Dark Photon Phenomenology

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Motivations

- Theoretical feasibility and constraints

arXiv:2005.01515

- Dark Photon as the oscillating DM
- Non-trivial Dark Sectors, dipole operators, Yukawa couplings
- LHC and FCC signatures: $H \to \gamma\gamma_D \quad Z \to \gamma\bar{\gamma}$
- Dark Photon explanations to flavour anomalies

Dark Photon (DP) theory and constraints

Lagrangian after diagonalization

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

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

Freedom to rotate

example

$$\sin\theta = 0$$

A' couples to both SM and DS fields

A couples only to SM fields

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

same as massive DP scenario

(see next slide)

Massless Dark-Photon scenario

$$\sin\theta = \varepsilon$$

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

Photon **A** couples to both SM and D

(millicharge)

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

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 q is fixed to

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

Photon and DP couple to both sectors

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

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

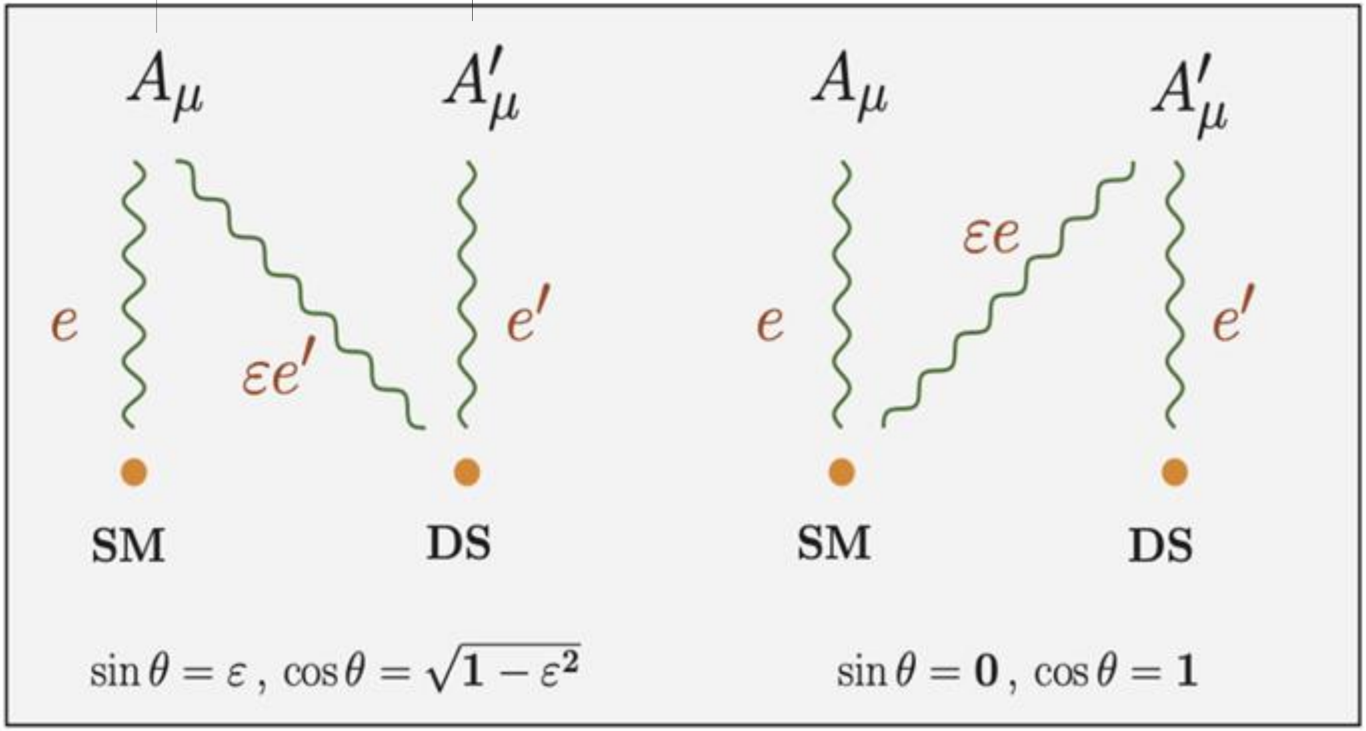
$$\mathcal{L} \supset -\frac{e\varepsilon}{\sqrt{1-\varepsilon^2}} J_\mu A'^\mu \simeq -e\,\varepsilon\, J_\mu A'^\mu$$

(see previous slide for comparison)

⇨ massive DP scenario

Summary of tree-level DP interactions

Photon **Dark-Photon**



Massless Dark-Photon

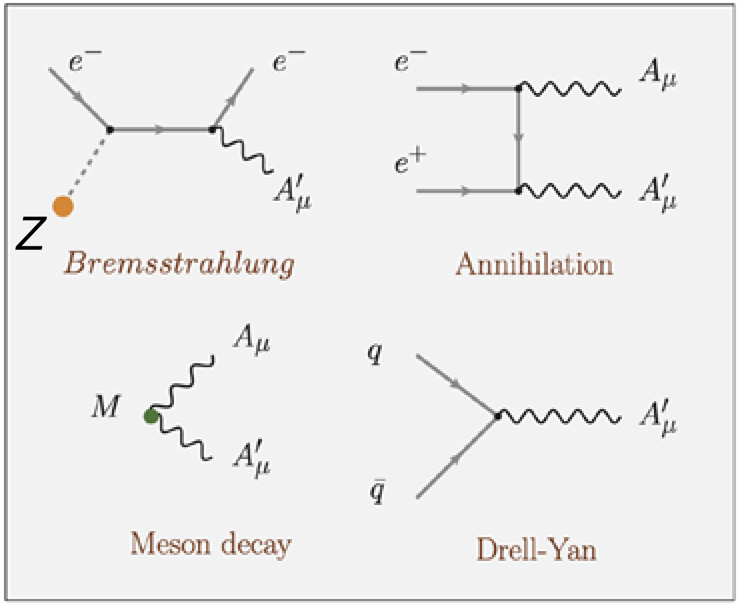
less explored scenario

Massive Dark-Photon

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

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

hadrons

Via **A-A**’ mixing

Detection of massive DP is based on its decay modes

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

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

Searching for e+e- or m+m- resonances

Collider experiments sensitive to regions $\varepsilon > 10^{-3}$

DP decay displaced vertex

Beam dump $e^-Z \to e^-ZA'$ experiments sensitive to regions $\varepsilon < 10^{-3}$

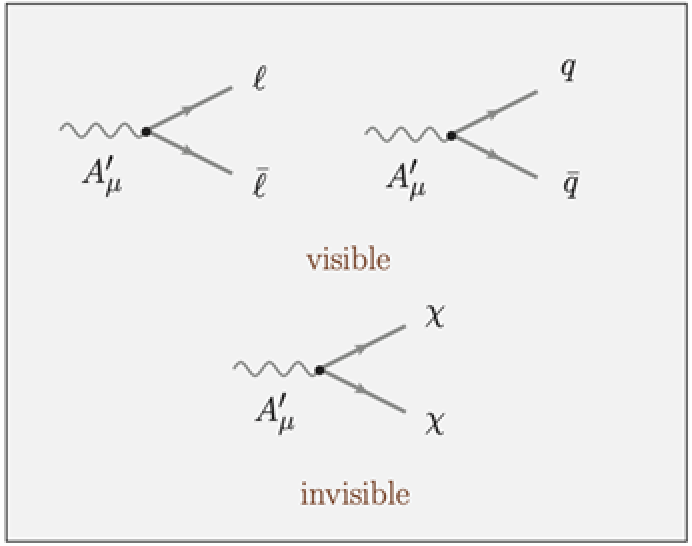
Detectable rate (visible) proportional to ε^4
(require high luminosity colliders)

long lived DP → require long decay volumes

- **Invisible decay**

Detection relies on missing momentum/energy techniques

Being independent on DP decay, rate scales as ε^2



From arXiv:2005.01515

Massive Dark Photon

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

Current limits

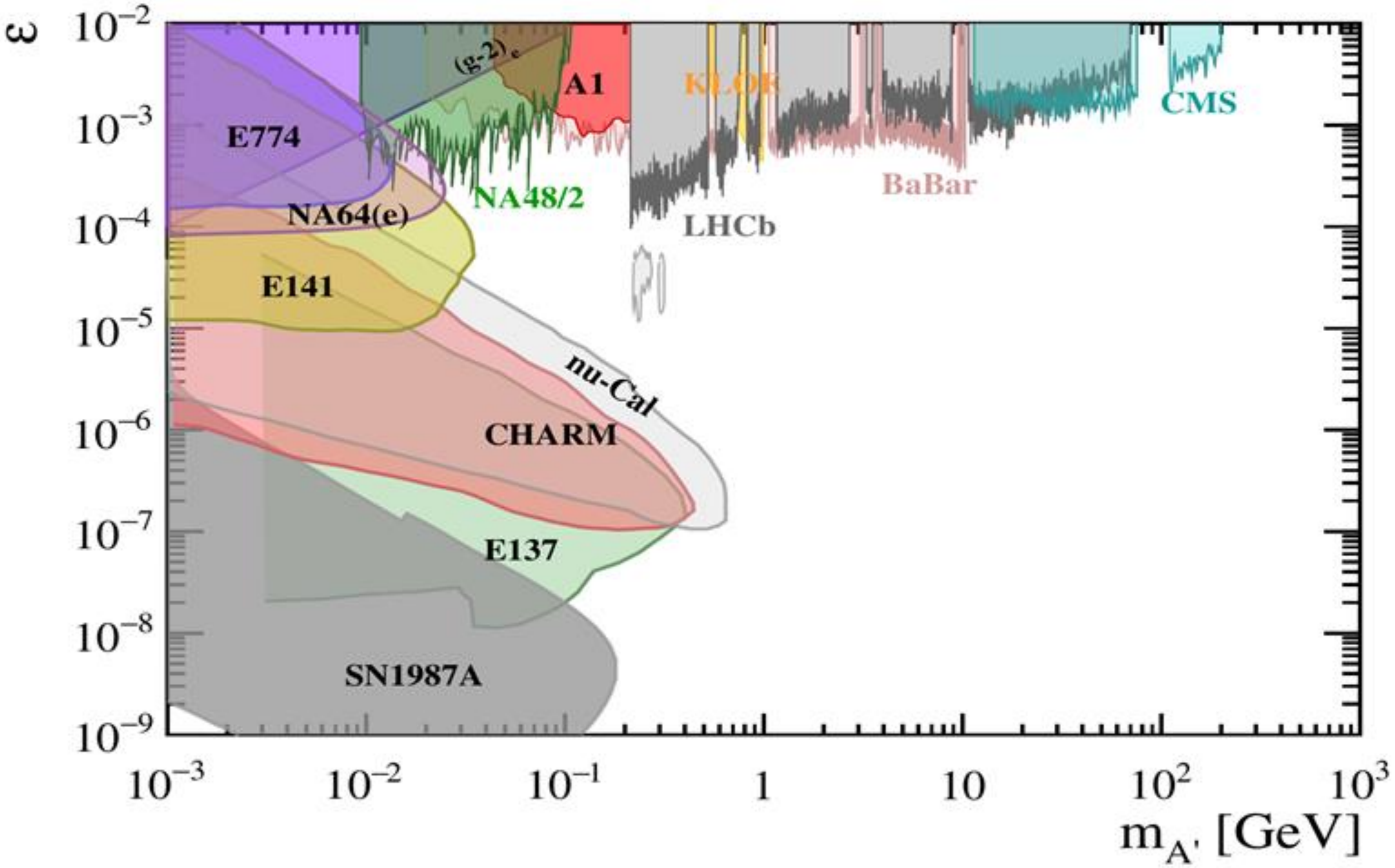


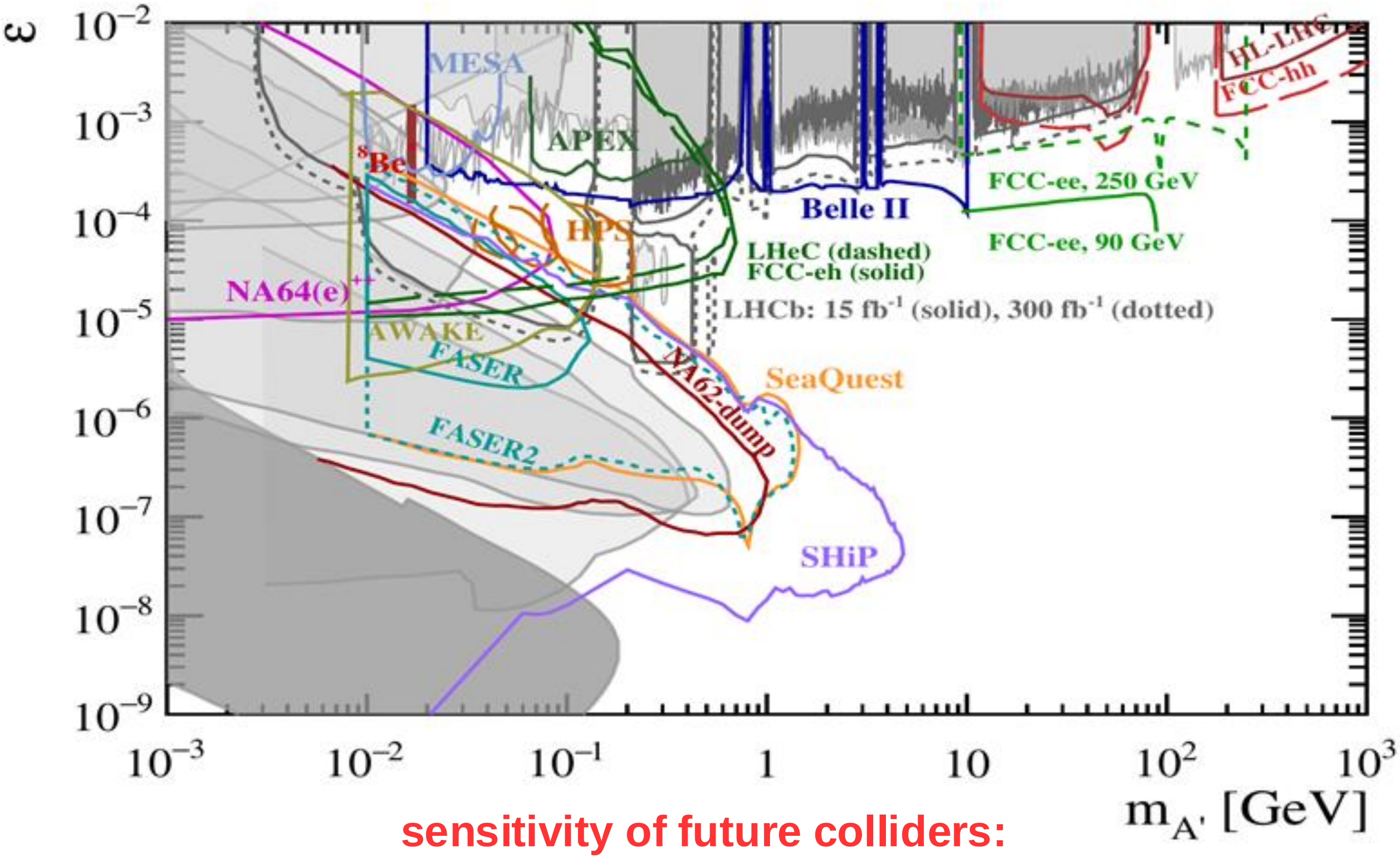
Figure 3.3: Existing limits on the massive dark photon for $m_{A'} > 1$ MeV from di-lepton searches at experiments at collider/fixed target (A1 [176], LHCb [177], CMS [178], BaBar [179], KLOE [180, 181, 182, 183], and NA48/2 [184]) and old beam dump: E774 [185], E141 [186], E137 [187, 188, 189]), ν-Cal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

From arXiv:2005.01515

Massive Dark Photon

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

Limits on massive **DP with mass below MeV**

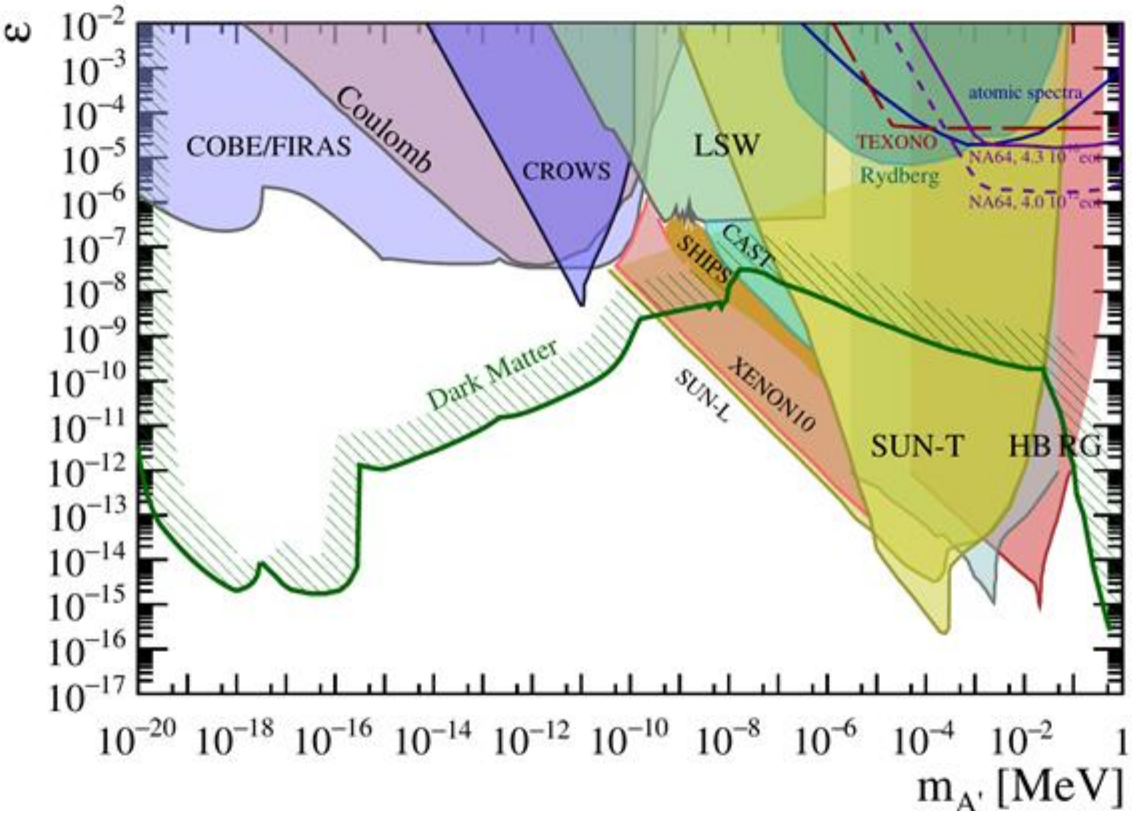


Figure 3.7: Current limits on massive dark photon for $m_{A'} < 1$ MeV. Bounds from cosmology (COBE/-FIRES [229, 230, 231, 232]), light through a wall (LSW) [233], CROWS [234], CAST [235], XENON10 [236], SHIPS [237], TEXONO [238], atomic experiments (Coulomb, Rydberg and atomic spectra [239]) and astrophysics: 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 << 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

Dark Photon as the DM

The Dark Sector (DS) consists only of DP

- Any classical scalar field with small mass oscillating with

$$V = m^2\varphi^2 + \text{small terms}$$

behaves as cold DM

- Axion is an example, but any other scalar with no SM motivation works

- Generalization: any spin 0, 1, 2 bosonic field will give the same result

provided the oscillation freaquency is much faster than cosmic time

DP is a perfect candidate for the DM of the Universe, remains to clarify why we do need it, what is its theoretical motivation

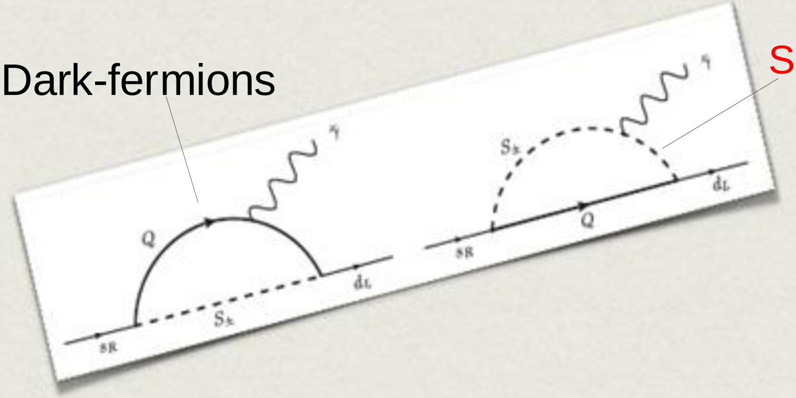
Non-trivial Dark Sector physics

massless dark photon (invisible)

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)

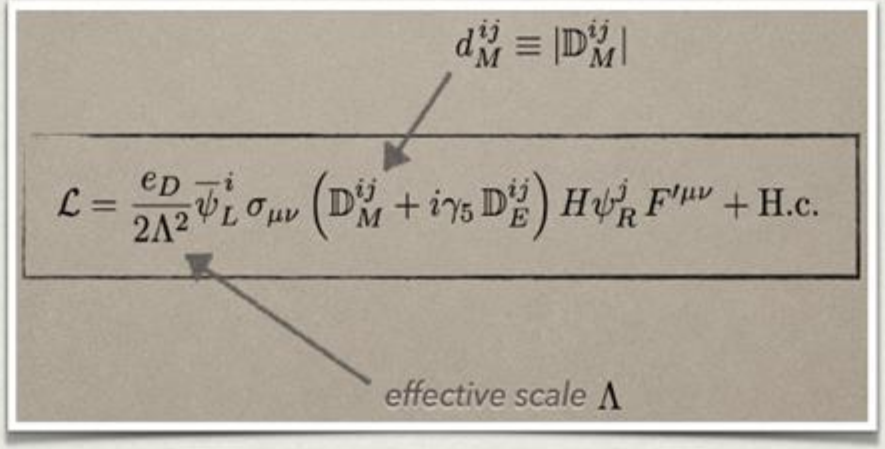
we need a specific benchmark



Dark-fermions

Scalar-messengers

coupling to SM particles induced at 1-loop



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

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

effective scale Λ

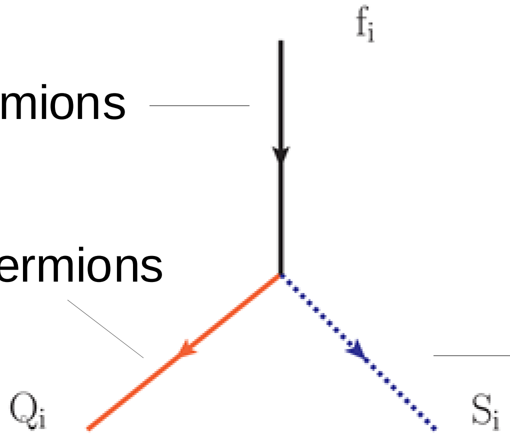
[hep-ph/0411004]

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

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



SM fermions

dark-fermions

Scalar-messenger fields

inspired by radiative-Yukawa couplings model of Flavor

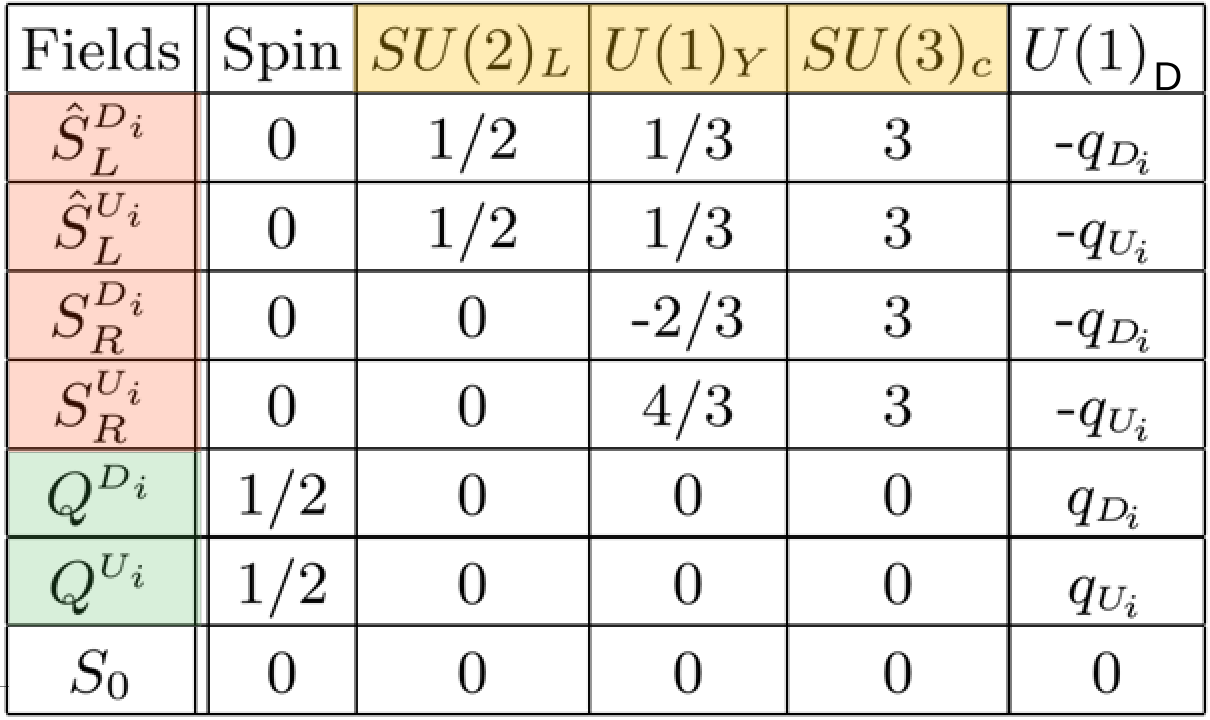
EG, M. Raidal, PRD 89 (2014)
1405.5196 [hep-ph]

Minimal (new) field content

Same replica also in lepton EW sector

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	$-q_{D_i}$
$\hat{S}_L^{U_i}$	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

$U(1)_D$ charges

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

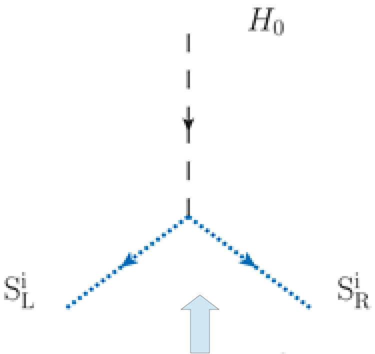
$$M_{Q_i} = \Lambda \exp\left\{-\frac{2\pi}{3\,\bar{\alpha}(\Lambda)q_i^2}+\frac{1}{4}\right\} \Rightarrow Y_f \sim M_{Q_f}/\Lambda$$

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

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

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

+ Lepton sector

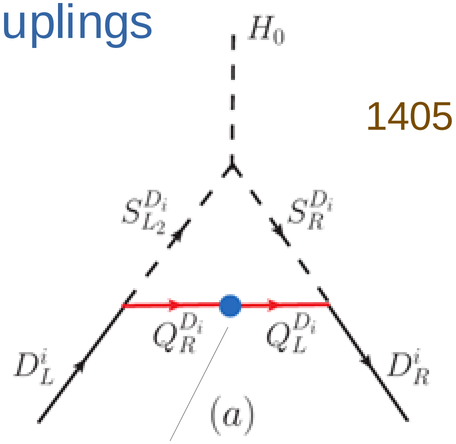


$$\mu_S \equiv \lambda_S \langle S_0 \rangle$$

S_0 vev

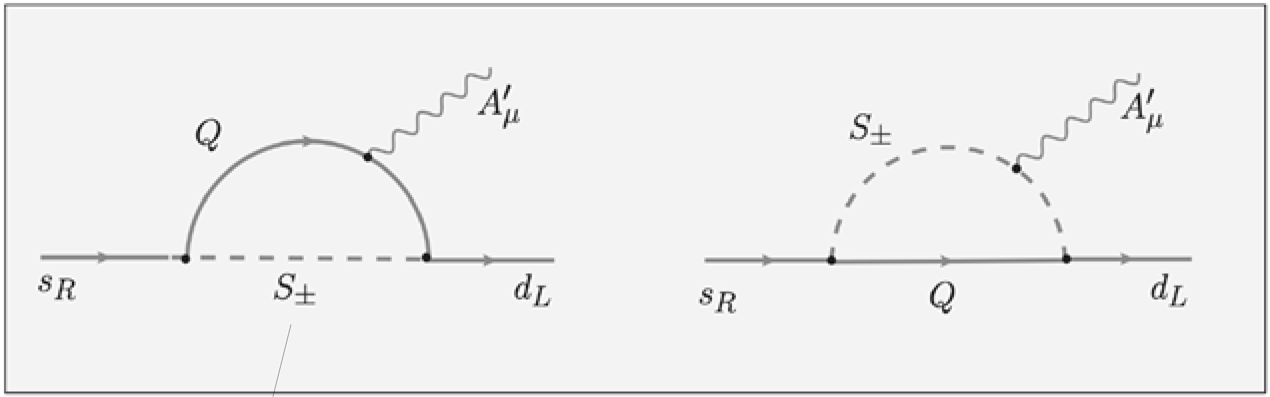
Diagram generating D-type Yukawa Y_D couplings

1405.5196 [hep-ph]



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

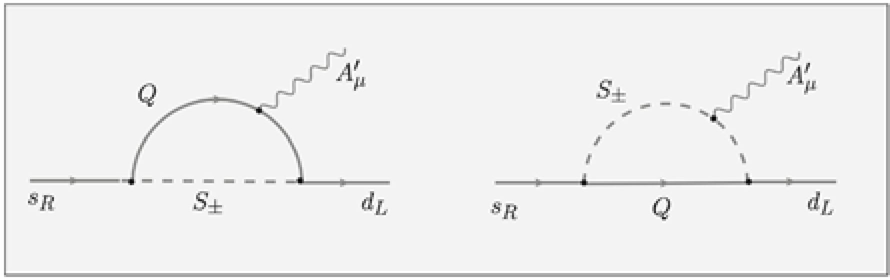
Magnetic-dipole interactions of DP with SM fermions (FCNC and Flavor conserving)



Messenger mass-eigenstates

Effective Lagrangian for magnetic-dipole interactions of DP

Model independent parametrization



Dark-U(1) coupling

absorbs messenger couplings and loop factors

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

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

$SU(2)_L$x $U(1)_Y$ invariant way

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

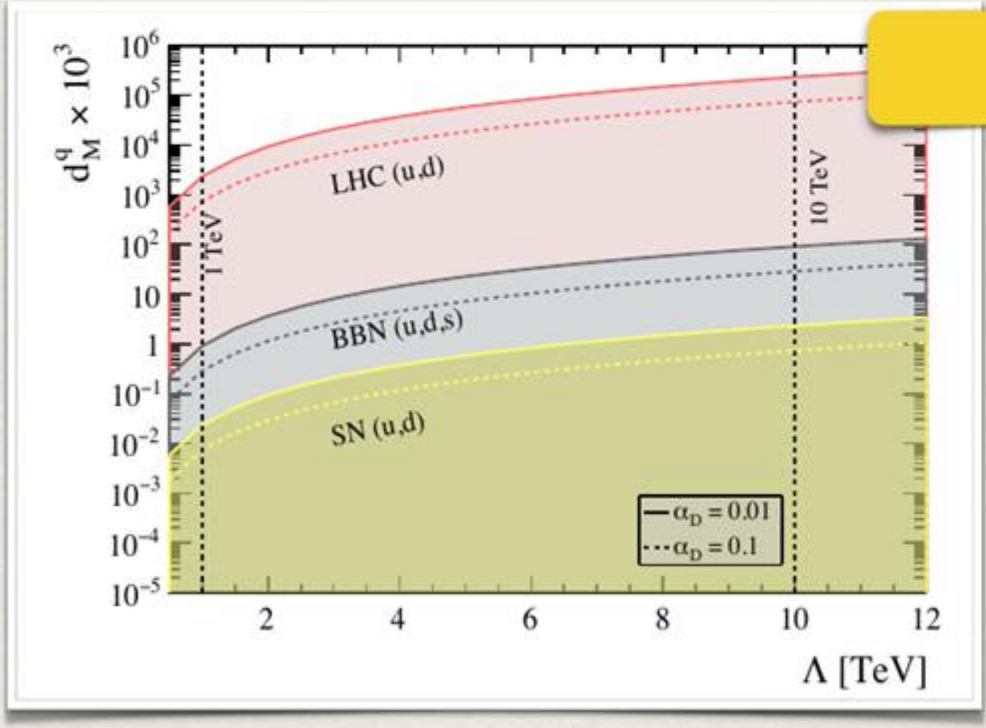
- This is the leading coupling of massless DP to SM fermions (lowest dim. operator)
- This effective coupling is also present in massive DP scenarios

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

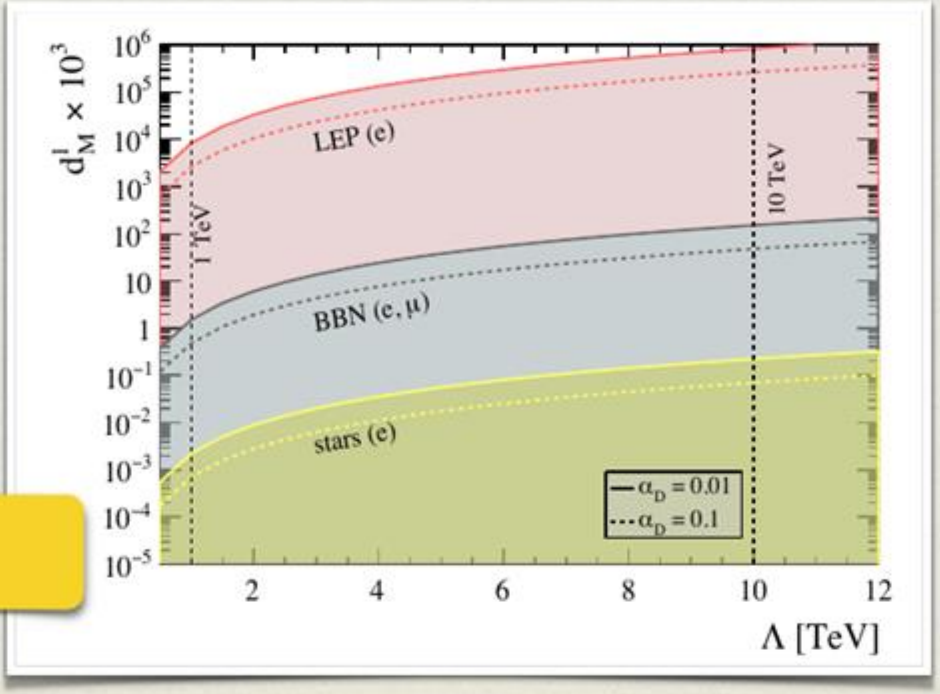
[from 2005.01515]



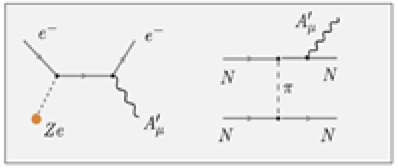
quarks

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.

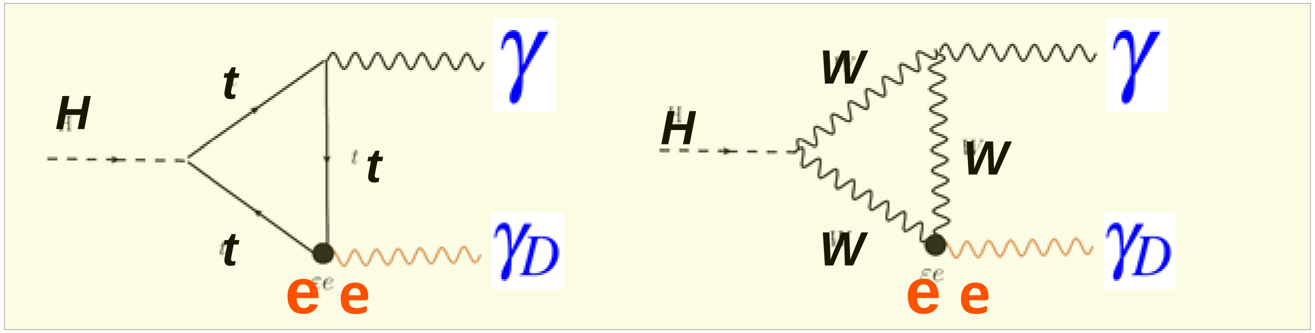
- SN • Supernovae. An additional limit is found from the neutrino signal of supernova 1987A, for which the length of the burst constrains anomalous energy losses in the explosion.

Collider signatures, LHC and FCC

$H \to \gamma\gamma_D$

- 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 e-mixing



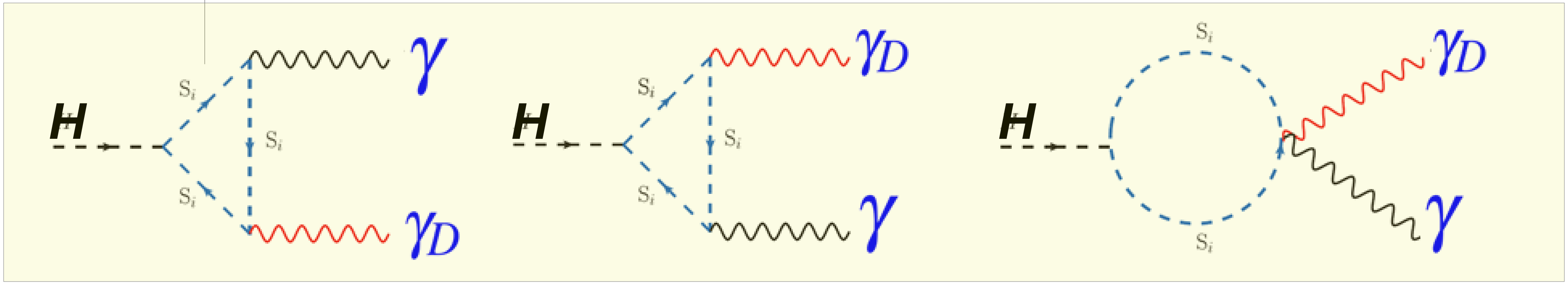
- For the massless case, there is no tree-level couplings → so it is vanishing
- For the massive case, via mixing is suppressed → $\mathrm{BR} \sim \varepsilon^2 \times \mathrm{BR}(H \to \gamma\gamma)$
- → outside the sensitivity range of any present and future experiment (e < 10^(-3))
- However, it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

- The discovery of $H \to \gamma\gamma_D$ 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

$H \to \gamma\gamma_D$

Why it is relevant for DP discovery

scalar messenger fields



Quantum amplitude

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

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

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

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

V is the SM Higgs vev

$0 \leq \xi \leq 1$ ⇨ Th. upper bound

lightest messenger mass

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

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 L

$$\boxed{H \rightarrow \gamma\gamma}$$

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

$$\boxed{H \rightarrow \gamma_D\gamma_D}$$

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

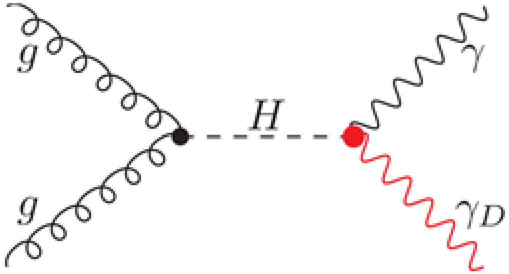
R_0 and R_1 contain products of U(1) charges

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

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

$H \to \gamma\ \gamma_D$ @ LHC

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

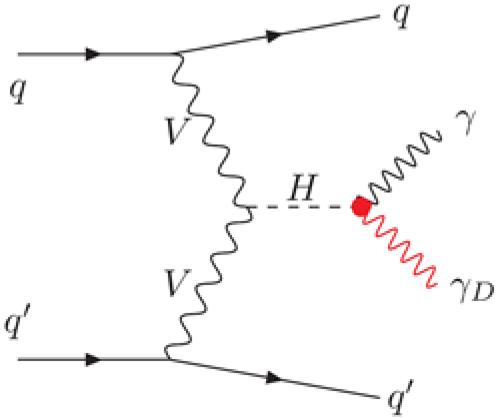


gluon-gluon fusion

gg + VBF analyzed in
EG, Heikinheimo, Mele, Raidal, PRD 90 (
Biswas, EG, Heikinheimo, Mele PRD 93 (

$$pp \to \gamma + \not{E}_T$$

Challenging → large QCD bckg
of jets faked as $\not{E}_T$

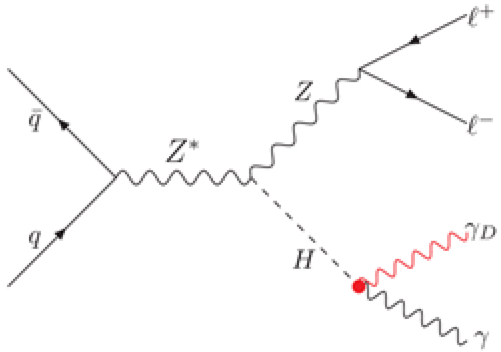


Vector Boson fusion

FB

$$pp \to \gamma + \not{E}_T + jets$$

ATLAS, CMS
run2



Z associated production

ATLAS, CMS
run2

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

Model independent parametrization of BRs

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

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

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

$$\chi = \pm 1$$

parametrizes relative sign of SM vs NP amplitudes

pure messenger contribution to the width

$$r_{\gamma\gamma} = \frac{\Gamma^{\mathrm{m}}(H\to\gamma\gamma)}{\Gamma^{\mathrm{SM}}(H\to\gamma\gamma)}$$

$$r_{\gamma_D\gamma_D}$$

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

$$r_{ij} \equiv \frac{\Gamma^{\mathrm{m}}_{ij}}{\Gamma^{\mathrm{SM}}_{\gamma\gamma}}$$

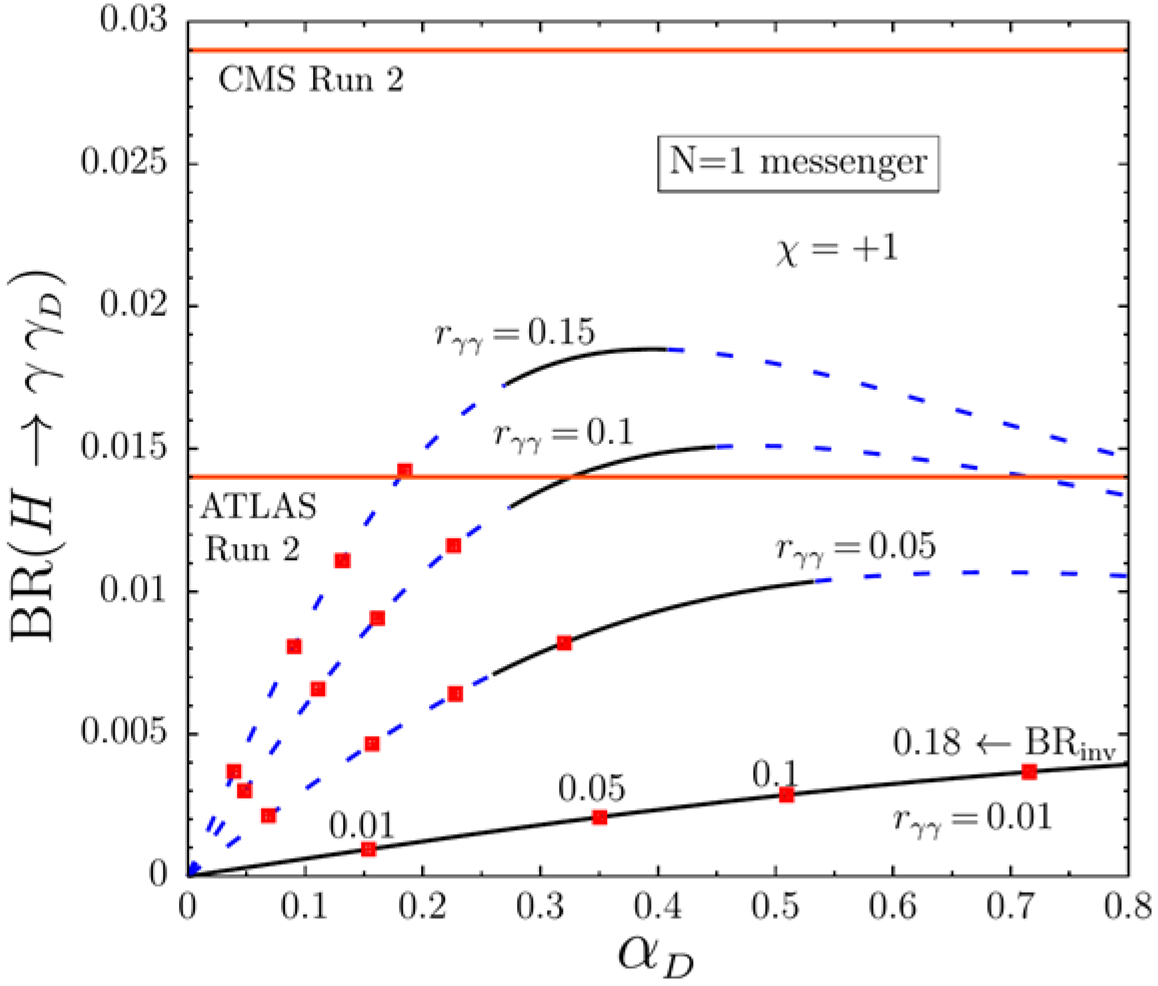
$$r_{gg} \equiv \frac{\Gamma^{\mathrm{m}}_{gg}}{\Gamma^{\mathrm{SM}}_{gg}}$$

$$\sigma_{gg\to H} = \sigma^{SM}_{gg\to H}\left(1-\chi\sqrt{r_{gg}}\right)^2$$

$$R_{\gamma\gamma} = \frac{\sigma_{gg\to H}\mathrm{BR}_{\gamma\gamma}}{\sigma^{\mathrm{SM}}_{gg\to H}\mathrm{BR}^{\mathrm{SM}}_{\gamma\gamma}} \quad \Rightarrow \quad R_{\gamma\gamma} = \frac{\mathrm{BR}_{\gamma\gamma}}{\mathrm{BR}^{\mathrm{SM}}_{\gamma\gamma}}\left(1-\chi\sqrt{r_{gg}}\right)^2$$

BR predictions in a simplified model (1 messenger)

Biswas,EG,Mele [arXiv:2206.05297]



observed upper limits
@ 95% C.L.

CMS → BR < 2.9 %

[arXiv:2009.14009]

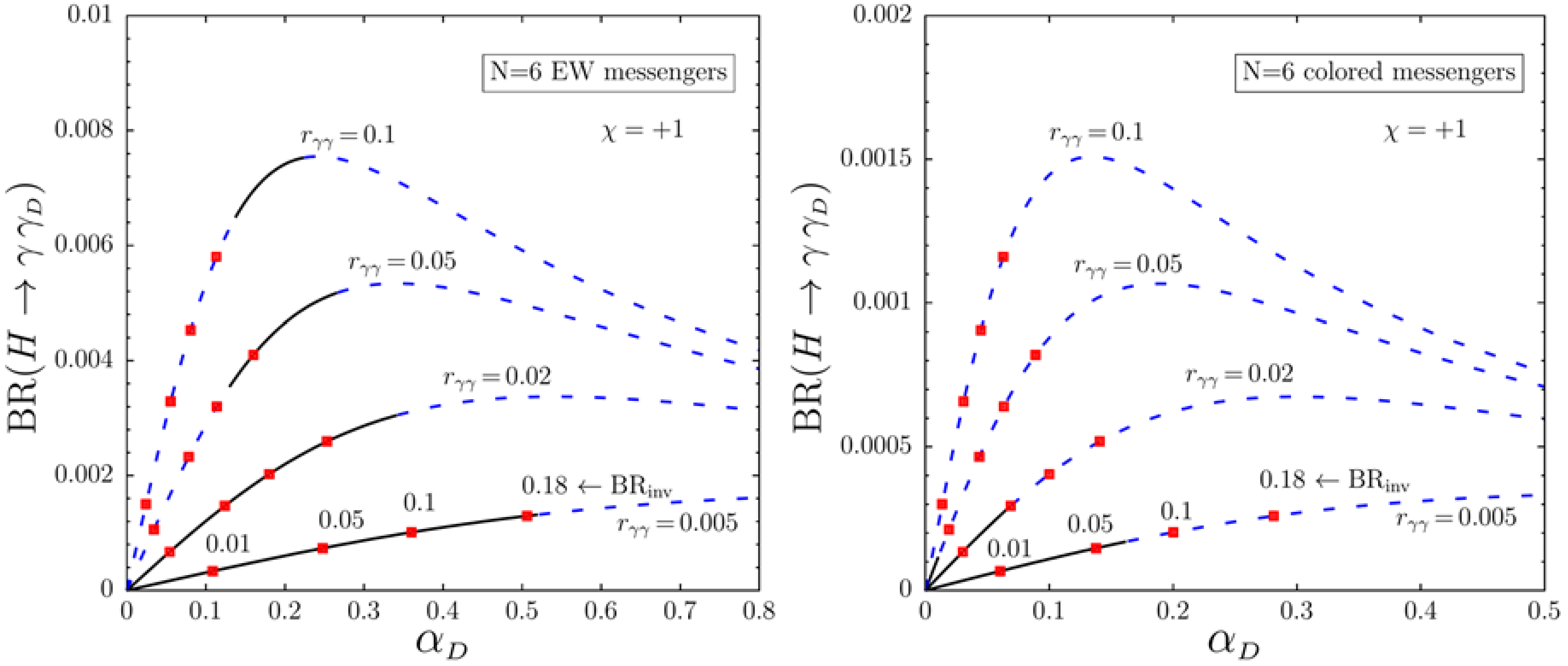
ATLAS → BR< 1.4 %

[arXiv:2109.00925]

- - - - **excluded by H → gg**
@ 95% C.L.

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

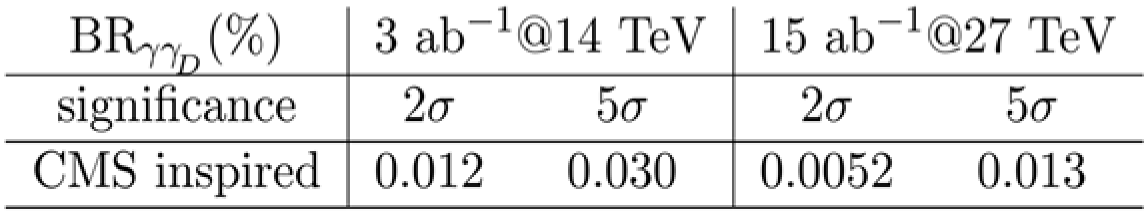
Inspired by Flavor model (radiative Yukawa)



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



$\mathrm{BR}_{\gamma\gamma_D}$ (%)	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

Dark-U(1) charge

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

$$\mathrm{BR}(Z \to \gamma\bar{\gamma}) \simeq \frac{2.52\,\alpha_D}{(\Lambda/\mathrm{TeV})^2}\left(|d_M|^2 + |d_E|^2\right) \times 10^{-8}$$

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

$$10^{-9}$$

α_D → 0.1
Λ → 1 TeV

$$4 \times 10^{-11}$$

$d_M \simeq 0.1$
→ small couplings in DS

$$10^{-6}$$

→ for non-perturbative dynamics in DS

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

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).

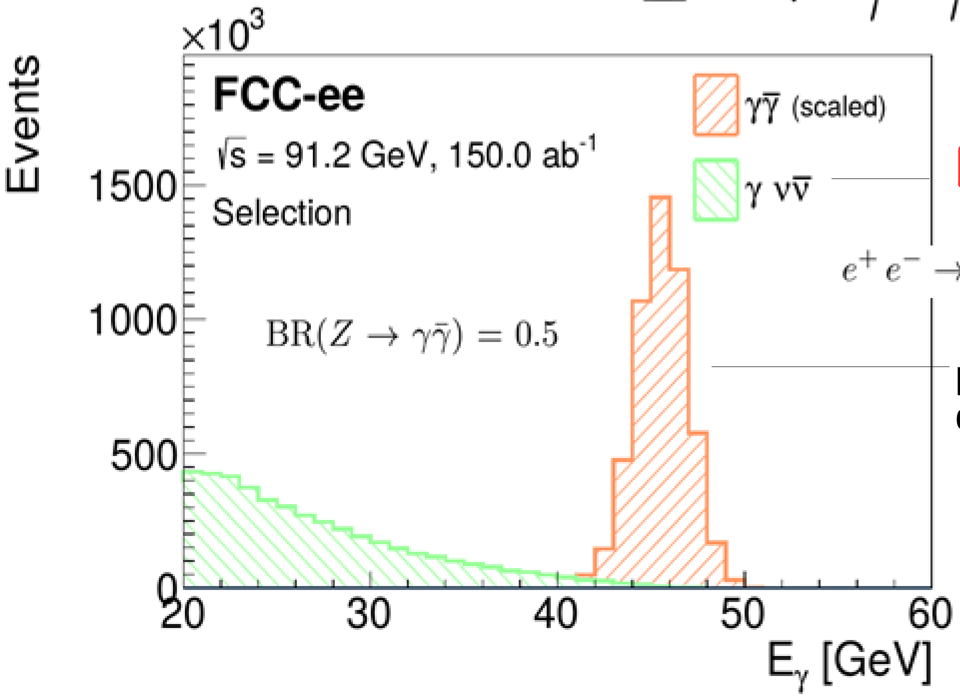
10^{13} of Z boson events at the FCC-ee

expected 10^2–10^4 of $Z \to \gamma\bar{\gamma}$ events

$Z \to \gamma\,\bar{\gamma}$ @ FCC-ee

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

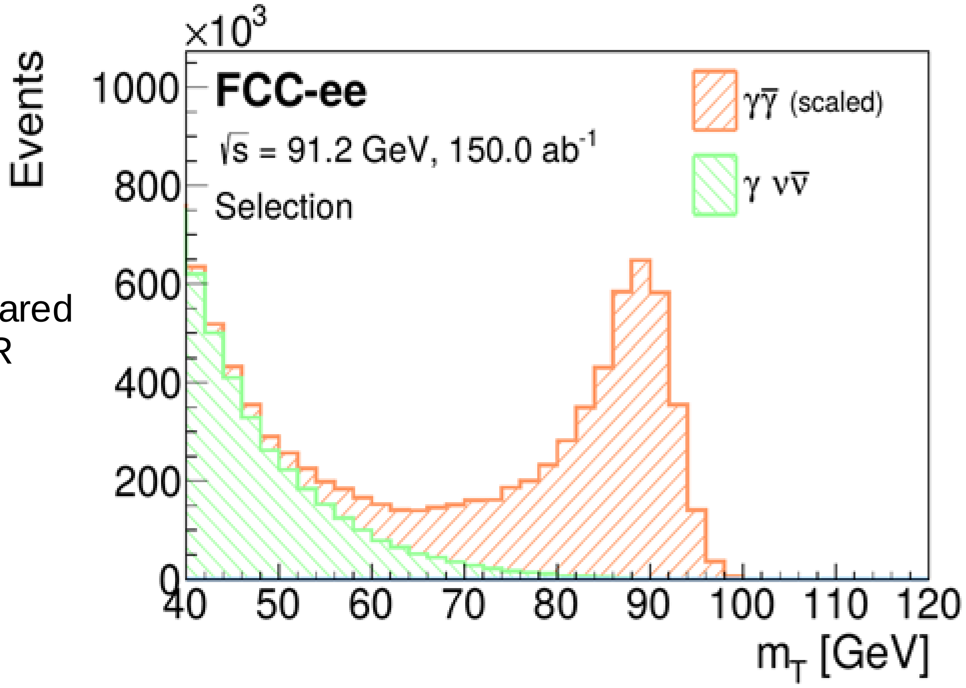
2006.15945 [hep-ph]



bckg

$e^+e^- \to \gamma\, e^+ e^-$

peak smeared due to ISR



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

upper limits on BR at 95% C.L.

			$\mathrm{BR}(Z \to \gamma\bar{\gamma})$	
	$\sqrt{s}$	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

Dark Photon and flavour anomalies

Belle II has observed an anomaly in $B^+ \to K^+\nu\bar{\nu}$

- Proceeds via $b \to s\nu\bar{\nu}$ and is one of the golden channels

$$\mathrm{BR}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SM}} = (4.29 \pm 0.23) \times 10^{-6}\,,$$

- Belle II result is claimed to be 3.5σ away

$$\mathrm{BR}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{exp}} = (2.3 \pm 0.7) \times 10^{-5}\,,$$

- Did Belle observe Dark Photon induced process?

$$B^+ \to K^+ Q_i \bar{Q}_i$$

Assume massless Dark Photon

- Interactions

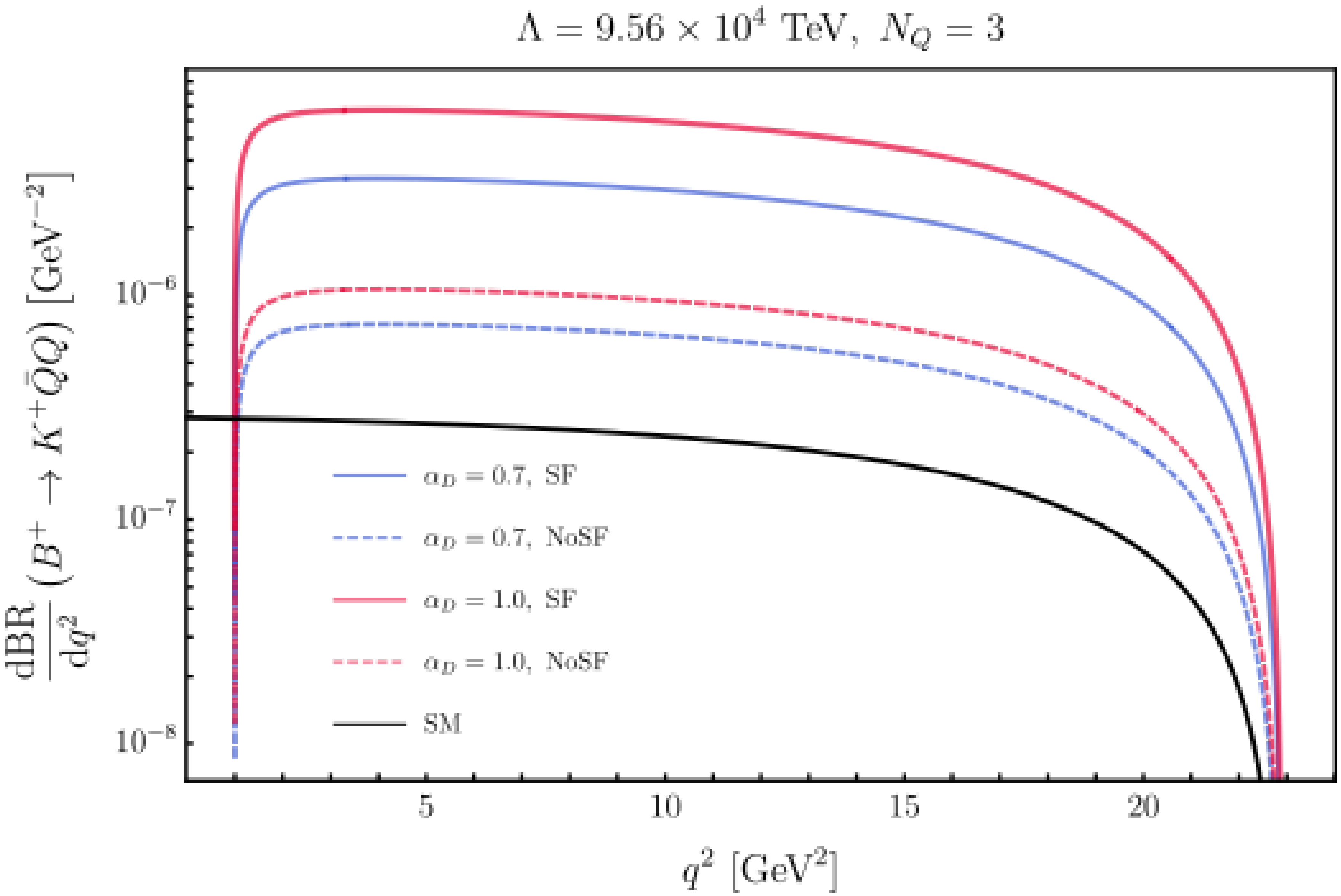
$$\mathcal{L}_{eff} = \frac{1}{2\Lambda}\left[\bar{s}\sigma_{\mu\nu}b\right]F_D^{\mu\nu} + h.c.\,, \qquad \mathcal{L}_{dark} = e_D\sum_i q_i\left[\bar{Q}_i\gamma_\mu Q_i\right]A_D^\mu\,,$$

$$\mathcal{M} = \frac{-ie_D}{\Lambda}\langle K|[\bar{s}\sigma_{\mu\nu}b]|B\rangle\frac{q^\nu}{s}\left[\bar{Q}\gamma^\mu Q\right]\,,$$

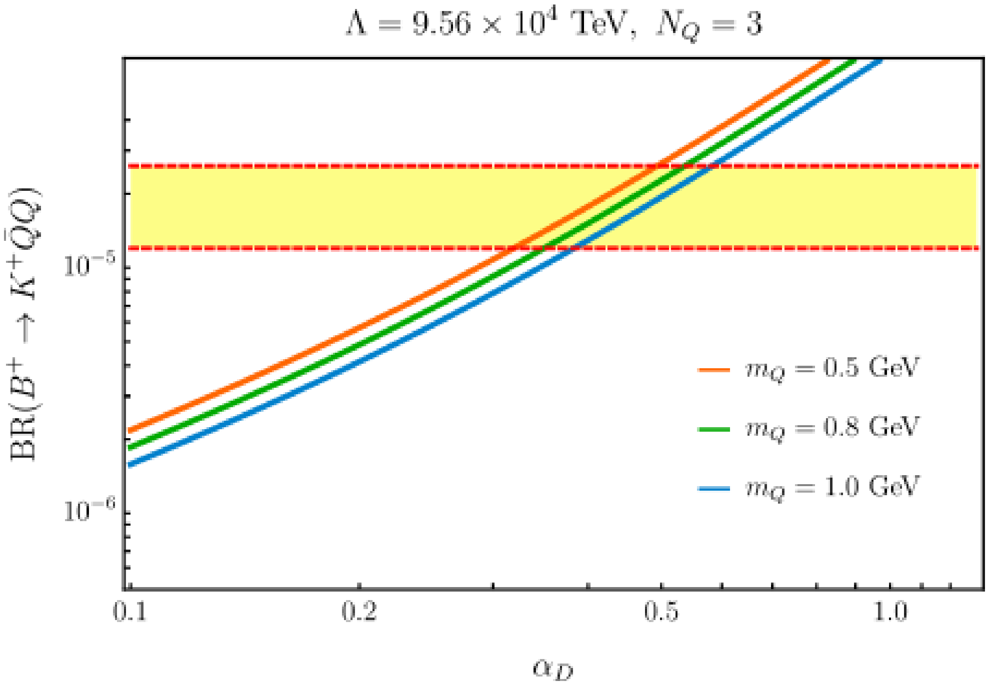
- We compute the dark magnetic dipole contribution and Sommerfeld
- Need to consider other $b \to s\gamma_D$ transitions
- $B^+ \to K^+\gamma_D$ is forbidden. Prediction: $B^0 \to K^*\gamma_D$ must be there

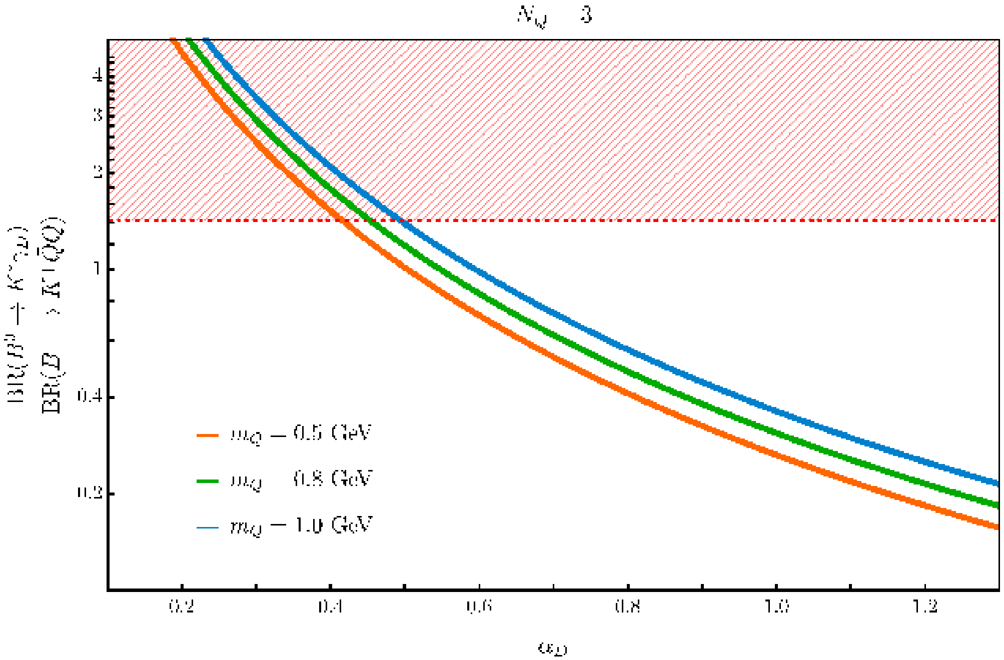
$$\mathrm{BR}(B^0 \to K^*\gamma_D) = 2.47\times10^{-5}\left(\frac{10^5\mathrm{TeV}}{\Lambda}\right)^2$$

New physics contribution can be large



Fits to data: the scenario is falsifiable





Future measurements can determine the needed parameter spave to explain the anomaly

Conclusions

- DP + DS = rich phenomenology
- Two distinct classes of DM: massive and massless
- Dedicated experiments look for light massive DP
- Colliders like LHC, FCC provide new promising channels: $H \to \gamma\,\gamma_D$
- DP may play significant role in explaining the SM Yukawa couplings
- DP may explain some recent flavour anomalies
- However, no positive signals yet, continue working