

Dark Photon Physics

Emidio Gabrielli

University of Trieste, Italy

NICPB, Tallinn, Estonia

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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

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

Free Lagrangian

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

Interactions with matter fields

$$\mathcal{L} = e \overset{\text{SM}}{\downarrow} J_\mu A_b^\mu + e' \overset{\text{DS}}{\downarrow} J'_\mu A_a^\mu$$

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

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

$\nearrow$ Dark Photon
 $\searrow$ Photon

If both $U(1) \times U(1)$ unbroken (zero mass term) $\rightarrow$ freedom to rotate $\rightarrow \theta$

- ▶ B. Holdom, PLB 166B, 196 (1986)
- ▶ B.A. Dobreascu, 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]

Lagrangian after diagonalization

$$\mathcal{L}' = \left[\frac{e' \cos \theta}{\sqrt{1 - \varepsilon^2}} J'_\mu + e \left(\sin \theta - \frac{\varepsilon \cos \theta}{\sqrt{1 - \varepsilon^2}} \right) J_\mu \right] A'^\mu + \left[-\frac{e' \sin \theta}{\sqrt{1 - \varepsilon^2}} J'_\mu + e \left(\cos \theta + \frac{\varepsilon \sin \theta}{\sqrt{1 - \varepsilon^2}} \right) J_\mu \right] A^\mu$$

Freedom to rotate

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

example

$$\sin \theta = 0$$

A' couple to both SM and Dark sector fields

A couples only to SM fields

$$\mathcal{L}' = \left[\frac{e'}{\sqrt{1 - \varepsilon^2}} J'_\mu - \frac{e\varepsilon}{\sqrt{1 - \varepsilon^2}} J_\mu \right] A'^\mu + e J_\mu A^\mu.$$

same as massive DP scenario (see next slide)

Massless Dark-Photon scenario

Dark photon **A'** couple only to its own Dark Sector

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

$$\mathcal{L}' = e' J'_\mu A'^\mu + \left[-\frac{e'\varepsilon}{\sqrt{1 - \varepsilon^2}} J'_\mu + \frac{e}{\sqrt{1 - \varepsilon^2}} J_\mu \right] A^\mu$$

millicharge

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

Massive Dark Photon scenario

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

1) Stuckelberg mass term

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

2) Mass term via spontaneous symmetry breaking of U(1) (Dark-Higgs)

In both cases, NO freedom of rotation and angle θ is fixed to

$$\sin \theta = \frac{\delta \sqrt{1 - \varepsilon^2}}{\sqrt{1 - 2\delta\varepsilon + \delta^2}} \quad \delta = M_b/M_a$$

Photon and DP couple to both sectors

$$\begin{aligned} \mathcal{L}'' &= \frac{1}{\sqrt{1 - 2\delta\varepsilon + \delta^2}} \left[\frac{e' (1 - \delta\varepsilon)}{\sqrt{1 - \varepsilon^2}} J'_\mu + \frac{e (\delta - \varepsilon)}{\sqrt{1 - \varepsilon^2}} J_\mu \right] A'^\mu \\ &+ \frac{1}{\sqrt{1 - 2\delta\varepsilon + \delta^2}} [e J_\mu - \delta e' J'_\mu] A^\mu. \end{aligned}$$

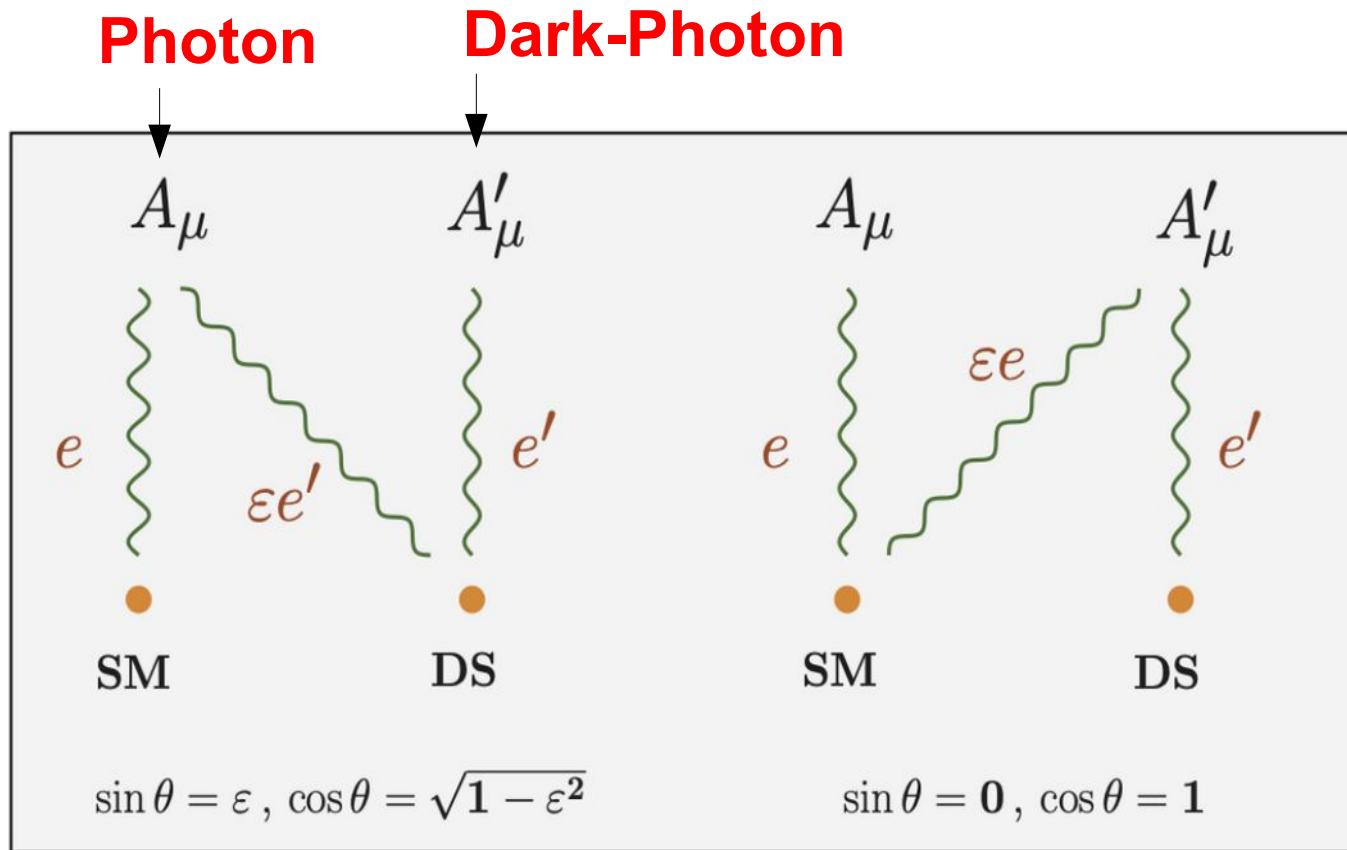
If only one U(1) is broken, $\delta \rightarrow 0 \Rightarrow \sin \theta = 0$ and we recover the standard massive DP scenario

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

(see previous slide for comparison)

 massive DP scenario

Summary of tree-level DP interactions



Massless Dark-Photon

less explored scenario

Massive Dark-Photon

most of experimental searches focus on massive DP scenario (tree-level couplings)

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 $t_W = \tan[\theta_W]$

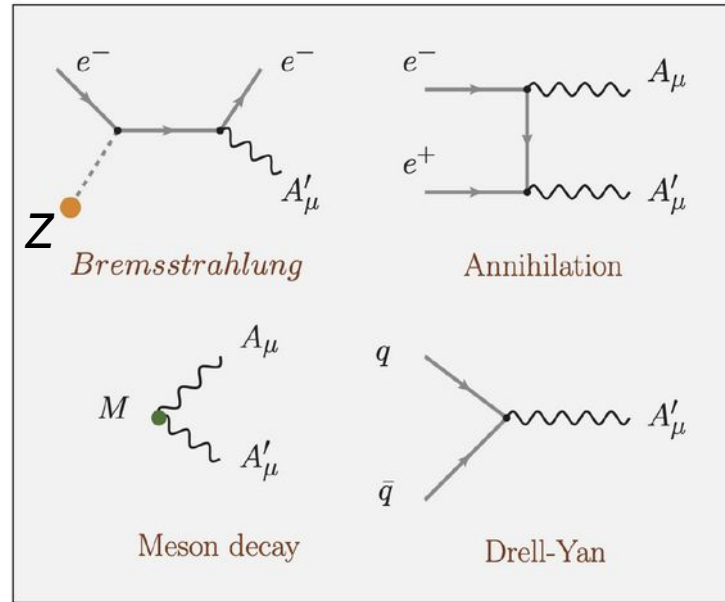
$$\mathcal{L} \supset -e \varepsilon J^\mu A'_\mu + \boxed{e' \varepsilon t_W J'^\mu Z_\mu} + e' J^{\mu'} A'_\mu$$

► 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 $m_{A'} > 2m_e$

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

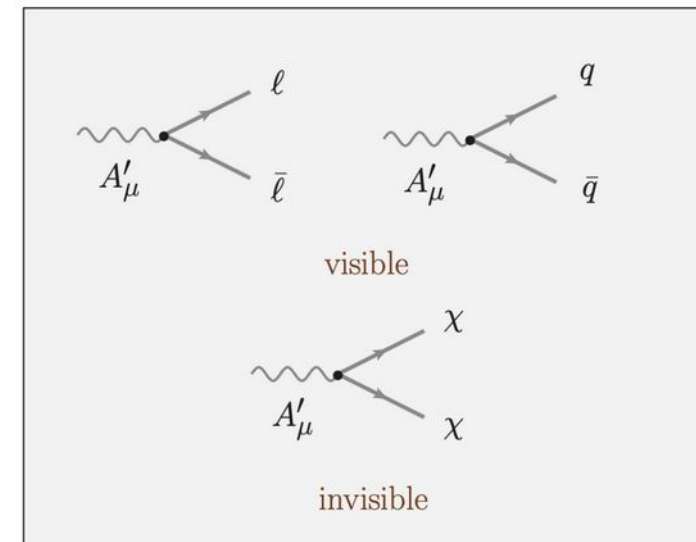
Searching for e^+e^- or $\mu^+\mu^-$ resonances

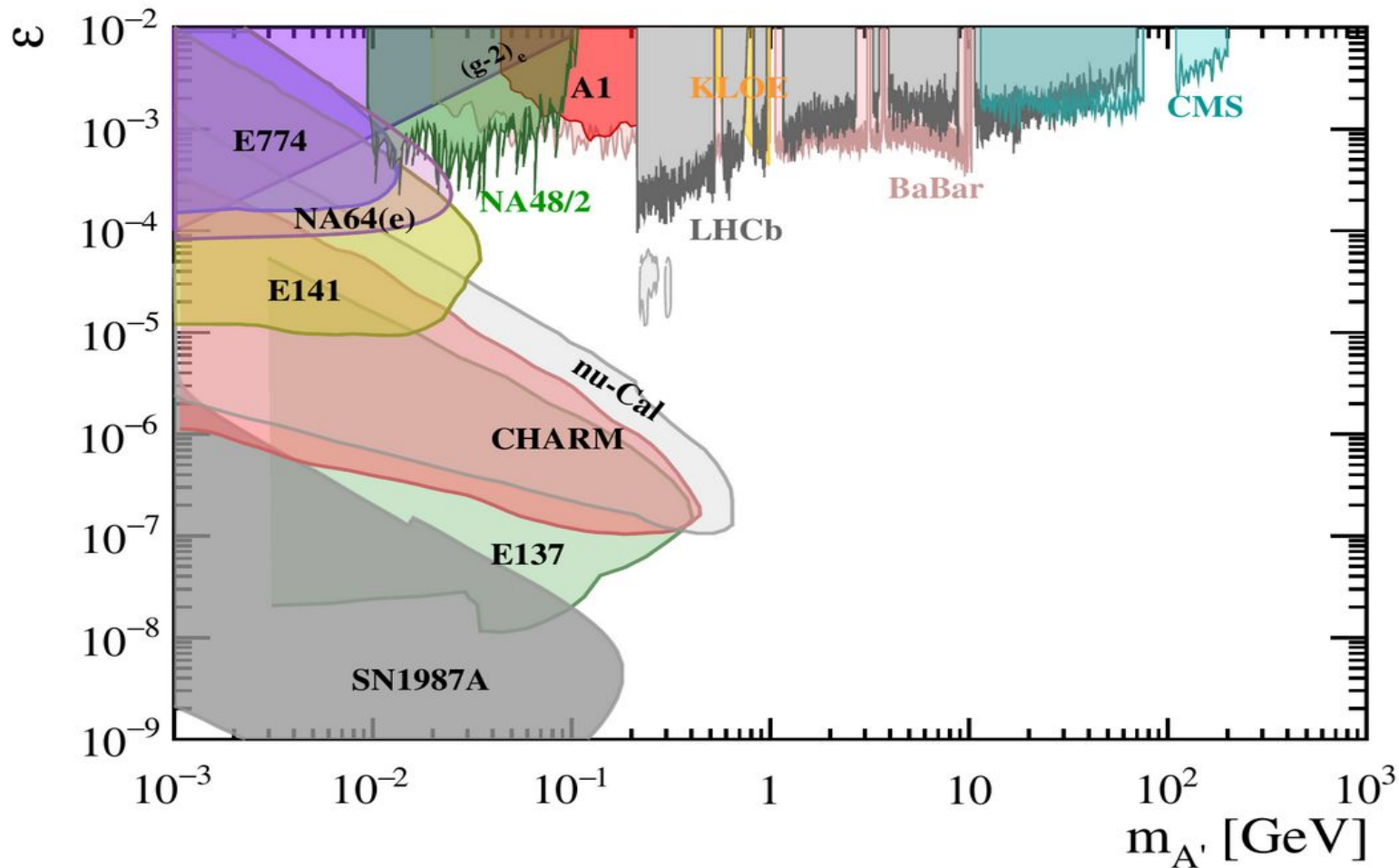
- **Collider** experiments sensitive to regions $\varepsilon > 10^{-3}$
- **Beam dump** ($e^- Z \rightarrow e^- Z A'$) experiments sensitive to regions $\varepsilon < 10^{-3}$
- **Detectable rate** (visible) proportional to ε^4 (require high luminosity colliders)
- long lived DP $\rightarrow$ require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



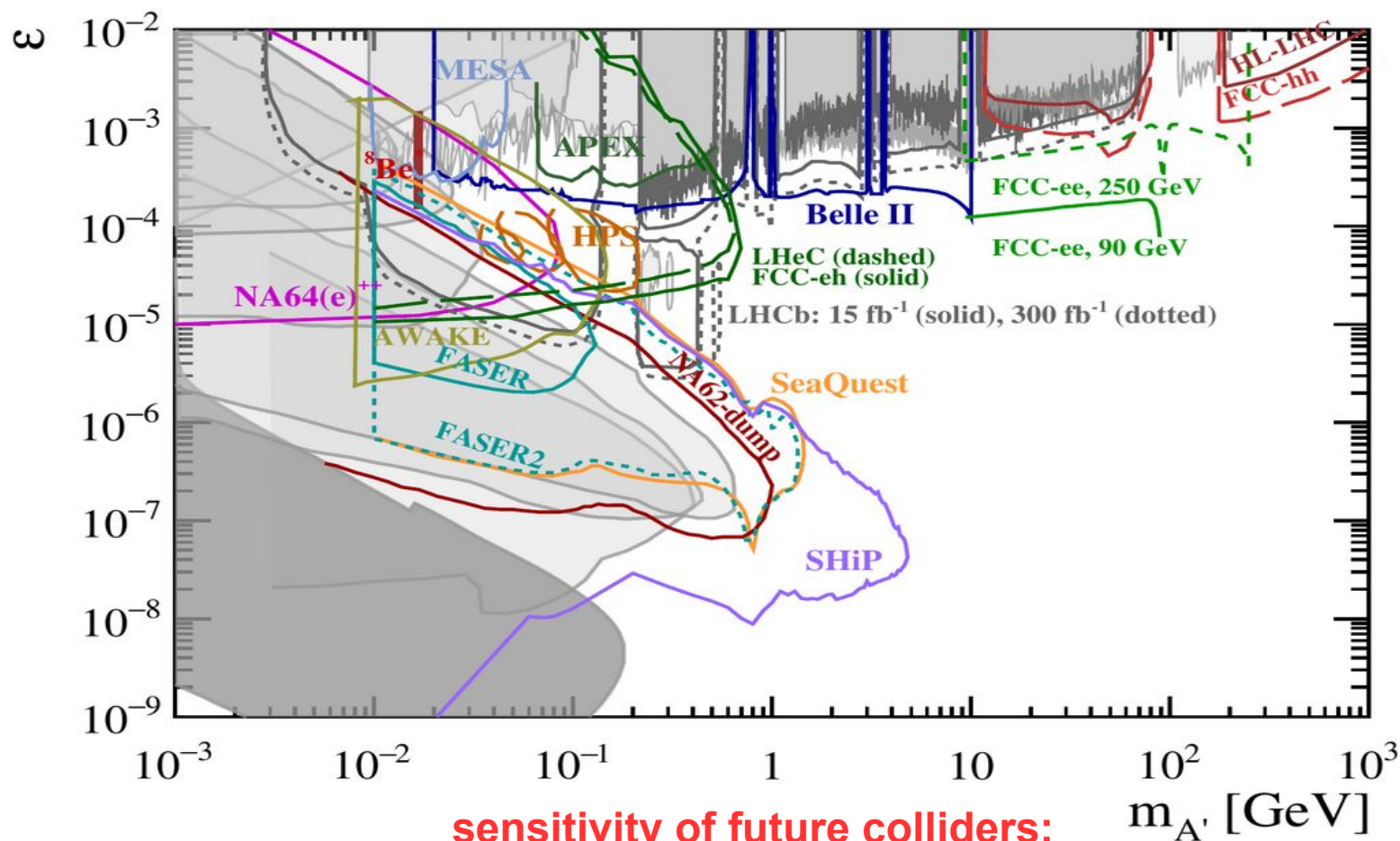
Limits on **visible decays**
(dilepton resonances)**Current limits**

(refs see backup slides)

Figure 3.3: Existing limits on the massive dark photon for $m_{A'} > 1$ MeV from di-lepton searches at experiments at collider/fixed target (A1 [176], LHCb [177], CMS [178], BaBar [179], KLOE [180, 181, 182, 183], and NA48/2 [184]) and old beam dump: E774 [185], E141 [186], E137 [187, 188, 189]), ν -Cal [190, 191], and CHARM (from [192]). Bounds from supernovae [193] and $(g - 2)_e$ [194] are also included.

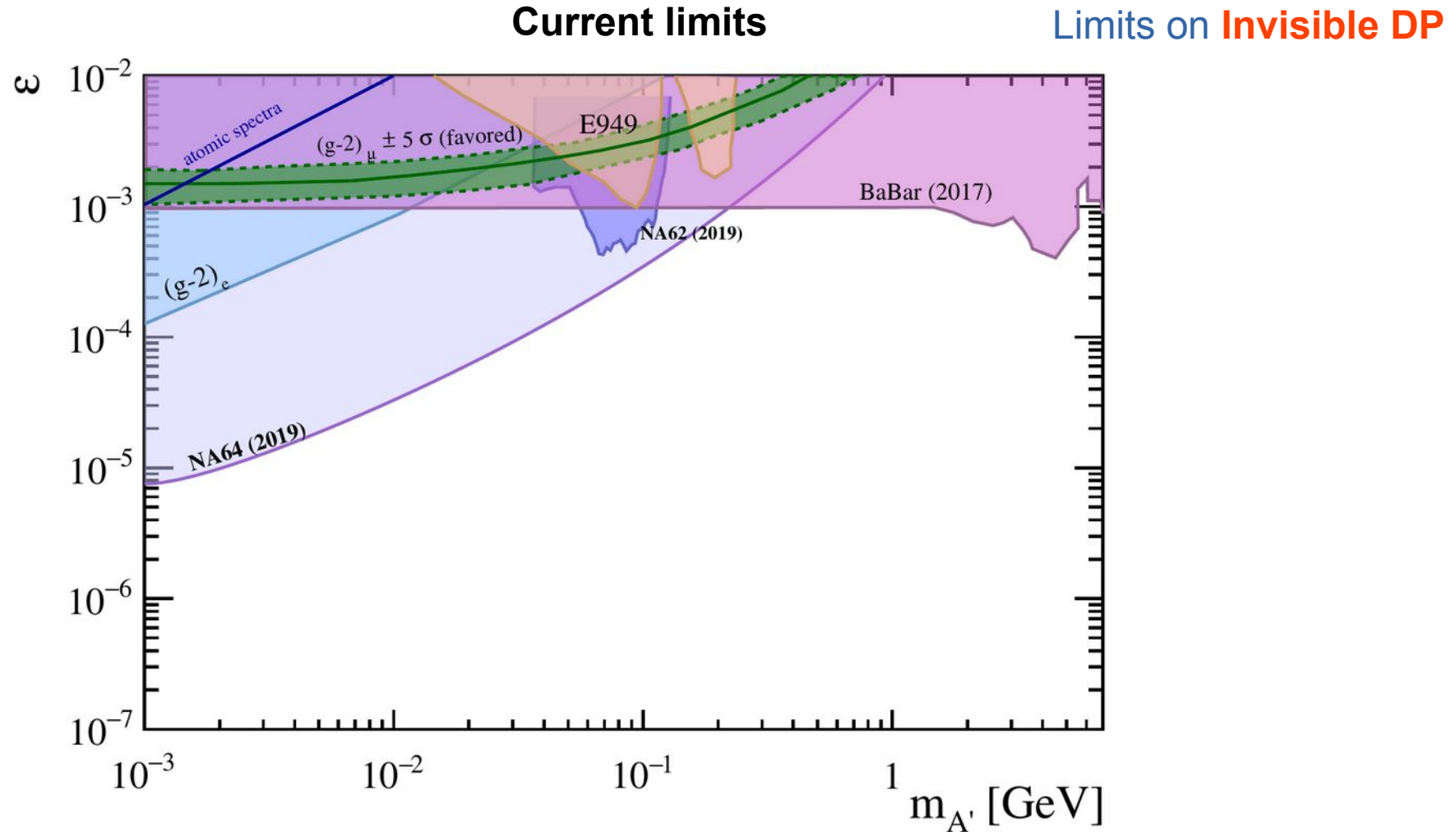
Limits on **visible decays**
(dilepton resonances)

Future prospects



sensitivity of future colliders:

- mainly covers large-masses and large-couplings range
- fully complementary to low-mass, low-coupling regime where beam-dump and fixed target experiments are more sensitive

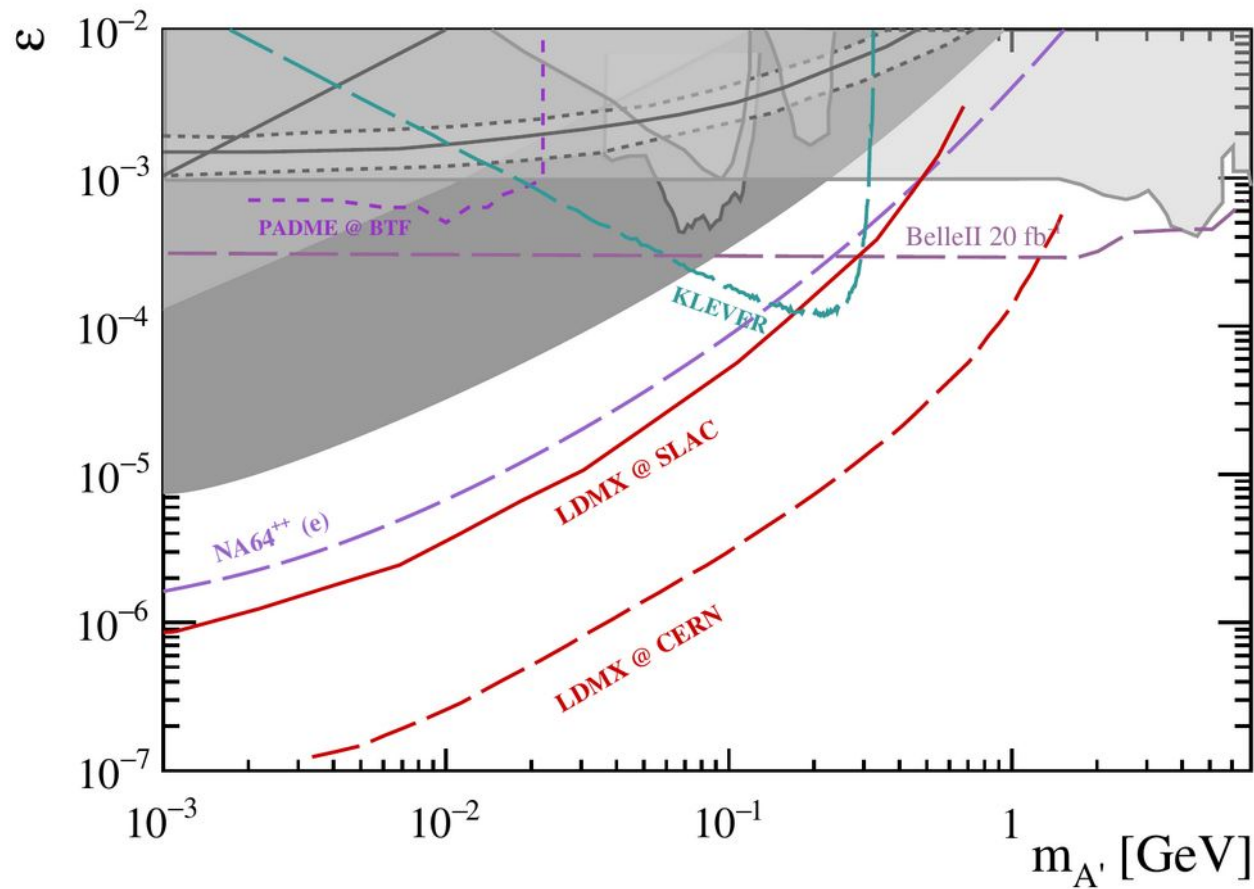


(refs see backup slides)

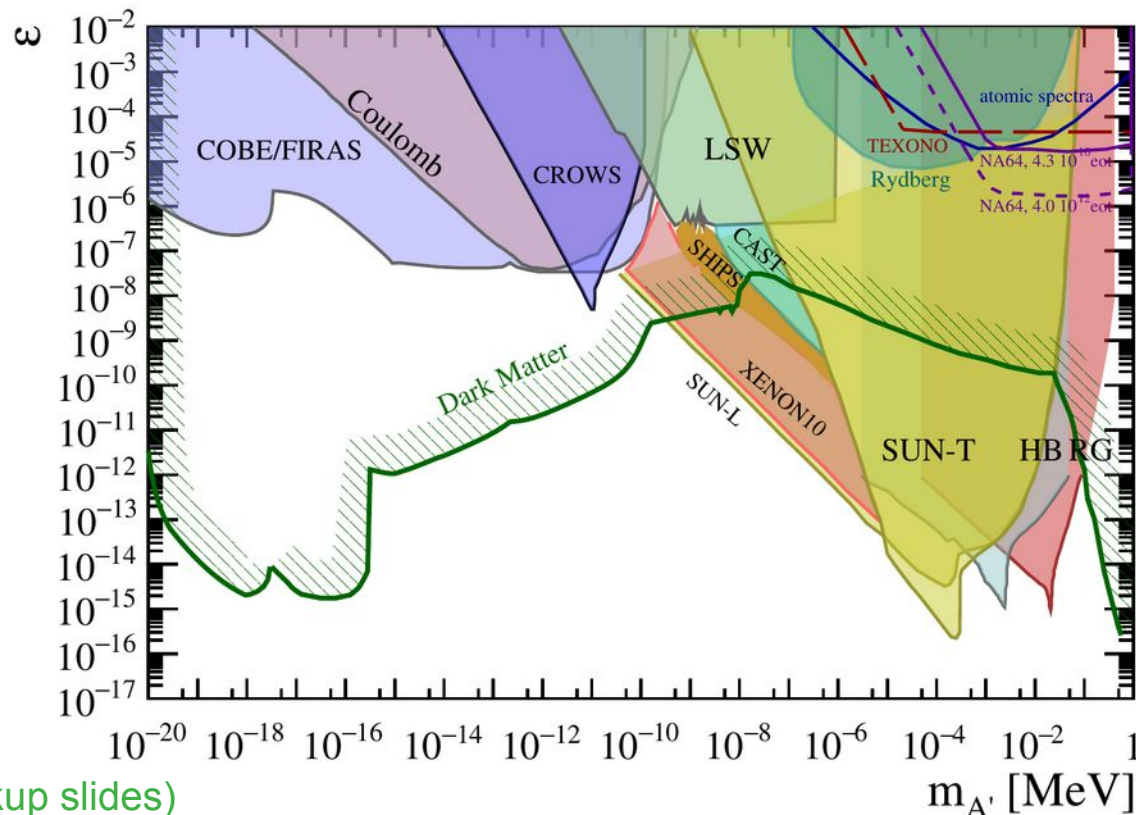
Figure 3.5: Existing limits for a massive dark photon going to invisible final states ($\alpha_D \gg \alpha \epsilon^2$). Existing limits from Kaon decay experiments (E787 [222], E949 [223], NA62 [224]), BaBar [225], and NA64(e) [226]. The constraints from $(g-2)_\mu$ [115] and $(g-2)_e$ are also shown.

Future prospects

Limits on Invisible DP



Limits on massive DP with mass below MeV



(refs see backup slides)

(refs see backup slides)

Figure 3.7: Current limits on massive dark photon for $m_{A'} < 1$ MeV. Bounds from cosmology (COBE/FIRAS [229, 230, 231, 232]), light through a wall (LSW) [233], CROWS [234], CAST [235], XENON10 [236], SHIPS [237], TEXONO [238], atomic experiments (Coulomb, Rydberg and atomic spectra [239]) and astrophysics: Solar lifetime (SUN-T and SUN-L), red giants (RG), horizontal branches (HB) [240, 241, 214]. Additional limits under the assumption that the dark photon is the dark matter: The curve “Dark Matter” includes the combination of the constraints from the references discussed in the main text.

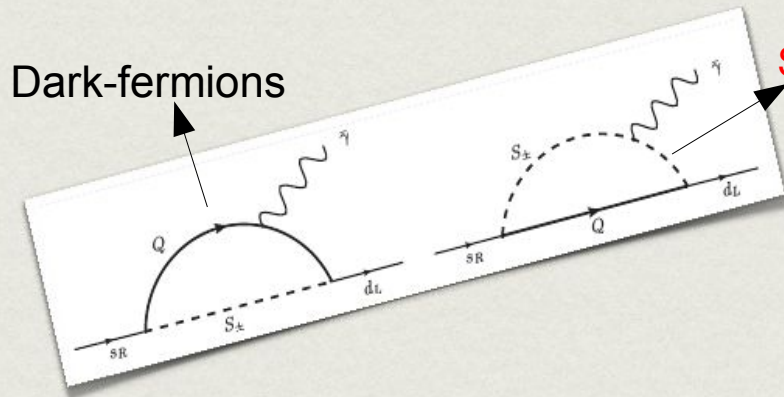
► Light Dark Photon (mass $\ll$ MeV) , **invisible**, is very much constrained at tree-level

► Effective loop-induced couplings could dominate at low energy (depending on the DS scale) for invisible DP

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]

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

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

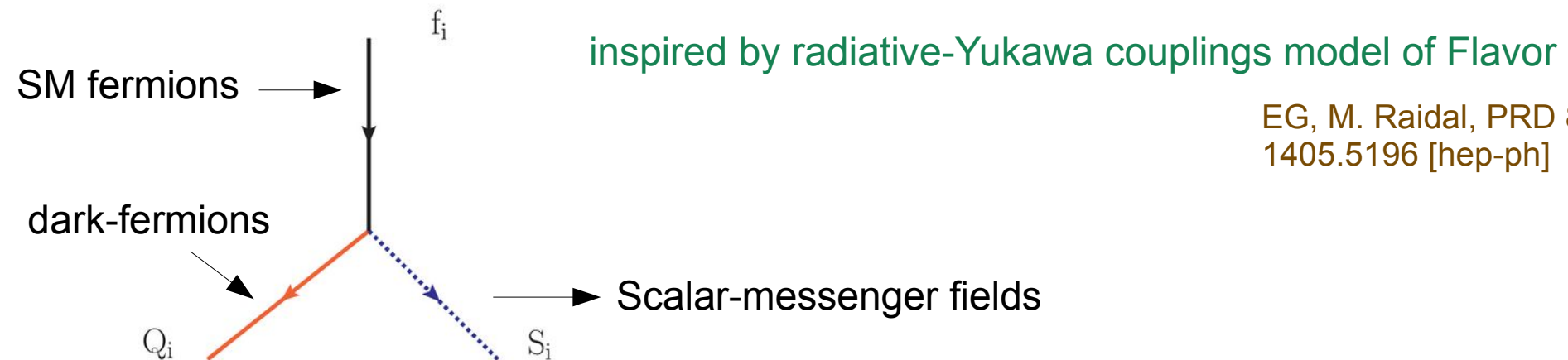
effective scale Λ

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

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

A simple UV complete benchmark portal model to Dark Sector

- scalar messenger fields (same quantum N. of squarks & sleptons)
- dark-fermion fields (SM singlets replica of SM fermions)
- messengers and dark-fermions both charged under $U(1)$ (dark photon)
- Yukawa-like interactions communicate between DS and SM fermions



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

Minimal (new) fields content

Same replica also in lepton EW sector

SM gauge group

	Fields	Spin	$SU(2)_L$	$U(1)_Y$	$SU(3)_c$	$U(1)_D$	
Scalar messengers	$\hat{S}_L^{D_i}$	0	1/2	1/3	3	$-q_{D_i}$	U(1) _D 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	$-q_{U_i}$	
Dark fermions	Q^{D_i}	1/2	0	0	0	q_{D_i}	
	Q^{U_i}	1/2	0	0	0	q_{U_i}	
Scalar singlet	S_0	0	0	0	0	0	

associated
DP field

S_0 needed to preserve at quantum level vanishing tree-level operators for the Yukawa couplings

- ▶ 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)

Can solve Flavor hierarchy problem

DP interactions in DS dynamically generate exponentially spread Dark fermion masses

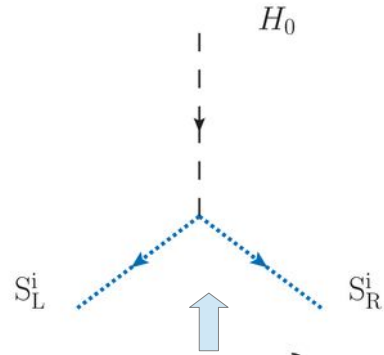
$$\Rightarrow M_{Q_i} = \Lambda \exp \left\{ -\frac{2\pi}{3 \bar{\alpha}(\Lambda) q_i^2} + \frac{1}{4} \right\} \Rightarrow Y_f \sim M_{Q_f} / \Lambda$$

transmitted to SM Yukawa's at 1-loop via messengers

Simplified model with Flavor Universal portal interaction → supported by MFV hypothesis

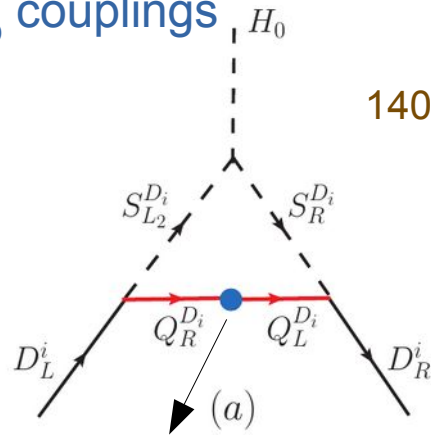
$$\begin{aligned} \mathcal{L}_{MS}^I = & g_L \left(\sum_{i=1}^{N_f} [\bar{q}_L^i Q_R^{U_i}] \hat{S}_L^{U_i} + \sum_{i=1}^{N_f} [\bar{q}_L^i Q_R^{D_i}] \hat{S}_L^{D_i} \right) \\ & + g_R \left(\sum_{i=1}^{N_f} [\bar{U}_R^i Q_L^{U_i}] S_R^{U_i} + \sum_{i=1}^{N_f} [\bar{D}_R^i Q_L^{D_i}] S_R^{D_i} \right) \\ & + \lambda_S S_0 \left(\tilde{H}^\dagger S_L^{U_i} S_R^{U_i} + H^\dagger S_L^{D_i} S_R^{D_i} \right) + h.c., \end{aligned}$$

+ Lepton sector



$$\mu_S \equiv \lambda_S \langle S_0 \rangle \longrightarrow S_0 \text{ vev}$$

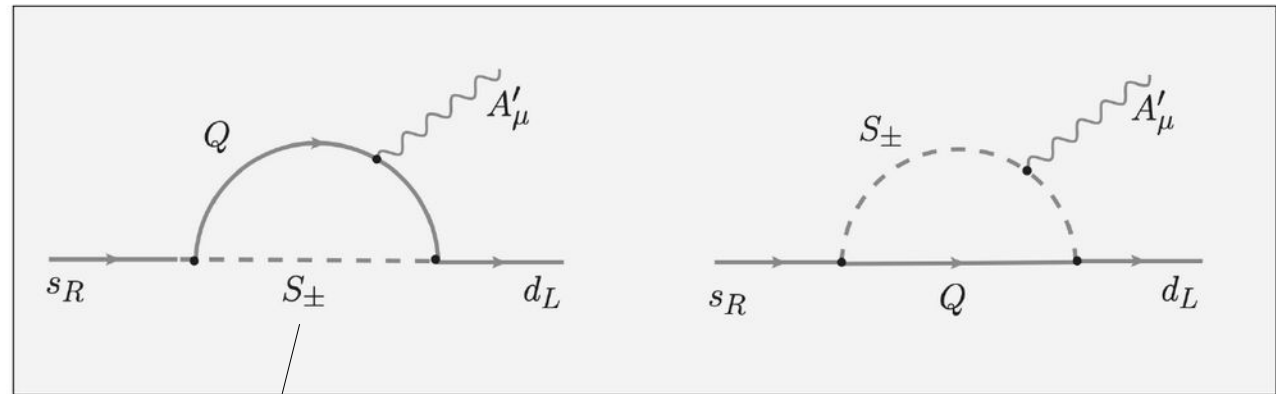
Diagram generating D-type Yukawa Y_D couplings



1405.5196 [hep-ph]

$$Y_f \sim \left(\frac{M_{Q_f} \mu_S}{\bar{m}^2} \right) \times \text{loop - functions}$$

Magnetic-dipole interactions of DP with SM fermions (FCNC and Flavor conserving)

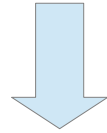


Messenger **mass-eigenstates**

Messenger spectrum (assuming flavor universality)

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

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



Mass matrix

after S_0 gets a vev

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

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

Simplified LR universal model

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

Messenger mass spectrum eigenvalues

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

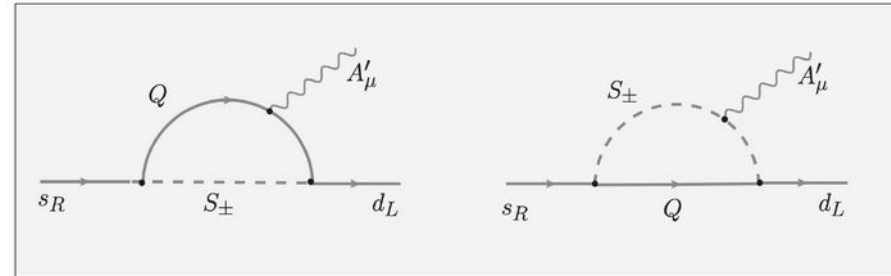
► similar features of squarks and sleptons spectrum of typical SUSY models

Effective Lagrangian for magnetic-dipole interactions of DP (dim.5 operator)

Model independent parametrization

Dark-U(1) coupling

absorbs messenger couplings and loop factors



$$\mathcal{L} = \frac{e_D}{2\Lambda_5} \bar{\psi}^i \sigma_{\mu\nu} \left(\mathbb{D}_M^{ij} + i\gamma_5 \mathbb{D}_E^{ij} \right) \psi^j F'^{\mu\nu}$$

$SU(2)_L \times U(1)_Y$ invariant way

Λ_5 scale of same order of heaviest messenger or Dark-fermion mass running in the loop

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

► This is the leading coupling of massless DP to SM fermions (lowest dim. operator)

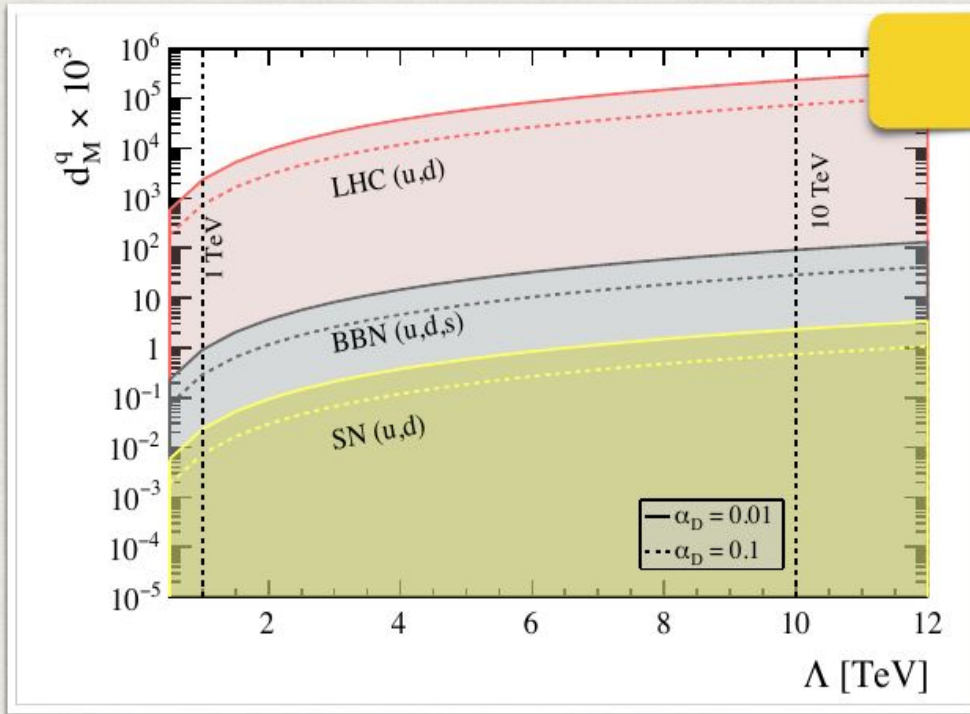
► This effective coupling is also present in massive DP scenarios

- 1) might dominate with respect to tree-level mixing (for light dark photons)
- 2) different production mechanisms respect to tree-level mixing

massless dark photon

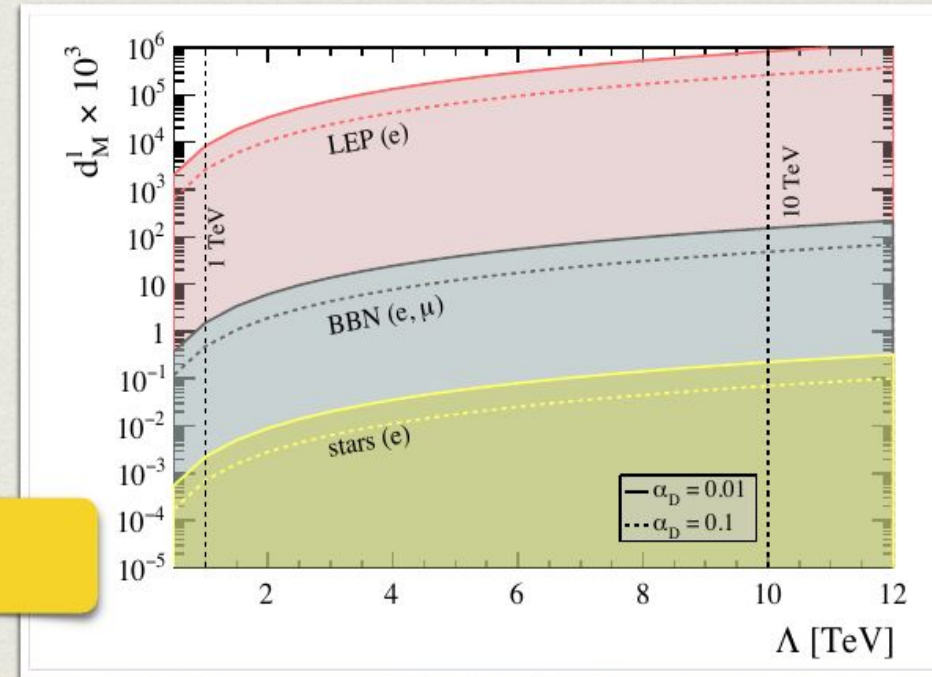
[from 2005.01515]

quarks



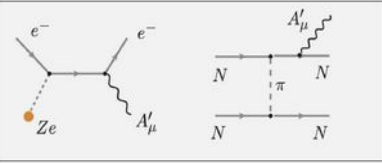
From SN

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



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.

Laboratory bounds on DP magnetic-dipole interactions

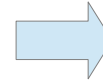
Magnetic-dipole operator of massless DP to SM fermions contributes to **spin-interaction potential**

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

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**

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



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



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

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

DP couplings to neutral boson sector of SM

Results apply to both massless and massive DP (via higher dimensional operators)

- Not constrained by astrophysics bounds
- Effective couplings to Higgs boson $\rightarrow$ dimension 5 operators $\rightarrow$ UV non-decoupling !
- Effective couplings to Z boson $\rightarrow$ dimension 6 operators $\rightarrow$ UV decoupling
- Being induced at loop are sensitive to less constrained couplings
- Higgs-Photon-DP coupling same as for massive and massless dark-photon scenarios

Discovery channel for both massive and massless DP scenarios!

invisible DP signatures at colliders

EG, Heikinheimo, Mele, Raidal, PRD 90 (2014)
Biswas, EG, Heikinheimo, Mele PRD 93 (2016), PRD 96 (2017)
Biswas, EG, Mele, Symmetry 2002, 14 (8), 15222



main discovery channels

LHC

$$H \rightarrow \gamma \gamma_D \rightarrow \gamma + \cancel{E}_T$$

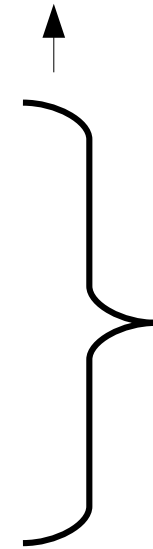
FCC-ee

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

→ (backup slides)

FCC-ee

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



→ **non decoupling features !**
(see next slides)



Z decay

$$Z \rightarrow \gamma \gamma_D$$

→ **evading Landau-Yang theorem**

Fabbrichesi, EG, Mele PRL 120 (2018)

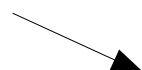


via

$$e^+ e^- \rightarrow \gamma \gamma_D \rightarrow \gamma + \cancel{E}$$

(backup slides)

Casarsa, Fabbrichesi, EG, PRD 105 (2022)



Via electron magnetic-dipole couplings

other DP productions mechanisms

Via FCNC magnetic-dipole interactions (apply to both massive and massless DP)

■ **Via FCNC processes** $f \rightarrow f' \gamma_D$ $f = t, b, c, s, \tau, \mu$
(not shown) EG, Mele, Raidal, Venturini, PRD 94 (2016)

- channels not yet explored in top, bottom, charm, and tau-lepton sectors
- sensitive to both massive and massless Dark Photons
- s-d transitions:

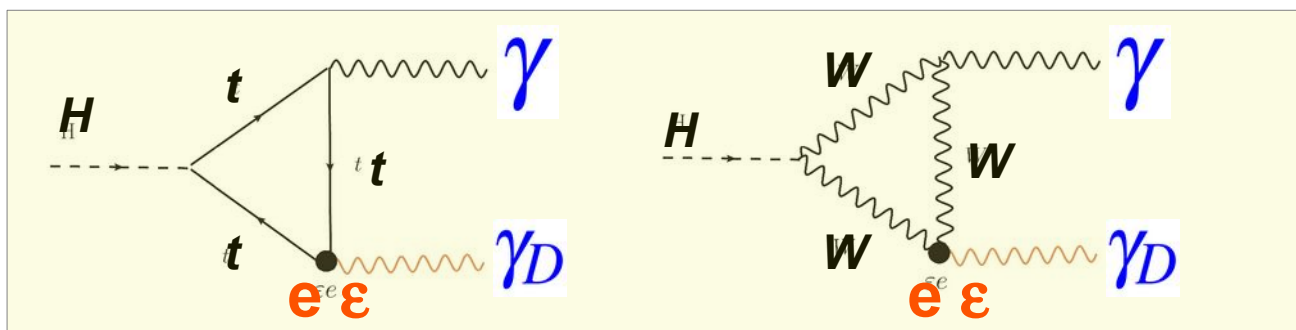
$K^+ \rightarrow \pi^+ \pi^0 \gamma_D$ relevant for NA62 Fabbrichesi, EG, Mele, PRL 119 (2017)

■ **Via polarized muon decay** $\mu^+ \rightarrow e^+ + \gamma_D$
(not shown) Fabbrichesi, EG, PRD 104 (2021)

→ possibility to disentangle spin via measurement of positron polarization

$$H \rightarrow \gamma \gamma_D$$

- 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 arise (mainly) from SM fermion loops via ϵ -mixing



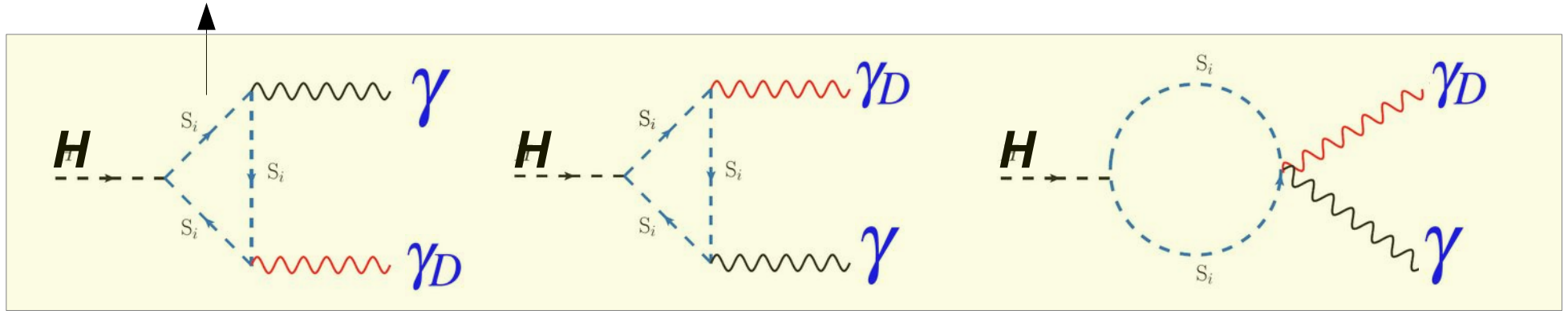
- For the **massless case**, there is no tree-level couplings $\rightarrow$ so it is vanishing
- For the **massive case**, **via mixing is suppressed** $\rightarrow$ $\text{BR} \sim \epsilon^2 \times \text{BR}(H \rightarrow \gamma \gamma)$
 $\rightarrow$ outside the sensitivity range of any present and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

$$H \rightarrow \gamma\gamma_D$$

Why it is relevant for DP discovery

scalar messenger fields



Quantum amplitude

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

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

Non-decoupling behavior (at fixed ξ) for messenger masses $\bar{m} \rightarrow \infty$

$$\Lambda_{\gamma\gamma_D} = \frac{6\pi v}{R\sqrt{\alpha\alpha_D}} \frac{1 - \xi^2}{\xi^2}$$

v is the SM Higgs vev

$$0 \leq \xi \leq 1 \rightarrow \text{Th. upper bound}$$

$$\xi < 1 - \frac{m_B^2}{\bar{m}^2} \rightarrow \text{Phen. upper bound}$$

lightest messenger mass

Messengers contribute also to $H \rightarrow \gamma\gamma$ and $H \rightarrow \gamma_D\gamma_D$

Same structure of amplitude as for photon-DP but with a different scale Λ

$$H \rightarrow \gamma\gamma$$



$$\Lambda_{\gamma\gamma} = \Lambda_{\gamma\gamma_D} \frac{R}{R_0} \sqrt{\frac{\alpha_D}{\alpha}}$$

$$H \rightarrow \gamma_D\gamma_D$$



$$\Lambda_{\gamma_D\gamma_D} = \Lambda_{\gamma\gamma_D} \sqrt{\frac{\alpha}{\alpha_D}} \frac{R}{R_1}$$

R_0 and R_1 contain products of U(1) charges

$$R_0 = 3N_c(e_U^2 + e_D^2)$$

$$R_1 = N_c \sum_{i=1}^3 (q_{U_i}^2 + q_{D_i}^2)$$

Monophoton Exotic Higgs Signature

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

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

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

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

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

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

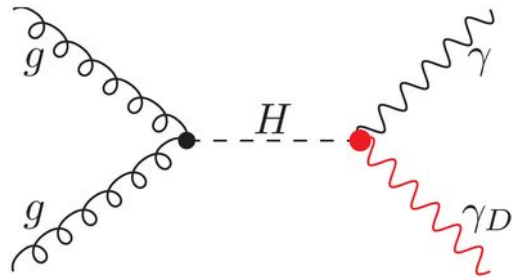
R_1 = product of U(1) charges

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

Messenger contributions to $H\text{-}\gamma\text{-}\gamma$ (constraints from decay $H \rightarrow \gamma\gamma$, see next slides)

Messenger contributions to $H\text{-gluon-gluon}$ (constraints from Higgs production $\rightarrow \xi < 0.88$)

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



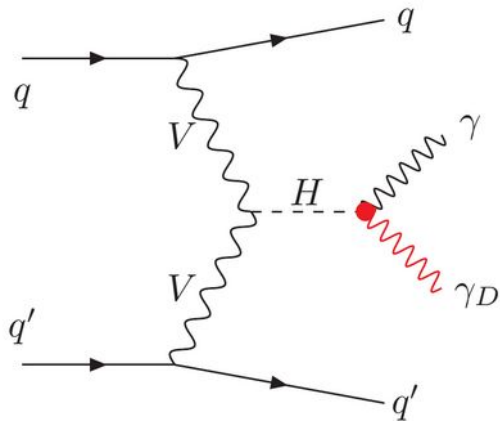
gluon-gluon fusion

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

gg + VBF analyzed in

EG, Heikinheimo, Mele, Raidal, PRD 90 (2014)
Biswas, EG, Heikinheimo, Mele PRD 93 (2015)

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

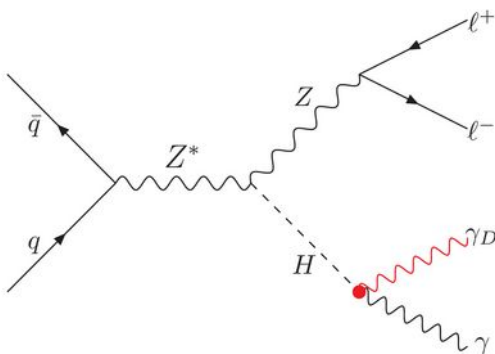


Vector Boson fusion

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

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

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

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

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

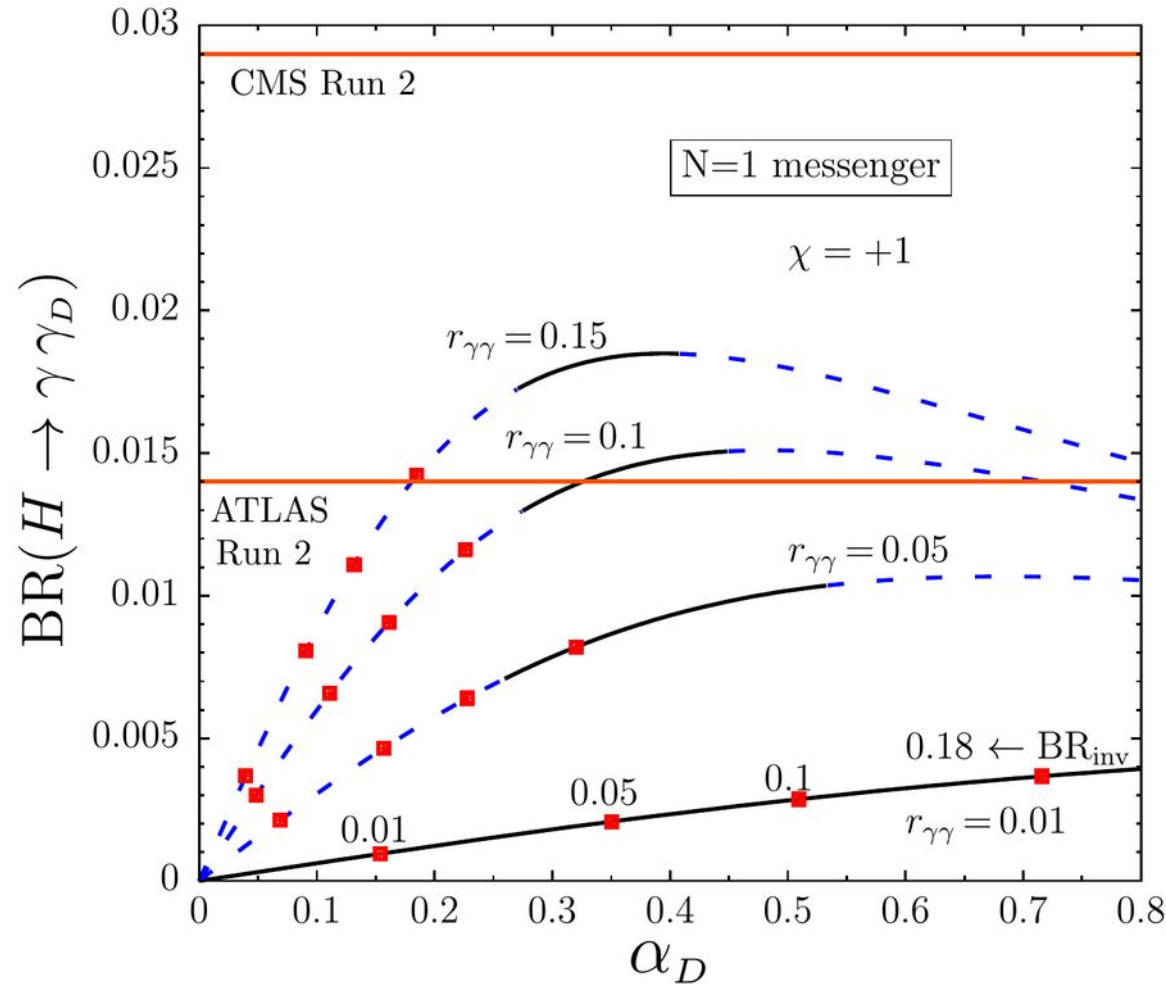
Model dependent constant
~ product of U(1) charges

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

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

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]

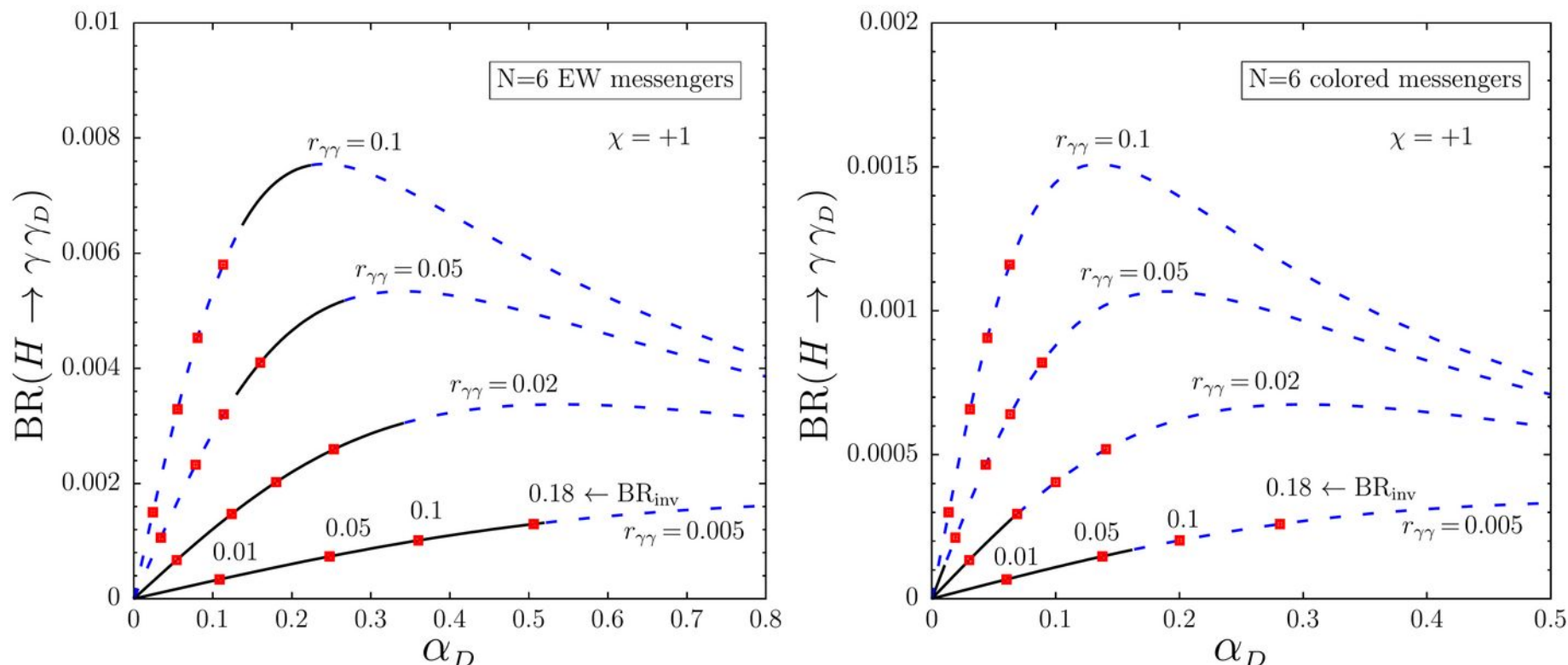
ATLAS $\rightarrow BR < 1.4 \%$

[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%**

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.)

FUTURE PERSPECTIVES @ LHC and future hadron colliders

2206.05297

$BR_{\gamma\gamma_D} (\%)$	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

$$Z \rightarrow \gamma \bar{\gamma}$$

Induced by DP **magnetic-dipole interactions** with SM fermions

● Possible due to the **magnetic-dipole** coupling of DP

● **generated at 1-loop**, sensitive to dark magnetic-dipole couplings of all SM fermions

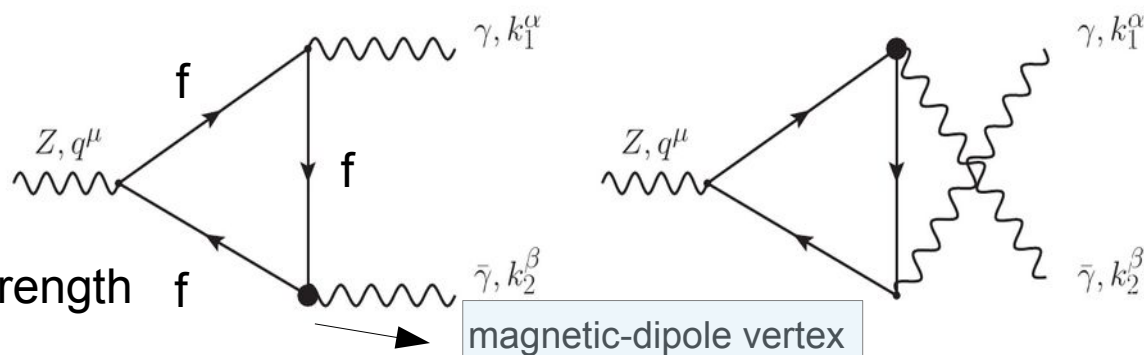
$$Z \rightarrow \gamma \bar{\gamma}$$

Fabbrichesi, EG, Mele PRL 120 (2018)]

f → run over all SM fermions

$$\mathcal{L} = \sum_f \frac{e_D}{2\Lambda} \bar{\psi}_f \sigma_{\mu\nu} \left(d_M^f + i\gamma_5 d_E^f \right) \psi_f B^{\mu\nu}$$

dark photon field strength f



■ **Landau-Yang theorem forbids $Z \not\rightarrow 2$ photons** → **amplitude vanishes**
avoided due to distinguishability of photon and dark-photon interaction vertices (blob)

■ **massive dark-photon couples also via magnetic dipole interaction**
 (results apply to both massless and massive)

■ **tree-level coupling of massive DP via mixing with photon is vanishing due to LY theorem**

$$\mathcal{L}_{eff} = \frac{e}{\Lambda M_Z} \sum_{i=1}^3 C_i \mathcal{O}_i(x)$$

C_i finite due to gauge invariance

dimension-six operators $\mathcal{O}_i$ are

$$\begin{aligned} \mathcal{O}_1(x) &= Z_{\mu\nu} \tilde{B}^{\mu\alpha} A^\nu_\alpha, \\ \mathcal{O}_2(x) &= Z_{\mu\nu} B^{\mu\alpha} \tilde{A}^\nu_\alpha, \\ \mathcal{O}_3(x) &= \tilde{Z}_{\mu\nu} B^{\mu\alpha} A^\nu_\alpha. \end{aligned}$$

$$\mathcal{L} = \sum_f \frac{e_D}{2\Lambda} \bar{\psi}_f \sigma_{\mu\nu} \left(d_M^f + i\gamma_5 d_E^f \right) \psi_f B^{\mu\nu}$$

Dark-U(1) charge

$$\text{BR}(Z \rightarrow \gamma\bar{\gamma}) \simeq \frac{2.52 \alpha_D}{(\Lambda/\text{TeV})^2} (|d_M|^2 + |d_E|^2) \times 10^{-8}$$

LEP upper bound of $\text{BR}(Z \rightarrow \gamma\bar{\gamma}) \simeq 10^{-6}$

M. Acciarri *et al.* [L3 Collaboration], Phys. Lett. B **412**, 201 (1997); O. Adriani *et al.* [L3 Collaboration], Phys. Lett. B **297**, 469 (1992); P. Abreu *et al.* [DELPHI Collaboration], Z. Phys. C **74**, 577 (1997); R. Akers *et al.* [OPAL Collaboration], Z. Phys. C **65**, 47 (1995).

10^{13} of Z boson events at the FCC-ee
expected 10^2 – 10^4 of $Z \rightarrow \gamma\bar{\gamma}$ events

$d_M \simeq 1/2$
→ large but perturbative couplings in DS

10^{-9}

$\alpha_D \rightarrow 0.1$
 $\Lambda \rightarrow 1 \text{ TeV}$

4×10^{-11}

$d_M \simeq 0.1$
→ small couplings in DS

10^{-6} for non-perturbative dynamics in DS

$$Z \rightarrow \gamma + X$$

■ Main characteristic signature:

- ▶ **isolated mono-chromatic photon** ($E_\gamma \sim M_Z/2$) + **missing energy (neutrino-like)**

■ Best place to look for: $e^+ e^-$ colliders as FCC-ee

- ▶ monochromaticity of photon mostly maintained (Z peak), slightly spread by initial beam radiation

$$e^+ e^- \rightarrow Z \rightarrow \gamma + X$$

■ once a signal is observed → possible to disentangle dark-photon from other scenarios that could mimic same signature

Comelato, EG, PRD 102 (2020),
2006.00973 [hep-ph]

Cobal, De Dominicis, Fabbrichesi, EG, J.
Magro, Mele, Panizzo PRD 102 (2020)
2006.15945 [hep-ph]

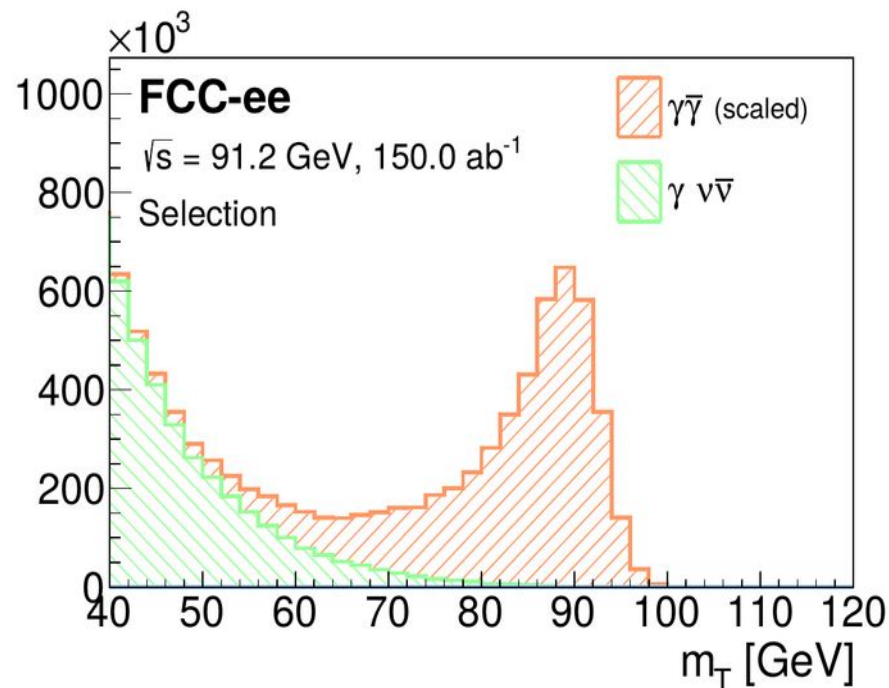
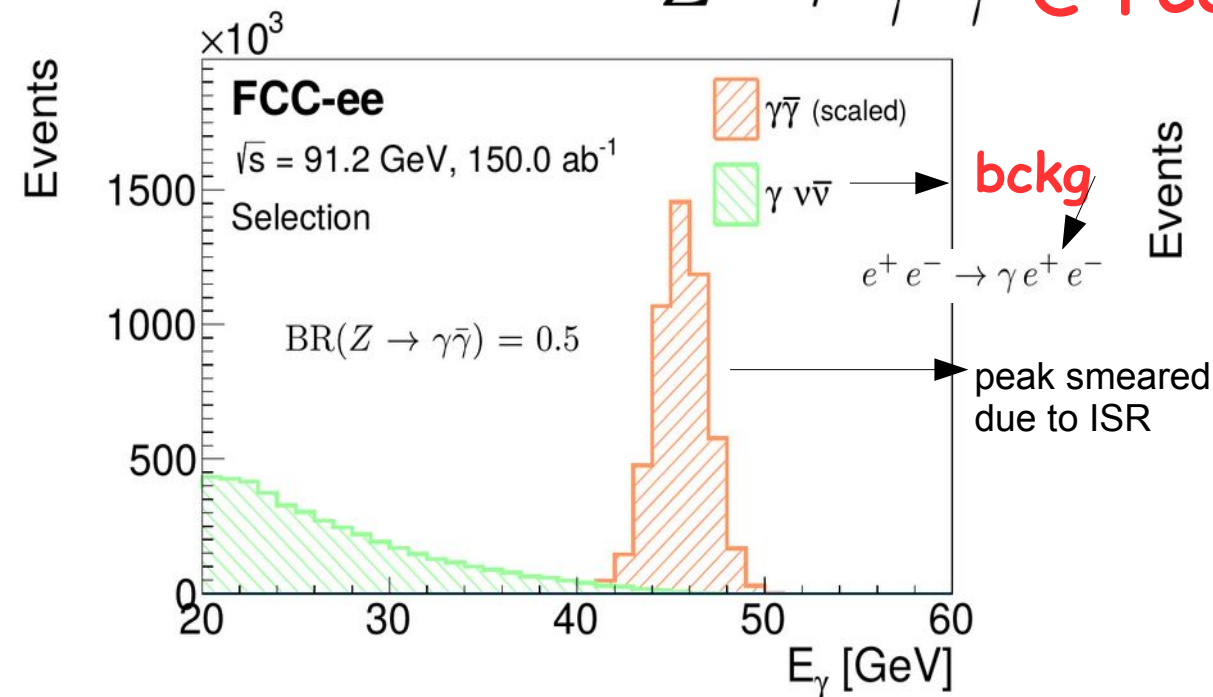
■ **X light boson invisible decays**

- ▶ **spin-1** (Dark-Photon)
- ▶ **spin-0** (ALP → effective couplings $\gamma\gamma$ and $Z\gamma$)
- ▶ **spin-2** (like KK gravity with low energy scale),..

$Z \rightarrow \gamma \bar{\gamma}$ @ FCC-ee

Cobal, De Dominicis, Fabbrichesi, EG, J. Magro, Mele, Panizzo, PRD 102 (2020)

2006.15945 [hep-ph]



transverse invariant mass simplifies here $M_T = 2p_T^\gamma$

upper limits on BR at 95% C.L.

BR($Z \rightarrow \gamma \bar{\gamma}$)				
	$\sqrt{s}$	L (ab^{-1})	M_T	E_γ
LHC	13 TeV	0.14	8×10^{-6}	5×10^{-5}
HL-LHC	13 TeV	3	2×10^{-6}	1×10^{-5}
FCC-ee	91.2 GeV	150	2×10^{-11}	3×10^{-11}
CEPC	91.2 GeV	16	7×10^{-11}	8×10^{-11}

Spin analysis: possibility to disentangle spin-0 from spin-1

Conclusions

- Present and future experimental searches mainly focused on massive DP searches based on tree-level interactions. Strong constraints hold on DP couplings for masses below < 1 GeV. High energy colliders can test larger couplings and higher masses. **Low mass range might be more sensitive to loop-induced interactions.**
- Massless DP scenario more appealing from theoretical side
- DP can mediate long-distance interactions among U(1) charged DM constituents → supported also by cosmological and astrophysical observations
- Massless DP scenario **less constrained** → interact via effective higher-dim operators with SM (not fully explored) different signatures required (invisible)
- $H \rightarrow \gamma \gamma_D$ promising DP **discovery channel** at LHC due to **non-decoupling effects** for both massless and massive scenario (require dark-sector mediated interactions)
- BR $< 1.4\%$ (**ATLAS**) and 2.9% (**CMS**) upper limits on BR @ 95% C. L. → one order of magnitude weaker than allowed range

Future perspective at LHC and FCC



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

Backup slides

Other realizations of massive DP scenarios

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No kinetic mixing
but non-diagonal
mass term with Z
Dark-Z scenarios

B-L gauged $\rightarrow$
U(1) associated to
DP $\rightarrow$ Direct
coupling with SM.
DP no longer dark

Extra-dimensions:
DP as Kaluza-Klein
state

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Bounds on massless DP from Galaxies formation

● DP can induce long-range interactions of DM constituents (more refs. in backup slides)

● may solve the small-scale structure formation problems in cosmology

D. N. Spergel and P. J. Steinhardt, Phys. Rev. Lett. **84**, 3760 (2000); M. Vogelsberger, J. Zavala and A. Loeb, Mon. Not. Roy. Astron. Soc. **423**, 3740 (2012).

● predict dark discs of galaxies

J. Fan, A. Katz, L. Randall and M. Reece, Phys. Rev. Lett. **110**, no. 21, 211302 (2013) [arXiv:1303.3271](#).

● obstacles on long range DM interactions come from collisionless dynamics of galaxies

● bounds from merging galaxies formation

● Ellipticity profile inferred from NCG720 galaxy gives:

Agrawal, Cyr-Racine, Randall, Scholtz JCAP, 1705 (2017), 1610.04611 [hep-ph]

(subject to a number of uncertainties and assumptions)

DM mass

$$m_\chi \left(\frac{0.01}{\alpha_D} \right)^{2/3} \gtrsim 300 \text{ GeV}$$

fine-structure constant of U(1) dark-photon

previously stronger bound from soft-scatterings

Ackerman, Buckley, Carroll, Kamionkowski, PRD 79 (2009), 0810.5126 [hep-ph]

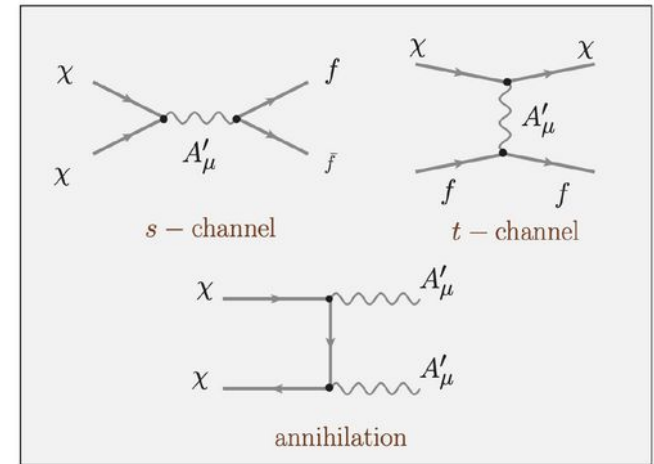
$$\frac{G_N m_\chi^4 N}{8\alpha_D^2} \gtrsim 50 \log \frac{G_N m_\chi^2 N}{2\alpha_D}$$

→ n. of DM particles

▶ Recent results on galaxies formations from N-body simulation in self-interacting DM cosmologies (using predicted ellipticities and DM density in central regions) support weaker bound above

- ▶ If DM is subject to long range U(1) interactions candidate for DM depends on the value of DP coupling to SM fermions into which they might annihilate

$$\chi\chi \rightarrow A'A' \quad \langle\sigma_{\chi\chi\rightarrow A'A'v}\rangle = \frac{2\pi\alpha_D^2}{m_\chi^2}$$



Relic density

$$\Omega_\chi h^2 \approx \frac{2.5 \times 10^{-10} \text{ GeV}^{-2}}{\langle\sigma_{\chi\chi\rightarrow A'A'v}\rangle}$$

for $\alpha_D \simeq 0.01$

- ▶ Only a percent of critical density for **DM masses up to < 1 TeV** (all light DM have been annihilated). **Ruled out!** Supported also by the limits on galaxy formation

- ▶ DM with masses **above > 1 TeV** can be DM
Dominant annihilation is not in DP but in SM fermions

$$\langle\sigma_{\chi\chi\rightarrow f\bar{f}v}\rangle \simeq \frac{2\pi\alpha_L^2}{m_S^2}$$

Critical relic density reproduced if

$$2\pi\alpha_L^2 \left(\frac{10 \text{ TeV}}{m_S}\right)^2 \simeq 0.1$$

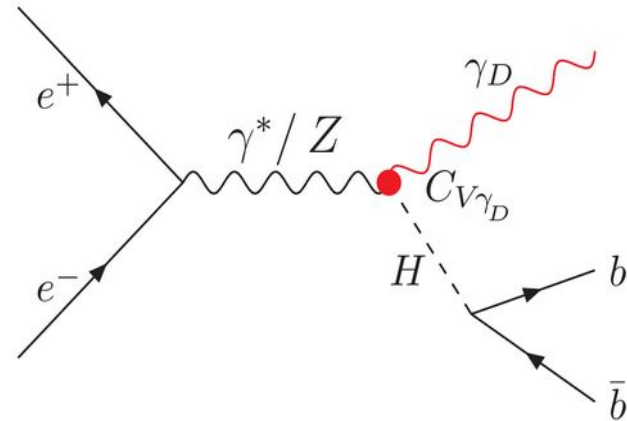
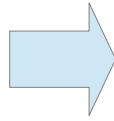
Loop-induced couplings of DP to SM fermions

messenger mass (see next slides)

DP production at Future e^+e^- colliders

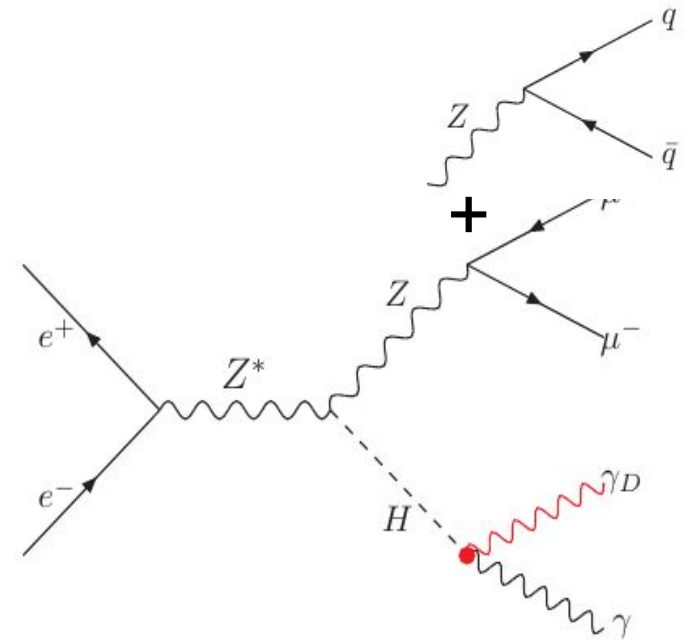
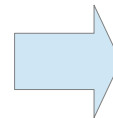
improved sensitivity on Higgs-photon-DP coupling

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



provides a better sensitivity

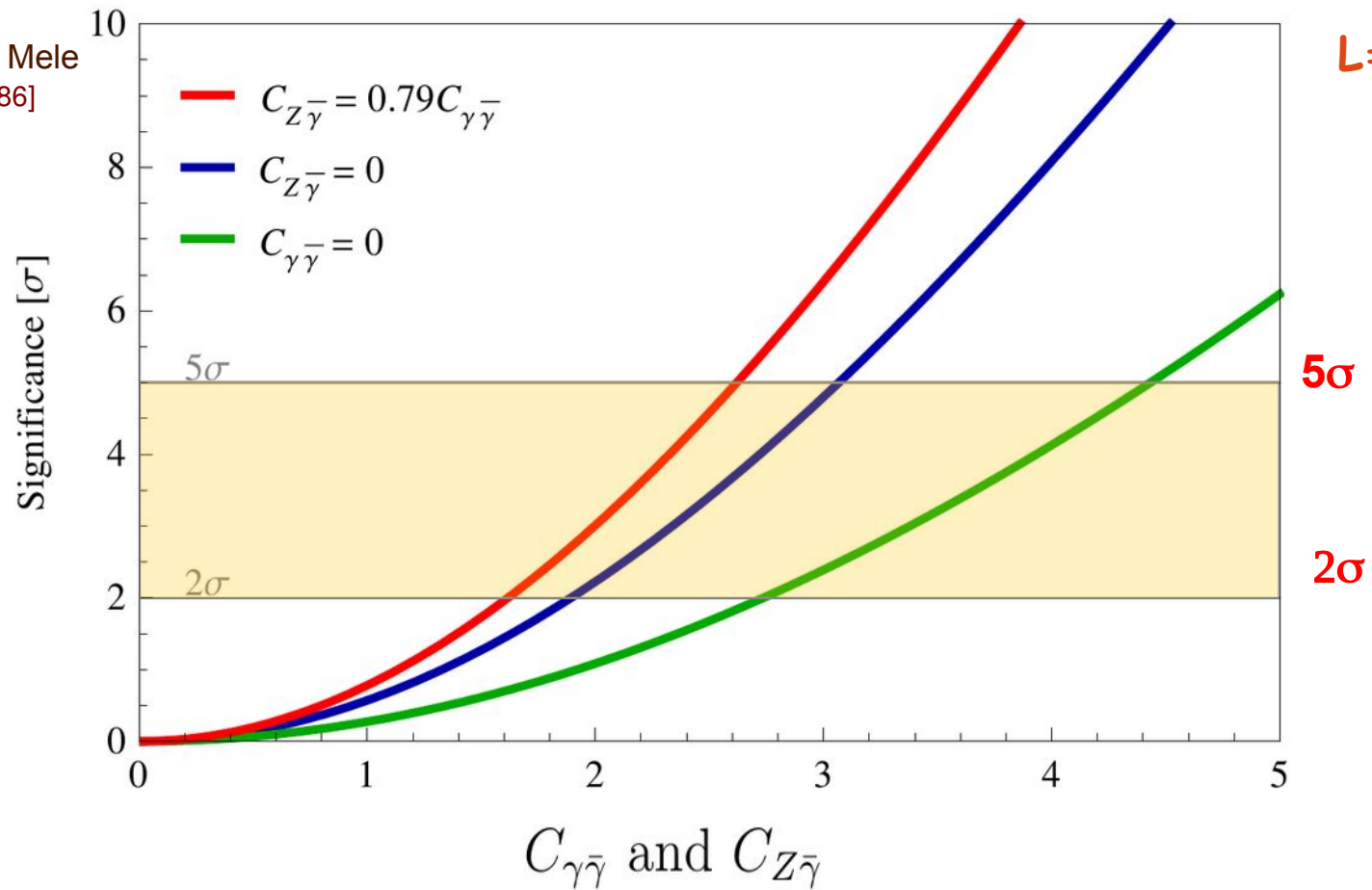
$$e^+e^- \rightarrow ZH \rightarrow Z(H \rightarrow \gamma\gamma_D)$$



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

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

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



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

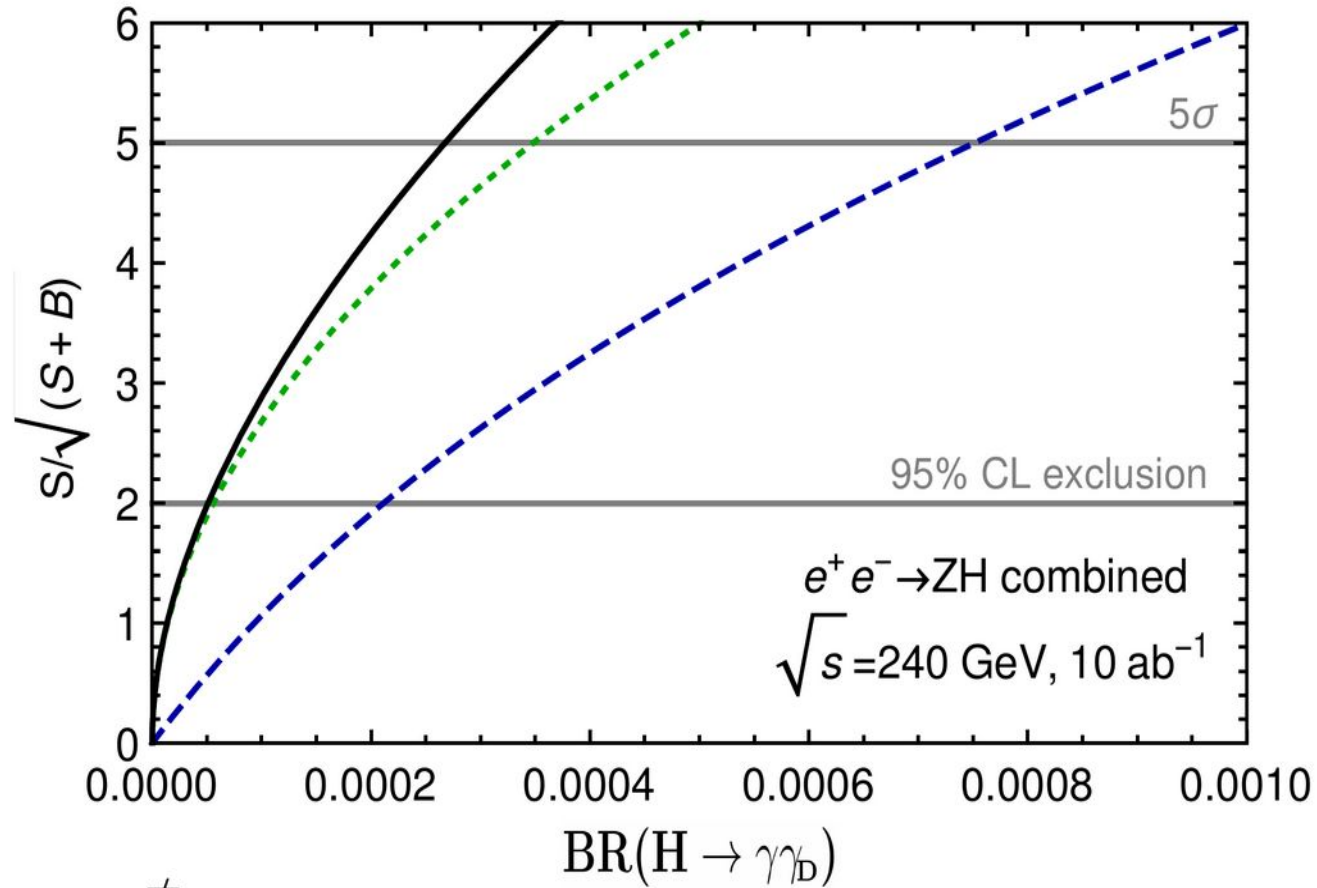
$$C_{Z\bar{\gamma}} > 2.7 \quad \Rightarrow \quad \text{BR}(H \rightarrow Z\bar{\gamma}) > 9 \text{ BR}_{SM}(H \rightarrow Z\gamma)$$

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

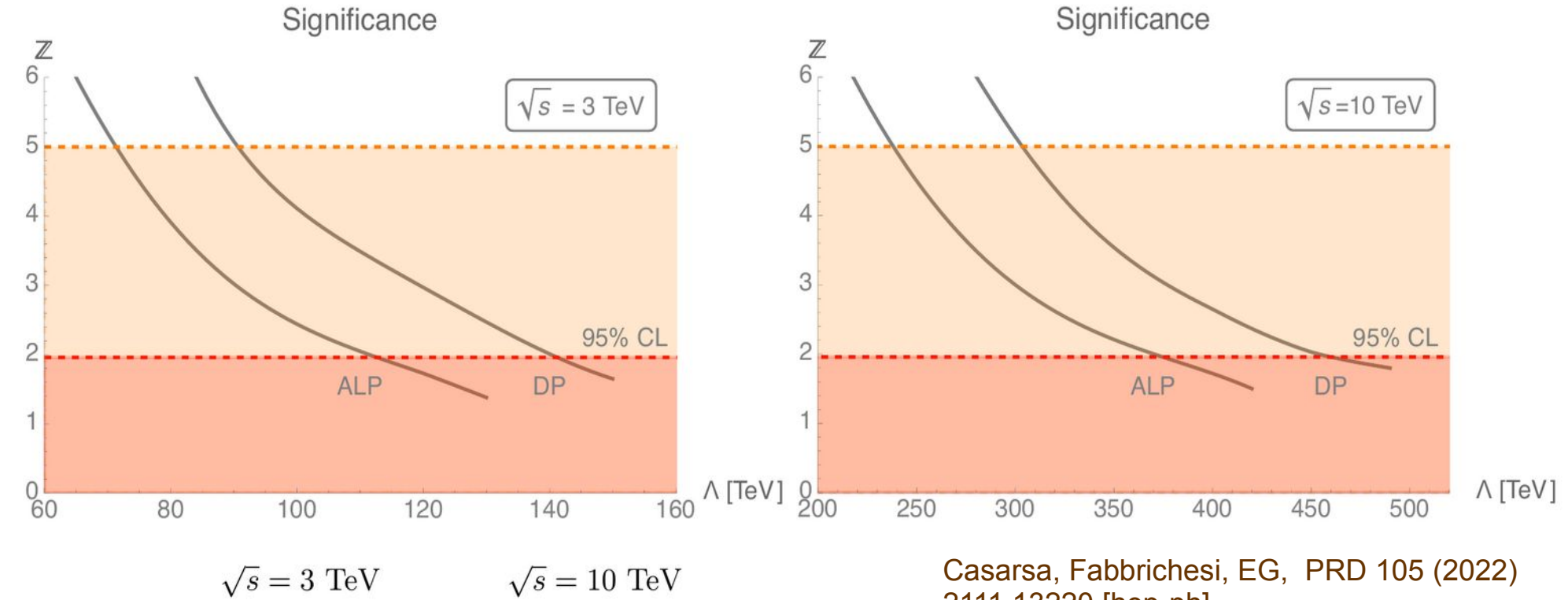
Biswas, EG, Heikeinheimo, Mele, PRD 96 (2017)

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

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



$$\mu^+ \mu^- \rightarrow \gamma \gamma_D \rightarrow \gamma + \cancel{E}$$



Casarsa, Fabbrichesi, EG, PRD 105 (2022) 2111.13220 [hep-ph]

	DP	ALP	DP	ALP
<u>Limit</u>	141 TeV	112 TeV	459 TeV	375 TeV
<u>Discovery</u>	92 TeV	71 TeV	303 TeV	238 TeV

$$\mathcal{L}_{\text{DP}}^{\text{dipole}} = \frac{1}{2\Lambda} (\bar{\mu} \sigma_{\mu\nu} \mu) F'^{\mu\nu}$$

DP field strength