M_Z

- **one-parameter study**
  (model-independent)

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



main backgrounds

- **leptonic** channel : resonant plus t-channel

$e^+e^- \to \mu^+\mu^-\nu\bar{\nu}\gamma$ $ZZ\gamma$ $e^+e^- \to \nu\bar{\nu}Z\gamma$

$WW\gamma$

$Z\gamma$ plus fake missing energy

- **hadronic** channel :

$e^+e^- \to q\bar{q}\nu\bar{\nu}\gamma$

$e^+e^- \to q\bar{q}\gamma \to jj\gamma$ plus fake missing energy

simulation

PYTHIA for signal and MadGraph5_aMC@NLO + PYTHIA for bckgrds

ISR/FSR effects described by PYTHIA

Finite detector resolutions for γ, μ, j

(as for **ILD** detector)

$$\Delta E/E = 16.6\%/\sqrt{E/\ \mathrm{GeV}} + 1.1\%.$$

$$\Delta p/p = 0.1\% + p_T/(10^5\ \mathrm{GeV})\ \text{for}\ |\eta| < 1$$

$$\Delta E/E_{\mathrm{j}} = 30\%/\sqrt{E/\ \mathrm{GeV}}$$

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

leptonic channel

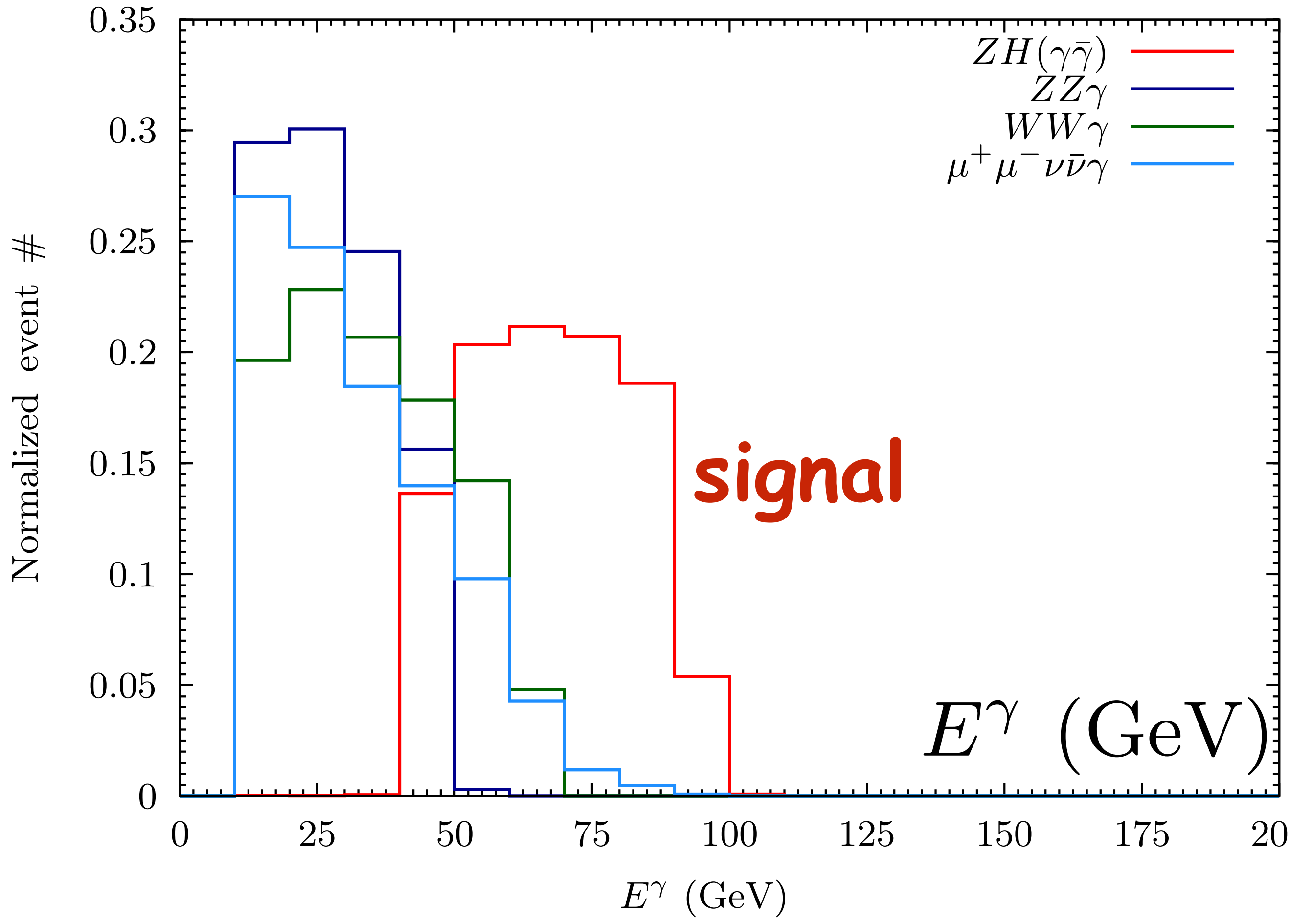
- **basic cuts** $p_T^\mu, p_T^\gamma > 10 \text{ GeV}$

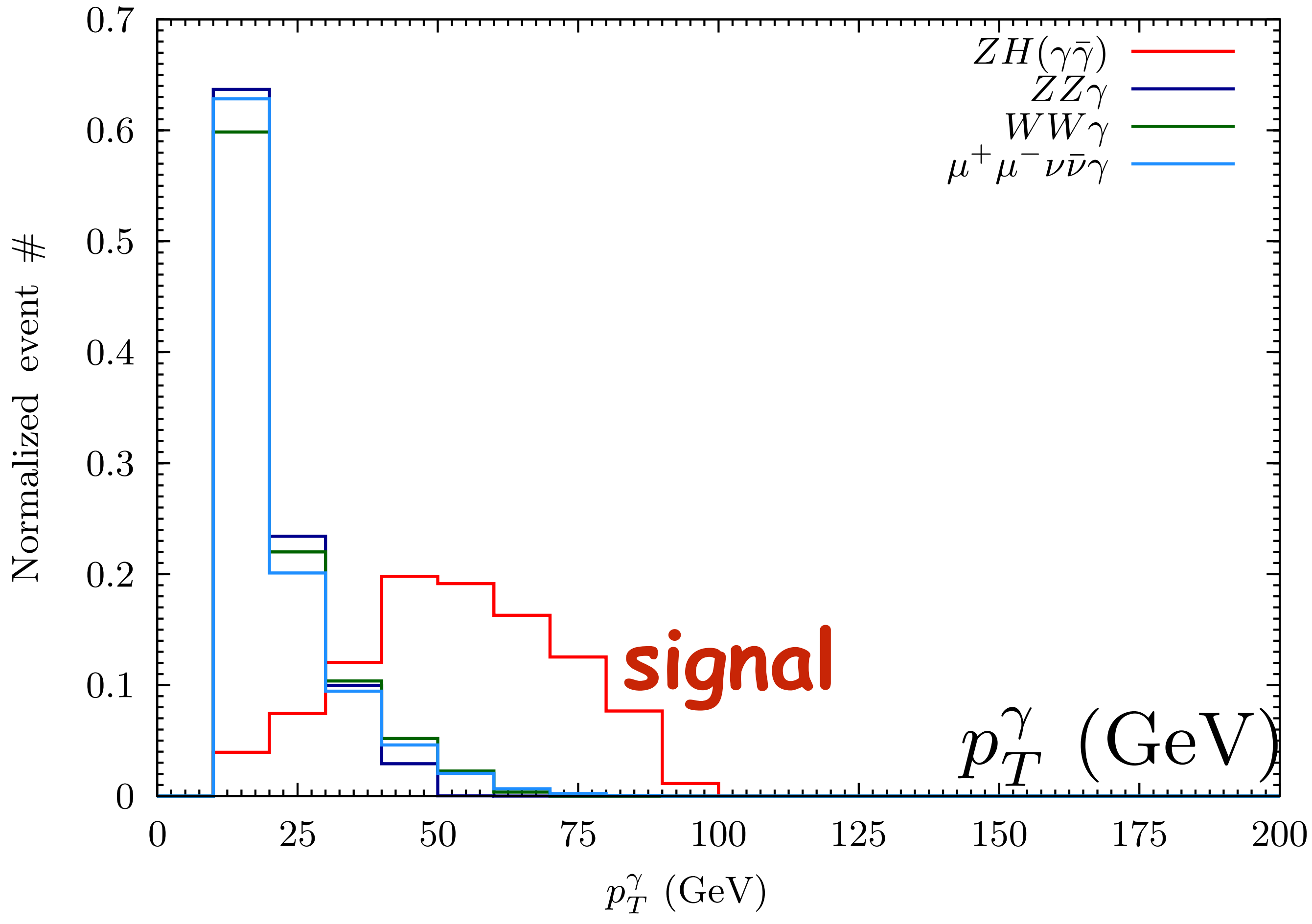
$$|\eta^\mu|, |\eta^\gamma| < 2.5 \qquad \Delta R > 0.2$$

between any two objects

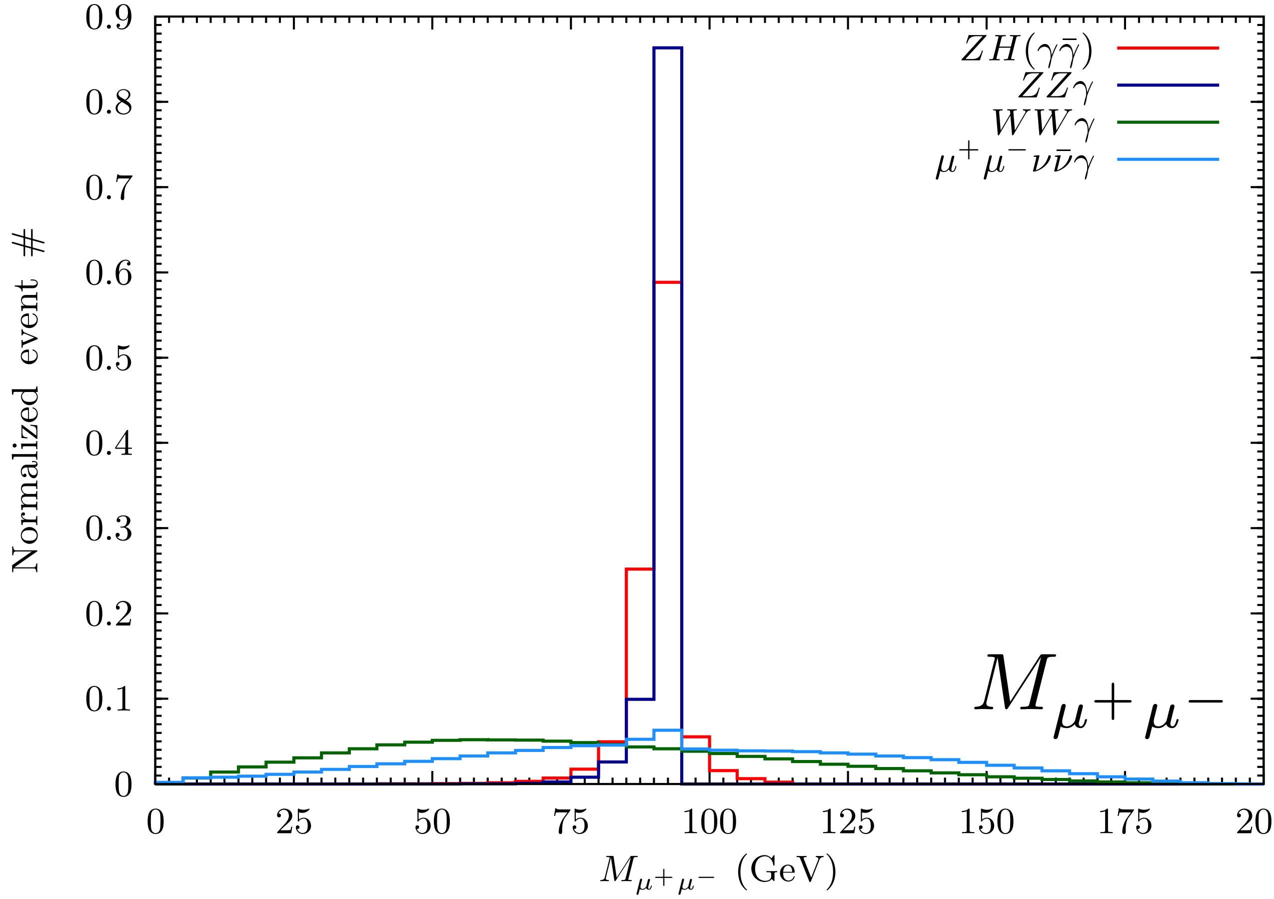
$$\not{E} > 10 \text{ GeV}$$

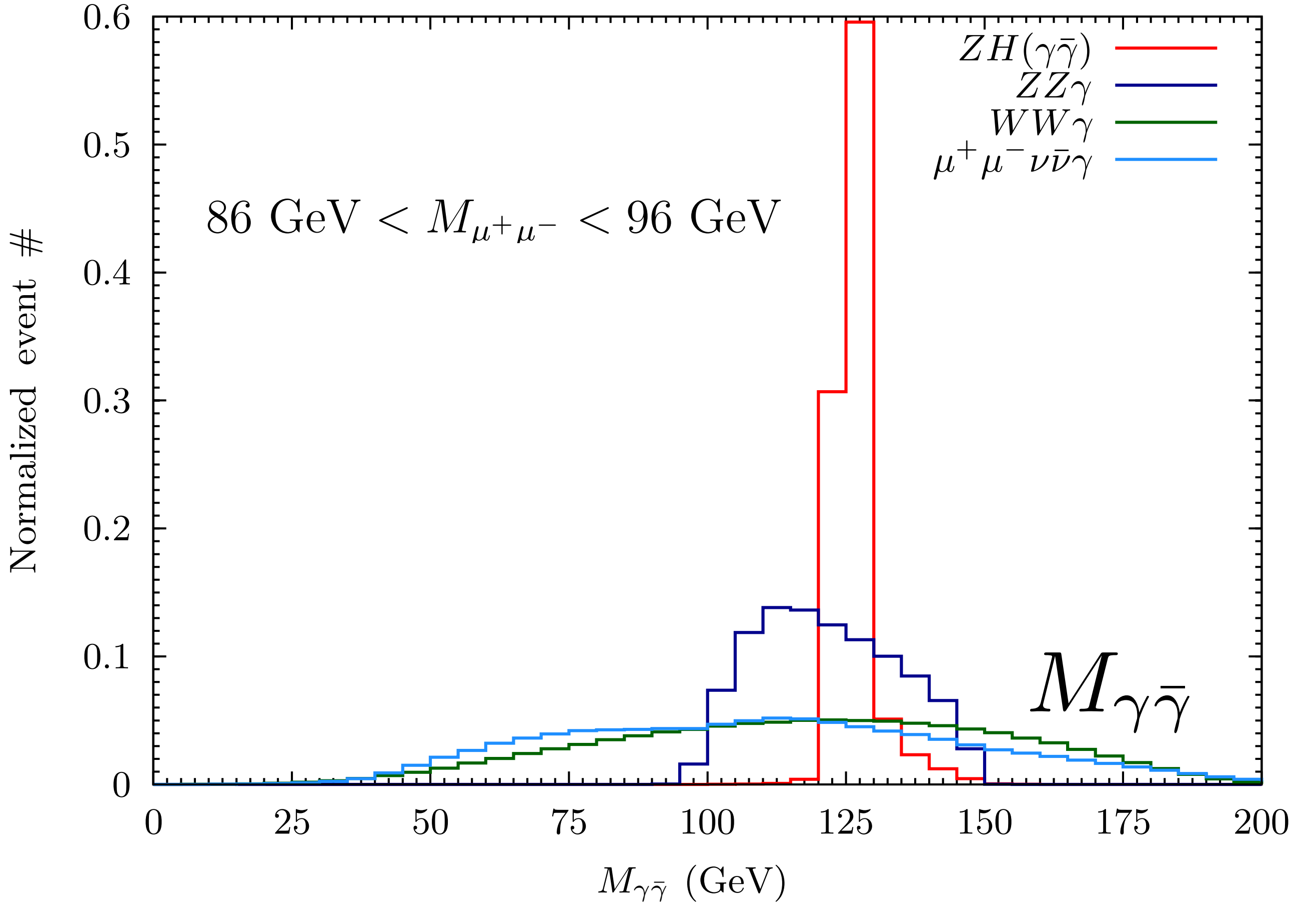
jet veto on : $p_T^j > 20 \text{ GeV}$

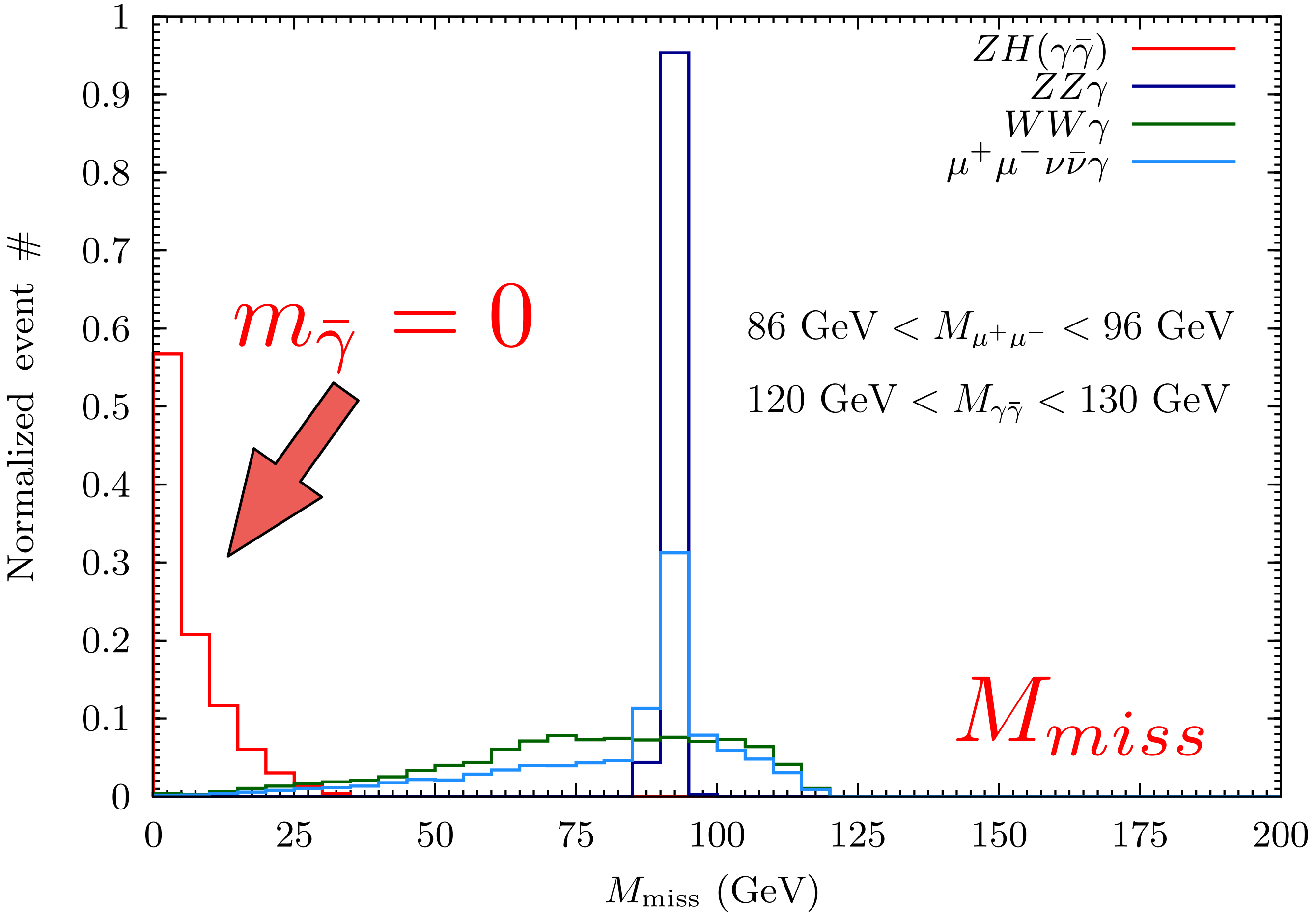


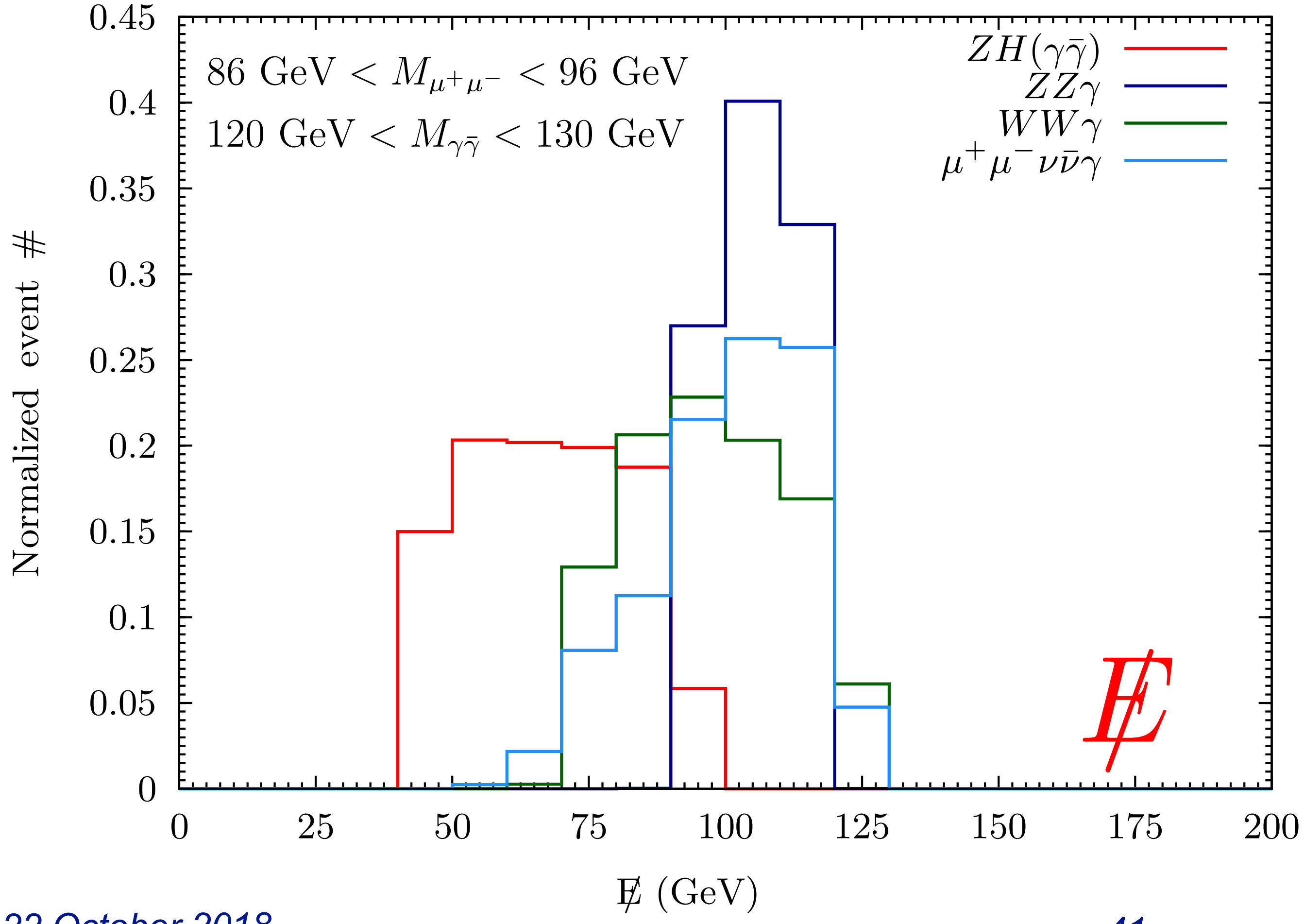


$e^+e^- \to ZH \to \mu^+\mu^- \gamma\bar{\gamma}$









Event yield (after sequential cuts)

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

$$BR_{\gamma\bar{\gamma}} = 0.1\%$$

for √S = 240 GeV ∫ L ~ 10 ab-1

Process	Basic cuts	$M_{\ell\ell}$ cut	$M_{\gamma\bar{\gamma}}$ cut	$M_{\rm miss}$ cut
$\mu^+\mu^-\gamma\bar{\gamma} \quad (BR_{\gamma\bar{\gamma}} = 0.1\%)$	65.3	54.9	49.7	47.3
$\mu^+\mu^-\nu\bar{\nu}\gamma$	5.00×10^4	5.73×10^3	1.09×10^3	15

$$86 \text{ GeV} < M_{\mu^+\mu^-} < 96 \text{ GeV}$$

$$120 \text{ GeV} < M_{\gamma\bar{\gamma}} < 130 \text{ GeV}$$

$$M_{\rm miss} < 20 \text{ GeV}$$

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

hadronic channel

- **basic cuts** $p_T^\gamma > 10\ \text{GeV},\ |\eta^\gamma| < 2.5$

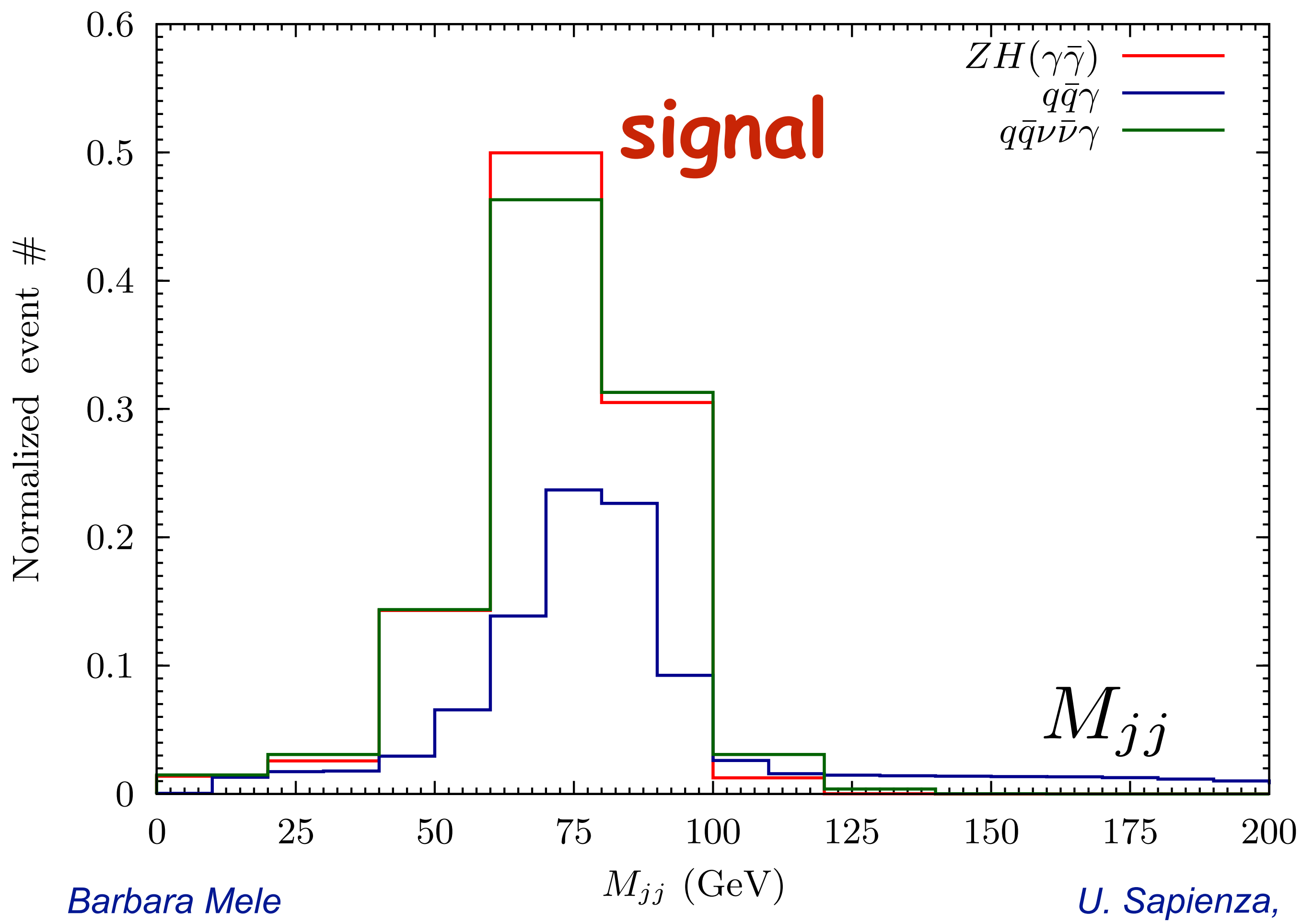
  $p_T^j > 20\ \text{GeV},\ |\eta^j| < 5.0$

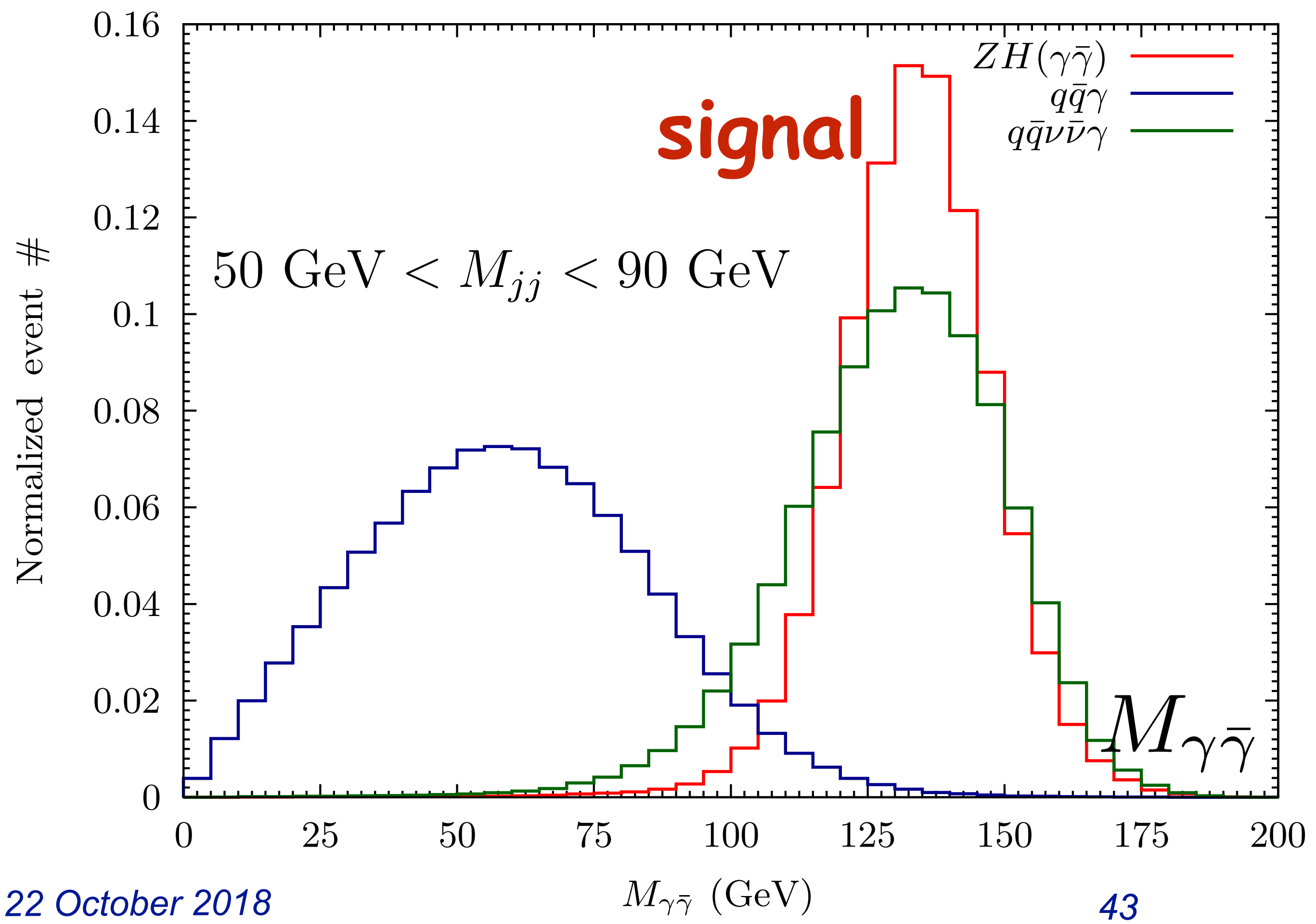
  $\not{E} > 10\ \text{GeV}$

$\Delta R > 0.4$

between any two objects

lepton veto on: $p_T^\ell > 10\ \text{GeV}\quad |\eta^\ell| < 2.5$

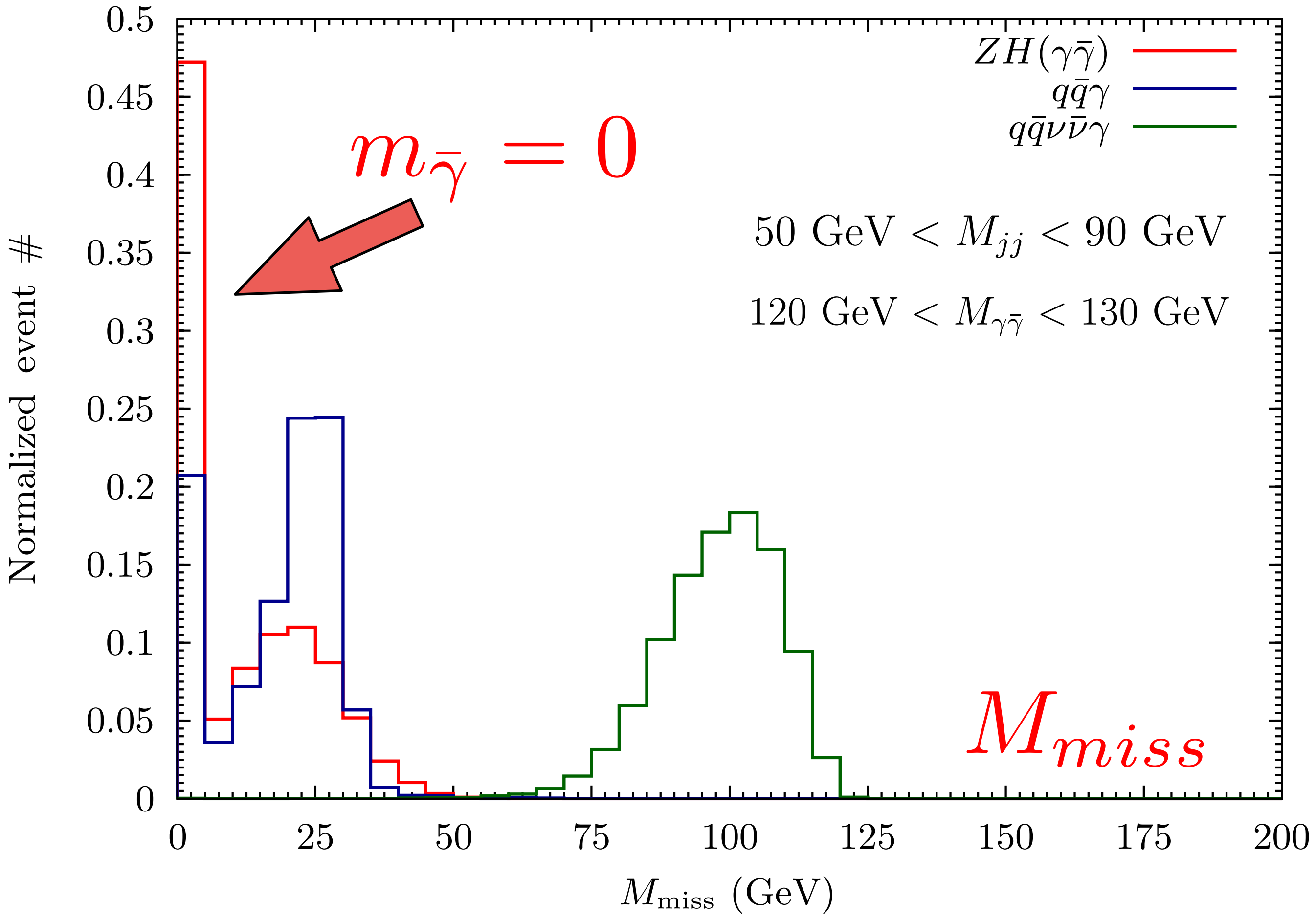


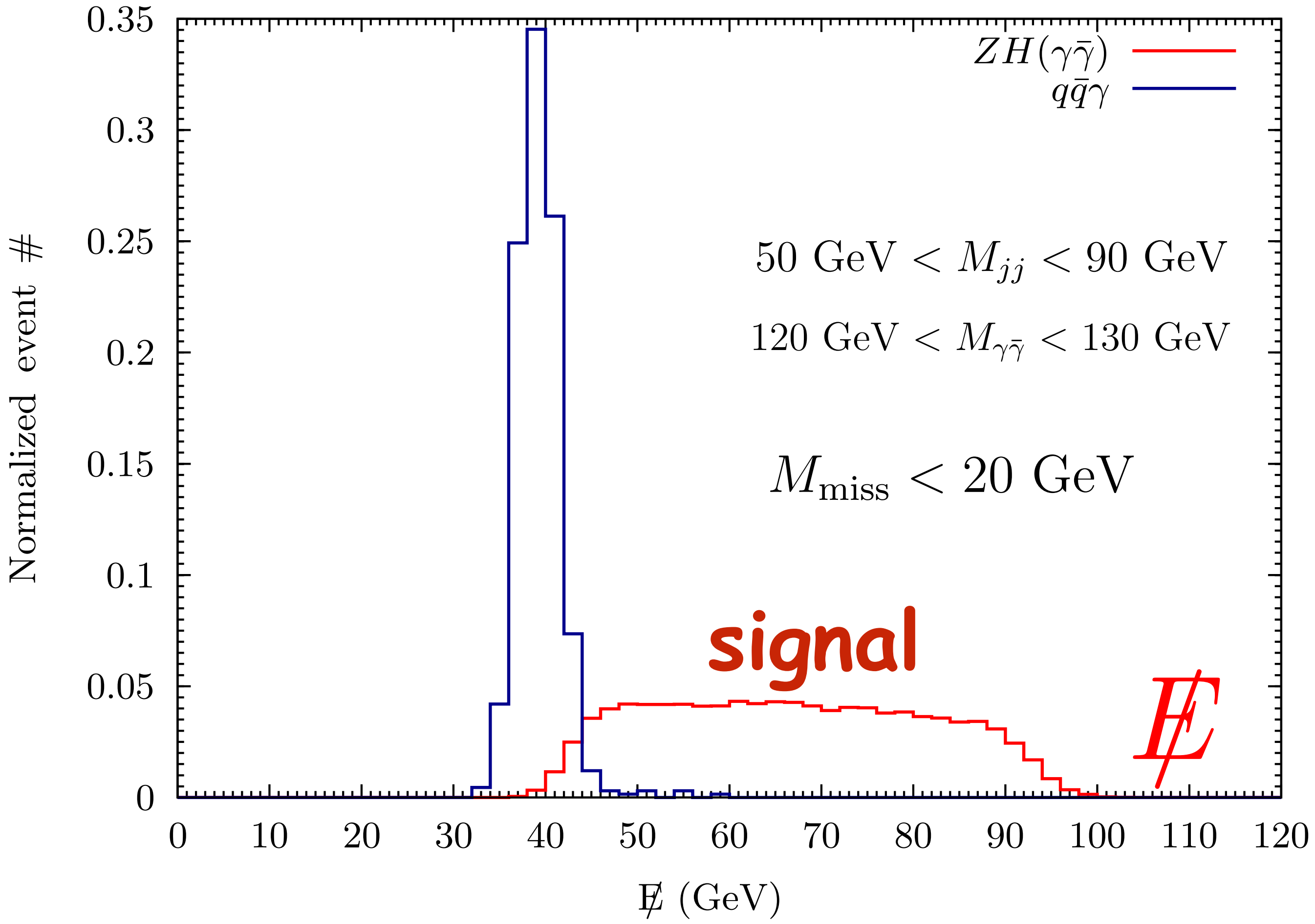


$e^+e^- \to ZH \to qq\ \gamma\bar\gamma$

hadronic channel

√S = 240 GeV





Event yield (after sequential cuts)

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

$$\boxed{BR_{\gamma\bar{\gamma}} = 0.1\%}$$

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

Process	Basic cuts	M_{jj} cut	$M_{\gamma\bar{\gamma}}$ cut	$M_{\rm miss}$ cut	$\not{E}$ cut
$jj\gamma\bar{\gamma}$ $(BR_{\gamma\bar{\gamma}} = 0.1\%)$	804	669	154	110	72
$jj\gamma$	3.39×10^7	2.26×10^7	1.47×10^5	6.5×10^4	–
$jj\nu\bar{\nu}\gamma$	3.9×10^4	3.1×10^4	5.9×10^3	2.2	–

$50 \text{ GeV} < M_{jj} < 90 \text{ GeV}$

$120 \text{ GeV} < M_{\gamma\bar{\gamma}} < 130 \text{ GeV}$

$M_{\rm miss} < 20 \text{ GeV}$

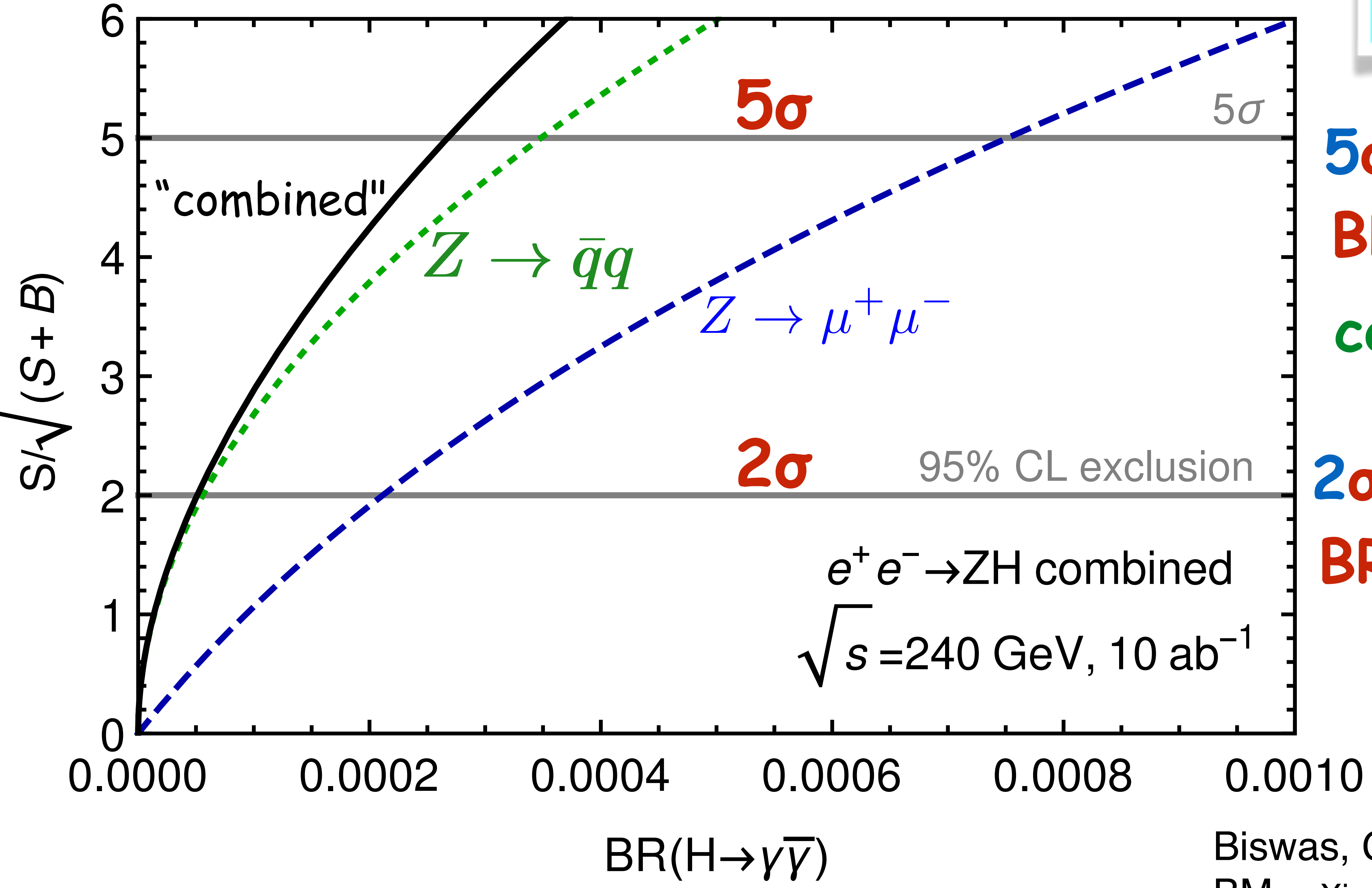
➡ $\not{E} > 59 \text{ GeV}$

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

✱ signal significance

hadronic Z
most sensitive
channel !

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



5σ sensitivity for

BR$_{DP}$ ~ 3×10^{-4} !!!

combined

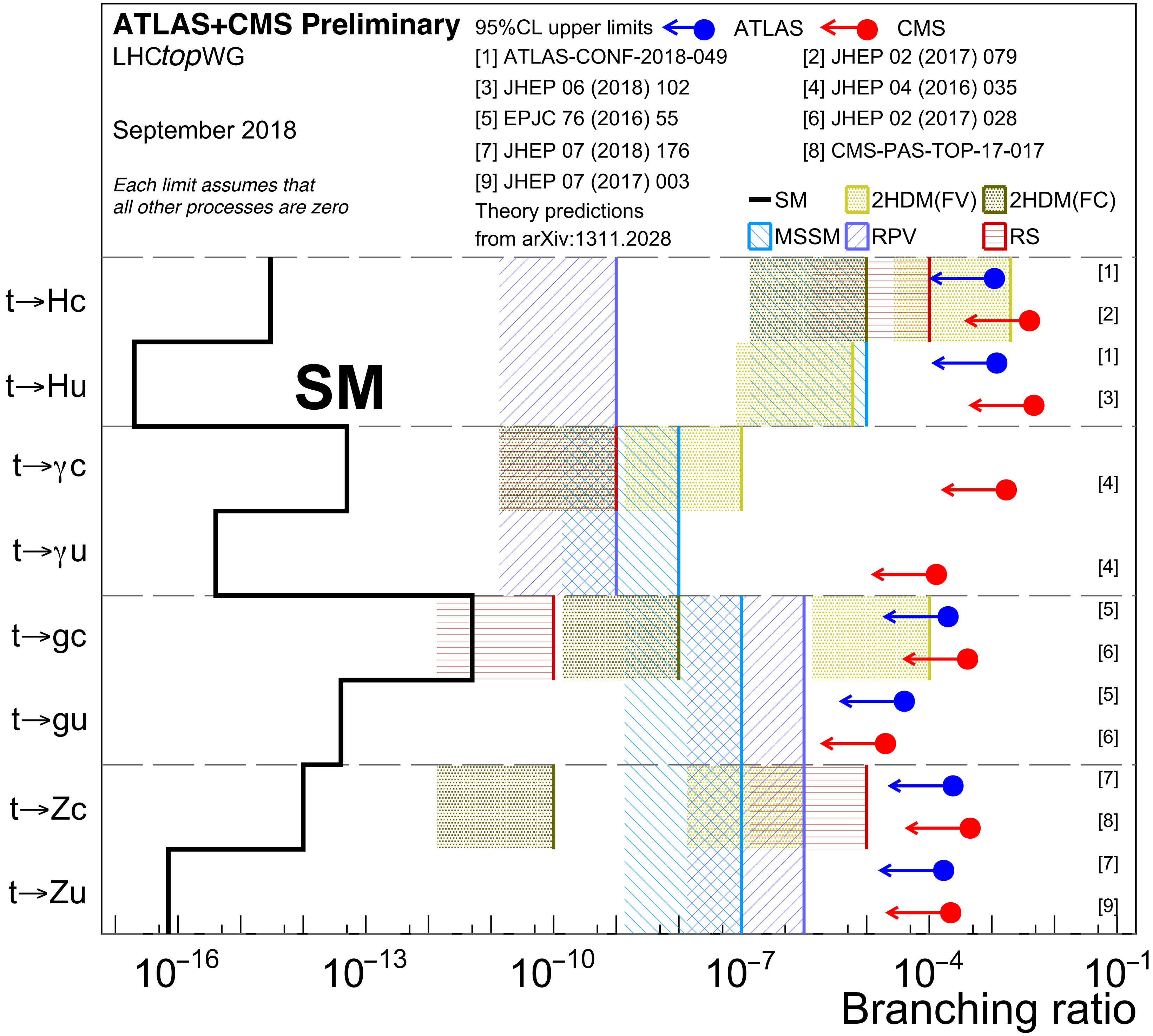
2σ sensitivity for

BR$_{DP}$ ~ 5×10^{-5} !!!

(2 times better than LHC 3 ab^{-1})

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

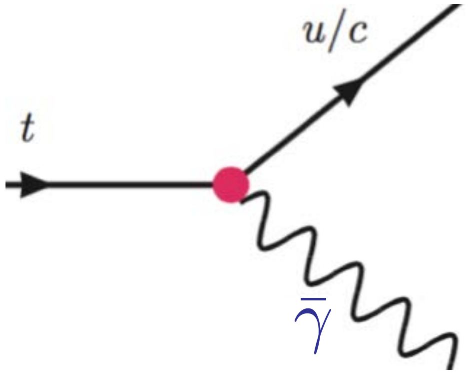
testing BSM via FCNC top interactions



- 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

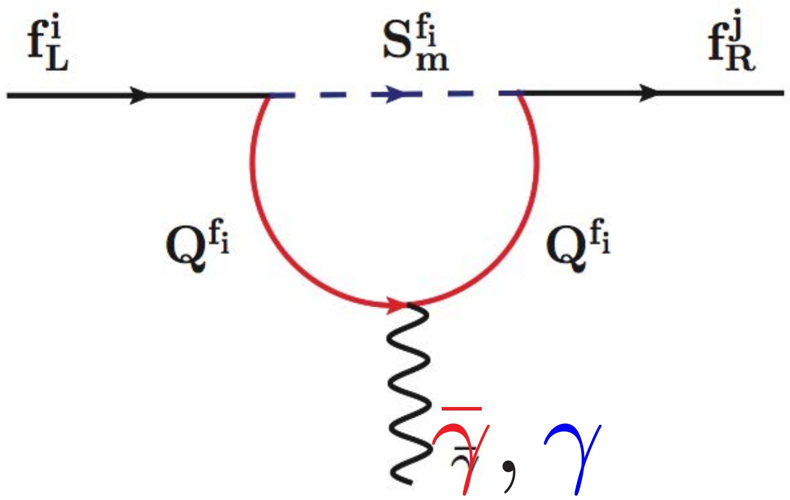
$$t \to (c,u)\,\bar{\gamma}$$



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 $f \to f'\gamma$

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

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

Gabrielli, BM, Raidal, Venturini, PRD 94 (2016) 115013

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

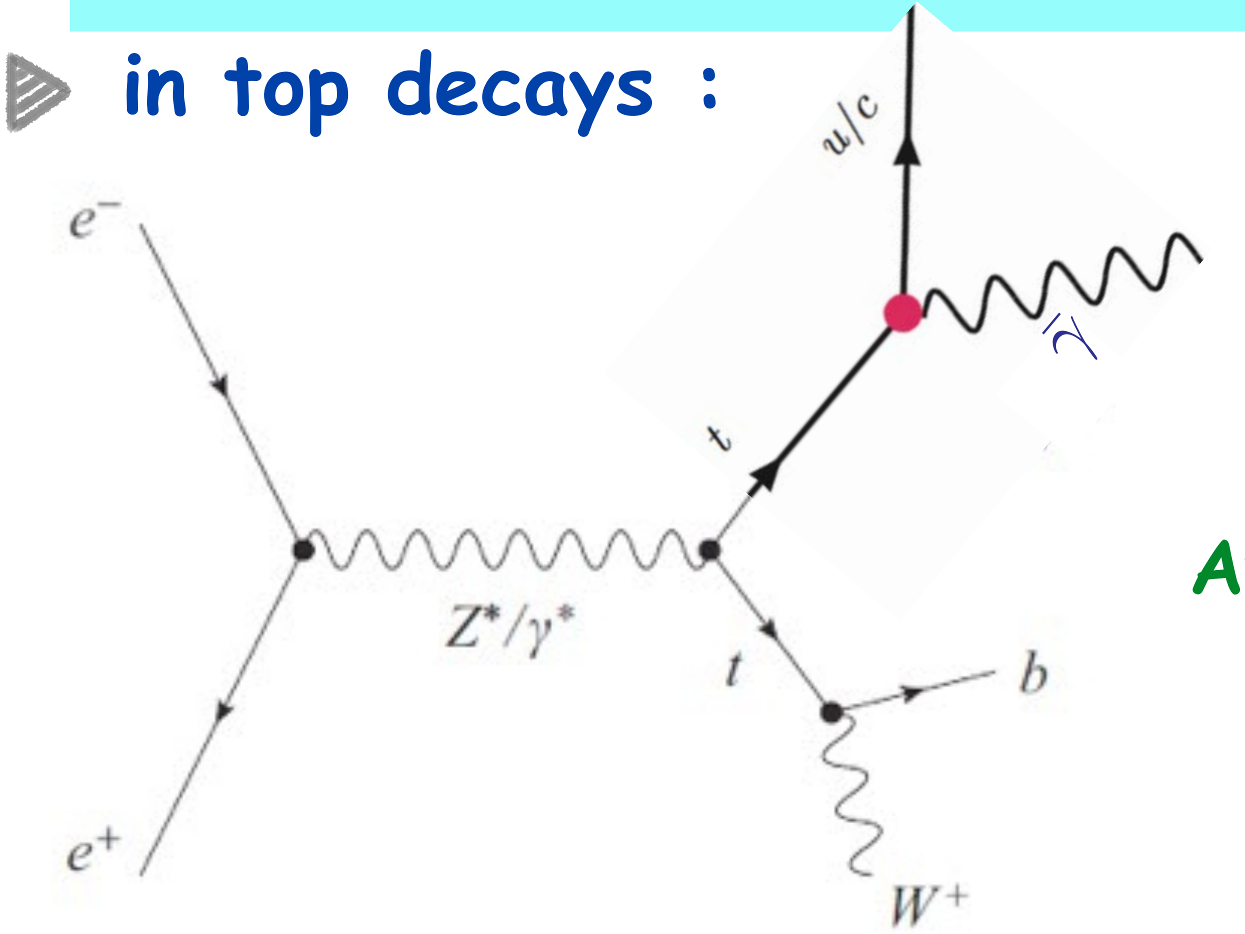
$$f \to f' \,\bar{\gamma}$$

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 :

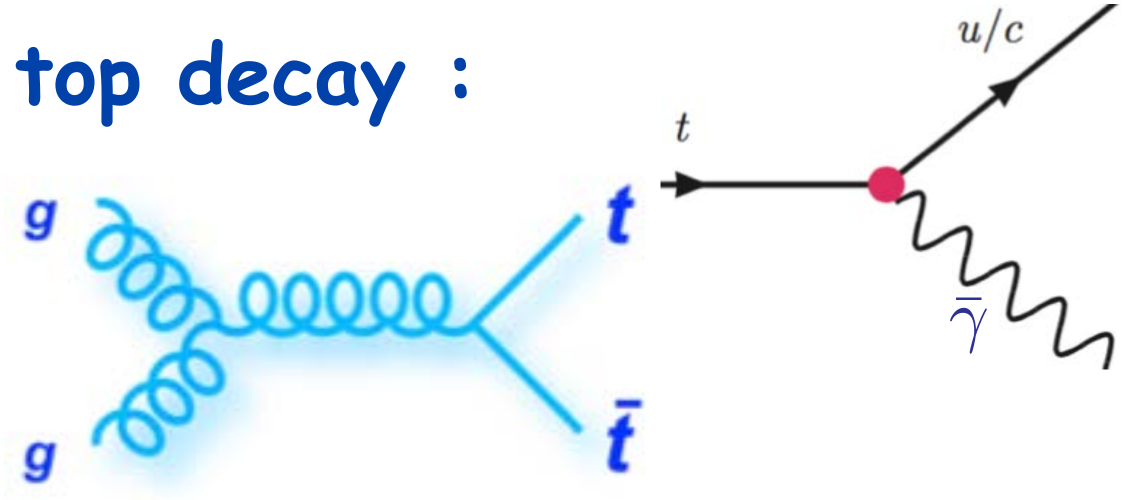


"top" + (mono-j + E_{miss})
resonant at m_{top}

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

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

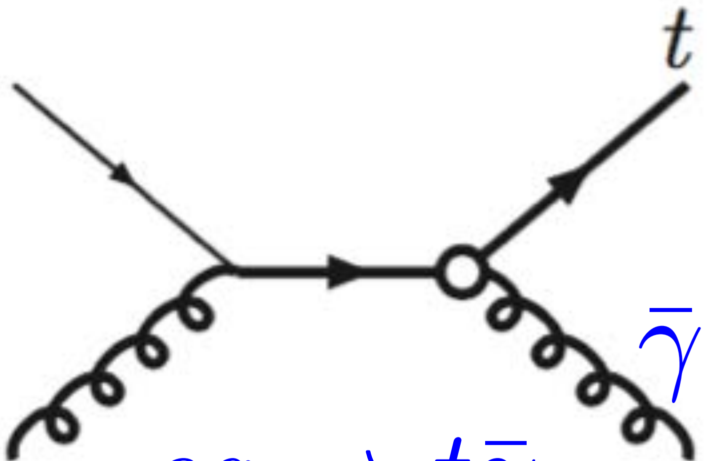
- in top decay :



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

[stop-like, for massless χ^0]

- in top production



$cg \to t\bar{\gamma}$

"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

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

allowed for massive DP

$$\left(K^+ \to \pi^+ \bar{\gamma} \right)$$

forbidden by angular momentum conservation

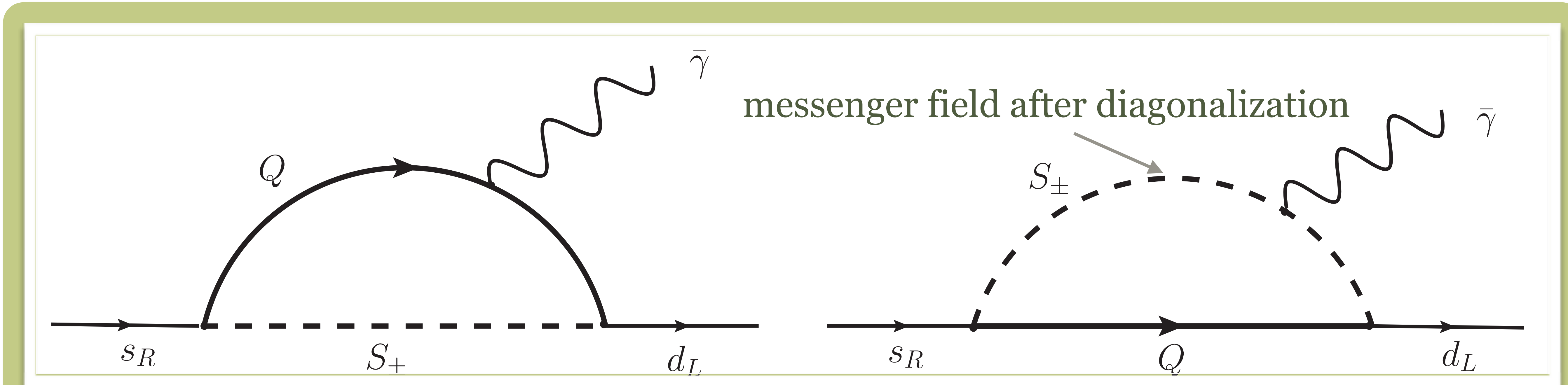
simplified model of dark sector

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



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

dipole operator (FCNC)

matrix element

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

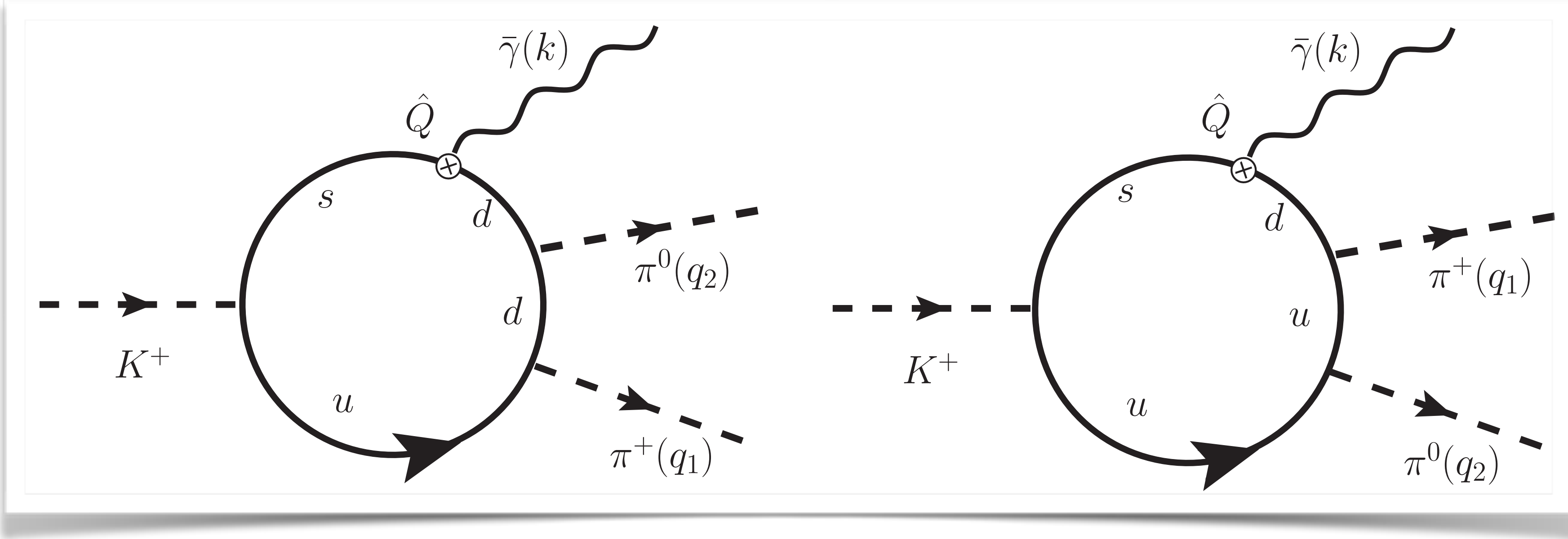
$$\mathcal{H}_{eff}^{\Delta S=1} = \frac{e_D}{64\,\pi^2} \frac{\xi}{\Lambda} \hat{Q}$$

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

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)



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

RG

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

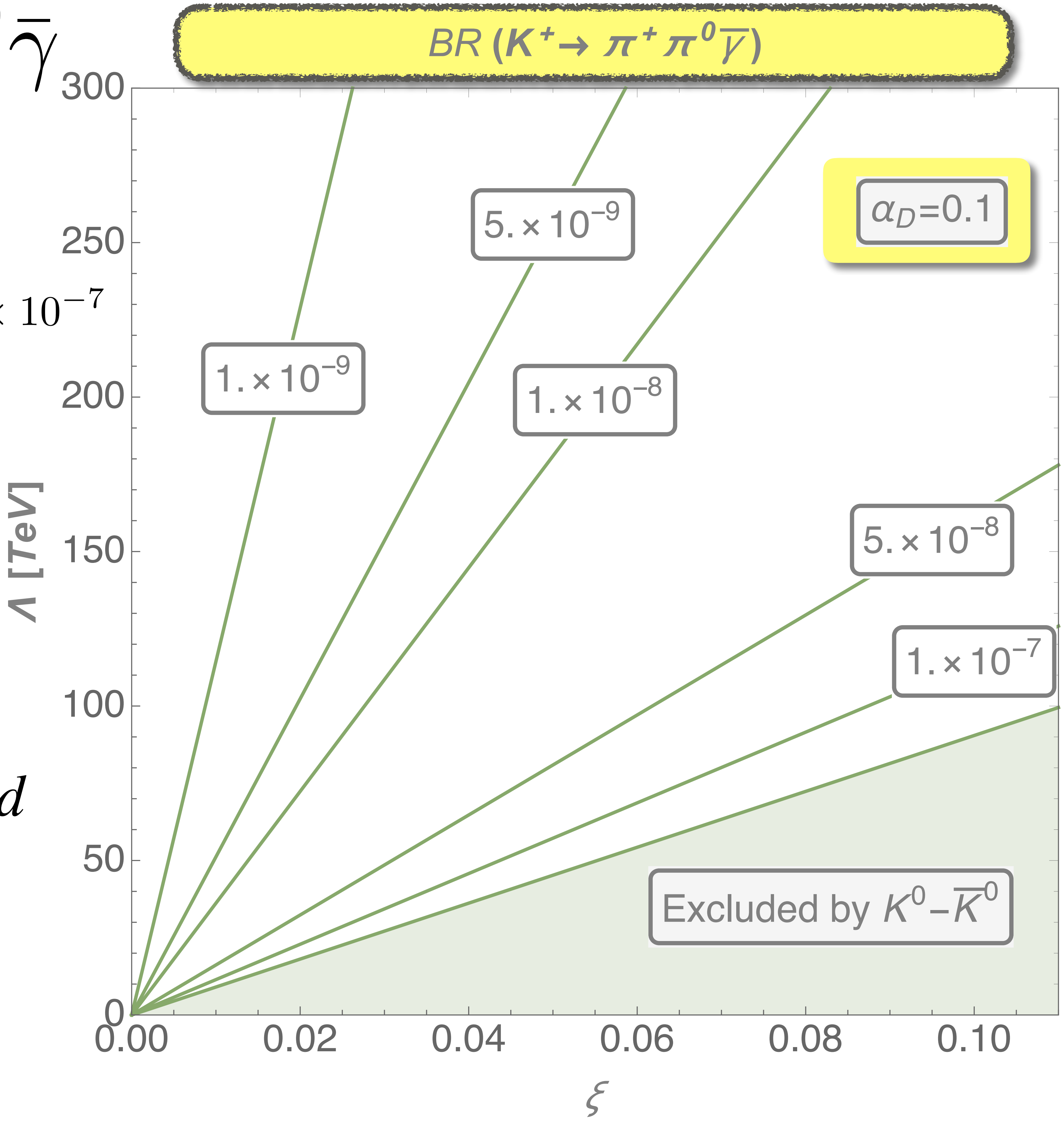
$$\xi = g_L g_R/2$$

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

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…)

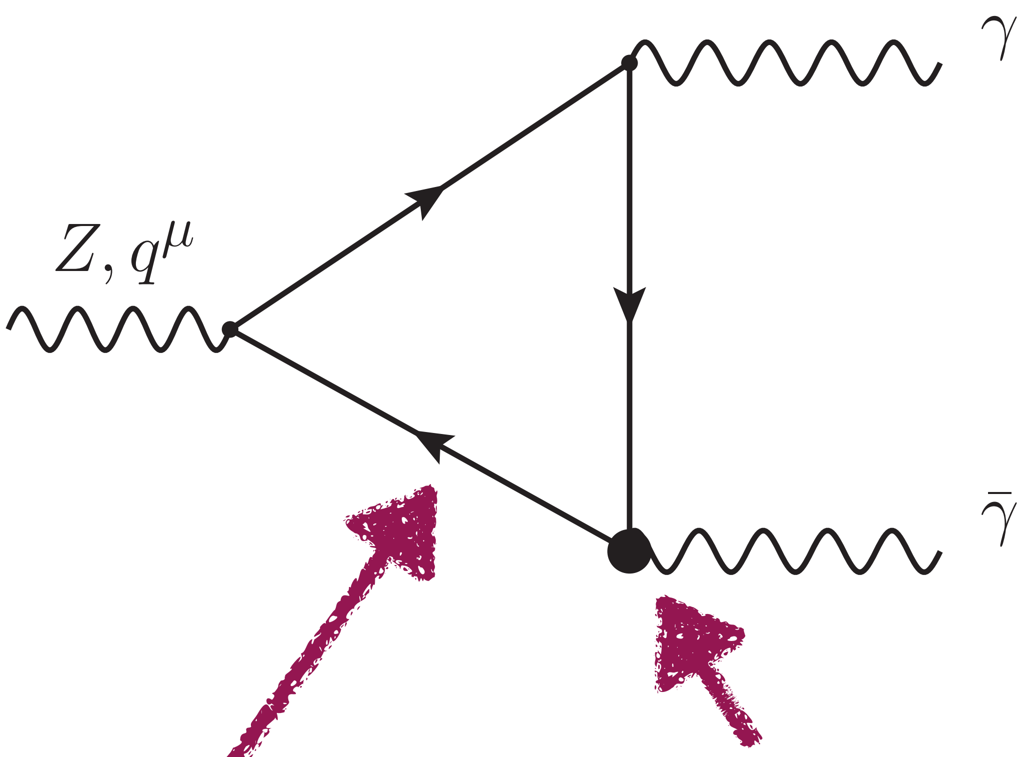


Z bosons as "source" of massless Dark Photons

Fabbrichesi, Gabrielli, BM,
arXiv:1712.05412 (PRL)

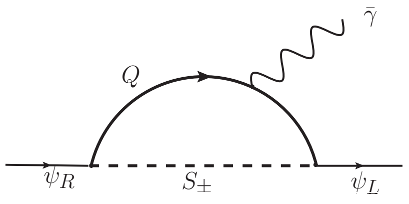
$$Z \to \gamma\bar{\gamma}$$

mono-photon
resonant signature at M_Z



SM fermions

$$\mathcal{L} \sim \bar{\psi}\,\sigma_{\mu\nu}\,(d_M + i\gamma_5\,d_E)\,\psi\,B^{\mu\nu}$$



evading Landau-Yang theorem !

BR < 10^{-6} from LEP

BR ~ 10^{-9} allowed in simplified models !

manageable at hadron colliders ???

200 evs at HL-LHC, 10^4 at FCC-hh,ee

Outlook

- 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
- massless Dark Photons theoretically appealing
  (evading most of present exp bounds on massive DP's !)
- Higgs boson as a 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
- implications for astro-part/cosmology (mostly yet to work out !)

A. Dark matter, relic density and galaxy dynamics

Barducci, Fabbrichesi, Gabrielli
arXiv:1806.05678 (PRD)

The messenger fields are heavier than the dark fermions; the latter are stable and provide a multicomponent candidate for dark matter whose relic density depends on the value of their couplings to the $U(1)_D$ dark photons and SM fermions (into which they annihilate) and masses.

Not all of the dark fermions contribute to the relic density when, as we do here, the $U(1)_D$ coupling is taken larger than the one in QED. If they are relatively light, their dominant annihilation is into dark photons with a thermally averaged cross section approximately given by

$$\langle \sigma v_0 \rangle \simeq \frac{\pi \alpha_D^2}{2 m_Q^2} \tag{3}$$

For a strength $\alpha_D \simeq 0.1$, all fermions with masses up to around 1 TeV have a large cross section and their relic density

$$\Omega\, h^2 \approx \frac{2.5 \times 10^{-10}\ \text{GeV}^{-2}}{\langle \sigma v_0 \rangle} \tag{4}$$

is only a percent of the critical one; it is roughly 10^{-4} the critical one for dark fermions in the 1 GeV range, even less for lighter states. These dark fermions are not part of dark matter; they have (mostly) converted into dark photons by the time the universe reaches our age and can only be produced in high energy events like the decays we discuss.

Heavier (that is, with masses closer to those of the messengers) dark fermions can be dark matter. The dominant annihilation for these is into SM fermions via the exchange of a messenger with a thermally averaged cross section now approximately given by

$$\langle \sigma v_0 \rangle \simeq \left(\frac{g_{L,R}^2}{4\pi} \right)^2 \frac{\pi}{2 m_S^2} \tag{5}$$

instead of Eq. (3). The critical relic density can be reproduced if, assuming thermal production,

$$\left(\frac{g_{L,R}^2}{4\pi} \right)^2 \left(\frac{10\,\text{TeV}}{m_S} \right)^2 \simeq 0.1\,. \tag{6}$$

Although dark matter is interacting via massless dark photons, limits from the collisionless dynamics of galaxies are satisfied because the light dark fermions have a negligible density in the galaxy (and do not count) while for the heavy dark fermions the bound on soft scattering [10], which is the strongest, is given (for N dark fermions of mass m_Q, G_N being the Newton constant) by

$$\frac{G_N^2 m_Q^4 N}{8 \alpha_D^2} \left[\ln \left(\frac{G_N m_Q^2 N}{2 \alpha_D^2} \right) \right]^{-1} \gtrsim 50\,. \tag{7}$$

The above bound can easily be satisfied because it is independent of the parameters entering the relic density. In our case, the above bound means that for $\alpha_D \simeq 0.1$ the heavy dark fermions present in the relic density must have masses larger than 8 TeV. This limit, together with Eq. (6), defines the allowed space of the parameters, namely, the couplings $g_{L,R}$ must be large but still in the perturbative regime.