Exotic Z decays

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Exotic Z decays

- Sensitivity on BSM physics at the Z-pole: **Giga-Z** and **Tera-Z** factories
- signatures: $Z \rightarrow \not{E} + \gamma$ $Z \rightarrow \not{E} + \gamma\gamma$ $Z \rightarrow \gamma\gamma\gamma$ $Z \rightarrow \not{E} + \ell^{+}\ell^{-}$
- correspond to several BSM physics scenarios : different final states (2,3,4 particles)
- benchmark models required (most inspired by dark-matter and dark-sector scenarios)
- axion-like particle (ALP)
- light-vector X coupled to anomalous currents
- magnetic inelastic DM, anomalous magnetic moment of neutrinos
- dark-photon (massive, massless scenarios)
- (light) massive spin-2 particles effectively coupled to SM sector
- Rare decays in SM particles (**ggg**, **gg+γ** , γγγ) sensitive to NP.

Pseudo-scalar (Axion-Like)

$$Z \to \not{E} + \gamma$$

$$Z \to \gamma\gamma\gamma$$

$$\mathscr{L}_a = \frac{1}{\Lambda_{aBB}} \left(a B^{\mu\nu} \tilde{B}_{\mu\nu} \right)$$

- QCD axions predicted by Peccei-Quinn mechanism to solve the CP problem of strong interactions
- Axion-like particles (ALP) as portal connecting DM with SM sector
- ultralight ALP as DM candidate
- couplings also with fermions $\partial_\mu a \bar{\psi} \gamma^\mu \psi$ but chirally suppressed
- ALP predicted by many UV theories (string-theory, SUSY, etc)
- **Z–γ–a** mixed vertex induced from SM hypercharge B-field after SM SSB
- Two main characteristic signatures at Z-pole : 2-body and 3-body final states

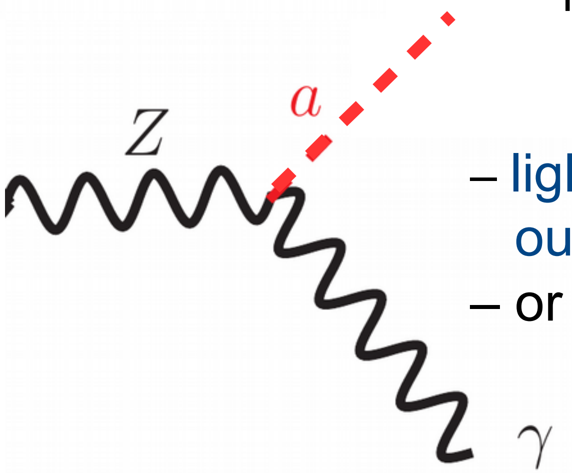
$$\Gamma(a \to \gamma\gamma) = \frac{1}{64\pi}\frac{1}{\Lambda_{aBB}^2}\cos\theta_w^4 m_a^3$$

$$\Gamma(Z \to \gamma a) = \frac{1}{96\pi}\frac{1}{\Lambda_{aBB}^2}\cos\theta_w^2 \sin\theta_w^2 m_Z^3 \left(1 - \frac{m_a^2}{m_Z^2}\right)^3$$

2-bodies

$Z \to \gamma + \not{E}$

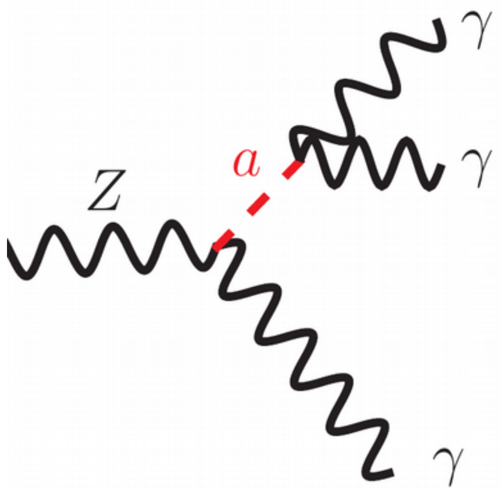
ALP as LLP detected as missing energy



– light ALP decaying in γγ outside detector
– or a → χ χ (χ invisible DM)

3-bodies

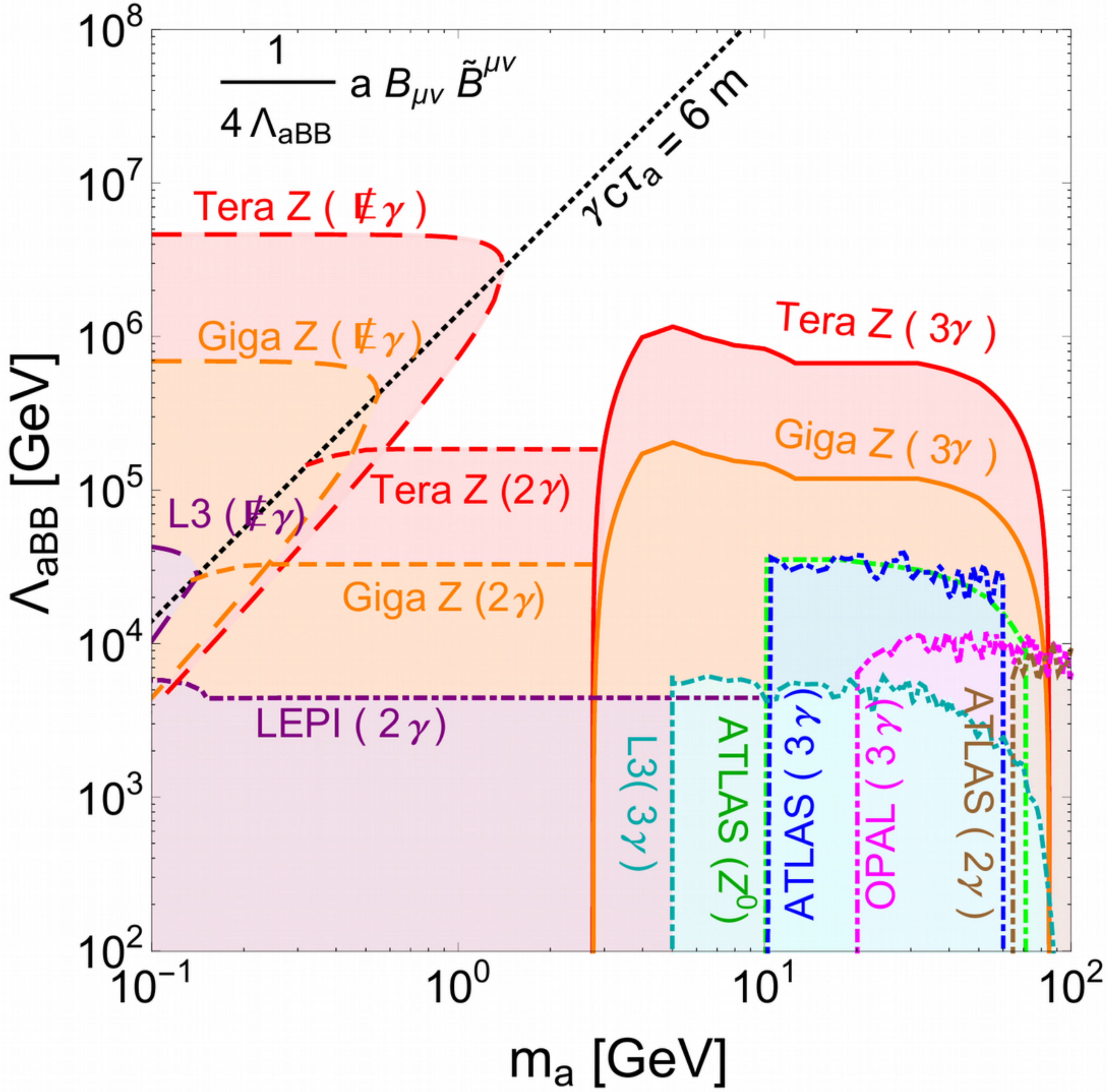
$Z \to \gamma\gamma\gamma$



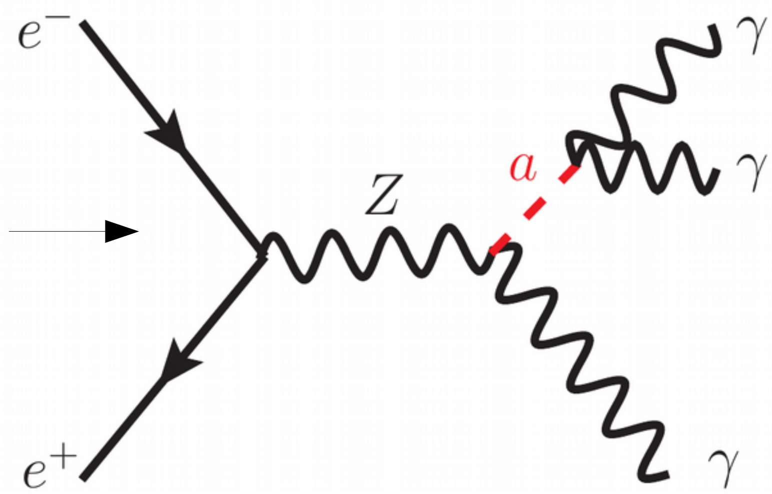
ALP decaying inside detector

3 → 2-bodies $Z \to \gamma\gamma$

if a-mass too small to resolve 2 photons



ALP searches: Tera/Giga Z widely extend present LEP/LHC bounds

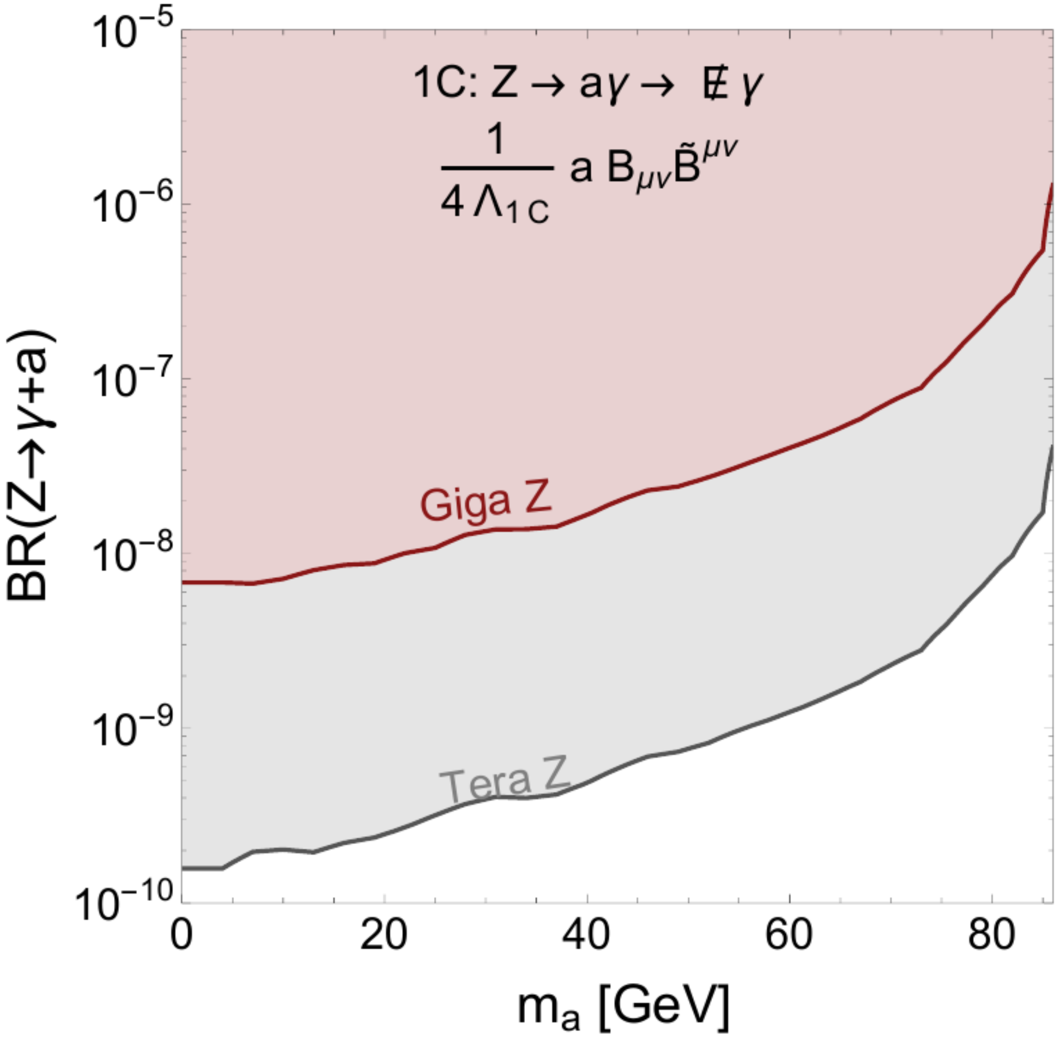


(3γ) →

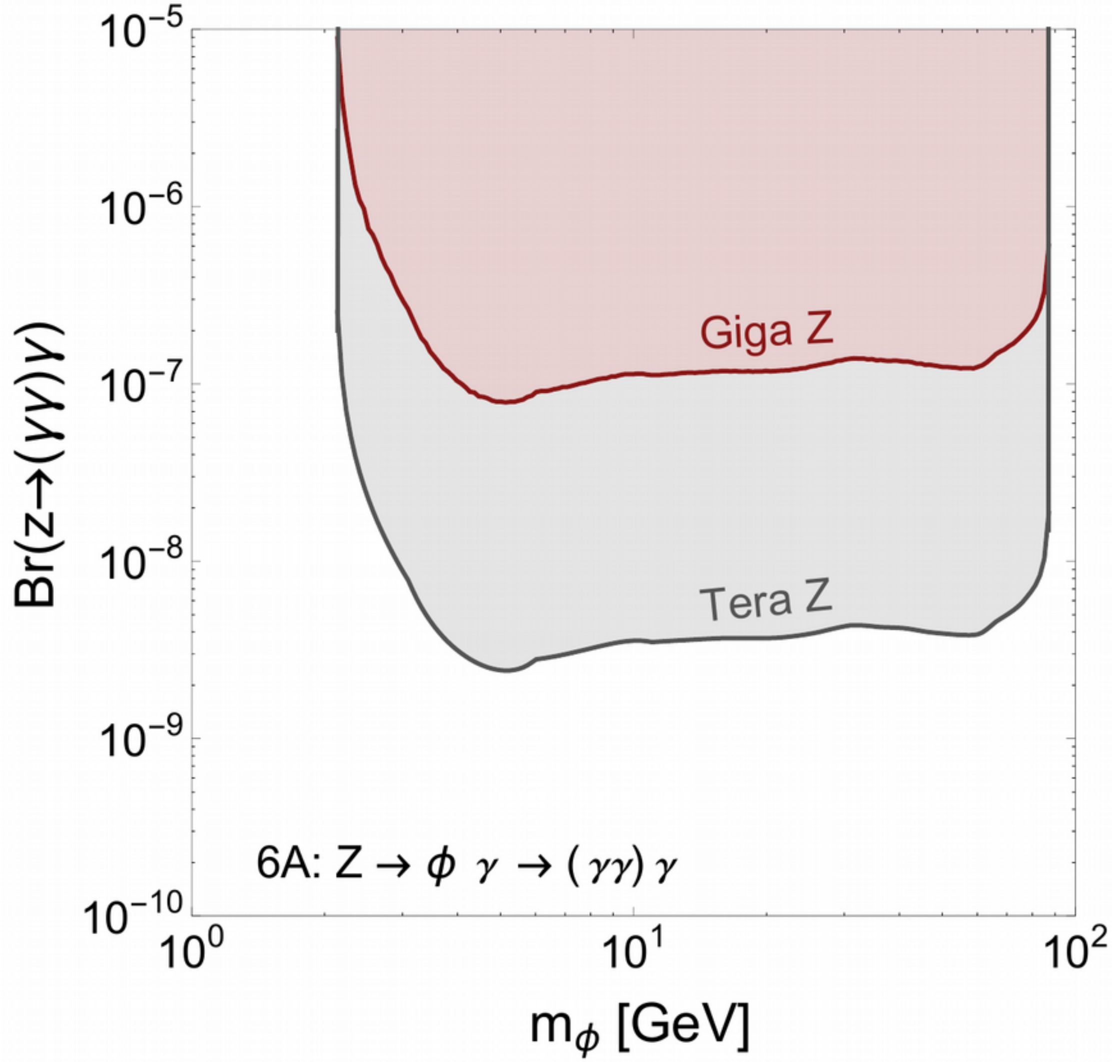
Liu, Wang, Wang, Xue, 1712.07237

(2γ) → refers to the case in which the mass of ALP is too small to resolve 2-photons seen as → 1 photon

$$Z \to \not{E} + \gamma$$



$$Z \to \gamma\gamma\gamma$$



Liu, Wang, Wang, Xue, 1712.07237

Magnetic inelastic and Reyleigh DM

$$Z \to \not{E} + \gamma$$

Dirac Majorana

$$\mathcal{L} = \bar{\chi}(i\not\partial - m_\chi)\chi - \frac{1}{2}\delta m \bar{\chi}^c \chi + \bar{\psi}(i\not{D} - M_\psi)\psi + (D^\mu \phi)^\dagger (D_\mu \phi) - M_\phi^2 \phi^\dagger \phi + (\lambda \bar{\psi}\chi\phi + h.c.)$$

χ is fermionic DM

heavy fermion and scalar fields
with same SM gauge charges

Sigurdson et al. Astro-ph/0406355 (PRD 70)
Masso-Mohanty-Rao 0906.1979 (PRD 80)
Chang-Weiner-Yavin 1007.4200 (PRD 82)
Weiner-Yavin 1206.2910 (PRD 86) ;
1209.1093 (PRD 86)

Spectrum: ⇨ two majorana fermion χ_1 and χ_2. assumed $m_{\chi_2} > m_{\chi_1}$

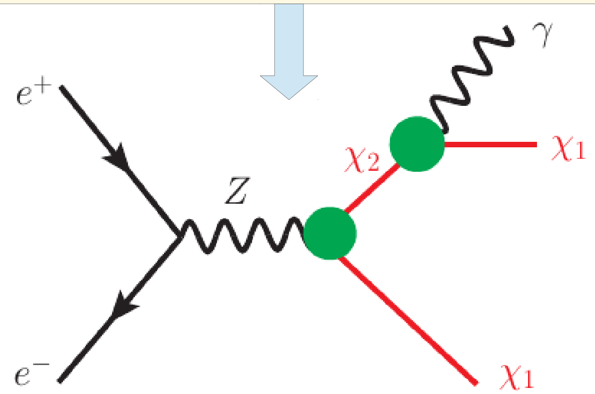
Reyleigh DM

$$O_{\rm RayDM} = \frac{1}{\Lambda^3_{\rm RayDM}} \bar{\chi}_1 \chi_1 B^{\mu\nu} B_{\mu\nu}$$

$$O^{\gamma_5}_{\rm RayDM} = \frac{i}{\Lambda^3_{\rm RayDM}} \bar{\chi}_1 \gamma_5 \chi_1 B^{\mu\nu} \tilde{B}_{\mu\nu}$$

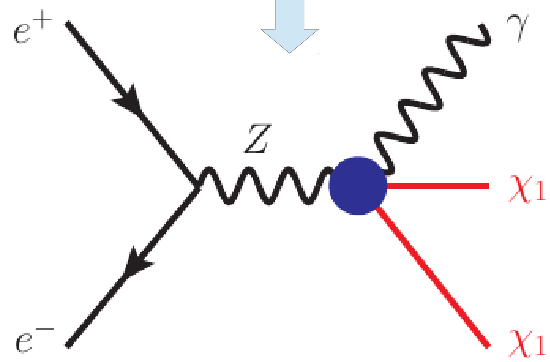
Integrating out ϕ and ψ generate effective magnetic operators

$$O_{\rm MIDM} = \frac{1}{\Lambda_{\rm MIDM}} \bar{\chi}_2 \sigma^{\mu\nu} \chi_1 B_{\mu\nu} + h.c.$$



$$\frac{1}{\Lambda_{\rm MIDM}} \approx \frac{\lambda^2 g_Y}{64\pi^2 M_\psi}$$

$$\frac{1}{\Lambda^3_{\rm RayDM}} \approx \frac{\lambda^2 g_Y^2}{48\pi^2 M_\psi^3}$$



– focus only on region where splitting is large for Z decay.

– in this case the relevant annihilation initial state is only χ_1

– relevant annhilation cross section for $m_{\chi_1} < m_Z$

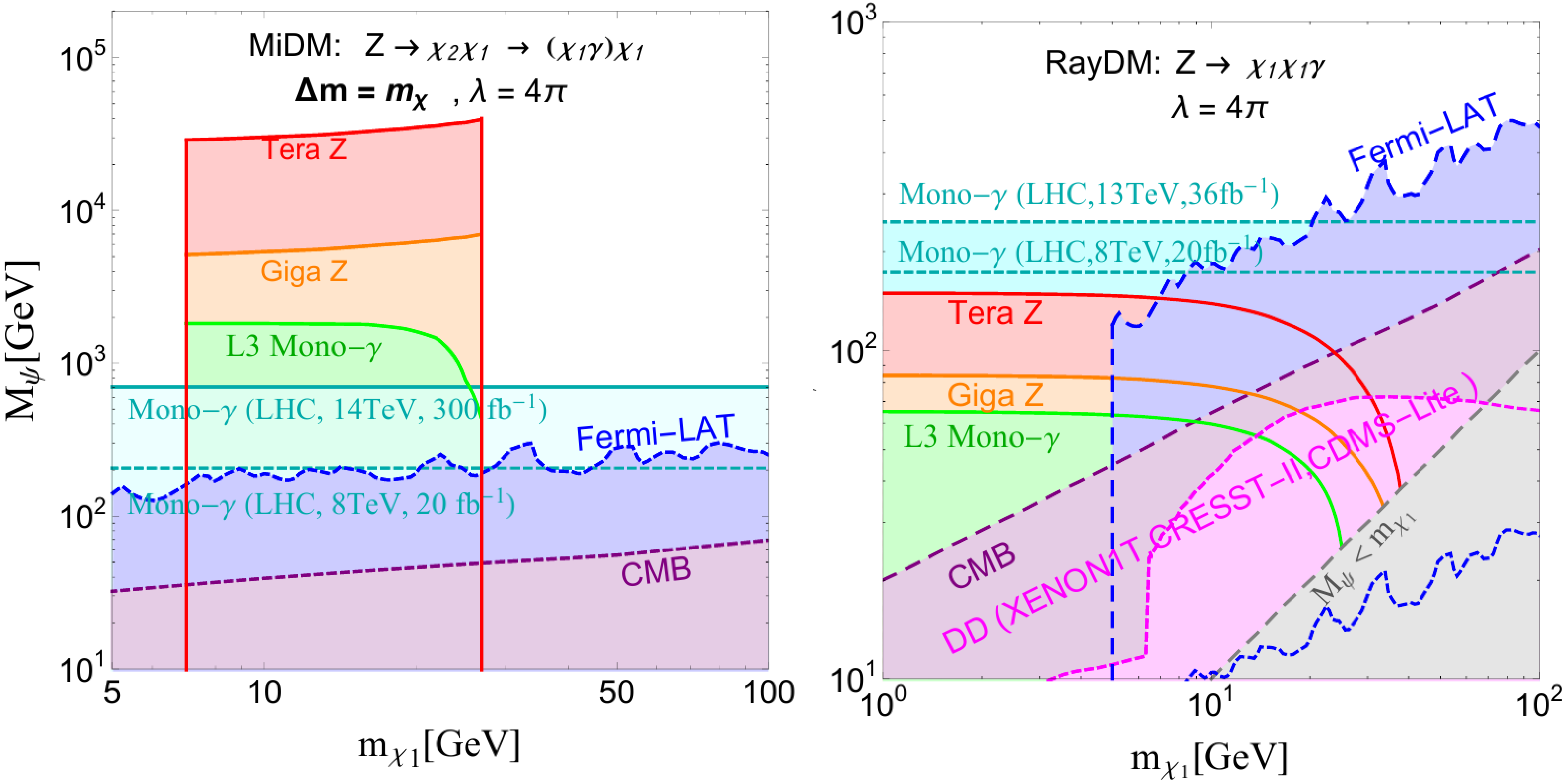
$$\sigma v(\chi_1\chi_1 \to \gamma\gamma)_{\rm MIDM} = \frac{\cos^2\theta_w m_{\chi_1}^2}{\pi\Lambda_{\rm MIDM}^4}\frac{16y^6 - 9y^4 - 2y^2 - 2}{y^4(y^2+2)^2},$$

$$\sigma v(\chi_1\chi_1 \to \gamma\gamma)_{\rm RayDM} = \frac{\cos^2\theta_w}{\pi}\frac{m_{\chi_1}^4}{\Lambda_{\rm RayDM}^6}v_{\rm rel}^2,$$

$$\sigma v(\chi_1\chi_1 \to \gamma\gamma)_{\rm RayDM}^{\gamma_5} = \frac{16\cos^2\theta_w}{\pi}\frac{m_{\chi_1}^4}{\Lambda_{\rm RayDM}^6},$$

$$\frac{1}{\Lambda_{\rm MIDM}} \approx \frac{\lambda^2 g_Y}{64\pi^2 M_\psi} \qquad \frac{1}{\Lambda_{\rm RayDM}^3} \approx \frac{\lambda^2 g_Y^2}{48\pi^2 M_\psi^3} \qquad y \equiv m_{\chi_2}/m_{\chi_1}$$

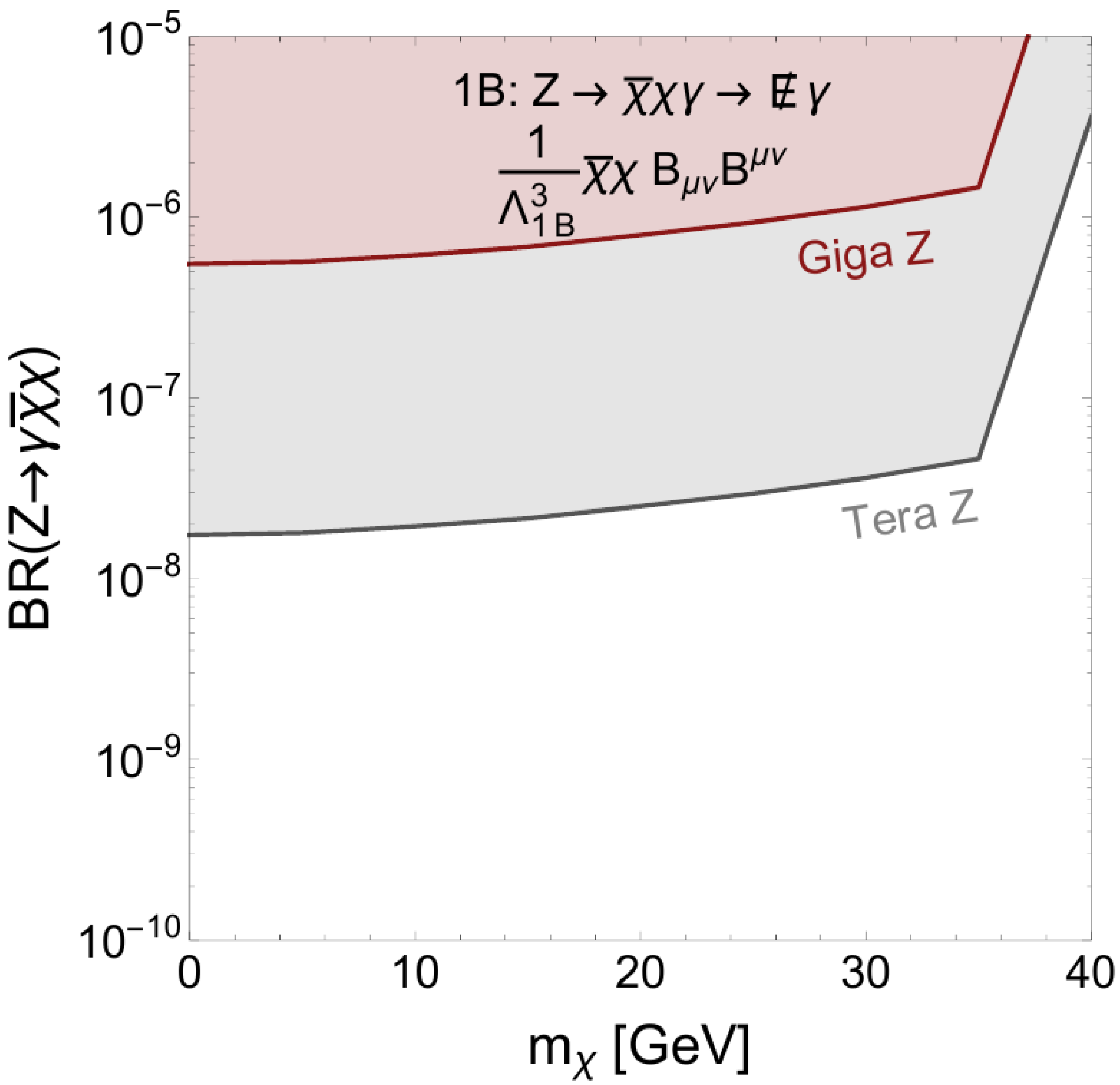
$$Z \to \not{E} + \gamma$$



Liu, Wang, Wang, Xue, 1712.07237

This signature refers to a 2-body decay with “on-shell” decay of $\chi_2 \to \chi_1 + \gamma$

$$Z \to \not{E} + \gamma$$



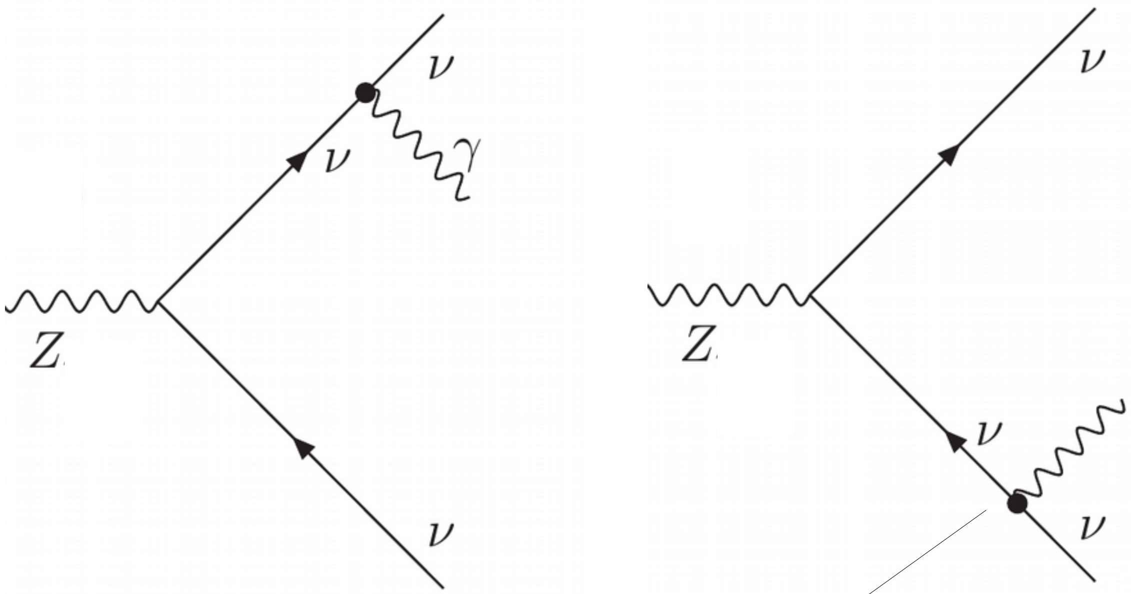
Liu, Wang, Wang, Xue, 1712.07237

Anomalous Magnetic moment of neutrinos

$$Z \to \not{E} + \gamma$$

missing energy from neutrino-antineutrino pair $\rightarrow$ truly 3-body decay

$$\mu_\nu \overset{\text{SM}}{=} \frac{3eG_F m_\nu}{8\pi^2\sqrt{2}} = 3.2 \times 10^{-19} \mu_B \left(\frac{m_\nu}{\text{eV}}\right)$$



$$\Gamma(Z \to \nu\bar{\nu}\gamma) = \frac{\mu_B^2 \alpha m_Z^3 \left(\sum_i |k_i|^2\right)}{512\pi^2 c_W^2 s_W^2}$$

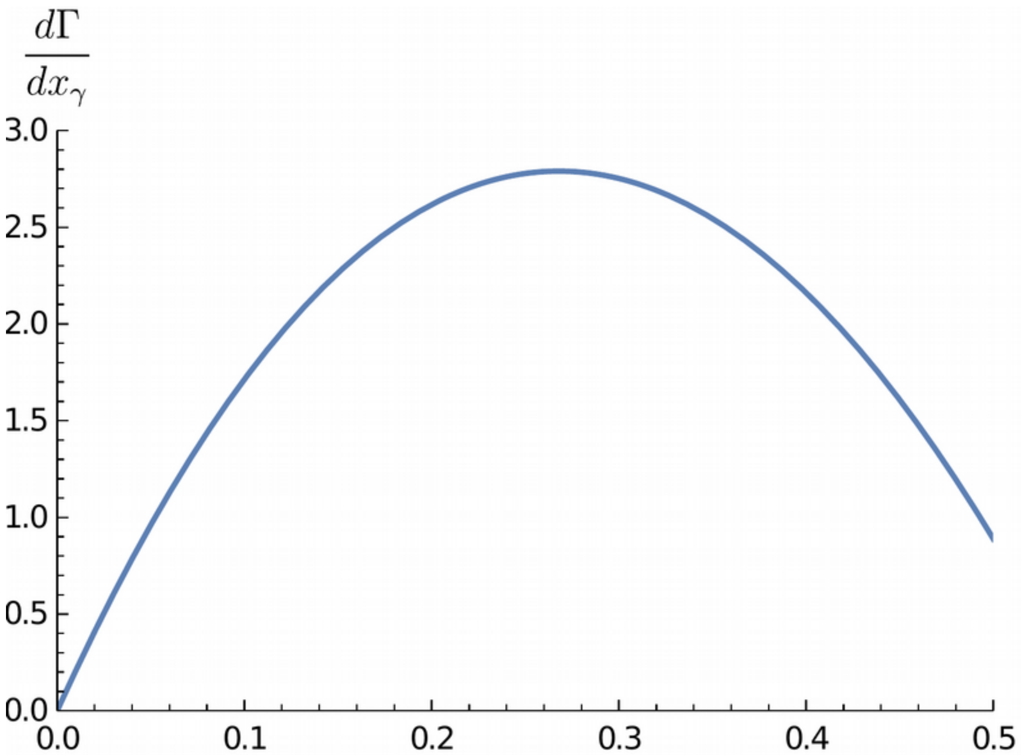
$$\mathcal{L}_\nu = \mu_B \sum_{i=e,\nu,\tau} k_i [\nu_i \sigma^{\mu\nu} \nu_i] F_{\mu\nu}$$

Bohr magneton

Gould-Rothstein hep-ph/9405216 (PLB)

Aydin-Bayar-Kilic hep-ph/0603080
Chin. Phys. C (2008)

photon energy spectrum at the Z-pole



$$E_\gamma^{\max} \simeq 24\,\mathrm{GeV}$$

$$\frac{d\Gamma}{dx_\gamma} = \frac{\mu_B^2\,\alpha\, m_Z^3\,\left(\sum_i |k_i|^2\right)}{24\pi^2 c_W^2 s_W^2} F(x_\gamma)$$

$$F(x) = x\left(1 - 2x + \frac{x^2}{3}\right)$$

$$k^2 \equiv \sum_i |k_i|^2$$

$$\mathrm{BR}(Z \to \nu\bar{\nu}\gamma) = 2.3 \times 10^5\, k^2$$

Improving bounds on MDM of neutrino-tau

naive estimations

Giga Z → $k < 6.6 \times 10^{-8}$

Tera Z → $k < 2.1 \times 10^{-9}$

From PDG

$$k_e < 2.9 \times 10^{-11}$$

$$k_\mu < 6.8 \times 10^{-10}$$

$$k_\tau < 3.9 \times 10^{-7}$$

relevant SM bckg from tale of non-resonant e+e- → ν ν γ

Light vectors coupled to anomalous currents

$$Z \to \not{E} + \gamma$$

Dror-Lasenby-Pospelov
1705.06726 (PRL)

- Consider vector field X coupled to anomalous currents (like B-L)
- X has vectorial couplings to SM fermions
- UV completion require anomaly cancellation at high energy
- Wess-Zumino term can arise at low energy

$$\mathcal{L} \supset C_B g_X g'^2 \epsilon^{\mu\nu\rho\sigma} X_\mu B_\nu \partial_\rho B_\sigma$$

$$+ C_W g_X g^2 \epsilon^{\mu\nu\rho\sigma} X_\mu (W^a_\nu \partial_\rho W^a_\sigma + \frac{1}{3} g \epsilon^{abc} W^a_\nu W^b_\rho W^c_\sigma)$$

- No choice for C_{WZ} that preserves both $U(1)_X$ and SM gauge group → assumed to break $U(1)_X$
- Massive X in the spectrum
- The longitudinal component (φ) of X acts as X=ALP coupled to Z and photon .

$$Z \to \gamma X$$

$$\Gamma_{Z\to\gamma X} \simeq \frac{\mathcal{A}^2}{1536\pi^5} g_X^2 g^2 g'^2 \frac{m_Z^3}{m_X^2}$$

$$\frac{\mathcal{A}}{16\pi^2} \frac{g_X \varphi}{m_X} (g^2 W^a \tilde{W}^a - g'^2 B\tilde{B}) =$$
$$\frac{\mathcal{A}}{16\pi^2} \frac{g_X \varphi}{m_X} \Big(g^2 (W^+ \tilde{W}^- + W^- \tilde{W}^+)$$
$$+ g g' (\cot\theta_w - \tan\theta_w) Z\tilde{Z} + 2 g g' Z \tilde{F})$$
$$- i e g^2 \tilde{F}^{\mu\nu} (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) + \ldots \Big)$$

Z,γ, field strengths

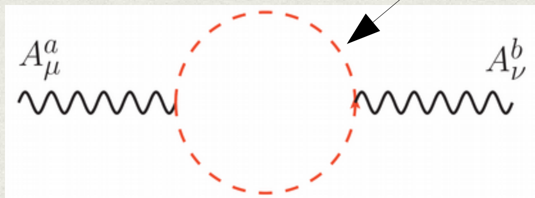
Dark Photon scenario

the vector portal

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

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

kinetic mixing always induced by renormalization effects, if messenger fields are present



no direct interaction with visible sector

J' → Dark current
A' → dark-photon

J → SM current
A → photon

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

massless

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

massive

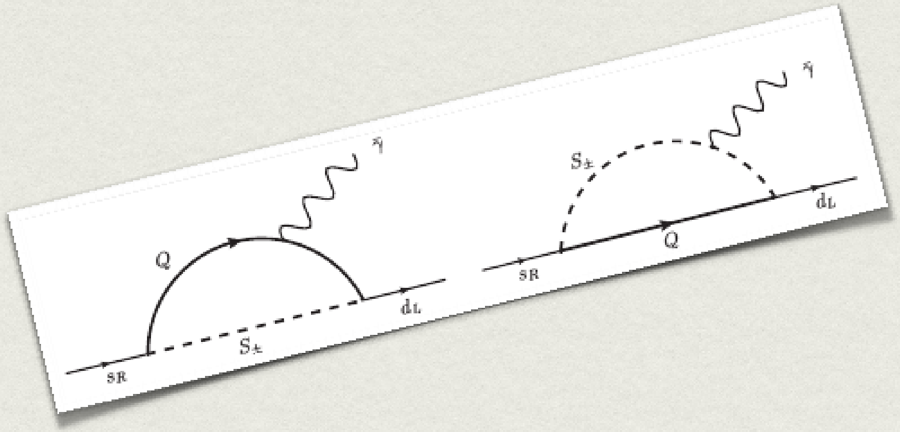
courtesy of M. Fabbrichesi

- B.Holdom, PLB 166B, 196 (1986)
- B.A. Dobreascu, PRL 94 151802 (2005); [hep-ph/0411004]
- EG, M. Fabbrichesi, G. Lanfranchi, “The dark photon” SpringerBriefs in Physics 2020; arXiv:2005.01515]

massless dark photon

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

we need a specific benchmark



[hep-ph/0411004]

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

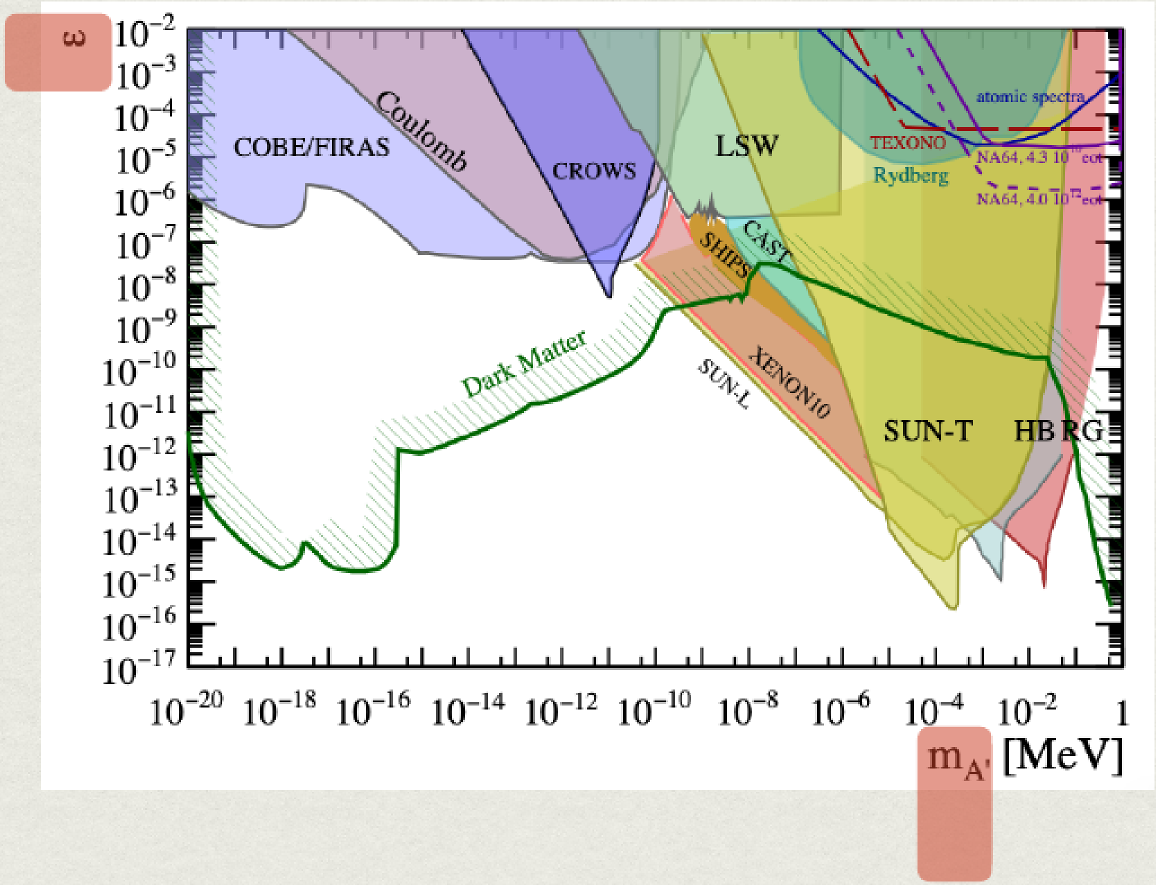
$$\mathcal{L} = \frac{e_D}{2\Lambda^2} \overline{\psi}_L^i \, \sigma_{\mu\nu} \left(\mathbb{D}_M^{ij} + i\gamma_5 \, \mathbb{D}_E^{ij} \right) H \psi_R^j \, F'^{\mu\nu} + \text{H.c.}$$

effective scale Λ

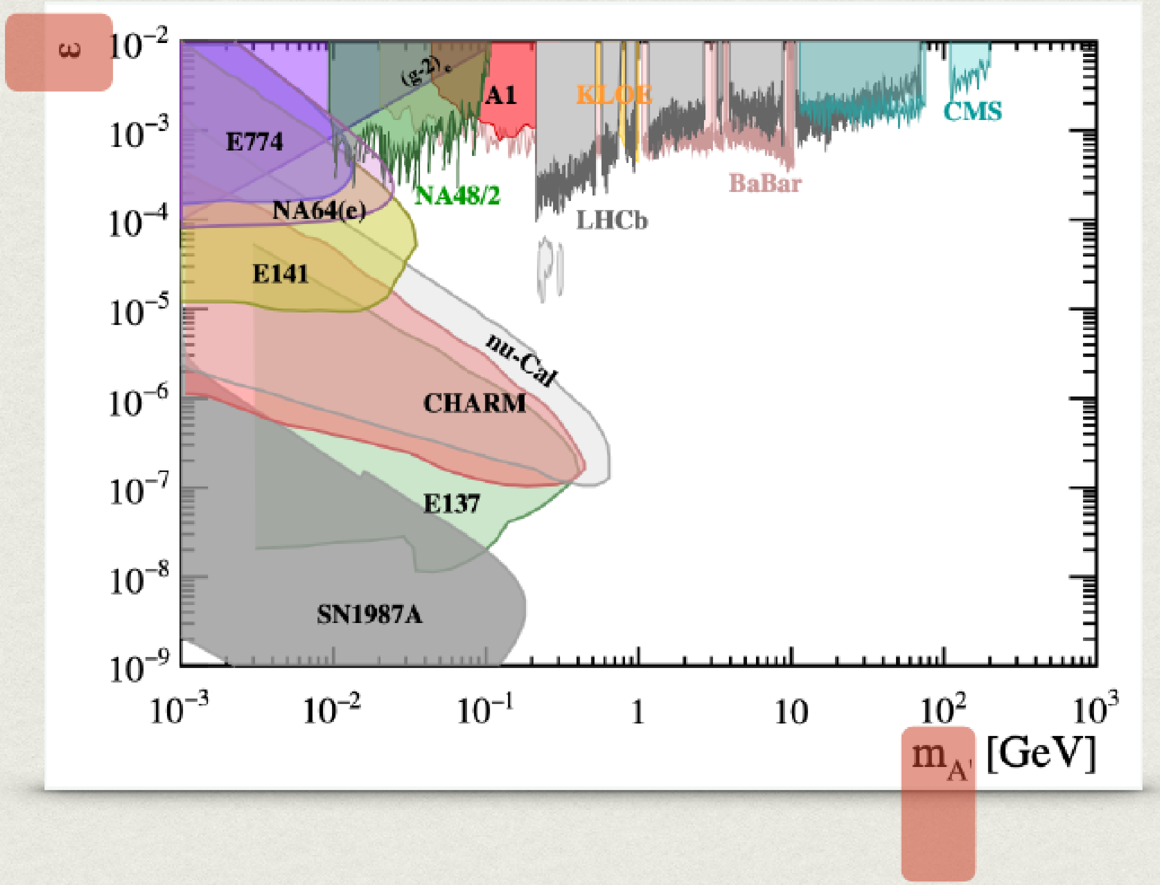
- **Massless dark photon interacts with SM particles via high dimensional operators → dim-5 (magnetic-dipole moments) leading contributions**

massive dark photon

invisible

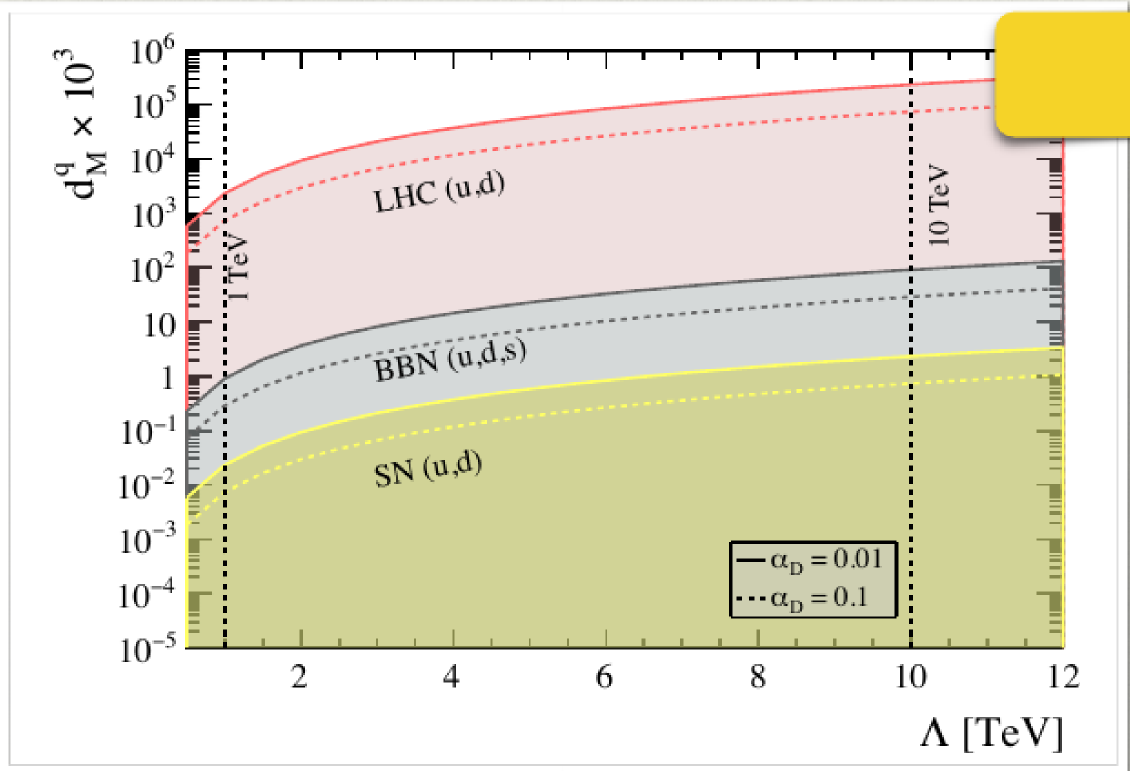


visible

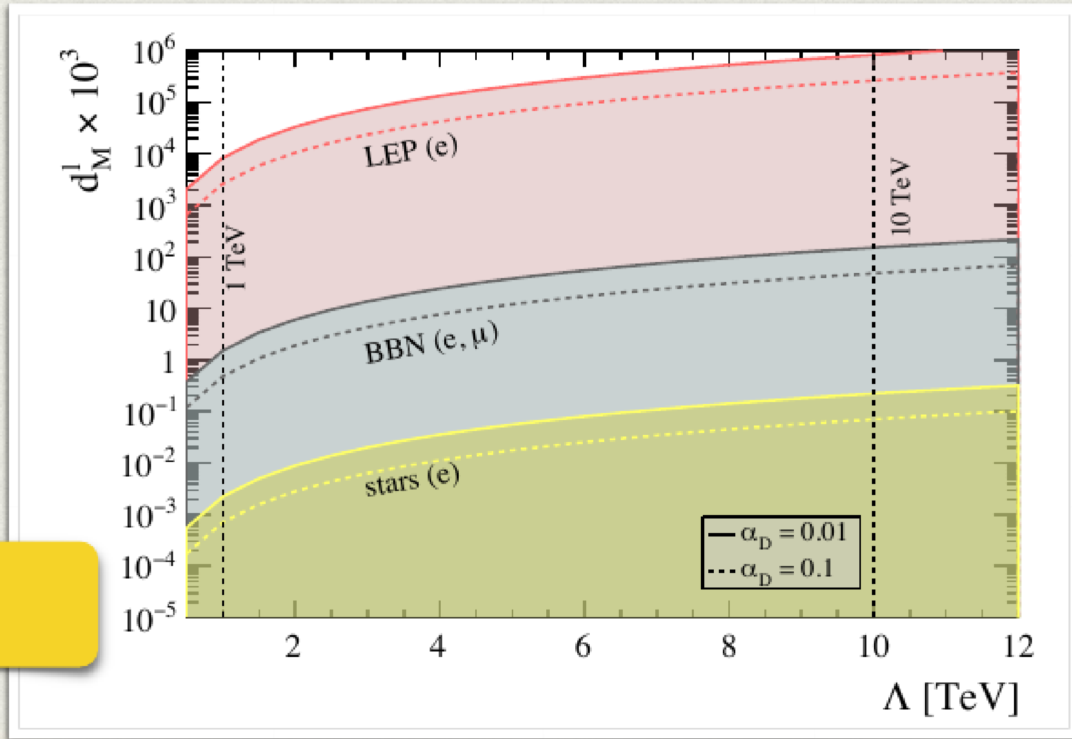


limits on massive dark photon [from arXiv:2005.01515]

massless dark photon



quarks



leptons

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.

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

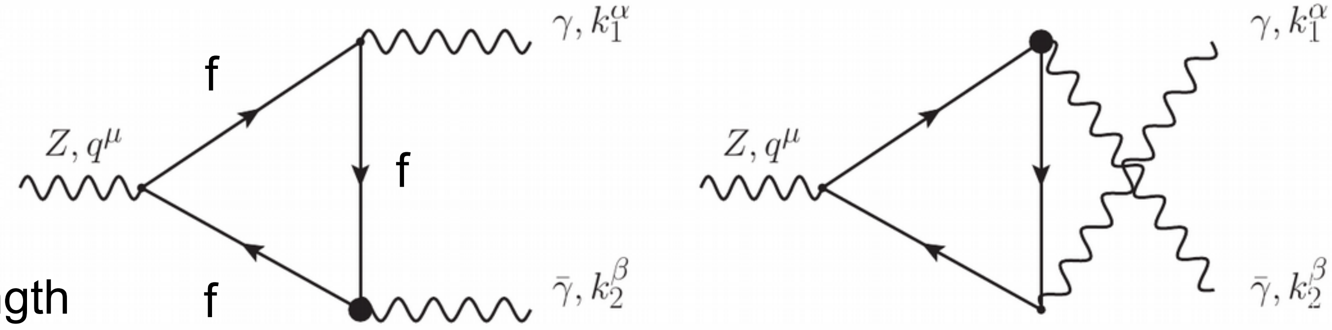
$$Z \to \gamma\bar{\gamma}$$

Fabbrichesi, EG, Mele
[1712.05412] (PRL)

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



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

- massive dark-photon couples also via magnetic dipole interaction, its tree-level coupling 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 gauge invariance

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

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

Dark-U(1) charge

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

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

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

10^{-9}

α_D → 0.1

Λ → 1 TeV

4×10^{-11}

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).

$d_M \simeq 0.1$
→ small couplings in DS

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

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

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

Spin-2 scenario

$Z \to \not{E} + \gamma$

$G_{\mu\nu}$ massive spin 2 field → Fierz-Pauli Lagrangian with mass m_G

Assume an effective coupling

$$L_G = -\frac{1}{\Lambda_G} T^{\mu\nu} G_{\mu\nu}$$

$T_{\mu\nu}$ → SM energy-momentum tensor (gravity m_G =0 $\Lambda_G^{-1} = \sqrt{8\pi G_N}$)

Λ_G → universal coupling

Lower masses below eV severely constrained by test on deviation from gravity law

we restrict to the scenario → $\mathrm{eV} \lesssim m_G \lesssim 1\,\mathrm{GeV}$

Requiring spin-2 not to decay inside detector (L=10m)

Comelato-EG [2006.00973] (PRD)

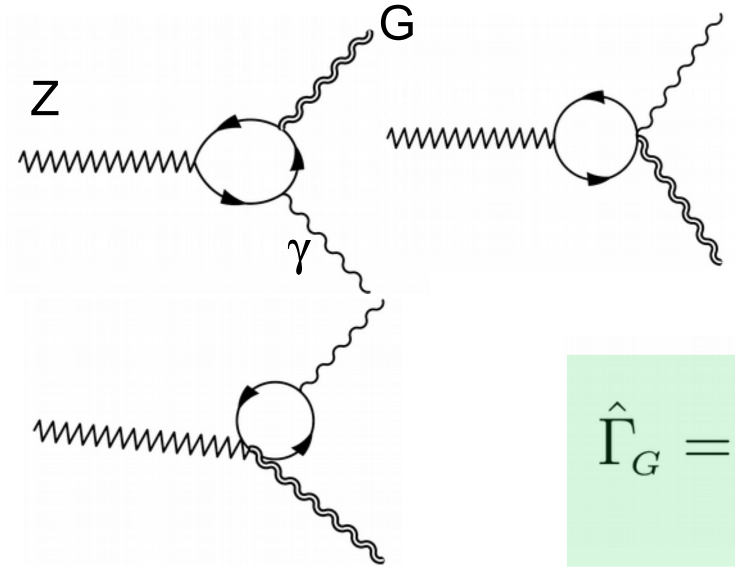
$$\Lambda_G \gtrsim 36 \left(\frac{m_G}{100\mathrm{MeV}}\right)^2 \mathrm{TeV}\,, \qquad 1\mathrm{eV} \lesssim m_G \lesssim 2m_\mu$$

$$\Lambda_G \gtrsim 113 \left(\frac{m_G}{100\mathrm{MeV}}\right)^2 \mathrm{TeV}\,, \qquad 2m_\mu \lesssim m_G \lesssim 1\mathrm{GeV}$$

$\Lambda_G > \mathcal{O}(1\mathrm{TeV})$ for all masses below 10MeV

Spin-2 scenario

$ZG\gamma$ →vertex induced at 1-loop
all SM particles running inside



Allanach et al
[0705.1953] (JHEP)

$$Z(p) \quad \rightarrow \quad \gamma(k)\ G(q)$$

amplitude

$$M_G \;=\; F_G \varepsilon_Z^{\mu}(p)\varepsilon_G^{\lambda\rho\star}(q)\varepsilon^{\nu\star}(k)V^G_{\mu\lambda\rho\nu}(k,q)$$

$$V^G_{\mu\lambda\rho\nu}(k,q) \;=\; (k_\lambda q_\nu - (k\cdot q)\eta_{\nu\lambda})\,(k_\rho q_\mu - (k\cdot q)\eta_{\mu\rho}) + \{\lambda \leftrightarrow \rho\}$$

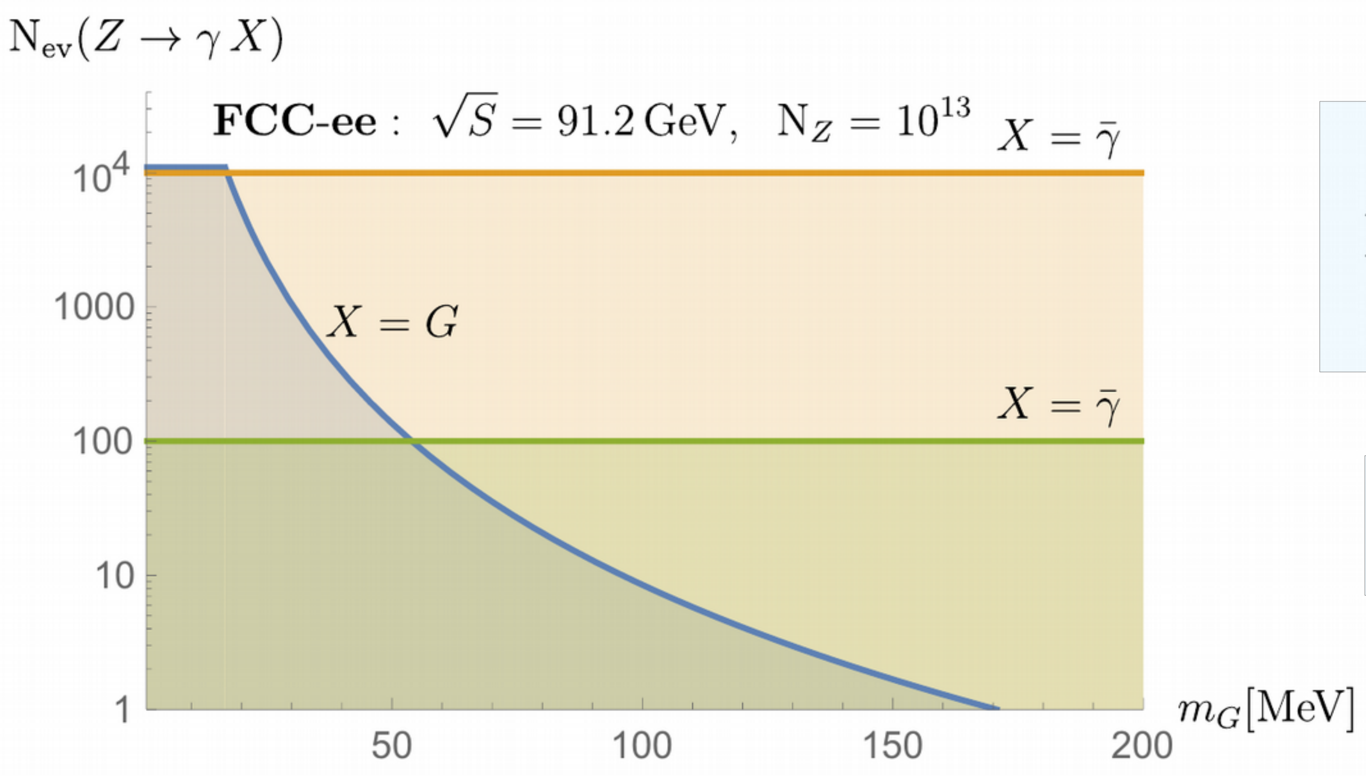
from 1-loop SM: finite result

$$F_G \;\simeq\; 0.41\frac{\alpha}{\Lambda_G M_Z^2 \pi}$$

Total width

$$\hat{\Gamma}_G = \frac{M_Z^7}{576\pi}\,(7+3r_G)\,(1-r_G)^5\,|F_G|^2$$

$$r_G = m_G^2/M_Z^2$$



$$\mathrm{BR}(Z \to \gamma G) = 1.1 \times 10^{-9}\left(\frac{1\mathrm{TeV}}{\Lambda_G}\right)^2$$

$$10^{-13} < \mathrm{BR}(Z \to \gamma G) < 10^{-9}$$

[2006.00973]

$$Z \to \not{E} + \gamma$$

signature with monochromatic photon (2 body decay)

Would it be possible to disentangle the spin S(X)=0,1,2 ?

[2006.00973]

Polarized decay $Z \to \gamma + X$

Polarizations: R → transverse, L → longitudinal

$\beta_Z \to 0$

$$z = \cos\theta$$

Spin-1 (massless)

$$\frac{1}{\hat{\Gamma}}\frac{d\Gamma^{(T)}}{dz} = \frac{3}{4}\left(1 - z^2\right)$$

$$\frac{1}{\hat{\Gamma}}\frac{d\Gamma^{(L)}}{dz} = \frac{3}{2}z^2$$

Spin-0 (massive)

$$\frac{1}{\hat{\Gamma}_I}\frac{d\Gamma_I^{(T)}}{dz} = \frac{3}{8}\left(1 + z^2\right)$$

$$\frac{1}{\hat{\Gamma}_I}\frac{d\Gamma_I^{(L)}}{dz} = \frac{3}{4}\left(1 - z^2\right)$$

(mass dependence cancels out)

Spin-2 (massive)

$$\frac{1}{\hat{\Gamma}_G}\frac{d\Gamma_G^{(T)}}{dz} = \frac{3}{8}\frac{\left(1 + z^2\left(1 - 2\delta_G\right) + 2\delta_G\right)}{1 + \delta_G}$$

$$\frac{1}{\hat{\Gamma}_G}\frac{d\Gamma_G^{(L)}}{dz} = \frac{3}{4}\frac{\left(1 - z^2\left(1 - 2\delta_G\right)\right)}{1 + \delta_G},$$

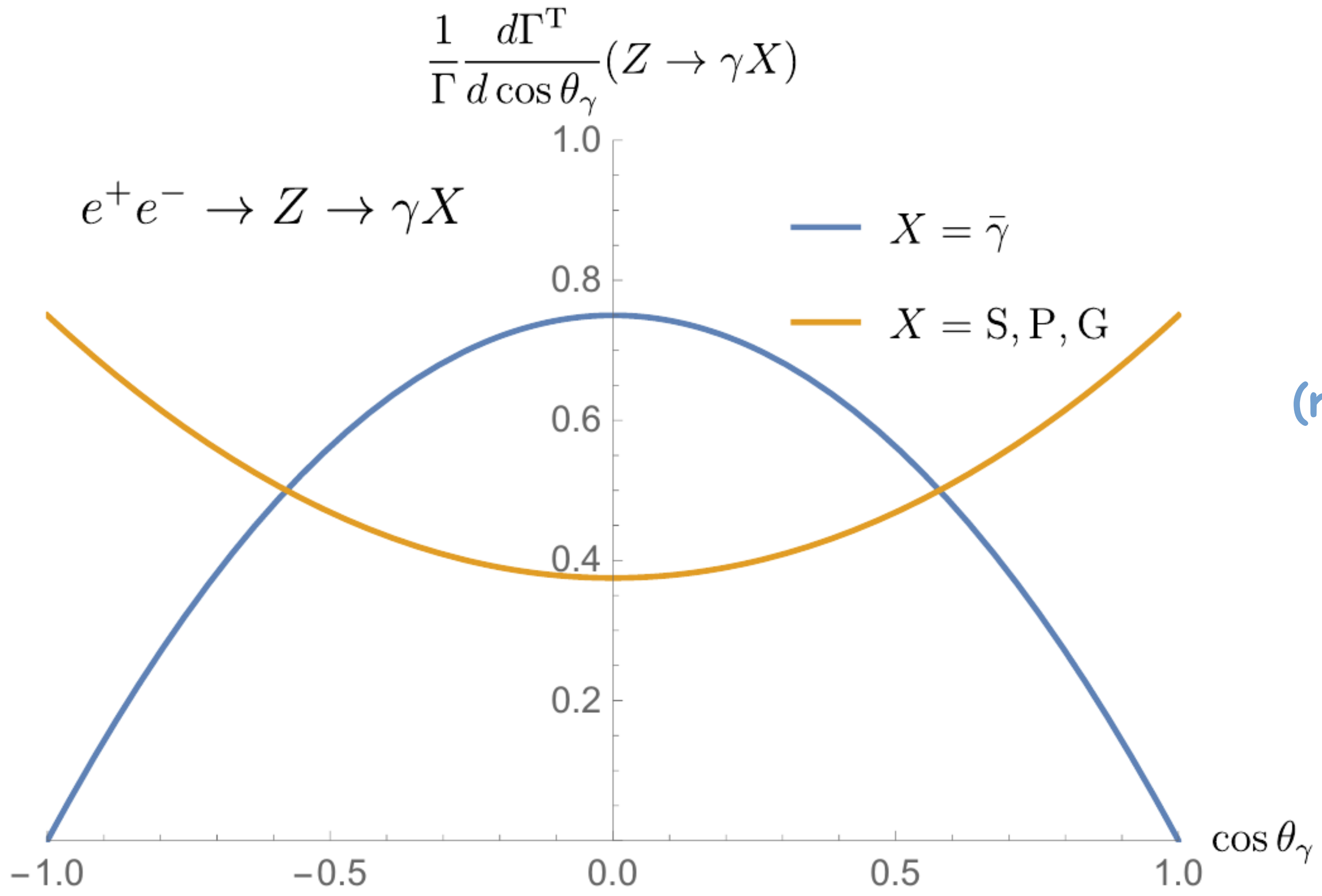
$$\delta_G = \frac{3}{7}r_G$$

$$r_G = m_G^2/M_Z^2$$

Z decays at e^+e^- colliders

Z boson comes out mainly transverse (T) polarized → due to angular momentum conservation

Possibility to disentangle spin-nature of X boson



angle θ_γ

between direction p
and initial e- beam c

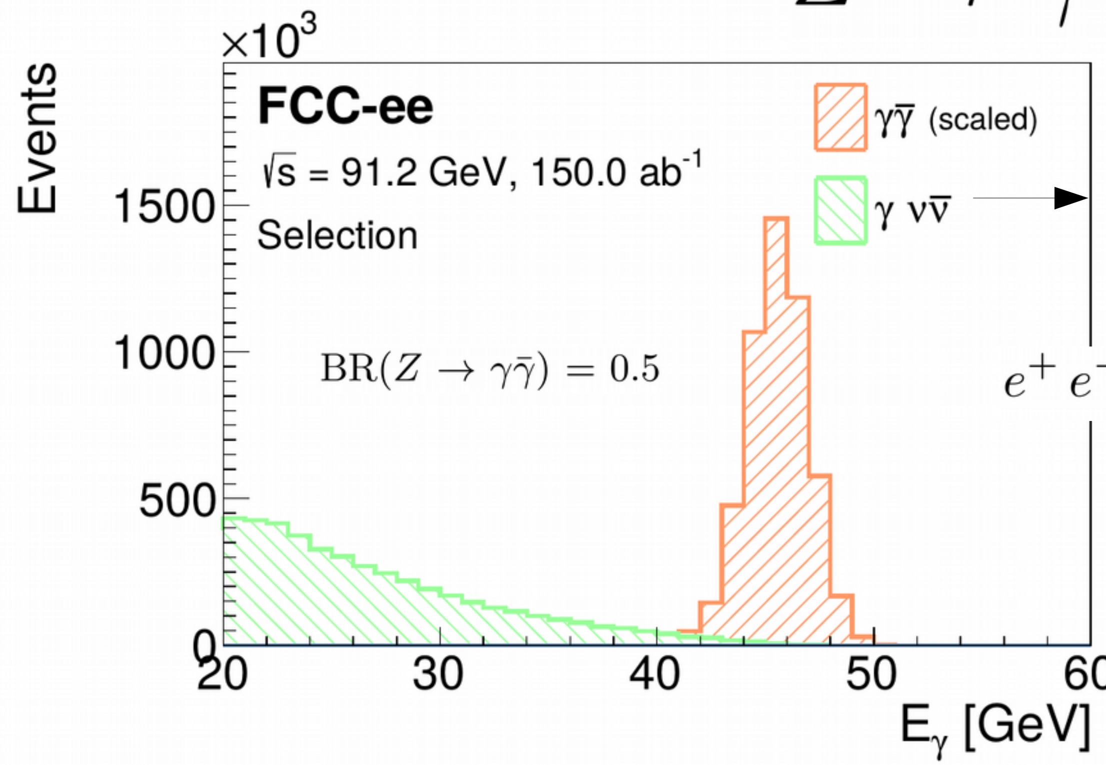
$(m_G \to 0)$

X spin can be disentangled → **spin-1:** photon mainly produced **central** and at large angles

→ **spin-0/2:** photon mainly produced along FB directions

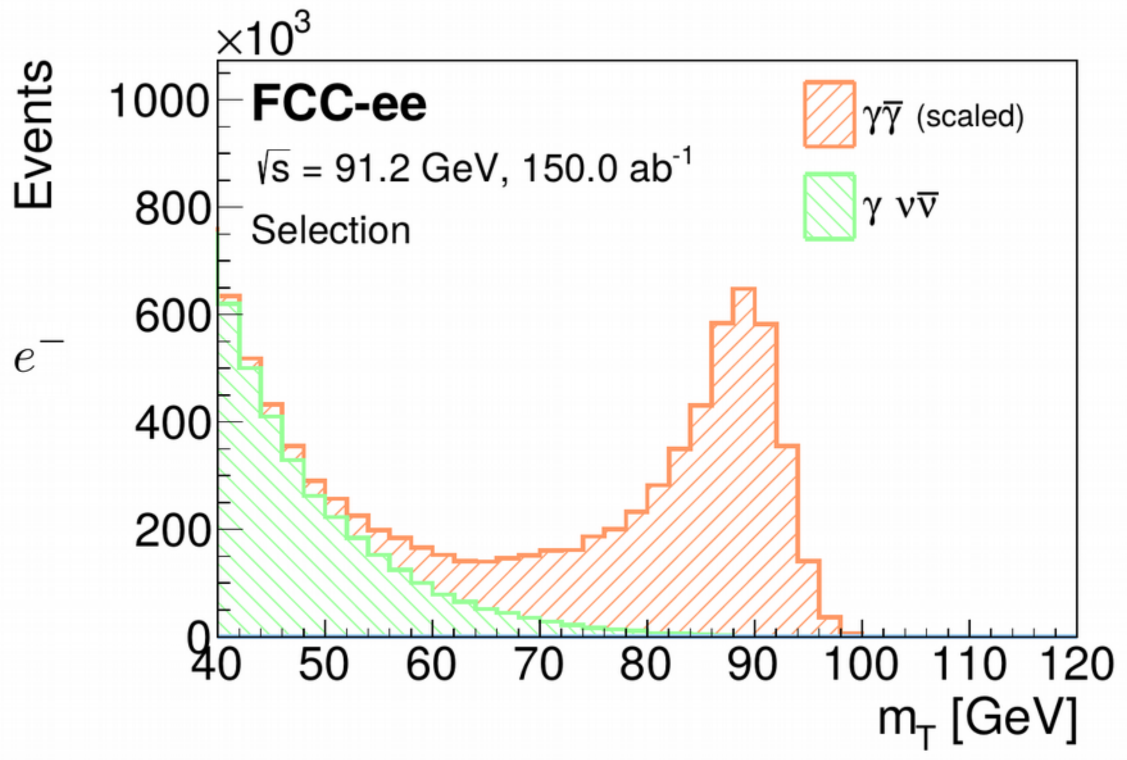
$Z \to \gamma\ \bar{\gamma}$ @ FCC-ee

M.Cobal et al [2006.15945] (PRD)



bckg

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



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}

Sensitivity on **BR up to 10^{-11}** can be reached at Z-factories

Spin analysis using test statistics

N=6 (N=17) → lower bound for expected (observed) N. of signal events needed to exclude the hypothesis under the $p_0(J^P = 1^-)$ assumption at 95% C.L.

other interesting signatures

$$Z \to \not{E} + \gamma\gamma$$

$$Z \to \not{E} + \ell^+\ell^-$$

$$Z \to \not{E} + JJ$$

N. resonances

$Z \to \not{E} + \gamma\gamma$	$Z \to \phi_d A', \phi_d \to (\gamma\gamma),\ A' \to (\bar{\chi}\chi)$	2	Vector portal
	$Z \to \phi_H \phi_A,\ \phi_H \to (\gamma\gamma),\ \phi_A \to (\bar{\chi}\chi)$	2	2HDM extension
	$Z \to \chi_2\chi_1,\ \chi_2 \to \chi_1\phi,\ \phi \to (\gamma\gamma)$	1	Inelastic DM
	$Z \to \chi_2\chi_2,\ \chi_2 \to \gamma\chi_1$	0	MIDM

Liu, Wang, Wang, Xue, 1712.07237

χ is assumed to be Majorana (DM like) → stable or decaying outside detector

Vector-portal A' (DP like)

$$\mathcal{L}_F = \bar{\chi} i \not{\partial} \chi + g_D \bar{\chi} A'_\mu \gamma^\mu \chi - m_D \bar{\chi}\chi + \left(\Phi^* \left(y_L \bar{\chi}^c P_L \chi + y_R \bar{\chi}^c P_R \chi\right) + h.c.\right)$$

once ϕ gets a vev χ gets a Majorana mass term , + Dirac mass → 2 Majorana χ_1 χ_2

n=1,2 resonances, depending on the masses of the res.

BR sensitivity of Giga Z is around $[10^{-8.4}, 10^{-6.7}]$

for Tera Z $[10^{-11}, 10^{-9.7}]$

contact term → zero resonance

$[10^{-8.4}, 10^{-7.4}]$ (Giga-Z)

$[10^{-10.3}, 10^{-9.2}]$ (Tera-Z)

N. resonances ↓

$Z \to \not{E} + \ell^+\ell^-$	$Z \to \phi_d A',\ A' \to (\ell^+\ell^-),\ \phi_d \to (\bar{\chi}\chi)$	2	Vector portal
	$Z \to A'SS \to (\ell\ell)SS$	1	Vector portal
	$Z \to \phi(Z^*/\gamma^*) \to \phi\ell^+\ell^-$	1	Long-lived ALP, Higgs portal
	$Z \to \chi_2\chi_1 \to \chi_1 A'\chi_1 \to (\ell^+\ell^-)\not{E}$	1	Vector portal and Inelastic DM
	$Z \to \chi_2\chi_1,\ \chi_2 \to \chi_1\ell^+\ell^-$	0	MIDM, SUSY
	$Z \to \bar{\chi}\chi\ell^+\ell^-$	0	RayDM, slepton, heavy lepton mixing

for **Giga-Z** $\mathrm{BR}(Z \to \not{E}\ell^+\ell^-)$ probed down to

$\sim 10^{-8.5}$ for n. res > 0

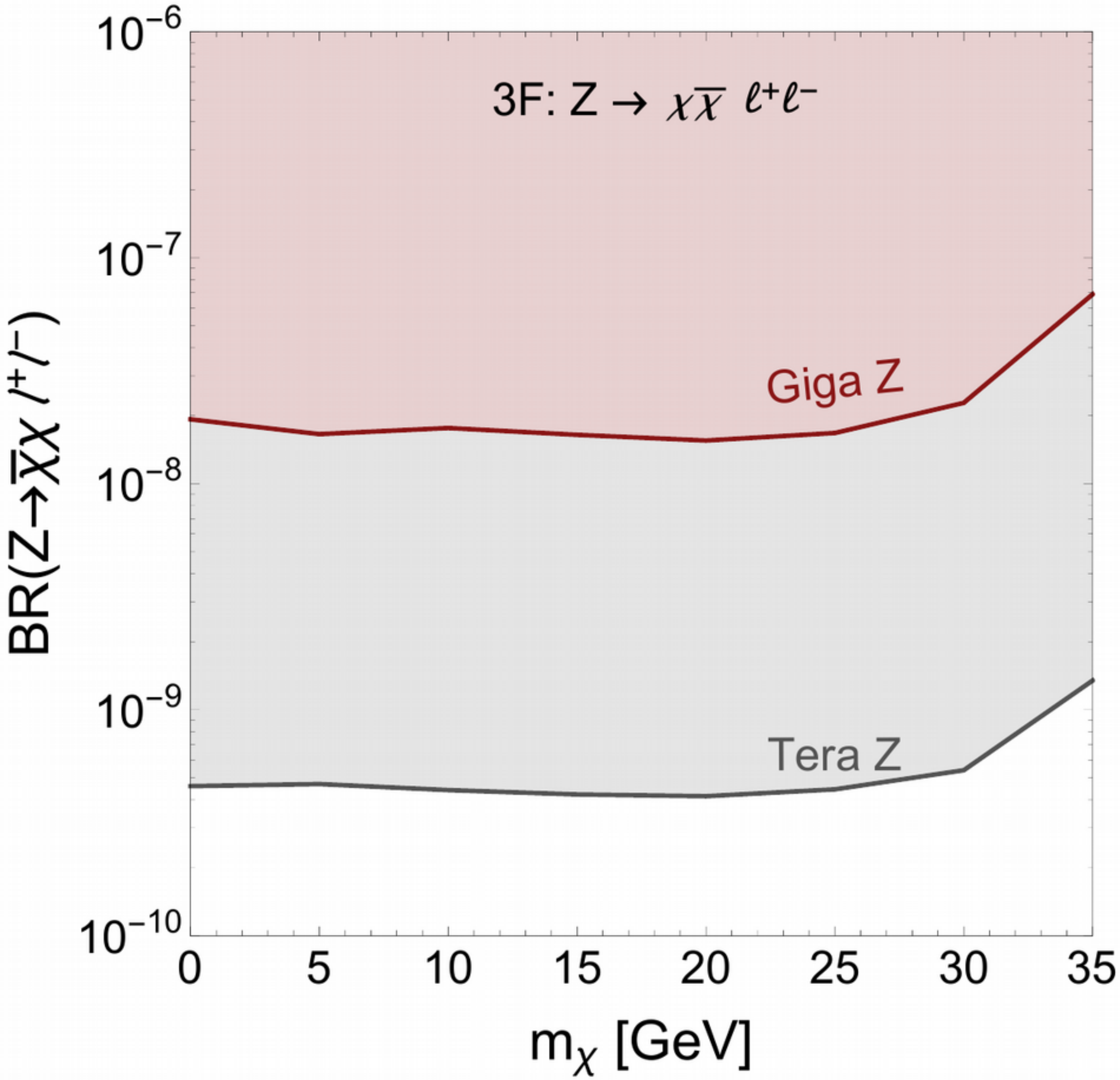
$\sim 10^{-8}$ for n. res = 0

for **Tera-Z** → sensitivity better by a factor $10^{1.5}$

1712.07237

$$Z \to \not{E} + \ell^+ \ell^-$$

Contact term → no resonances



1712.07237

		N. resonances	
	$Z \to \phi_d A', \phi_d \to jj, A' \to jj$	2	Vector portal + Higgs portal
$Z \to (JJ)(JJ)$	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to jj$	2	vector portal + Higgs portal
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to b\bar{b}$	2	vector portal + Higgs portal

for **Giga-Z** $\mathrm{BR(Z \to (JJ)(JJ))}$ probed down to

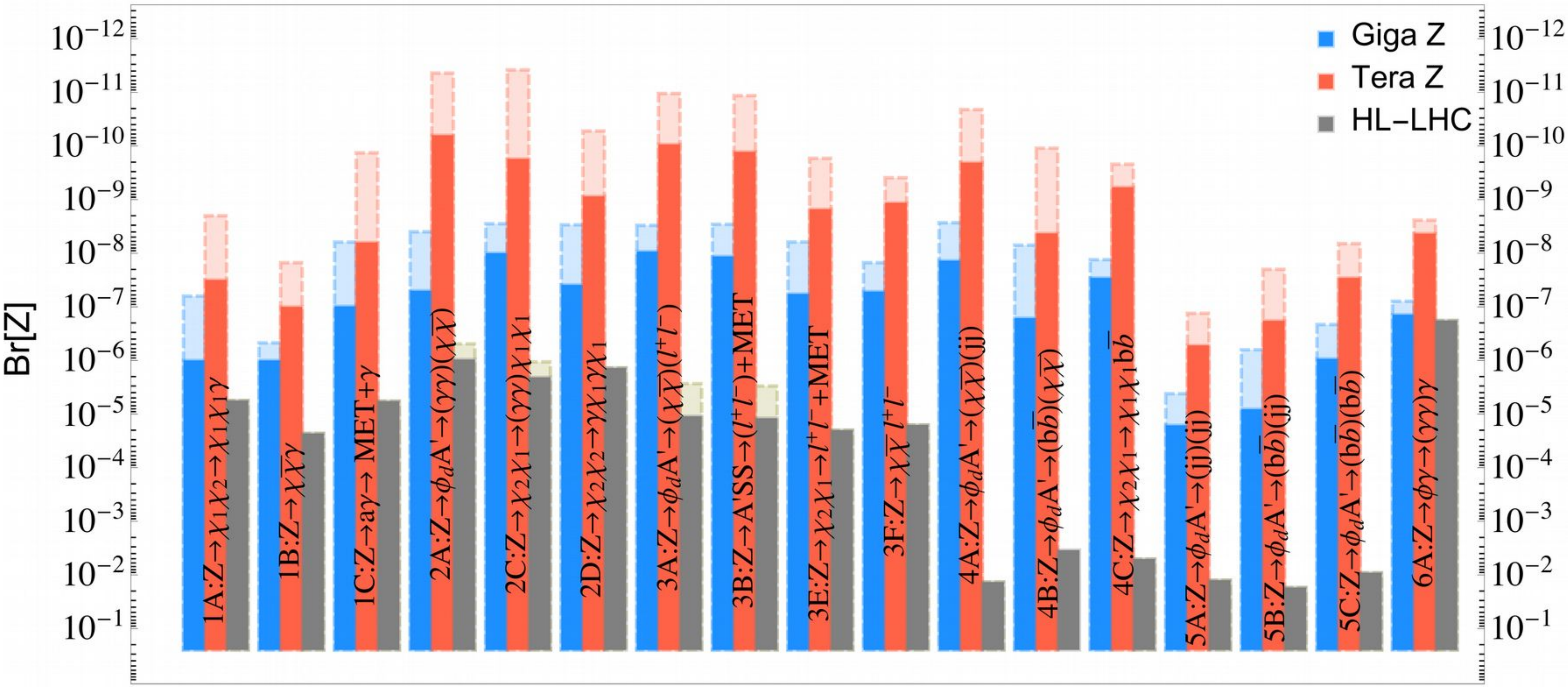
$\sim 10^{-5}$ for $(jj)(jj)$

$\sim 10^{-6}$ for $(jj)(bb)$

$\sim 10^{-6.5}$ for $(bb)(bb)$

for **Tera-Z** $\to$ sensitivity better by a factor $10^{1.5}$

1712.07237

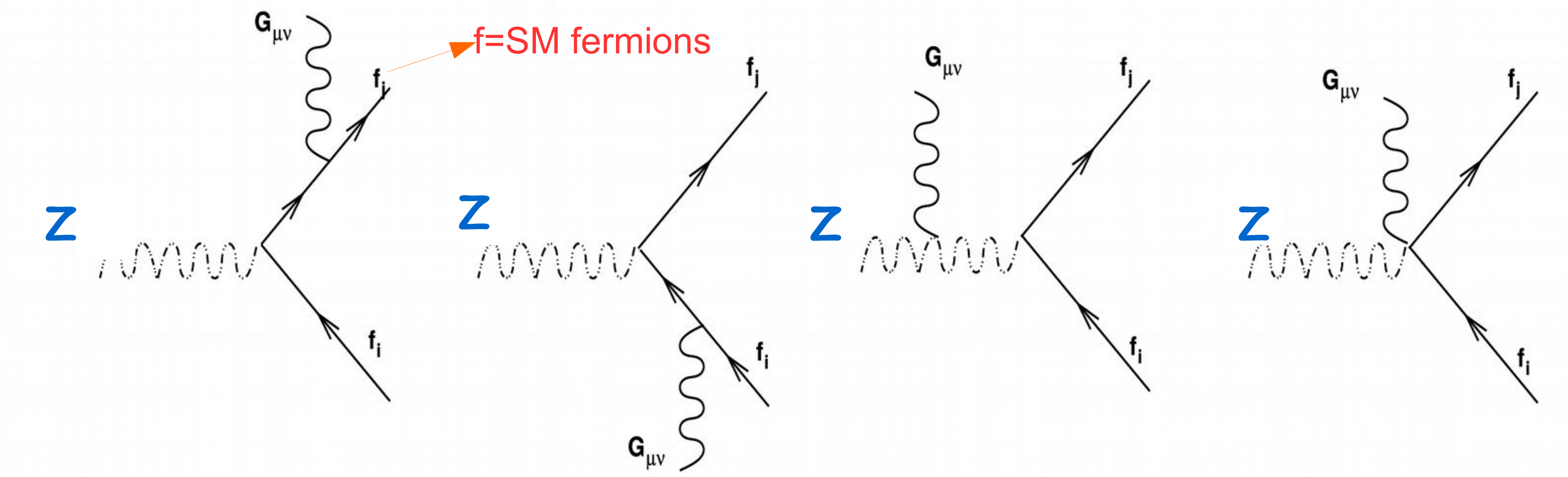

Giga Z
Tera Z
HL−LHC
Br[Z]
1A:Z→χ1χ2→χ1χ1γ
1B:Z→χχ̄γ
1C:Z→aγ→ MET+γ
2A:Z→φdA'→(γγ)(χχ̄)
2C:Z→χ2χ1→(γγ)χ1χ1
2D:Z→χ2χ2→γχ1γχ1
3A:Z→φdA'→(χχ̄)(l+l−)
3B:Z→A'SS→(l+l−)+MET
3E:Z→χ2χ1→l+l−+MET
3F:Z→χχ̄ l+l−
4A:Z→φdA'→(χχ̄)(jj)
4B:Z→φdA'→(bb̄)(χχ̄)
4C:Z→χ2χ1→χ1χ1bb̄
5A:Z→φdA'→(jj)(jj)
5B:Z→φdA'→(bb̄)(jj)
5C:Z→φdA'→(bb̄)(bb̄)
6A:Z→φγ→(γγ)γ

Exotic scenarios: $Z \to f\bar{f} + G$

Massive spin-2

SM EM tensor

(Light) massive spin-2 G resonance, effectively (universally) coupled to SM ⇨ $L_G = -\frac{1}{\Lambda_G} T^{\mu\nu} G_{\mu\nu}$



EG-Mele, hep-ph/0205099, NPB 647 (2002)

Signature expected

$$Z \to \not{E} + \ell^+ \ell^-$$

done for QG scenarios (ADD) → continuous spectrum

missing analysis for a light (invisible) spin-2 scenario, with low-energy couplings

New lines of investigation

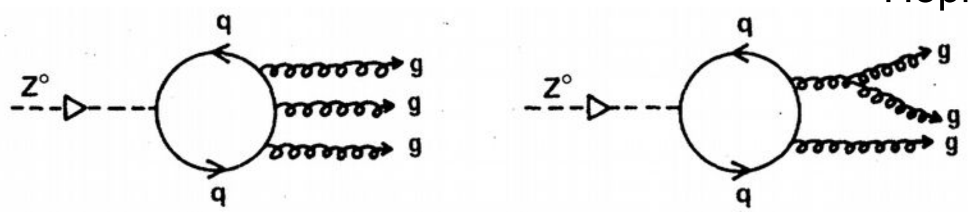
– study of sensitivity to the Λ scale including SM background

– analysis to disentangle other spin-X =ALP, massless-DP scenarios (behaving as missing energy)

Loop induced decays

Laursen-Mikaelian-Samuel PRD 23, (1981)
Hopker-van-der-Bij PRD 49 (1994)

$$Z \to g\,g\,g$$



$$\mathrm{BR}(ggg) \;=\; 1.8 \times 10^{-6}$$

Infrared finite. Difficult to observe due to large Z → qq g background

Γ(ggg)/Γ(had) < 1.6 x10^{-2} 95% C.L. (LEP)

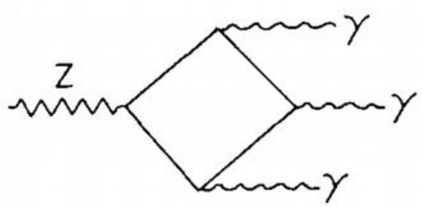
Laursen-Mikaelian-Samuel PRD 23, (1981)
Berneuther-et al LEP Physics workshop (1989)

$$Z \to g\,g + \gamma$$

$$\mathrm{BR}(gg\gamma) \;=\; 8 \times 10^{-7}$$

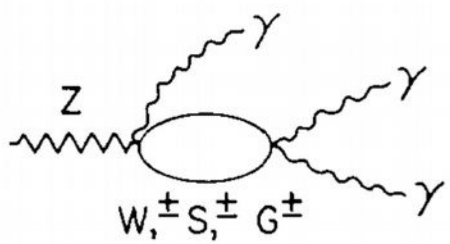
Baillargeon-Boudjema PLB 272, (1991)
Glover-Morgan Z. Phys C 60 (1993)

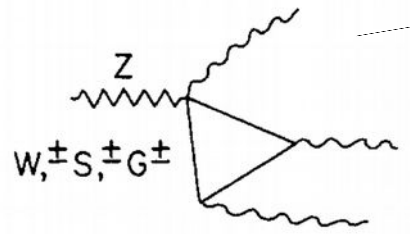
$$Z \to \gamma\gamma\gamma$$



$$\mathrm{BR}(\gamma\gamma\gamma) \;=\; 5.4 \times 10^{-10}$$

BR < 2.2 x10^{-6} 95% C.L. (ATLAS)





4.5 smaller

Loop induced decays: sensitivity to NP

Few studies in the literature, mainly in contexts of specific models.

Expected effective Lagrangians, dim. 8 operators with field-strengths (F,G,Z) couplings

$$\mathcal{L}_Z^{eff} = \frac{1}{\Lambda_1^2}(F\,F\,F\,Z) + \frac{1}{\Lambda_2^2}(G^a\,G^a\,F\,Z) + \frac{1}{\Lambda_3^2}(G^a\,G^b\,G^c\,Z)f^{abc}$$

F → photon   Z → Z^0 G → gluons   (contractions of Lorentz indices in all possible ways)

studied in the context of 331 minimal model $SU(3)_c \times SU(3)_L \times U(1)_Y$

$Z \to g\,g + \gamma$

A. Flores-Tlalpa, J. Montaño, F. Ramírez-Zavaleta, and J. J. Toscano

0908.3728, PRD 80 (2009) 077301

0906.1852, PRD 80 (2009) 033006

$Z \to g\,g\,g$

M. A. Pérez, G. Tavares-Velasco, and J. J. Toscano

hep-ph/0305227, Int.J. Mod. Phys A 19 (2004)

$Z \to \gamma\gamma\gamma$

- A complete EFT model independent analysis is missing (anomalous couplings, EFT)
- SM results a bit outdated, old computations rely on several approximations.

Backup slides

Effective Lagrangian for $Z \to \gamma\bar{\gamma}$

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

[arXiv:1712.05412]

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

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

$$\begin{aligned} C_1 &= -\sum_f \frac{d_M^f X_f}{4\pi^2}\left(5 + 2B_f + 2C_f\left(m_f^2 + M_Z^2\right)\right) \\ C_2 &= -3\sum_f \frac{d_M^f X_f}{4\pi^2}\left(2 + B_f\right), \\ C_3 &= 2\sum_f \frac{d_M^f X_f}{4\pi^2}\left(4 + 2B_f + C_f M_Z^2\right). \end{aligned}$$

SM fermion contributions

	b	t	s	c	τ	μ	
X_f	4.80	0.82	0.014	4.78	1.30	0.017	$\times 10^{-9}$

$$X_f \equiv \frac{m_f}{M_Z} N_c^f g_A^f Q_f e_D$$

$N_c = 1(3)$ for leptons (quarks)

$$\begin{aligned} B_f &\equiv \mathrm{Disc}[B_0(M_Z^2, m_f, m_f)], \\ C_f &\equiv C_0(0, 0, M_Z^2, m_f, m_f, m_f) \end{aligned}$$

B_0 and C_0 are the scalar two- and three-point Passarino-Veltman functions