

Higgs boson as a portal to Dark Photons at the LHC and Beyond

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Motivations

- accessible sector of NP could be **light** and **feebly interacting** (FI) with SM
- **Dark Sector**: a natural theoretical framework for physics of FI Particles
 - ▶ made by particles neutral under SM gauge interactions
 - ▶ might contain **Dark Matter**, but not necessarily
- observing DS in lab experiments require existence of portals (vector, scalar, fermions)
 - ▶ mediated by: **renormalizable** and **non-renormalizable** (**effective**) interactions
- DS particles naturally feebly if coupled to SM via non-renormalizable interactions
- DS might possess rich internal structure and its own interactions
- could contain light or massless gauge bosons → **dark photon** (acting as vector-portal)

Dark Photon scenario

The vector portal → Via kinetic mixing

$$U(1)_a \times U(1)_b$$

Free Lagrangian

$$\mathcal{L}_0 = -\frac{1}{4}F_{a\mu\nu}F_a^{\mu\nu} - \frac{1}{4}F_{b\mu\nu}F_b^{\mu\nu} - \frac{\varepsilon}{2}F_{a\mu\nu}F_b^{\mu\nu} \quad + \text{ mass terms}$$

Interactions with matter fields SM DS  J, J' = currents

$$\mathcal{L} = e J_\mu A_b^\mu + e' J'_\mu A_a^\mu$$

Fields A_a and A_b can be diagonalized (in canonical form) up to a rotation

$$\begin{pmatrix} A_a^\mu \\ A_b^\mu \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{1-\varepsilon^2}} & 0 \\ -\frac{\varepsilon}{\sqrt{1-\varepsilon^2}} & 1 \end{pmatrix} \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} A'^\mu \\ A^\mu \end{pmatrix}$$

 Dark Photon
 Photon

- ▶ B. Holdom, PLB 166B, 196 (1986)
- ▶ B.A. Dobrescu, PRL 94 151802 (2005); [hep-ph/0411004]
- ▶ M. Fabbrichesi, EG, G. Lanfranchi, "The physics of the Dark photon"
SpringerBriefs in Physics 2020, [arXiv:2005.01515]

Massless DP scenario

B. Holdom, PLB 166B, 196 (1986)

Unbroken $U(1)_a \times U(1)_b$

Zero mass term $\rightarrow$ Freedom to rotate

$$\sin \theta = \varepsilon$$

$\rightarrow$ choice of massless DP

Dark Photon **A'** couples **only**
to its own Dark Sector

Photon **A** couples to **both** SM and
Dark sector (millicharge)

Massive DP scenario

$$\mathcal{L}_{Stu} = -\frac{1}{2}M_a^2 A_{a\mu}A_a^\mu - \frac{1}{2}M_b^2 A_{b\mu}A_b^\mu - M_a M_b A_{a\mu}A_b^\mu$$

Mass term breaks $U(1) \rightarrow$ **NO** freedom of rotation and angle θ is fixed

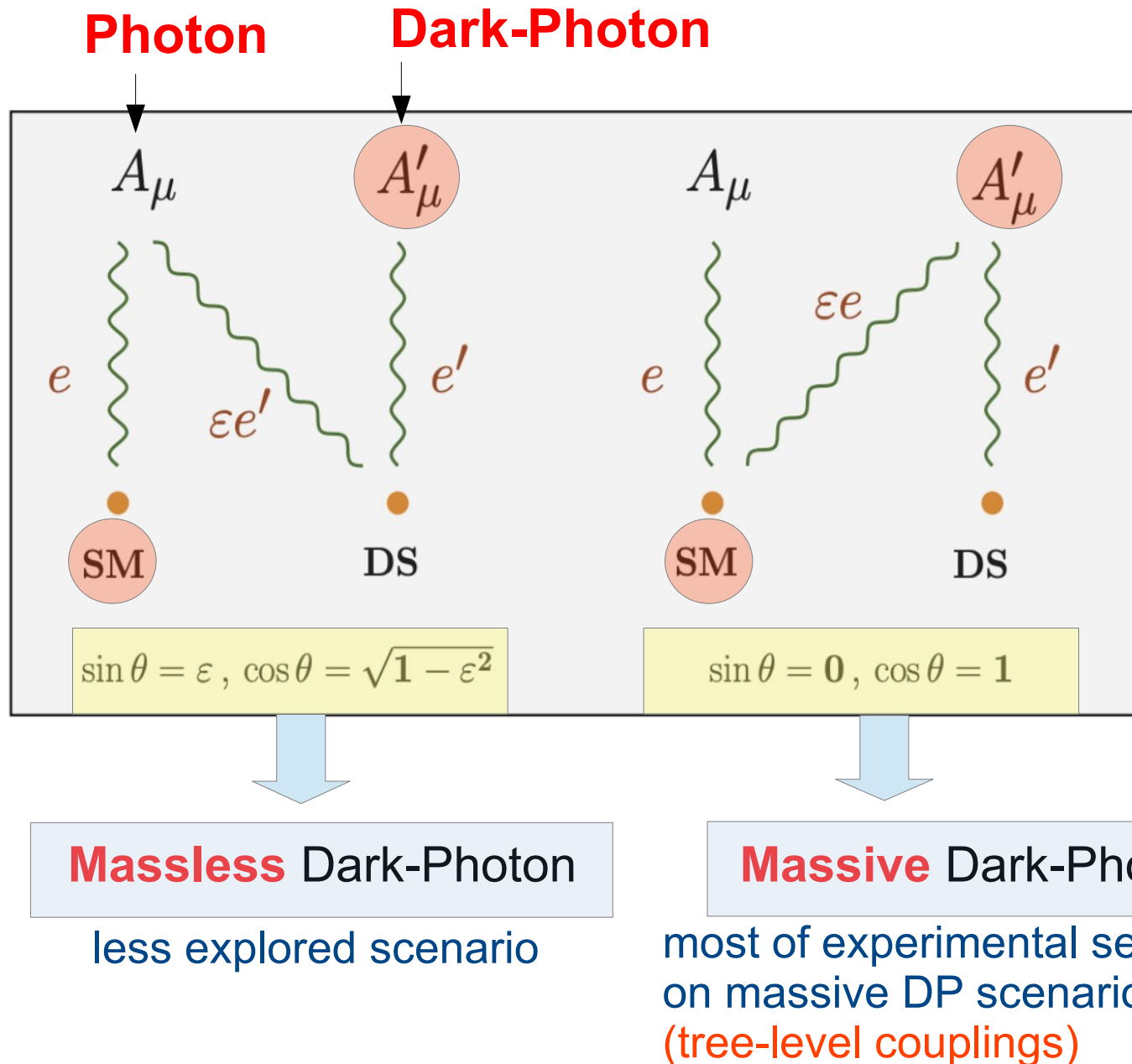
DP couples tree-level to both sectors

$$\sin \theta = 0$$

$$\mathcal{L} \supset -\frac{e\varepsilon}{\sqrt{1-\varepsilon^2}} J_\mu A'^\mu \simeq -e\varepsilon J_\mu A'^\mu$$

$\longrightarrow$ tree-level (millicharge)
couplings with SM

Summary of tree-level DP interactions



Detection of massive DP is based on its decay modes

- ▶ With visible final states (rates scales as ϵ^4)

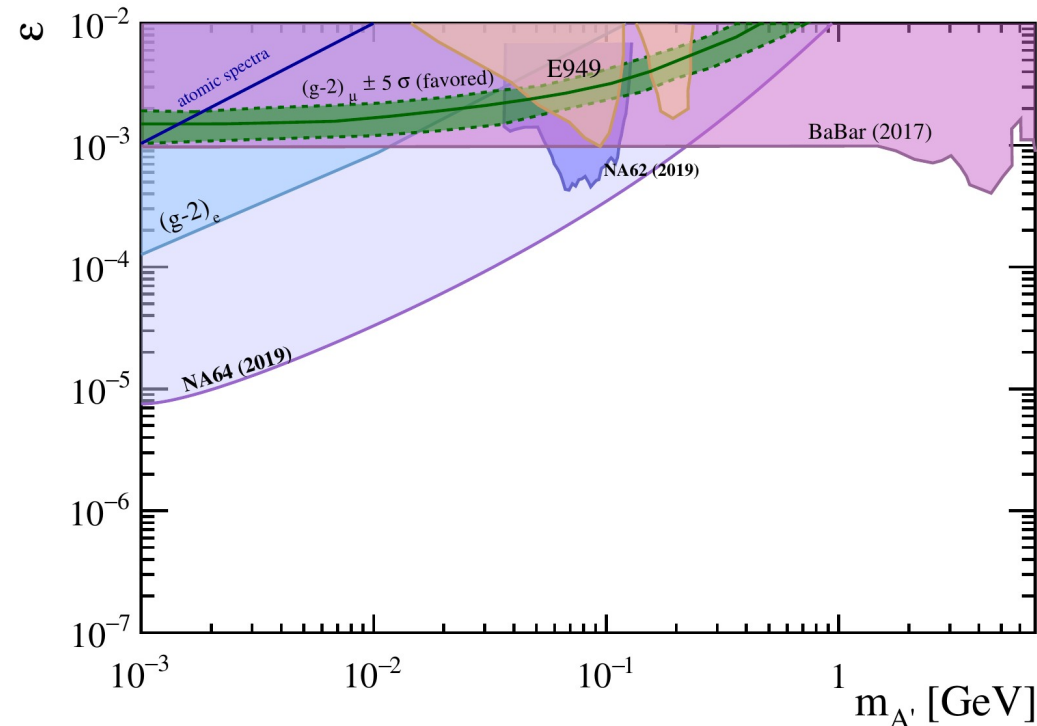
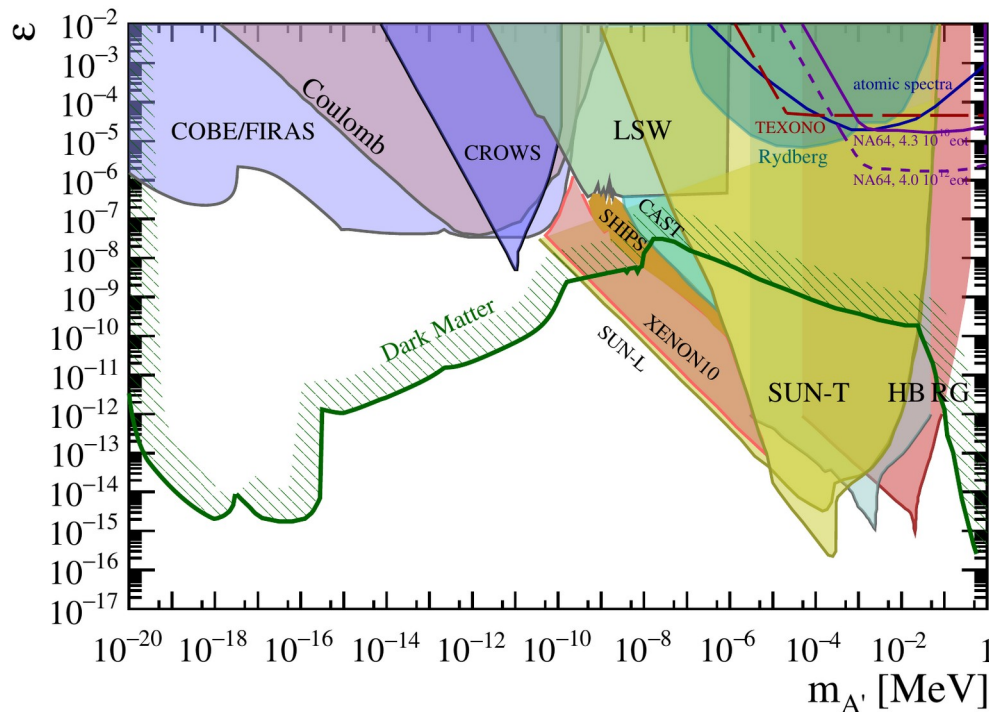
We focus here on

- ▶ massless DP or **massive** with invisible decay
 - detection relies on **missing momentum/energy** techniques
 - being independent on DP decay, **rate scales as ϵ^2** (for $\text{BR}(\text{inv})=1$)
 - **massless DP** couples to SM fields **via higher dimensional operators**
 - **massive DP** scenario via tree-level mixing is very constrained **$\epsilon \ll 1$**

Massive (invisible) Dark Photon

From arXiv:2005.01515

Current limits on tree-level couplings to SM fermions



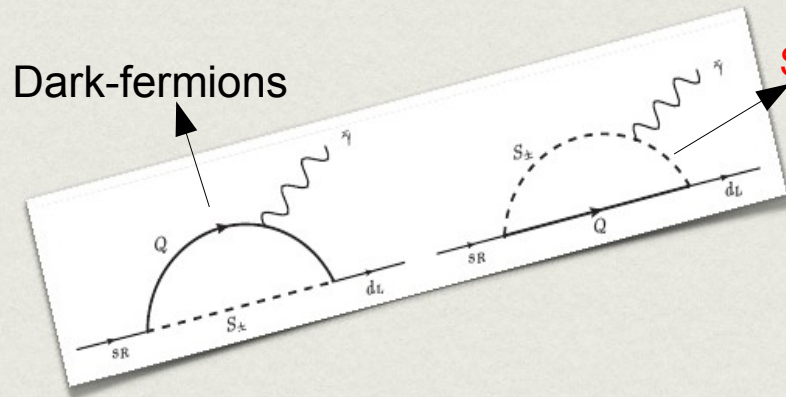
► Light Dark Photon (mass $\ll$ MeV) , **invisible**, is very much constrained at tree-level

► **Effective couplings** with high-dim. operators could dominate at low energy with respect to tree-level couplings (depending on the DS scale)→ mainly unexplored

the **massless** dark photon is not
the massless limit of the **massive** dark photon

no tree-level couplings with SM fermions (can be rotated away)

we need a specific
benchmark



coupling to SM particles induced at 1-loop



[hep-ph/0411004]

$$\mathcal{L} = \frac{e_D}{2\Lambda^2} \bar{\psi}_L^i \sigma_{\mu\nu} \left(\mathbb{D}_M^{ij} + i\gamma_5 \mathbb{D}_E^{ij} \right) H \psi_R^j F'^{\mu\nu} + \text{H.c.}$$

$d_M^{ij} \equiv |\mathbb{D}_M^{ij}|$

effective scale Λ

only **massive** dark-photon can have tree-level couplings with SM fermions via kinetic mixing

► Same loop-induced couplings holds also for **massive DP**

► **DP** also couples to Higgs boson via dim-5 operators

Higgs boson as a portal to Dark Photons

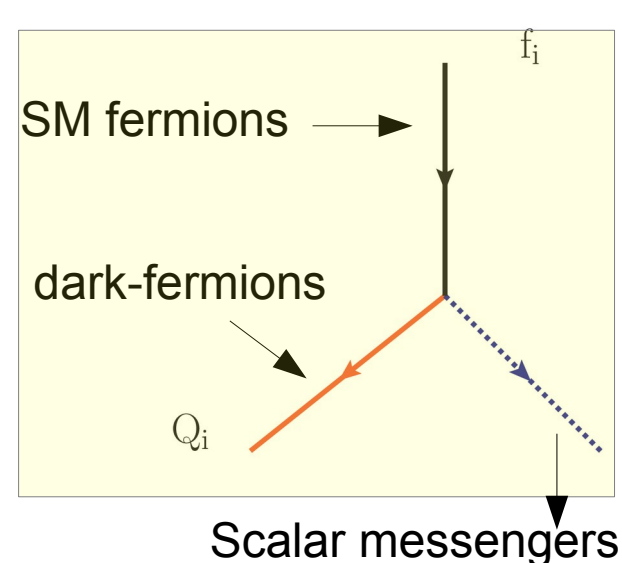
Motivations

- Effective couplings to Higgs boson $\rightarrow$ dim. 5 operators $\rightarrow$ require a scale Λ
- Λ not constrained by astrophysics bounds (contrary to magnetic-dipoles)
- advantages: Λ could show potential UV non-decoupling !
- being loop induced the couplings are less sensitive to experimental constraints
- and are the same as in massive and massless DP scenarios
- to generate scale Λ in the Higgs couplings to Dark Photons we need a UV complete benchmark model for the dark sector
- New DS interactions with SM fields mostly fixed by quantum N^0 of SM fields

Benchmark model to Dark Sector

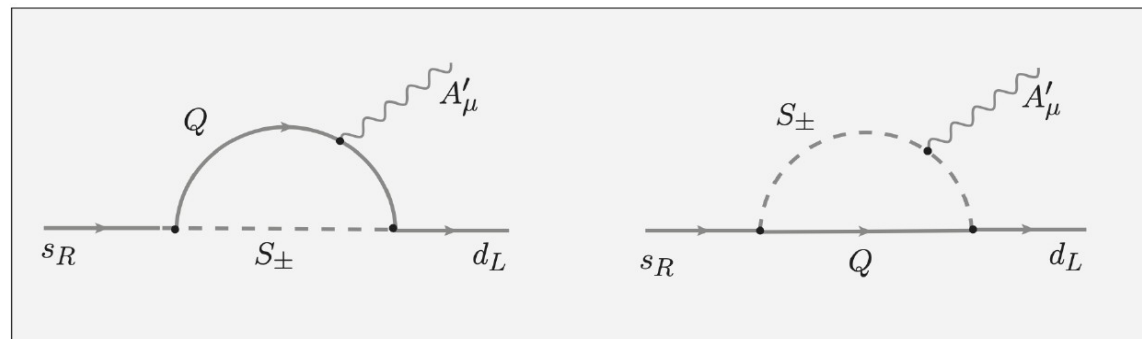
new fields requirements

- scalar messenger fields (quantum N^0 of squarks & sleptons of SUSY models)
- dark-fermion fields (SM singlets replica of SM fermions)
- messengers and dark-fermions both charged under $U(1)$ (dark photon)
- Yukawa-like interactions connect DS and SM fermions



EG, M. Raidal, PRD 89 (2014)
1405.5196 [hep-ph]

Magnetic-dipole interactions $\rightarrow$ scale Λ strongly constrained by astrophysics



Benchmark model: minimal fields content

EG, M. Raidal, PRD 89 (2014)
1405.5196 [hep-ph]

SM gauge group						associated DP field
Fields	Spin	$SU(2)_L$	$U(1)_Y$	$SU(3)_c$	$U(1)_{D'}$	
$\hat{S}_L^{D_i}$	0	1/2	1/3	3	$-q_{D_i}$	DP charges
$\hat{S}_L^{U_i}$	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	

Scalar
messengers

Dark
fermions

Scalar singlet

Same replica also in lepton EW sector

- ▶ **Dark fermions** are Dirac (SM singlet) fields
- ▶ Messengers have same Quantum N. of **squarks** and **slepton** of SUSY models
- ▶ Dark-fermions and messenger fields both charged under $U(1)_D$ (dark)

Messenger spectrum (assuming flavor universality)

$$\mathcal{L}_S^0 = \partial_\mu \hat{S}^\dagger \partial^\mu \hat{S} - \hat{S}^\dagger M_S^2 \hat{S} + \lambda_S S_0 \left(\tilde{H}^\dagger S_L^{U_i} S_R^{U_i} + H^\dagger S_L^{D_i} S_R^{D_i} \right)$$

$$\hat{S} = (S_L, S_R)$$

after S_0 gets a vev

$$\mu_S \equiv \lambda_S \langle S_0 \rangle$$

Mass matrix

$$M_S^2 = \begin{pmatrix} m_L^2 & \Delta \\ \Delta & m_R^2 \end{pmatrix} \quad \Delta = \mu_S v$$

Simplified LR universal model

$$m_L \simeq m_R \equiv \bar{m} \longrightarrow \text{average mass}$$

Messenger mass spectrum eigenvalues

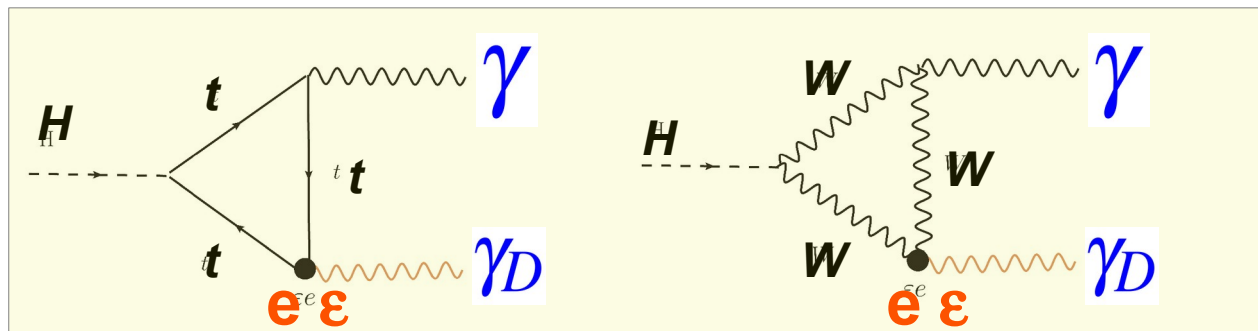
$$m_\pm^2 = \bar{m}^2 (1 \pm \xi) \quad \xi = \Delta / \bar{m}^2 \quad \text{mixing parameter}$$

► similar features of squarks and sleptons spectrum of typical SUSY models

Anatomy of Higgs decay

$$H \rightarrow \gamma\gamma_D$$

- Both massless and massive (invisible) DP give rise to same signature:
resonant mono-chromatic photon + transverse missing energy (neutrino like)
- If observed at LHC this signature cannot get dominant contribution from SM loops, via tree-level ϵ -mixing for massive DP (see below)



via SM loop +
tree-level DP
couplings

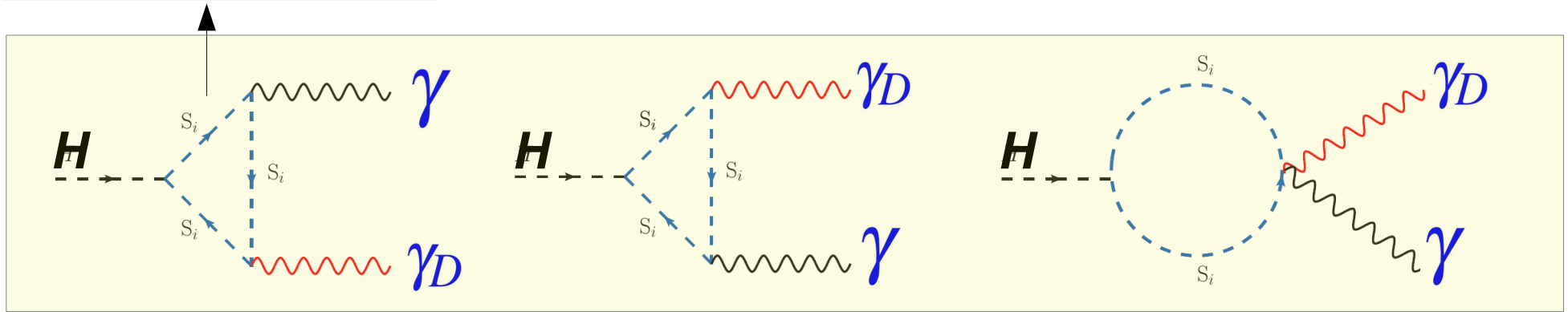
- For the **massless case**, there is no tree-level couplings $\rightarrow$ so it is vanishing
- For the **massive case**, **via mixing is suppressed** $\rightarrow$ $\text{BR} \sim \epsilon^2 \times \text{BR}(H \rightarrow \gamma\gamma)$
 $\rightarrow$ outside the sensitivity range of any present and future experiment ($\epsilon < 10^{-3}$)
- However, it can proceed via **UV New Physics** running in the loop (see next slide)

- The discovery of $H \rightarrow \gamma\gamma_D$ signal would be a direct observation of **long-range forces** in the DS and an indirect evidence of NP coupled to both the SM and DS

$$H \rightarrow \gamma \gamma_D$$

Generated via loop with benchmark model

scalar messenger fields



Quantum amplitude

$$M_{\gamma\gamma_D} = \frac{1}{\Lambda_{\gamma\gamma_D}} T_{\mu\nu}(k_1, k_2) \varepsilon_1^\mu(k_1) \varepsilon_2^\nu(k_2)$$

↗ photon
↗ Dark Photon

↘ **Effective scale**

Decay width

$$\Gamma(H \rightarrow \gamma\gamma_D) = \frac{m_H^3}{32 \pi \Lambda_{\gamma\gamma_D}^2}$$

- **Non-decoupling** (at fixed ξ) : for messenger masses $\bar{m} \rightarrow \infty$ effective scale turns out to be proportional to Higgs vev **v**

- Other Higgs decays generated including contributions to **H**→ **$\gamma\gamma$** and **gg**

Higgs boson decays in Dark Photons

EG, Heikinheimo, Mele, Raidal, PRD 90 (2014)

$$H \rightarrow \gamma \gamma_D$$

$$H \rightarrow Z \gamma_D$$

Invisible decay

$$H \rightarrow \gamma_D \gamma_D$$

Effective Lagrangian

$$\mathcal{L}_{\text{DPH}} \simeq \frac{\alpha}{\pi} \left(\frac{C_{\gamma\gamma_D}}{v} F^{\mu\nu} F_{\mu\nu}^D H + \frac{C_{Z\gamma_D}}{v} Z^{\mu\nu} F_{\mu\nu}^D H + \frac{C_{\gamma_D\gamma_D}}{v} F^{D\mu\nu} F_{\mu\nu}^D H \right)$$

↓ Higgs vev

$$C_{Z\gamma_D} = R_{Z\gamma} C_{\gamma\gamma_D} \longrightarrow \text{(small mixing } \xi \text{ limit)}$$

$$R_{Z\gamma}^q \simeq 0.79$$

$$R_{Z\gamma}^l \simeq 0.045$$

$$C_{\gamma\gamma_D} = \sqrt{\frac{\alpha_D}{\alpha}} \sum_{i=q,l} \frac{R_1^i}{12} \frac{\xi_i^2}{1 - \xi_i^2}$$

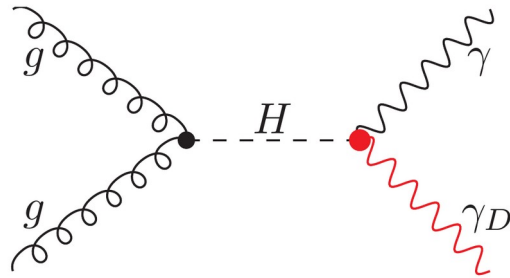
R_1 = product of U(1) charges

C_i coefficients depend only by mixing parameter and U(1) couplings

■ Potential non-decoupling → effective scale set by Higgs vev

■ dark-fine structure constant α_D could be large (potentially allowed if DP is massless)

DP production mechanisms via $H\gamma\gamma_D$ effective vertex



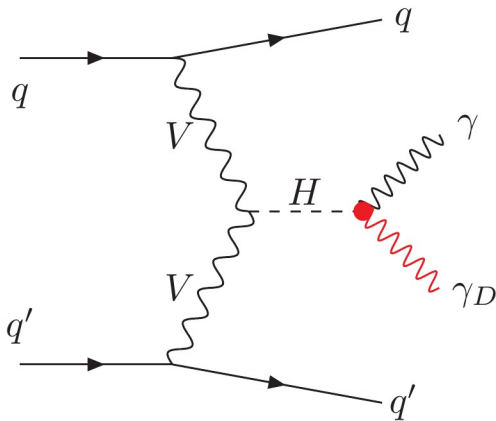
gluon-gluon fusion

$$pp \rightarrow \gamma + \cancel{E}_T$$

gg + VBF analyzed in

EG, Heikinheimo, Mele, Raidal, PRD 90 (2014)
Biswas, EG, Heikinheimo, Mele PRD 93 (2016)

Challenging → large QCD bckg of jets faked as $\cancel{E}_T$

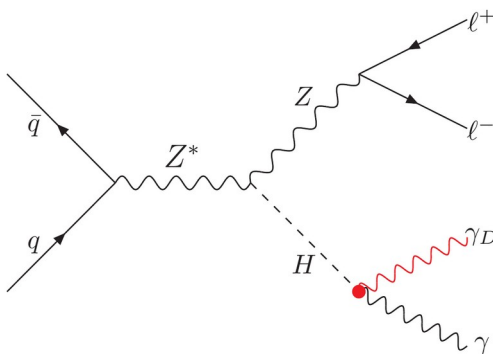


Vector Boson fusion

$$pp \rightarrow \gamma + \cancel{E}_T + jets$$

FB

ATLAS, CMS
run2



Z associated production

$$pp \rightarrow ZH \rightarrow (Z \rightarrow \ell^- \ell^+) (H \rightarrow \gamma \gamma_D)$$

ATLAS, CMS
run2

Model independent parametrization of BRs

$$\text{BR}_{\gamma\gamma_D} = \text{BR}_{\gamma\gamma}^{\text{SM}} \frac{r_{\gamma\gamma_D}}{1 + r_{\gamma_D\gamma_D} \text{BR}_{\gamma\gamma}^{\text{SM}}},$$

$$\text{BR}_{\gamma_D\gamma_D} = \text{BR}_{\gamma\gamma}^{\text{SM}} \frac{r_{\gamma_D\gamma_D}}{1 + r_{\gamma_D\gamma_D} \text{BR}_{\gamma\gamma}^{\text{SM}}},$$

$$\text{BR}_{\gamma\gamma} = \text{BR}_{\gamma\gamma}^{\text{SM}} \frac{(1 + \chi\sqrt{r_{\gamma\gamma}})^2}{1 + r_{\gamma_D\gamma_D} \text{BR}_{\gamma\gamma}^{\text{SM}}},$$

$$\chi = \pm 1 \rightarrow \text{parametrizes relative sign of SM vs NP amplitudes}$$

$$\sigma_{gg \rightarrow H} = \sigma_{gg \rightarrow H}^{\text{SM}} (1 - \chi\sqrt{r_{gg}})^2$$

$$R_{\gamma\gamma} = \frac{\sigma_{gg \rightarrow H} \text{BR}_{\gamma\gamma}}{\sigma_{gg \rightarrow H}^{\text{SM}} \text{BR}_{\gamma\gamma}^{\text{SM}}} \Rightarrow R_{\gamma\gamma} = \frac{\text{BR}_{\gamma\gamma}}{\text{BR}_{\gamma\gamma}^{\text{SM}}} (1 - \chi\sqrt{r_{gg}})^2$$

pure messenger contribution to the width

$$r_{\gamma\gamma} = \frac{\Gamma^{\text{m}}(H \rightarrow \gamma\gamma)}{\Gamma^{\text{SM}}(H \rightarrow \gamma\gamma)}$$

$$r_{\gamma_D\gamma_D} \rightarrow \text{parametrizes invisible decay}$$

$$r_{\gamma\gamma_D} = C \left(\frac{\alpha_D}{\alpha} \right) r_{\gamma\gamma}$$

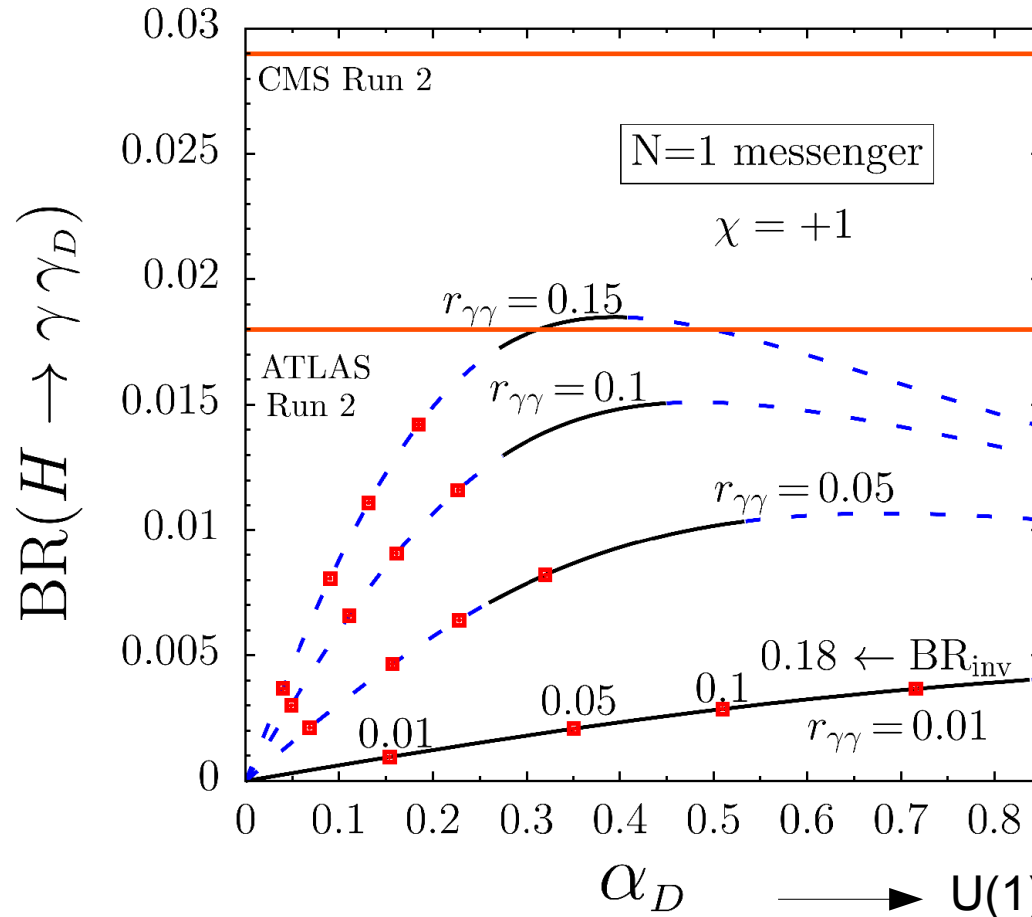
Model dependent constant
~ product of U(1) charges

$$r_{ij} \equiv \frac{\Gamma_{ij}^{\text{m}}}{\Gamma_{\gamma\gamma}^{\text{SM}}}$$

$$r_{gg} \equiv \frac{\Gamma_{gg}^{\text{m}}}{\Gamma_{gg}^{\text{SM}}}$$

BR predictions in a simplified model (1 messenger)

Biswas,EG,Mele [arXiv:2206.05297]



observed upper limits
@ 95% C.L.

CMS $\rightarrow$ BR < 2.9 %

[arXiv:2009.14009]

ATLAS $\rightarrow$ BR < 1.8 %

[arXiv:2109.00925]

--- excluded by $H \rightarrow \gamma\gamma$
@ 95% C.L.

Allowed regions of **BR**, consistent with all model parameters and LHC constraints, for minimal model, naturally lie below **1%**

FUTURE PERSPECTIVES @ LHC and future hadron colliders

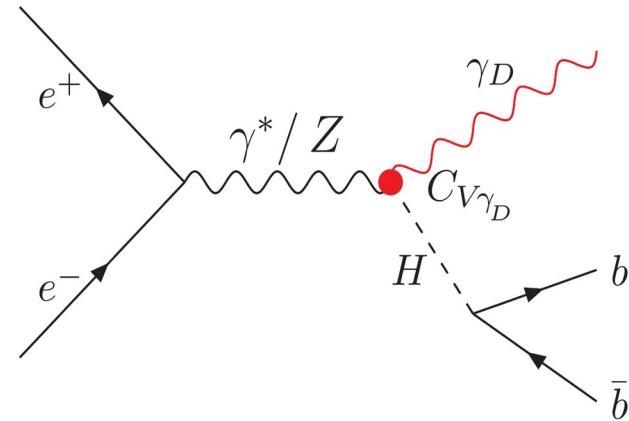
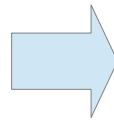
BR $_{\gamma\gamma_D}$ (%)	3 ab ⁻¹ @14 TeV		15 ab ⁻¹ @27 TeV	
significance	2 σ	5 σ	2 σ	5 σ
CMS inspired	0.012	0.030	0.0052	0.013

we used a similar analysis
as in CMS at 8 TeV to control
 γ jet and jet jet backgrounds

DP production at Future e^+e^- colliders

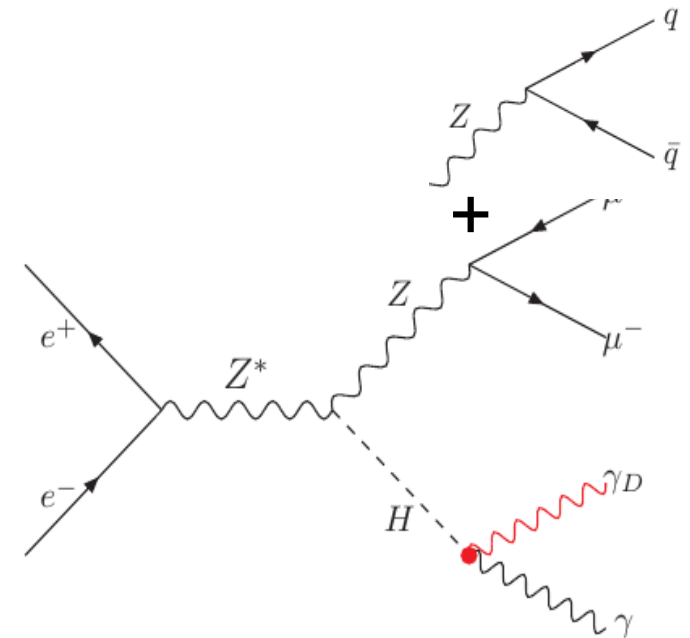
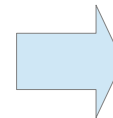
improved sensitivity on Higgs-photon-DP coupling

$$e^+e^- \rightarrow H\gamma_D$$



provides a better sensitivity

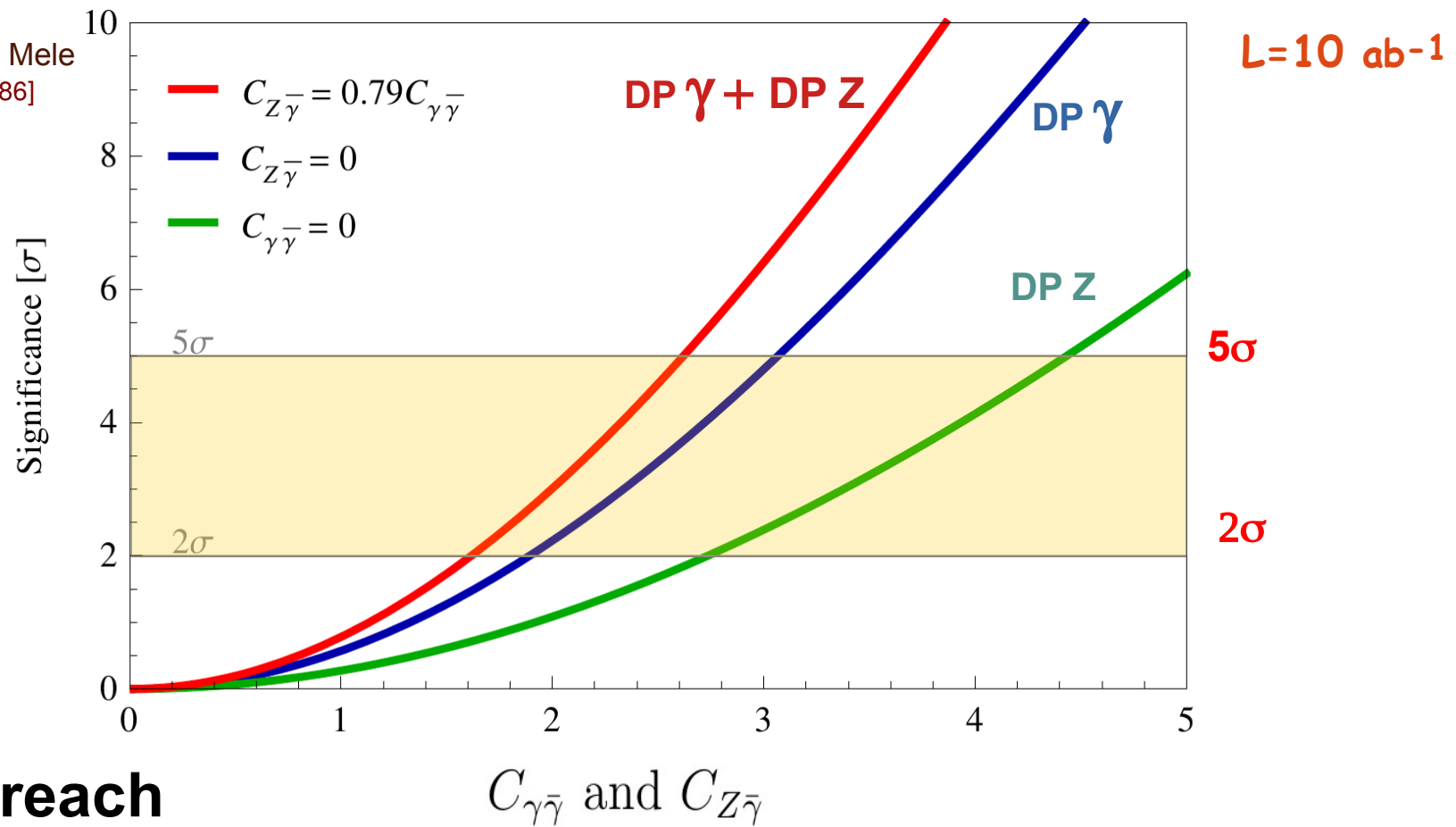
$$e^+e^- \rightarrow ZH \rightarrow Z(H \rightarrow \gamma\gamma_D)$$



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

$$\sqrt{s} = 240 \text{ GeV}$$

Biswas, EG, Heikeinheimo, Mele
JHEP 06 (2015) [arXiv:1503.05386]



Sensitivity reach

$$C_{\gamma\bar{\gamma}} > 1.9 \quad \Rightarrow \quad \text{BR}(H \rightarrow \gamma\bar{\gamma}) > 3 \text{ BR}_{SM}(H \rightarrow \gamma\gamma) \sim 6 \times 10^{-3}$$

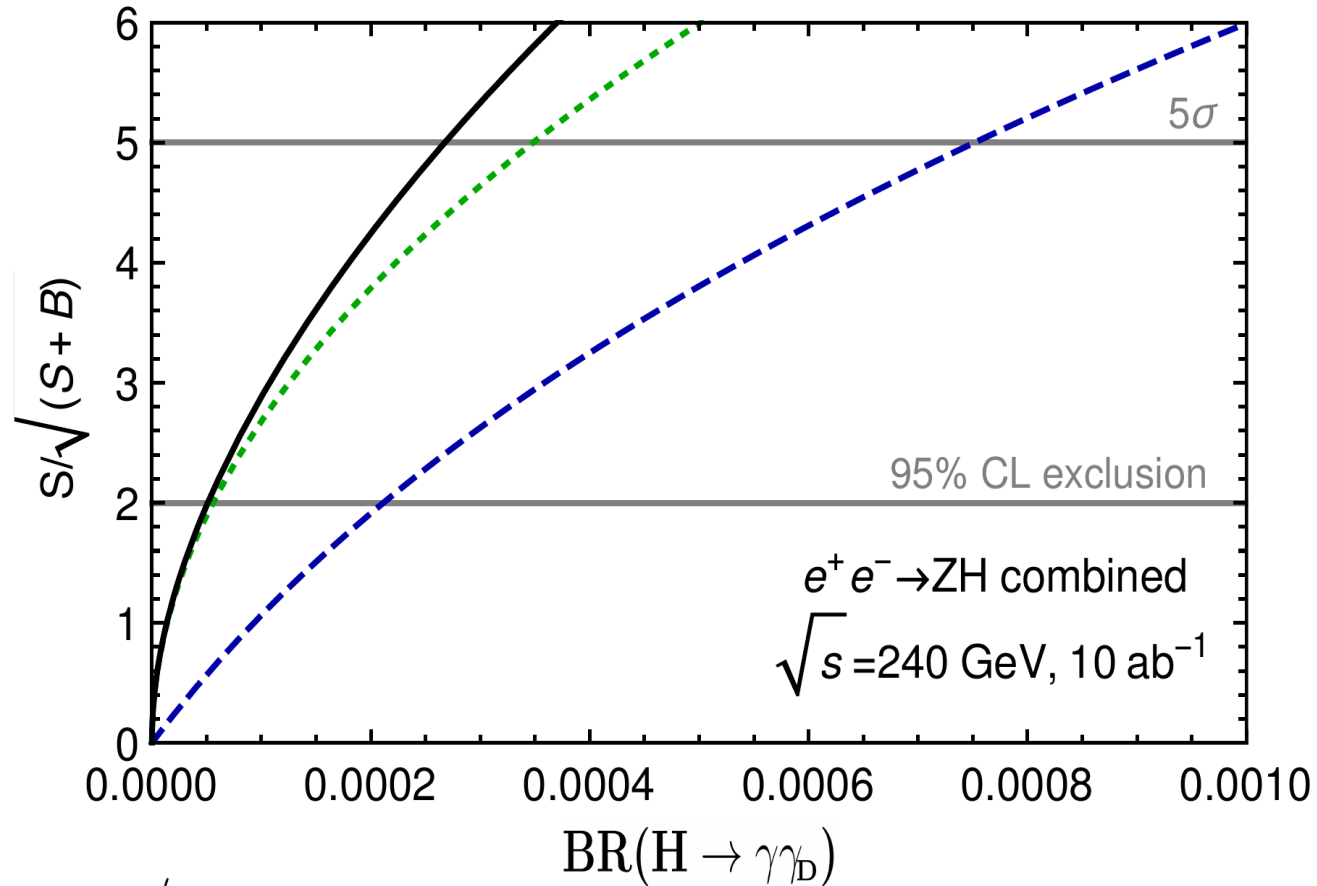
$$C_{Z\bar{\gamma}} > 2.7 \quad \Rightarrow \quad \text{BR}(H \rightarrow Z\bar{\gamma}) > 9 \text{ BR}_{SM}(H \rightarrow Z\gamma)$$

$$e^+e^- \rightarrow ZH \rightarrow (\mu^+\mu^-, q\bar{q})(\gamma\bar{\gamma})$$

Biswas, EG, Heikeinheimo, Mele, PRD 96 (2017)

$\sqrt{s} = 240 \text{ GeV}$

$L = 10 \text{ ab}^{-1}$



- dimuon+ γ + $\cancel{E}$
- dijet+ γ + $\cancel{E}$
- combined

Conclusions

- DP search via Higgs boson decays very promising (exploration just started)
- less constrained → interact via effective higher-dim operators with SM
- Potential non-decoupling limits on effective couplings with Higgs suggests $\text{BR}(H \rightarrow \gamma \gamma_D)$ could be large even if dark sector is very heavy
- $H \rightarrow \gamma \gamma_D$ potential DP discovery channel at LHC for both massive (invisible) and massless DP scenario
- $\text{BR} < 1.8\%$ (ATLAS) and 2.9% (CMS) upper limits on BR @ 95% C. L. → ~ one order of magnitude weaker than expected viable ranges (permille level)
- permille level sensitivity on $\text{BR}(H \rightarrow \gamma \gamma_D)$ could be reached at HiLumi LHC and FCC
- Future lepton colliders (including muon colliders) ideal place where to explore dark photon searches in Higgs boson decays → high sensitivity expected

Backup slides

Kinetic mixing with hypercharge

Massive DP scenario

$$\tilde{\mathcal{L}} = -\frac{\varepsilon}{2 \cos \theta_W} \tilde{F}'_{\mu\nu} B^{\mu\nu}$$

► Diagonalization involves 3 fields W^3, B, A'

$$\begin{pmatrix} W_\mu^3 \\ B_\mu \\ \tilde{A}'_\mu \end{pmatrix} = \begin{pmatrix} c_W & s_W & -s_W \varepsilon \\ -s_W & c_W & -c_W \varepsilon \\ t_W \varepsilon & 0 & 1 \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \\ A'_\mu \end{pmatrix}$$

difference with ordinary mixing of $U(1)_{\text{EM}}$, is that now **Z acquires a millicharge coupling** to Dark sector, proportional to $t_W = \tan[\theta_W]$

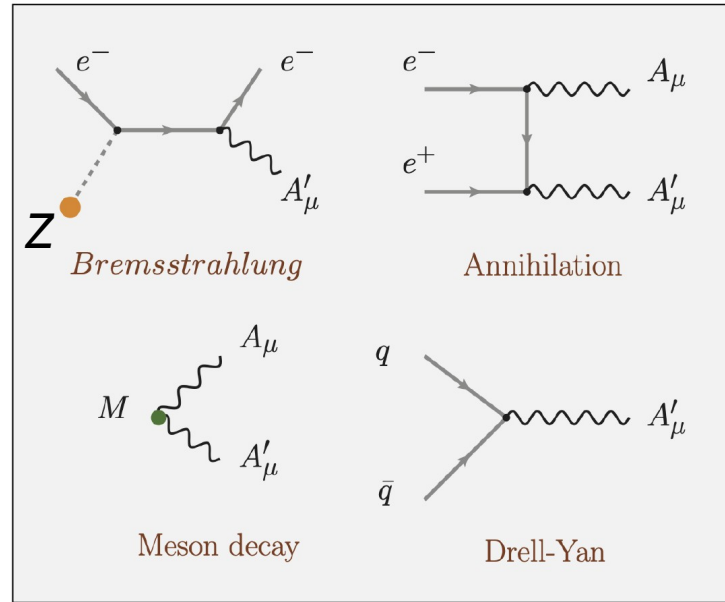
$$\mathcal{L} \supset -e \varepsilon J^\mu A'_\mu + \boxed{e' \varepsilon t_W J'^\mu Z_\mu} + e' J^{\mu'} A'_\mu$$

► After integrating out the Z fields → the massive DP to SM fields is recovered $\sim -e\varepsilon$

other implementations of massive DP scenario considered in the literature (see backup slide)

Main production mechanisms of (massive) Dark Photons

(tree-level couplings)



List does not end here...

1-loop induced processes

→ via resonant **Higgs**
and **Z** boson decays,
FCNC fermion decays, etc
(see later slides)

- **Bremsstrahlung** $e^- Z \rightarrow e^- Z A'$ (A1)
- **Annihilation** $e^+ e^- \rightarrow \gamma A'$ (BaBar, KLOE)
- **Meson decay** $M \rightarrow \gamma A'$ (NA48/2)
- **Drell Yan** $q\bar{q} \rightarrow A' (\rightarrow \ell^+ \ell^- \text{ or } h^+ h^-)$ (LHCb)
 Via **A-A'** mixing

hadrons

Detection of massive DP is based on its decay modes

► With visible final states $m_{A'} > 2m_e$

$$\Gamma(A' \rightarrow \ell^+ \ell^-) = \frac{1}{3} \alpha \varepsilon^2 m_{A'} \sqrt{1 - \frac{4m_\ell^2}{m_{A'}^2}} \left(1 + \frac{2m_\ell^2}{m_{A'}^2}\right)$$

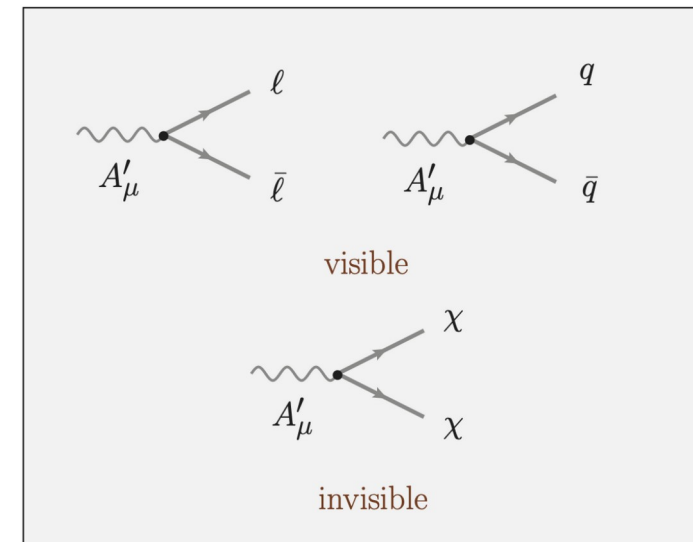
Searching for e^+e^- or $\mu^+\mu^-$ resonances

- **Collider** experiments sensitive to regions $\varepsilon > 10^{-3}$
- **Beam dump** ($e^- Z \rightarrow e^- Z A'$) experiments sensitive to regions $\varepsilon < 10^{-3}$
- **Detectable rate** (visible) proportional to ε^4 (require high luminosity colliders)
- long lived DP $\rightarrow$ require long decay volumes

DP decay
displaced vertex

► Invisible decay

- Detection relies on **missing momentum/energy** techniques
- Being independent on DP decay, **rate scales as** ε^2



Laboratory bounds on DP magnetic-dipole interactions

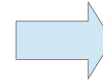
Magnetic-dipole operator of massless DP to SM fermions contributes to **spin-interaction potential**

$$V(r) = -\frac{\alpha_D v^2 d_M^a d_M^b}{4\Lambda^4 r^3} \left[\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b - 3(\boldsymbol{\sigma}_a \cdot \hat{\mathbf{r}})(\boldsymbol{\sigma}_b \cdot \hat{\mathbf{r}}) \right]$$

2005.01515 [hep-ph]

Bounds

► From 2^3P_2 - 2^3P_1 transitions in helium He



$$\frac{\Lambda^2}{\sqrt{\alpha_D} d_M^e} \gtrsim 872 \text{ GeV}^2$$

► From macroscopic forces between



Electrons

$$\frac{\Lambda^2}{\sqrt{\alpha_D} d_M^e} \gtrsim 1.61 \text{ TeV}^2$$

Electrons and nucleons

$$\frac{\Lambda^2}{\sqrt{\alpha_D} \sqrt{d_M^e d_M^q}} \gtrsim 1.94 \text{ TeV}^2$$

► From contribution to **g-2**

$$a_{\ell}^{A'} = -\frac{3}{2} \frac{\alpha_D}{\pi} \left(\frac{m_{\ell} v_h d_M^{\ell}}{\Lambda^2} \right)^2 \left[\frac{5}{4} + \log \frac{\mu^2}{m^2} \right]$$



$$\frac{\Lambda^2}{\sqrt{\alpha_D} d_M^e} \gtrsim 0.075 \text{ TeV}^2 \quad \text{electron}$$



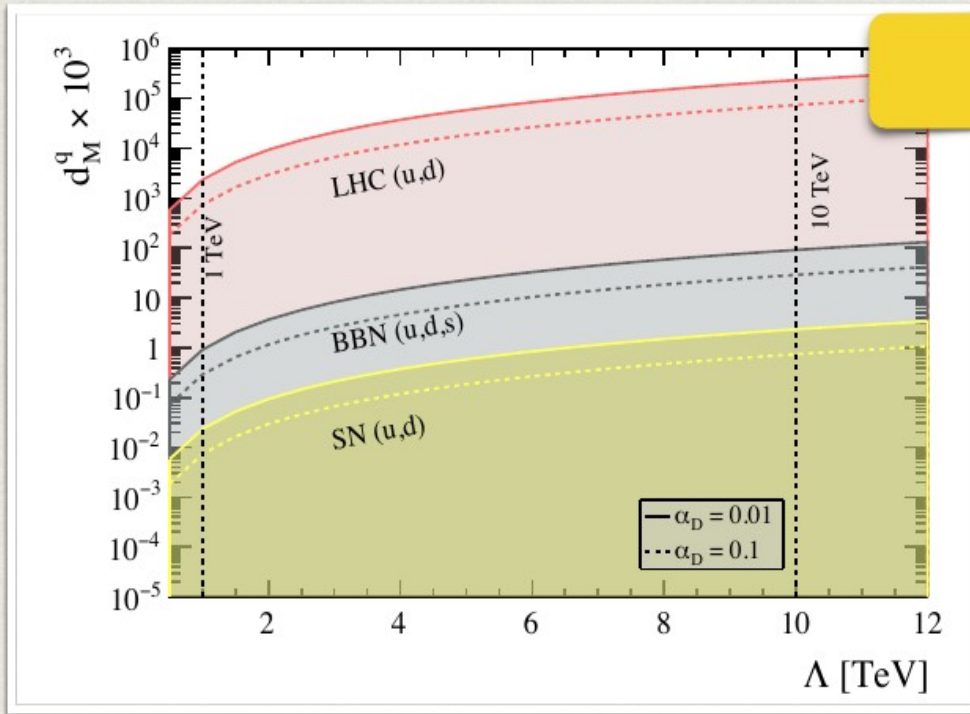
$$\frac{\Lambda^2}{\sqrt{\alpha_D} d_M^{\mu}} \gtrsim 0.5 \text{ TeV}^2 \quad \text{muon}$$

$$\frac{\Lambda^2}{\sqrt{\alpha_D} d_M^{\mu}} \simeq 0.27 \text{ TeV}^2 \longrightarrow \text{to explain current discrepancy in muon (g-2)}$$

massless dark photon

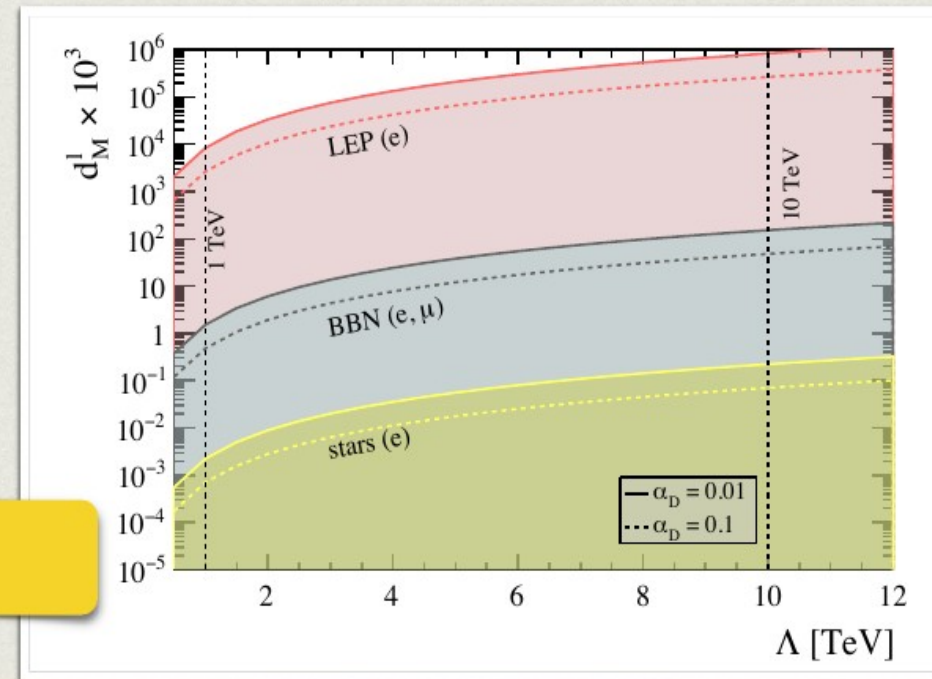
[from 2005.01515]

quarks



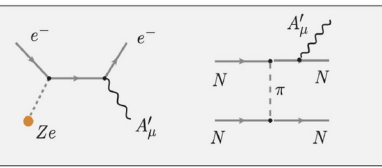
From SN

$$\frac{\Lambda^2}{\sqrt{\alpha_D} d_M^q} \gtrsim 4.3 \times 10^5 \text{ TeV}^2$$



leptons

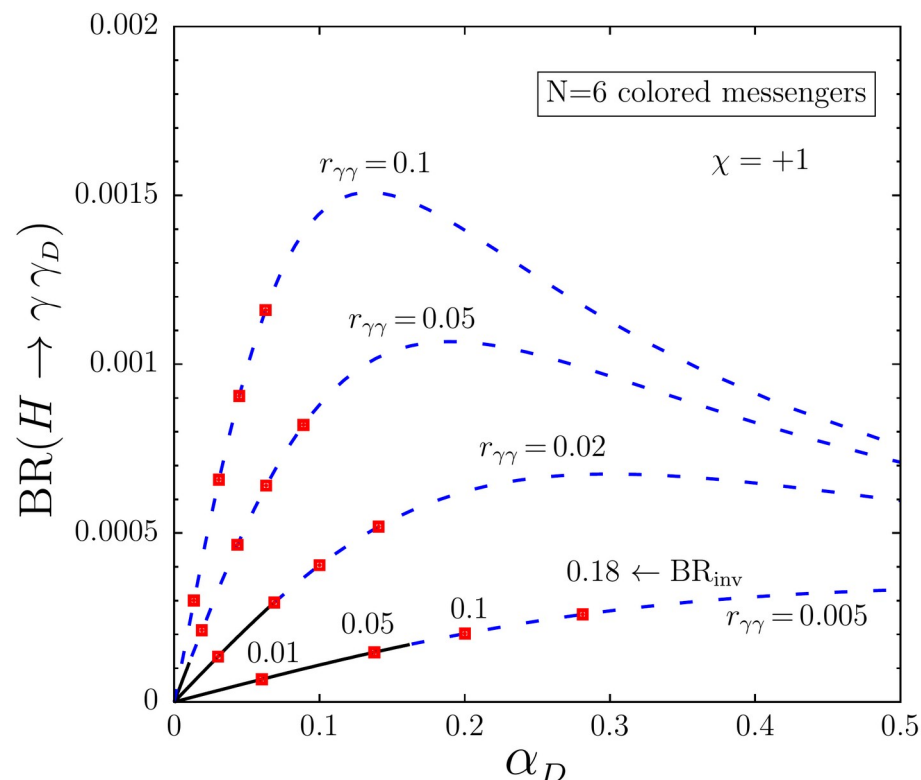
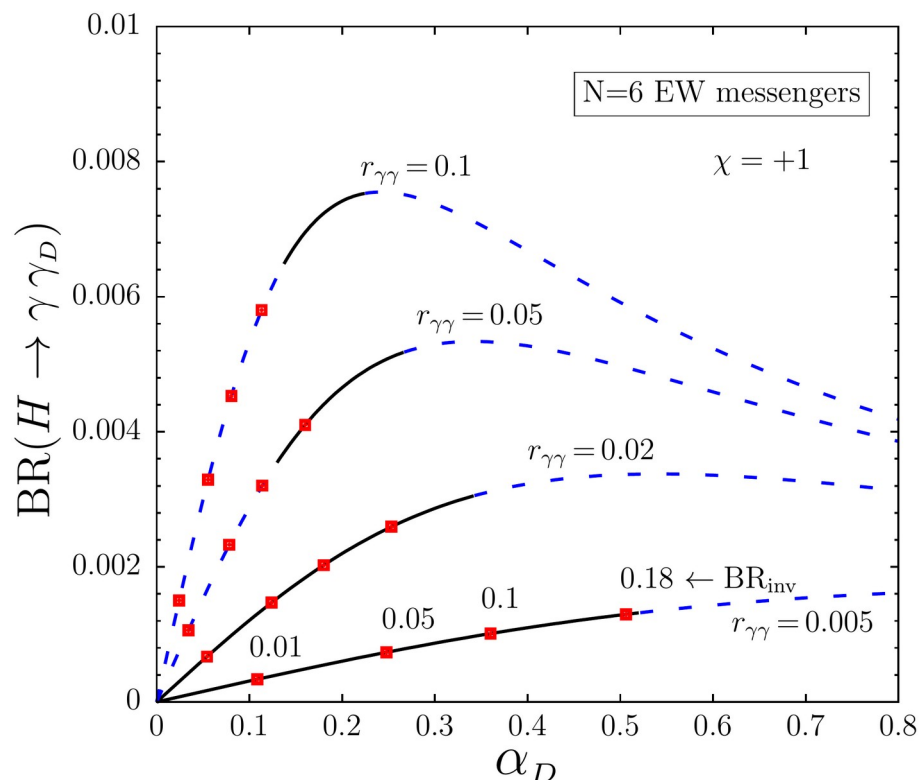
Bremsstrahlung of massless DP from electrons in a star and from nucleons in a supernova



BBN • Big bang nucleosynthesis. A cosmological bound for the dark photon operator comes from the determination of the effective number of relativistic species in addition to those of the SM partaking in the thermal bath—the same way the number of neutrinos is constrained.

SN • Supernovae. An additional limit is found from the neutrino signal of supernova 1987A, for which the length of the burst constrains anomalous energy losses in the explosion.

Inspired by Flavor model (radiative Yukawa)



Allowed regions of **BR**, consistent with all model parameters and LHC constraints, naturally lie **below 0.4 %** (EW mess.) and **0.3 %** (colored mess.)