Untangling the spin of a dark boson in Z decays

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based on: A.Comelato, EG, PRD 102 (2020); [arXiv:2006.00973]

M. Fabbrichesi, EG, B. Mele, PRL 120 (2018) 171803; [arXiv:1712.05412]

M. Cobal, C. De Dominicis, M. Fabbrichesi, EG, J. Magro, B. Mele, G. Panizzo, PRD 102 (2020); [arXiv:2006.15945]

Outlook

- Dark Sector
- Z decay into a photon + invisible boson X
- X-spin dependence of Z polarizations
- Phenomenology at FCC-ee
- Conclusions

The Dark Sector

- Accessible sector of New Physics could be light and feebly coupled
- Dark Sector (DS): neutral under SM gauge interactions
- Dark Matter could reside in a Dark Sector
- DS might possess rich internal structure and its own interactions
- could contain light or massless gauge bosons:
  - i.e. Dark Photons mediating long-range EM-like forces between charged Dark particles
- dark photons ($\bar{\gamma}$) can be also produced in Z decay $Z \to \gamma\bar{\gamma}$
- massless or ultralight dark photons behave as missing energy in the detector

$Z \to \gamma + X$

A.Comelato, EG [arXiv:2006.00973]

- Main characteristic signature:

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

- Best place to look for at e+ e- colliders (FCC-ee) $e^+e^- \to Z \to \gamma + X$
  - monochromaticity of photon mostly maintained (Z peak), slightly spread by initial beam radiation

- once a signal is observed, is possible to disentangle dark-photon from other scenarios that could mimic the same signature ?

- X light boson → three possible spin scenarios
  - spin-1 (dark-photon)
  - spin-0 (ALP → effective couplings $\gamma\gamma$ and $Z\gamma$)
  - spin-2 (KK gravity),...

How Dark Sector interacts with SM

via non-renormalizable interactions
→ high-dimensional operators

i.e. vector-portals like dark-photon

renormalizable interactions

SM $\longleftrightarrow$ **Messenger sector** $\longleftrightarrow$ Dark sector

heavy → scalars, vectors, fermions, → renormalizable interactions

At low energy ~ EW scale

Effective interactions between SM and Dark sector fields mediated by high-dimensional operators

(D=5,6 dimensions, the most relevant ones)

naturally suppressed by $1/\Lambda^{D-4}$

- Λ >> TeV → effective scale of the order of messenger-masses/couplings
- to discover Dark Sector high intensity (low energy) experiments favored !

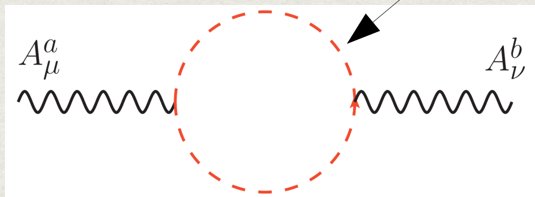
Dark Photon scenario

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

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

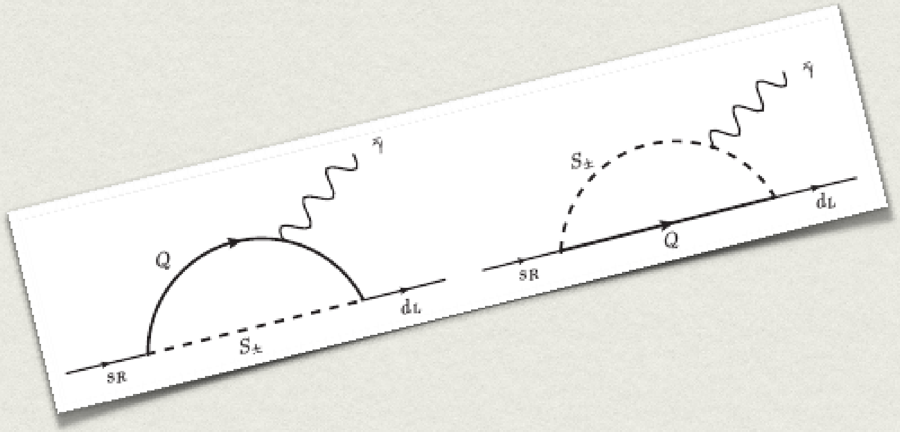
massive

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



[hep-ph/0411004]

we need a specific benchmark

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

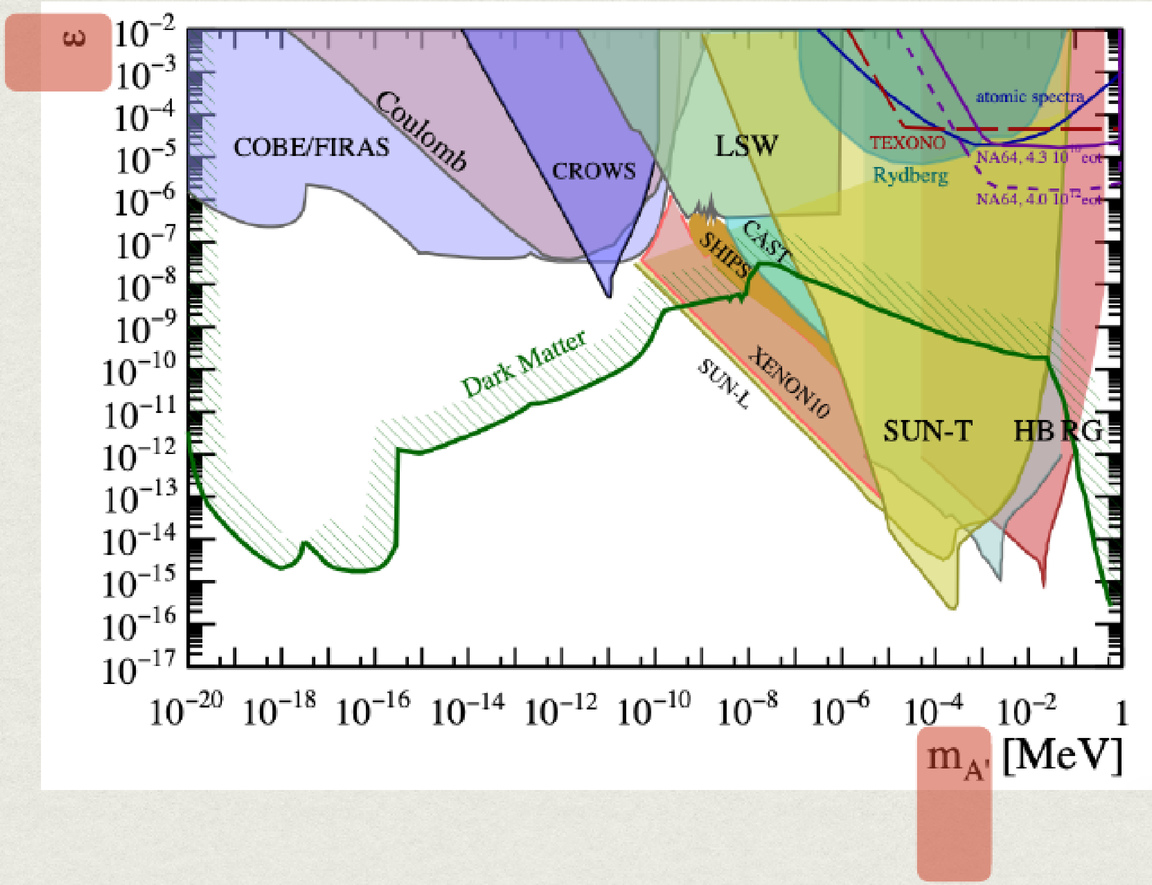
$$\mathcal{L} = \frac{e_D}{2\Lambda^2} \overline{\psi}_L^i \sigma_{\mu\nu} \left(\mathbb{D}_M^{ij} + i\gamma_5 \mathbb{D}_E^{ij}\right) H \psi_R^j F'^{\mu\nu} + \text{H.c.}$$

effective scale Λ

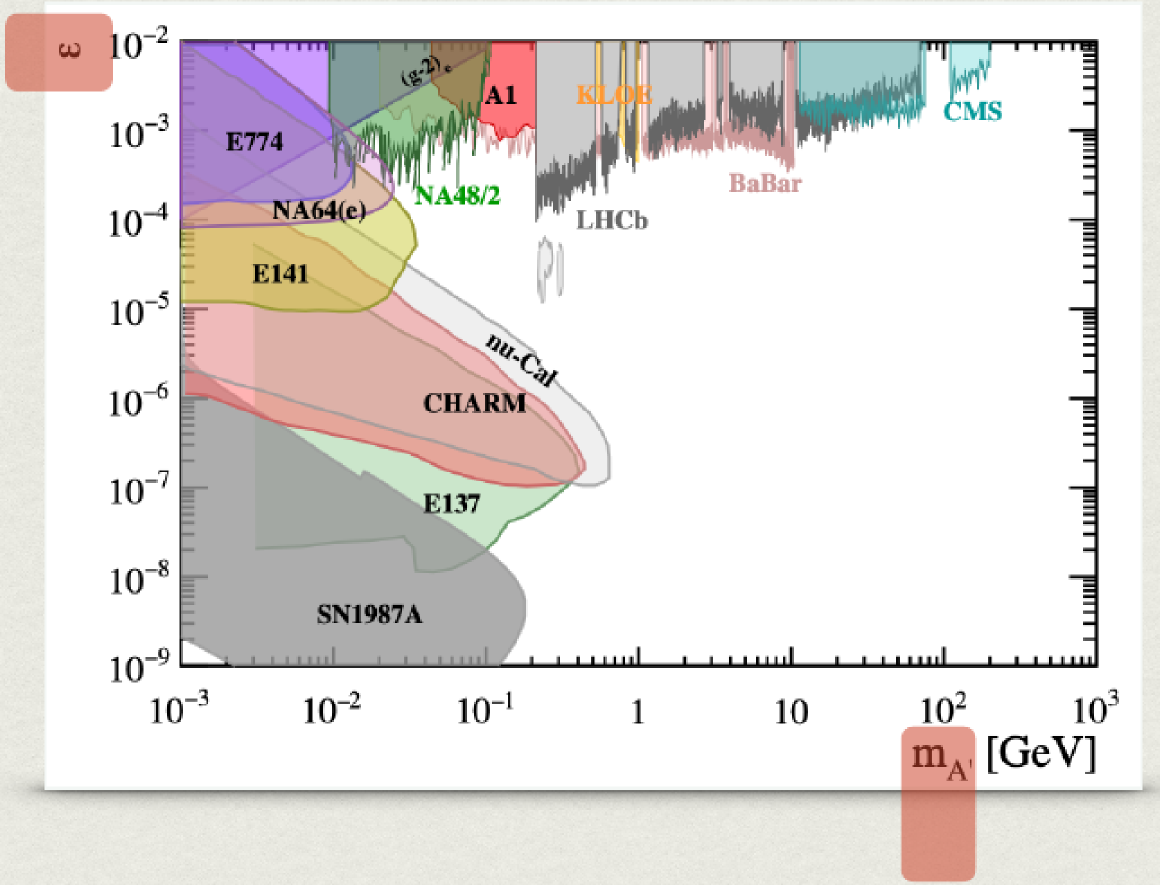
- **Massless dark photon interacts with SM particles via high dimensional operators → dim-5 (magnetic-dipole moments) leading contributions**

massive dark photon

invisible

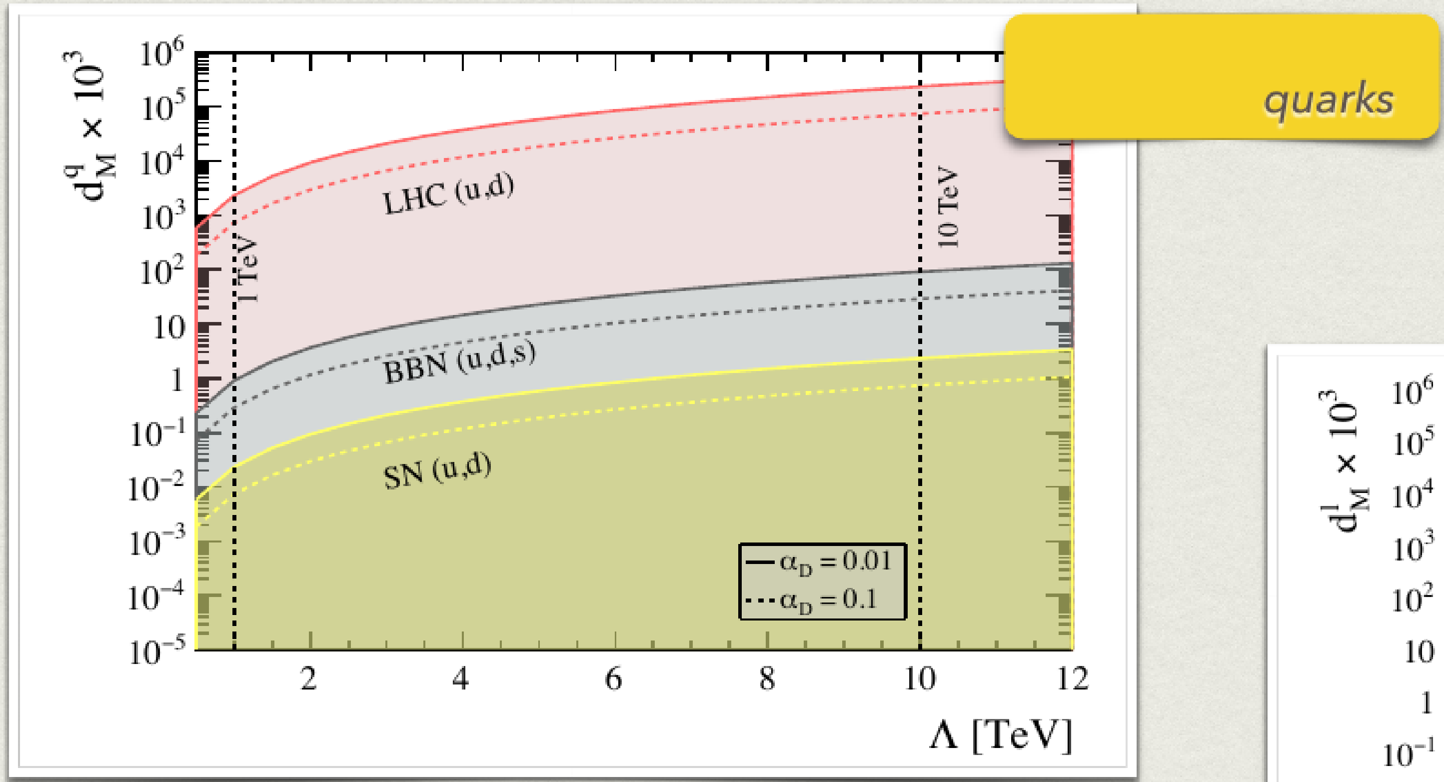


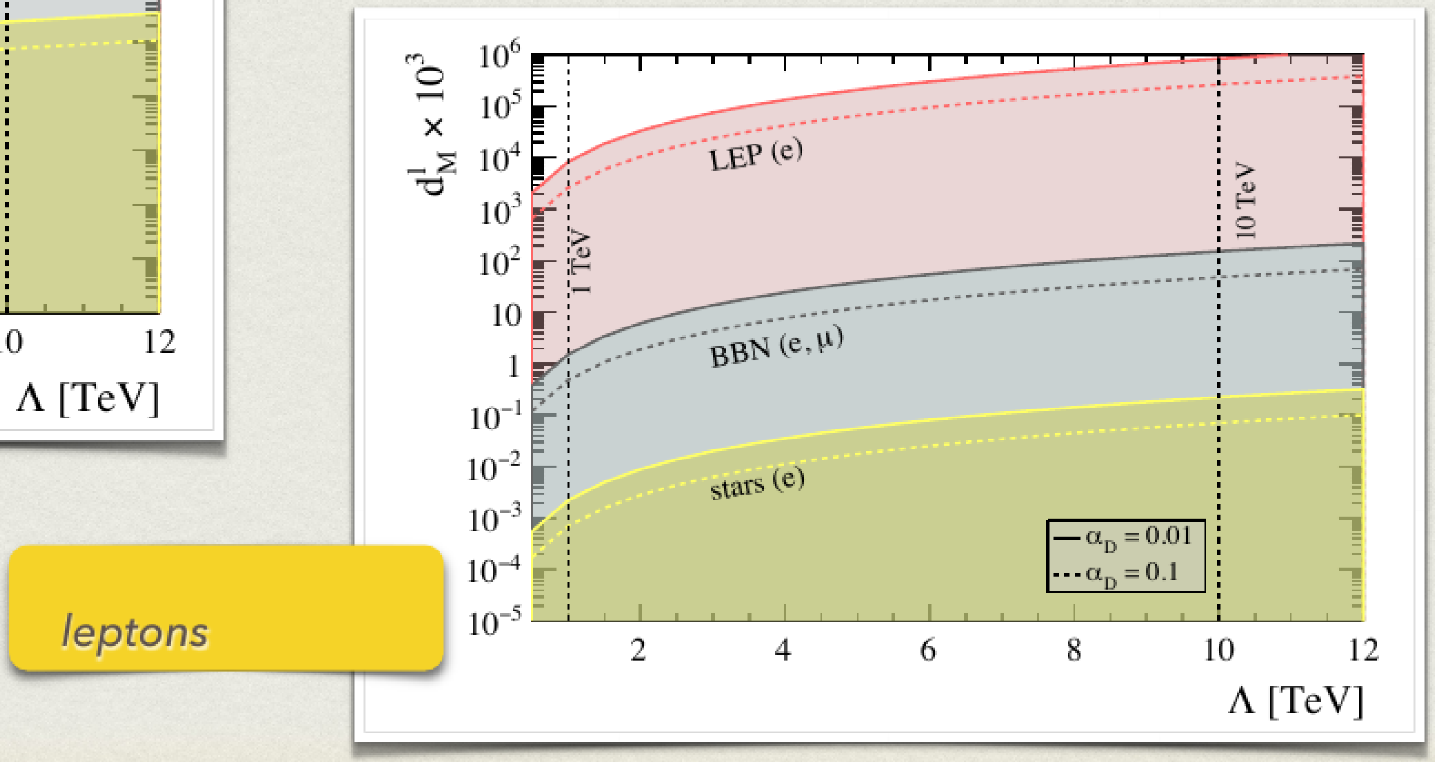
visible



limits on massive dark photon [from arXiv:2005.01515]

massless dark photon





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

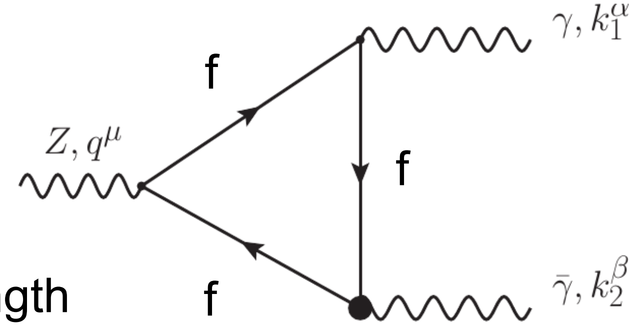
$$Z \to \gamma\bar{\gamma}$$

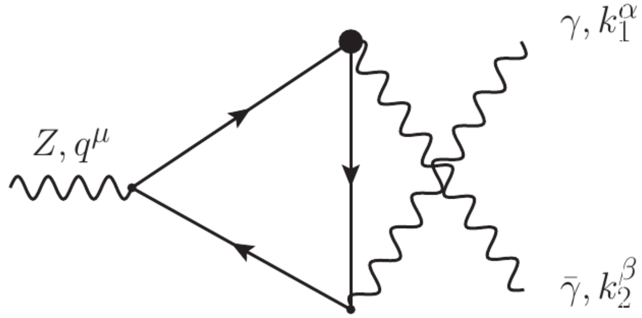
M. Fabbrichesi, EG, B. Mele
[arXiv:1712.05412]

f $\longrightarrow$ 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

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

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}

$d_M \simeq 0.1$
→ 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).

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

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

ALP scalar/pseudoscalar scenario

A={S,P}

$$\mathcal{L}^S_{eff} = \frac{1}{\Lambda_S}\varphi_S Z_{\mu\nu}F^{\mu\nu}$$
$$\mathcal{L}^P_{eff} = \frac{1}{\Lambda_P}\varphi_P Z_{\mu\nu}\tilde{F}^{\mu\nu}$$
$$\mathcal{L}^S_{eff} \supset \frac{1}{\Lambda_S^{\gamma\gamma}}\varphi F_{\mu\nu}F^{\mu\nu}$$

$$\hat{\Gamma}(Z\to\gamma\varphi_A) = \frac{C_A M_Z^3}{24\pi\Lambda_S^2}(1-r_A)^3$$

$C_S = 1$ and $C_P = 4$,

$r_A = m_A^2/M_Z^2$

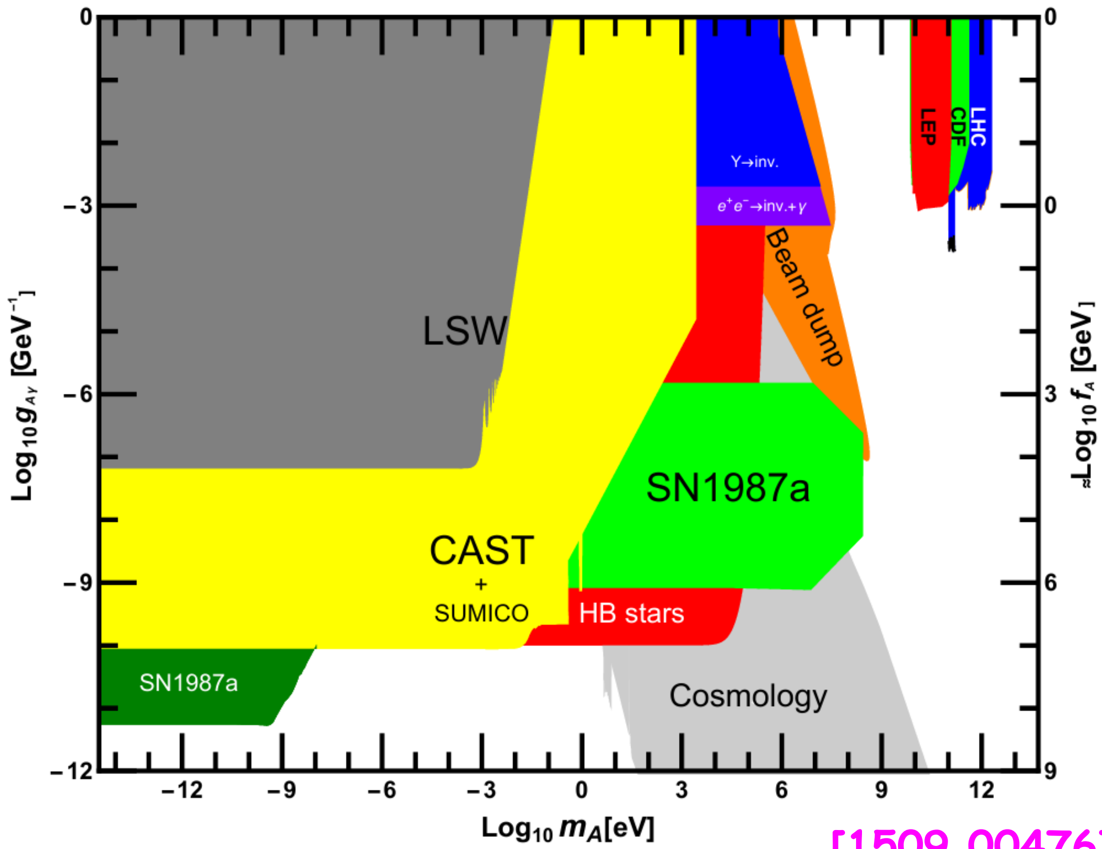
assume $\Lambda_S^{\gamma\gamma} \sim \Lambda_S$ → in UV completions these two scale are related by linear combination with coefficients of O(1) proportional to cosθ_W and sinθ_W → Weinberg angle

From astrophysics and other lab constraints

$m_S < 100\,\mathrm{MeV}$ $\quad \Lambda_S > 10^5 - 10^6\,\mathrm{TeV}$

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

too small to be detected @ FCC-ee

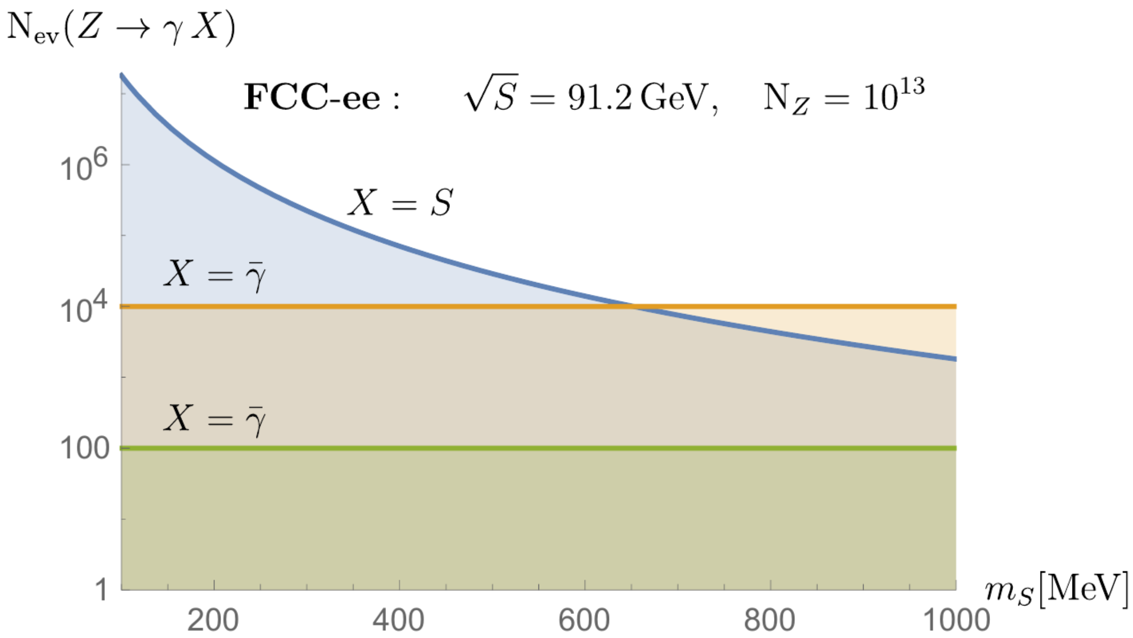


[1509.00476]

ALP scalar/pseudoscalar scenario

By requiring that the ALP does not decay inside the detector, that we conservatively take of length $L = 10\mathrm{m}$ for e^+e^- colliders, and assuming $\hat{\Gamma}(S \to \gamma\gamma)$ as the total width of ALP, we get

$$\Lambda_S \gtrsim 47 \left(\frac{m_S}{100\,\mathrm{MeV}}\right)^2 \mathrm{TeV}$$



we restrict to the range of ALP mass
100 MeV - 1 GeV

$$\mathrm{BR}(Z \to \varphi\gamma) \simeq 1.8 \times 10^{-6}(10^{-10})$$

[arXiv:2006.00973]

Spin-2 scenario

$G_{\mu\nu}$ 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

[arXiv:2006.00973]

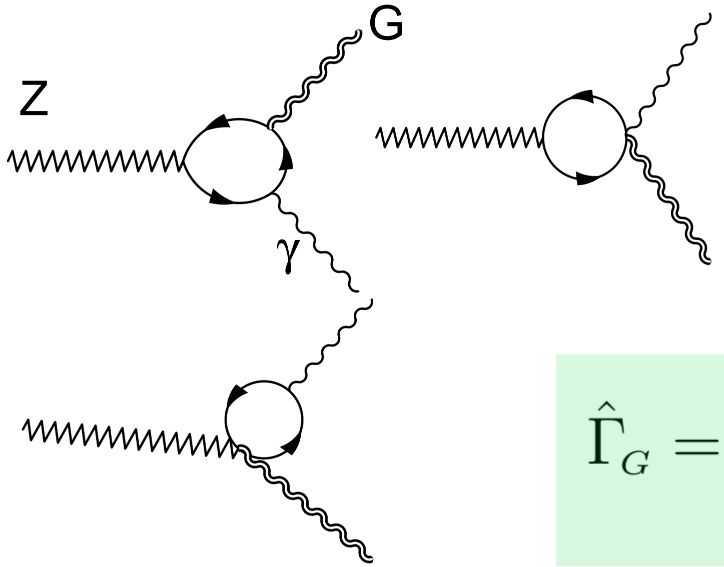
$$\Lambda_G \gtrsim 36 \left(\frac{m_G}{100\mathrm{MeV}}\right)^2 \mathrm{TeV}\,, \qquad 1\mathrm{eV} \lesssim m_G \lesssim 2m_\mu$$

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

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

Spin-2 scenario

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



B.C. Allanach et al, JHEP 11 089 (2007) [arXiv:0705.1953]

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

amplitude

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

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

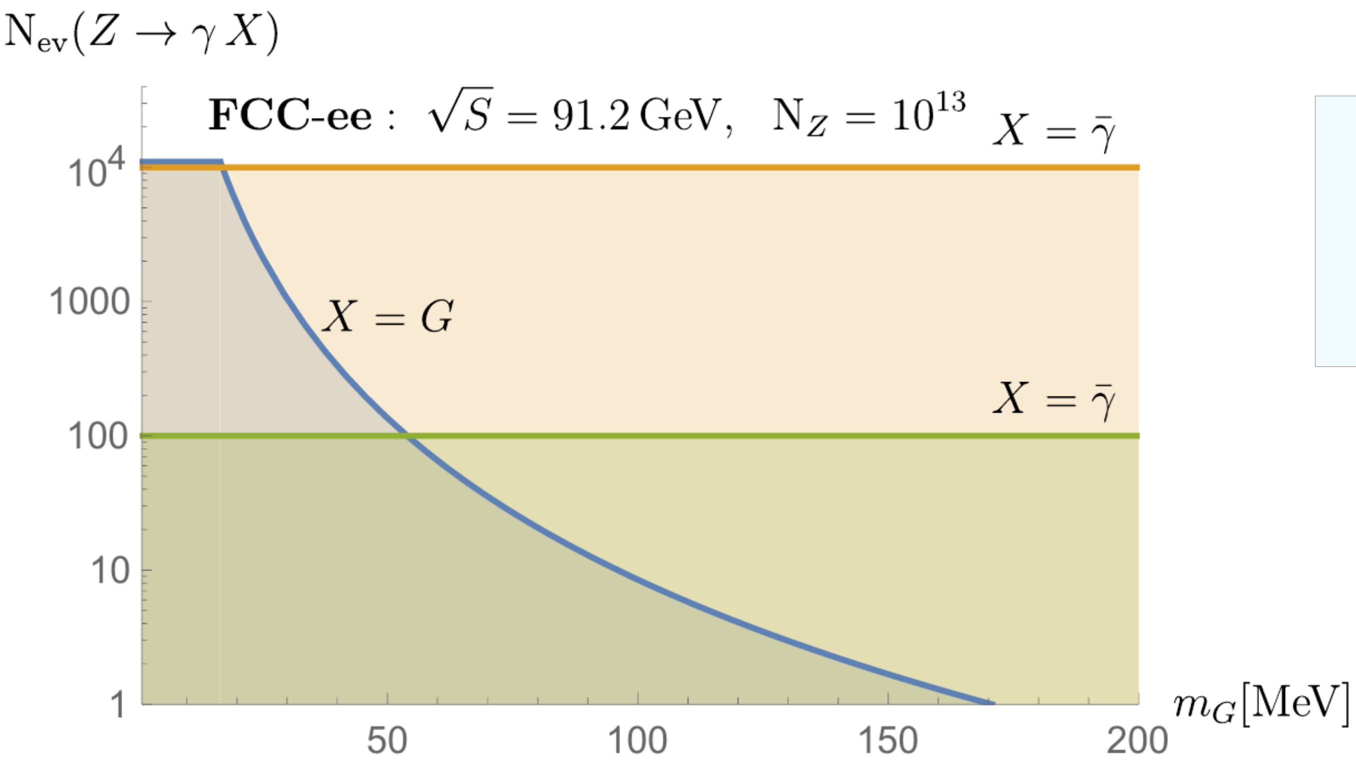
from 1-loop SM: finite result

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

Total width

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

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



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

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

[arXiv:2006.00973]

Polarized $Z \rightarrow \gamma + X$ decay

- Assuming a few signal events will be observed
- wonder if we can distinguish the spin (spin-1 not ruled out by LY theor.)
- angular distribution of photon is non trivial only for polarized Z decays
- angular distributions are different for X spin-1 and spin-0/2 (see next)
- Z comes out naturally polarized at e+ e- if Z is produced in resonance !
- e+e- offers unique opportunity to disentangle the X spin in $Z \rightarrow \gamma X$

Polarized $Z \to \gamma + X$ spin-1 case

case of boosted Z → Z-momentum defines a special direction [arXiv:2006.00973]

$$p_Z = E_Z(1,0,0,\beta)$$ $\beta = \sqrt{1-\frac{M_Z^2}{E_Z^2}}$ is the Z velocity

Consider Longitudinal (L) and Transverse (T) polarizations with respect to the Z-momentum

$$\frac{1}{\hat{\Gamma}}\frac{d\Gamma^{(T)}}{dz} = \frac{3}{4}\left(\frac{M_Z}{E_Z}\right)^5 \frac{1-z^2}{(1-\beta z)^4}$$
$$\frac{1}{\hat{\Gamma}}\frac{d\Gamma^{(L)}}{dz} = \frac{3}{2}\left(\frac{M_Z}{E_Z}\right)^3 \frac{(\beta-z)^2}{(1-\beta z)^4}$$

$\xrightarrow{\beta=0}$

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

$z \equiv \cos\theta_\gamma$

T-polarizations includes the average ½ factor over initial polarizations

θ_γ → angle between Z and photon 3-momenta

unpolarized process

$$\frac{d\Gamma}{dz}\Big|_{\beta=0} = \left(\frac{2}{3}\frac{d\Gamma^{(T)}}{dz} + \frac{1}{3}\frac{d\Gamma^{(L)}}{dz}\right)_{\beta=0} = \frac{\hat{\Gamma}}{2}$$

non-trivial angular distribution cancels out in unpolarized decay as expected

$\hat{\Gamma}$ → total width

Polarized $Z \to \gamma + X$

$\beta=0$

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)

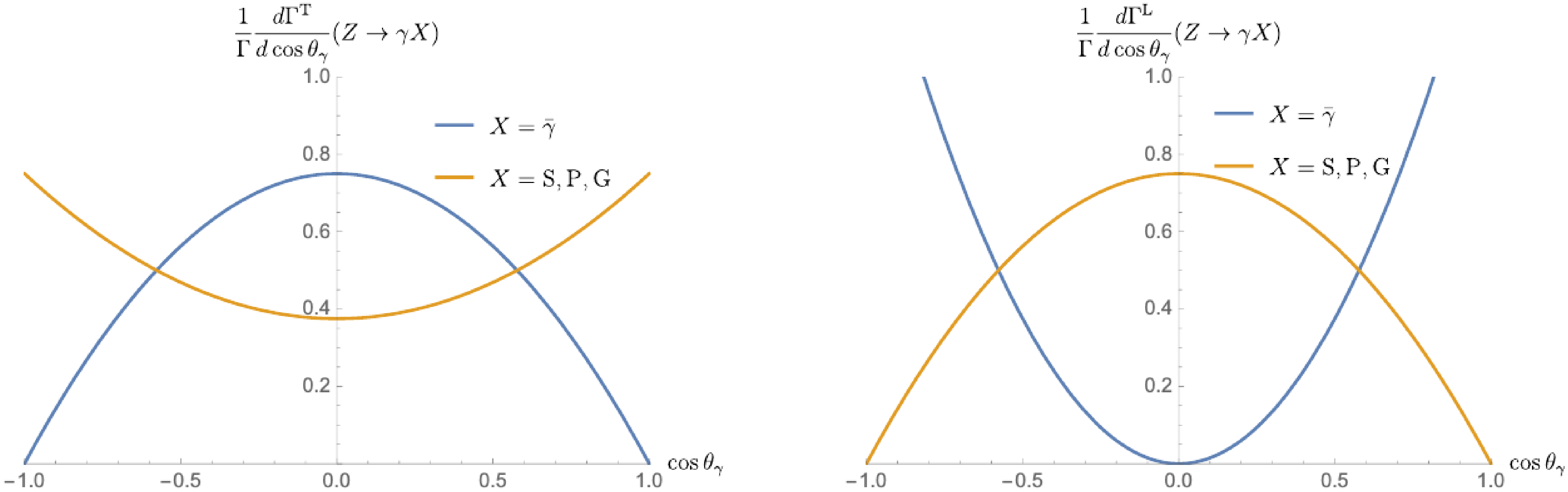
$$\frac{1}{\hat{\Gamma}_G}\frac{d\Gamma_G^{(T)}}{dz} = \frac{3}{8}\frac{\left(1+z^2\left(1-2\delta_G\right)+2\delta_G\right)}{1+\delta_G}$$

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

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

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

[arXiv:2006.00973]



Normalized distributions in $\cos\theta_\gamma$ for the polarized $Z \to \gamma X$ decay in the Z rest frame, with Γ the corresponding unpolarized total width, for the scenarios of X as massless dark-photon ($\bar{\gamma}$), scalar/pseudoscalar (S/P) and spin-2 (G) particles. Here θ_γ is the angle between the directions of photon momentum and the J_z spin axis of the Z The distributions of transverse T and longitudinal L polarizations of the Z, corresponding to $J_z = \pm 1$ and $J_z = 0$ respectively, are shown in the left and right plots respectively.

[arXiv:2006.00973]

Z decays at e^+e^- colliders

$$e^+e^- \to Z \to \gamma X \qquad \text{at the } Z \text{ peak}$$

Work in center of mass frame $p_{e^-} = (E, 0, 0, E)$ $\quad E = \sqrt{S}/2$ c.o.m. energy

$$p_{e^+} = (E, 0, 0, -E)$$

Consider Transverse and Longitudinal Z polarizations w.r.t. the beam z-axis

For a Z at rest

Transverse

$$\varepsilon_Z^{\mu\,(\pm)} = \frac{1}{\sqrt{2}}(0, 1, \pm i, 0)$$

Longitudinal

$$\varepsilon_Z^{\mu\,(L)} = (0, 0, 0, 1)$$

that for a boosted Z along beam generalize to

$$\varepsilon_Z^{\mu\,(L)} = \frac{1}{M_Z}(k_Z, 0, 0, E_Z)$$

Transverse polarizations correspond to the spin Z J_Z = +/- 1 along the beam axis polar angle   azimuthal angle

Photon 4-momentum $k_\gamma = \frac{E}{2}(1, \sin\theta_\gamma \cos\phi_\gamma, \sin\theta_\gamma \sin\phi_\gamma, \cos\theta_\gamma)$

angle θ_γ is between photon-momentum and initial e- beam direction

useful factorization for a generic final state X_f

$$d\Gamma_f(e^+e^- \to Z \to X_f) = C_Z^+ d\Gamma_f^+ + C_Z^- d\Gamma_f^- + C_Z^L d\Gamma_f^L$$

$d\Gamma_f^\pm$ $(d\Gamma_f^L)$ are the differential Z widths for polarized $Z \to X_f$ decay

For a Z boson at rest (neglecting m_e) we have

$$C_Z^\pm = \frac{1}{2}\left(1 \mp \frac{2g_V^e g_A^e}{(g_V^e)^2 + (g_A^e)^2}\right), \quad C_Z^L = \mathcal{O}(m_e/M_Z)$$

for a boosted Z
(β along axis)

$$C^\pm = \frac{1}{2}\left(1 \mp \frac{2g_V^e g_A^e}{(g_V^e)^2 + (g_A^e)^2}\frac{(1-\beta)^2}{1-\beta^2}\right)$$

Z boson comes out mainly T polarized → consequence of spin-1 nature and angular momentum conservation

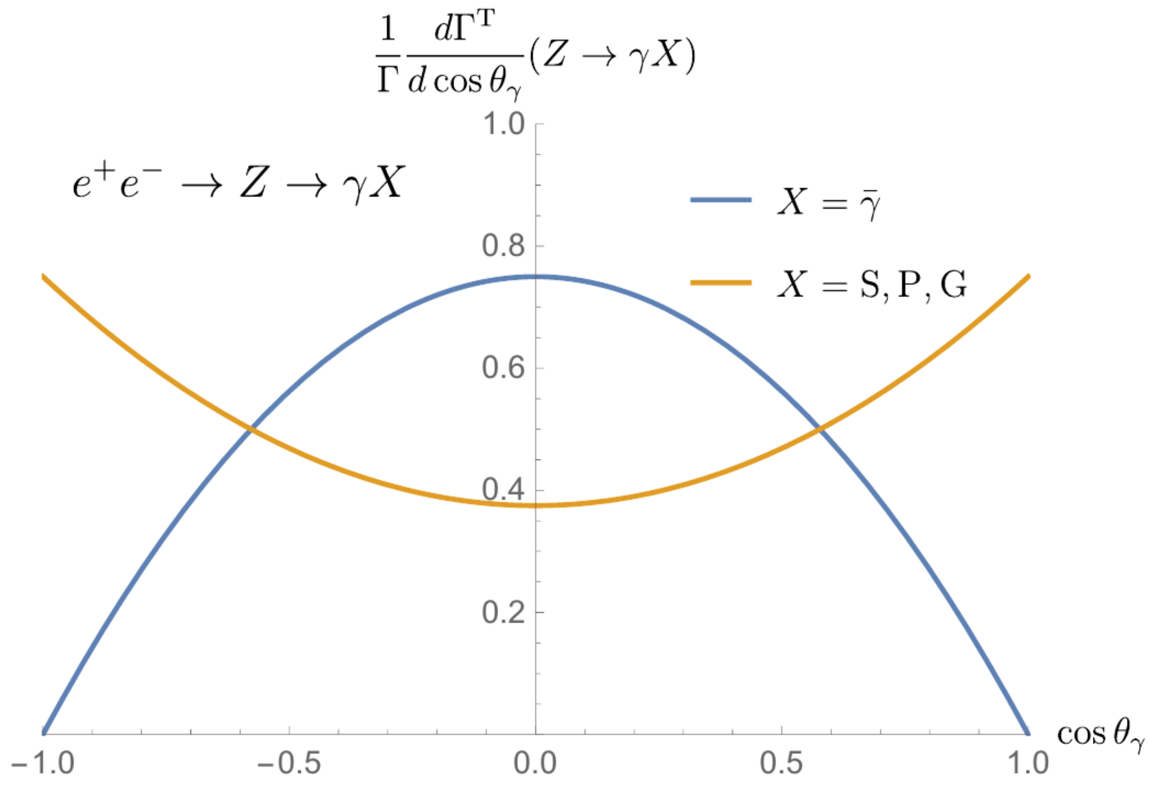
For $Z \to \gamma X$ $\Rightarrow$ $$\frac{d\Gamma^+}{dz} = \frac{d\Gamma^-}{dz}$$

which means the $C^{\pm}$ enter in combination → $C^+ + C^- = 1$

interactions relevant for the Z → γ X process do not induce a parity violation

angle θ_γ

between direction photon
and initial e- beam direction



($m_G \to 0$)

X spin can be disentangled → spin-1: photon mainly produced central and at large angles
spin-0/2: " " " along Forward-Backward dir.

Why $Z \to \gamma\,\bar{\gamma}$ amplitude vanishes for FB photons ?

e+ e- center of mass frame

consider massless dark-photons

{ chiral conservation of vectorial currents }

$e^+e^- \to Z$

due to angular momentum conservation
Z comes out (mainly) Transverse polarized

$J_z(e+) = +½$ $J_z(e-) = +½$ $m_e \to 0$ $J_Z(Z) = +1$

(analogous for $J_Z = -1$)

p_{e+} p_{e-} $Z(p_Z=0)$

p_γ θ_γ Z-axis $p_{\bar{\gamma}}$

$$\theta_\gamma = 0, \pi$$

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

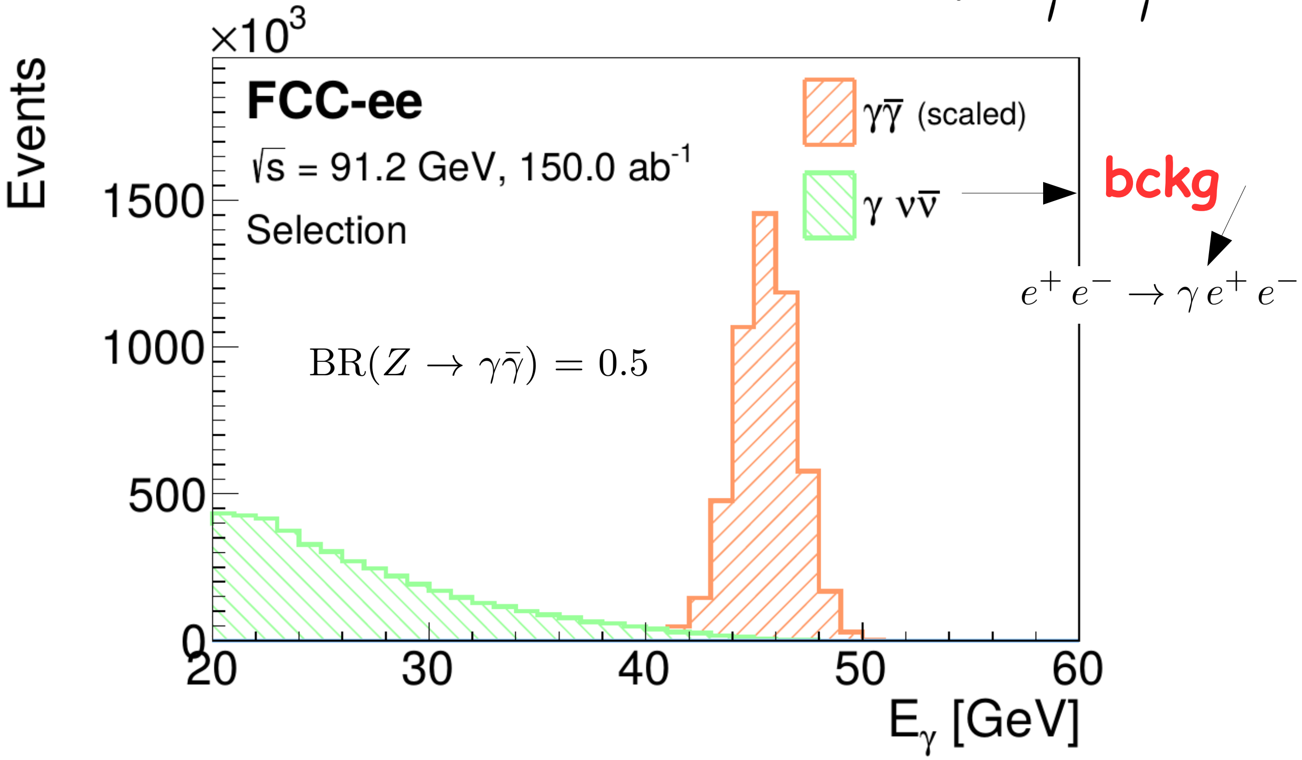
$L = 0$ $J_Z(\bar{\gamma}) = \pm 1$ $J_Z(\gamma) = \pm 1$

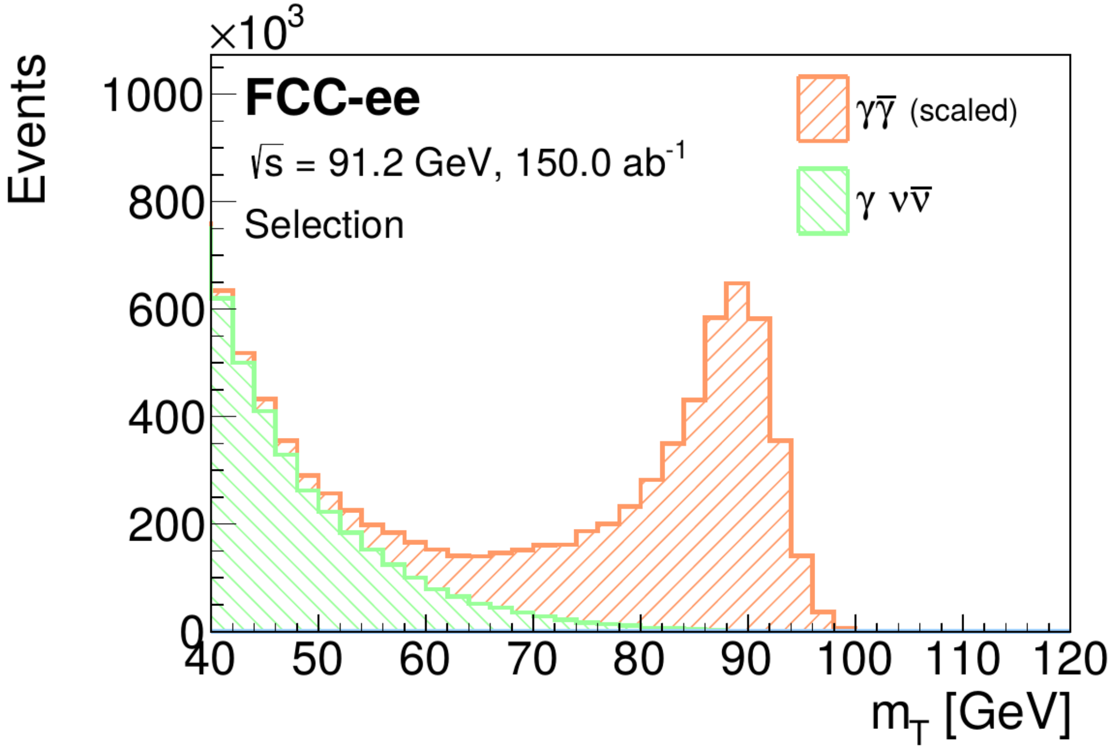
$$|J_Z^{\mathrm{tot}}| = 2, 0$$

$p_{\bar{\gamma}}$ p_γ

due to angular momentum conservation
Amplitude at FB directions must vanish

$Z \to \gamma\,\bar{\gamma}$ @ FCC-ee [arXiv:2006.15945]





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 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.

Conclusions

- $Z \to \gamma X$ with X a light long-lived dark (invisible) boson

- Main signature → monochromatic photon + missing energy (neutrino-like)

- Potential scenarios of X matching the same signature
  - spin-1 Dark Photon: massless case allowed by LY theorem (due to distinguishability)
  - massive spin-0 ALP (axion-like particles)
  - massive spin-2 particles (KK gravitons, composite spin-2, etc)

- largest expected BR in the range $10^{-12} \lesssim \mathrm{BR}(Z \to \gamma X) \lesssim 10^{-6}$,

- best place to search for this signature @ e+ e- colliders, FCC-ee with $10^{13}\ Z$

- Z comes out mainly polarized at e+e- → non trivial angular photon distribution

  - different γ–angular distributions → spin-1 (large angles) spin-0/2 (mainly FB)
  - possible to disentangle spin-1 and spin-0/2,
  - spin-2 can be disentangled from spin-0 only for large spin-2 masses

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)

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

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

Spin analysis using test statistics

The exclusion of the $J^P = 0^-$ hypothesis in favor of the dark photon $J^P = 1^-$ hypothesis is evaluated in terms of the corresponding $\mathrm{CL_s}(0^-)$, defined as:

$$\mathrm{CL_s}(0^-) = \frac{p_0(J^P = 0^-)}{1 - p_0(J^P = 1^-)}$$

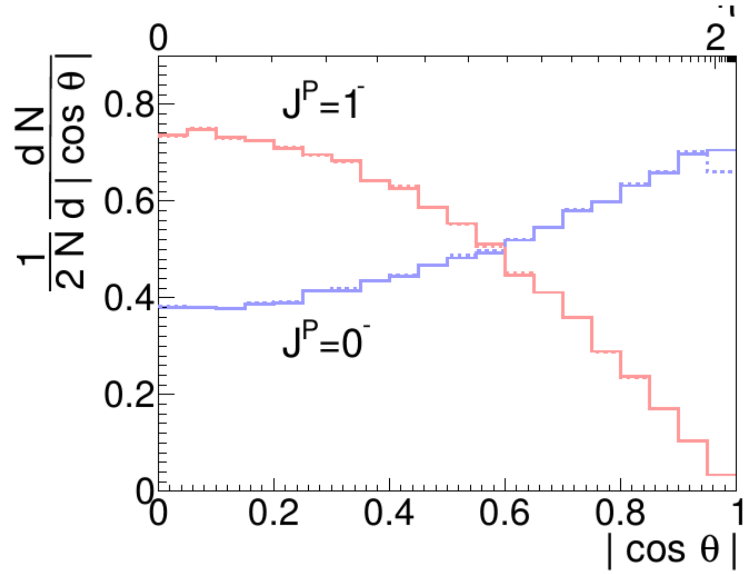


Figure 6. Differential cross section as a function of the cosine of the detected photon polar angle θ when produced in association with a pseudoscalar (blue) or vector (red) massless dark particle, after background subtraction. Dashed lines describe the corresponding distribution when including detector smearing effects. The upper axis maps the same range in photon pseudorapidities.

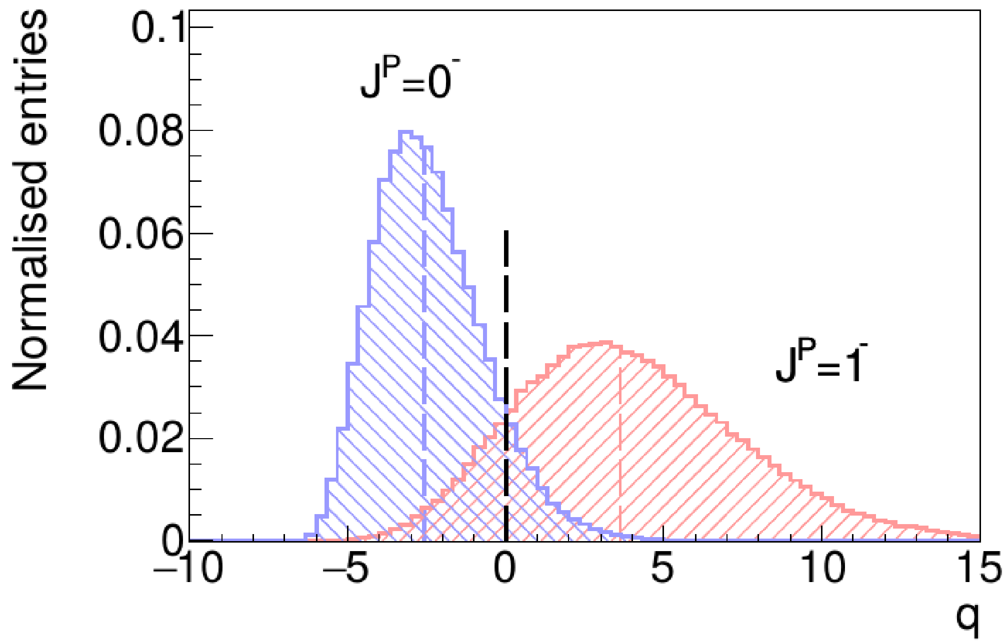


Figure 7. Expected distributions of the log likelihood ratio test statistics q under the $J^P = 0^-$ and $J^P = 1^-$ spin hypotheses, both for the $J^P = 0^-$ (left) and $J^P = 1^-$ (right) signals. Distributions are obtained using $n_{\mathrm{toys}} = 160000$ and assuming $N = 10$ signal events. The expected medians are indicated by vertical dashed lines, and analogously the hypothetical observed value is assumed to occur at $q = 0$.

$$q = \log \frac{\mathcal{L}(J^P = 1^-, \hat{\hat{\mu}}_{1^-}, \hat{\hat{\boldsymbol{\theta}}}_{1^-})}{\mathcal{L}(J^P = 0^-, \hat{\hat{\mu}}_{0^-}, \hat{\hat{\boldsymbol{\theta}}}_{0^-})}$$

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.