Dark Matter and Axion Like Particles

exposing dark sectors with future Z-factories

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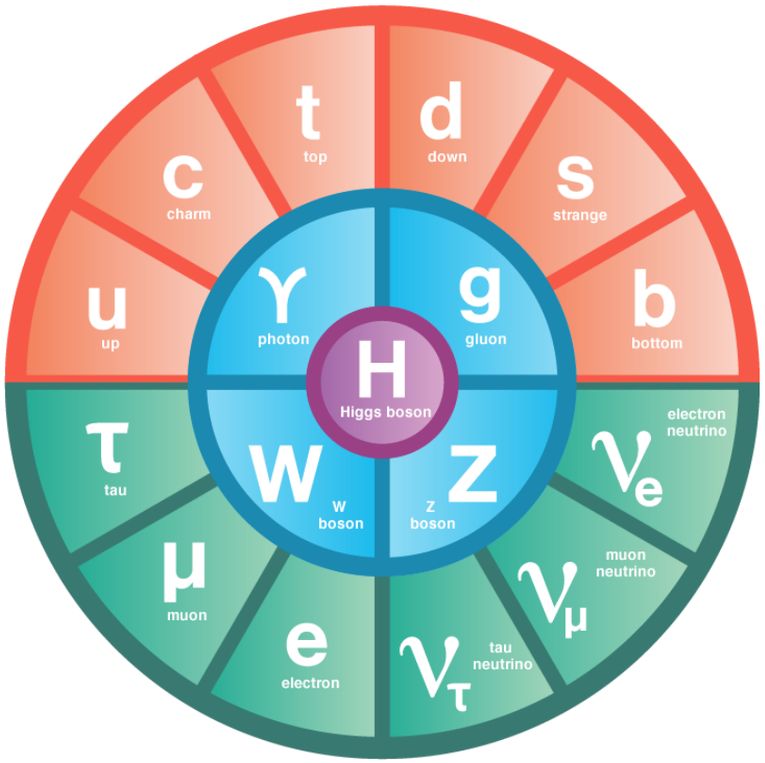
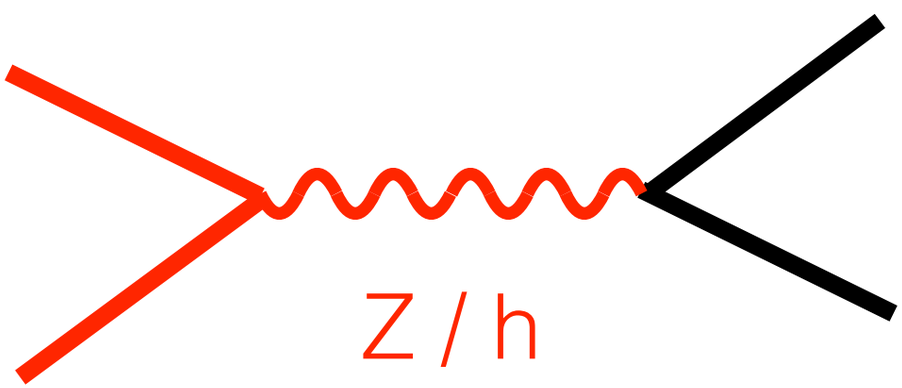
with Jia Liu, Liantao Wang, Xiaoping Wang
arXiv: 1712.07237 PRD

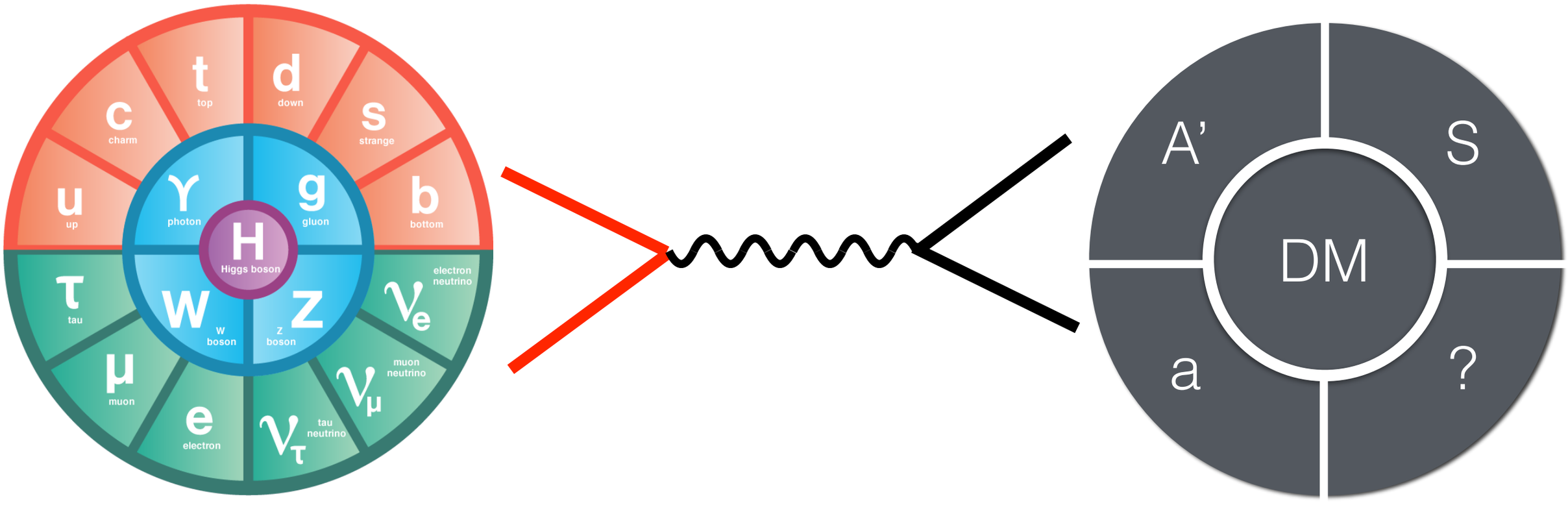
WIMP

weakly interacting massive particles



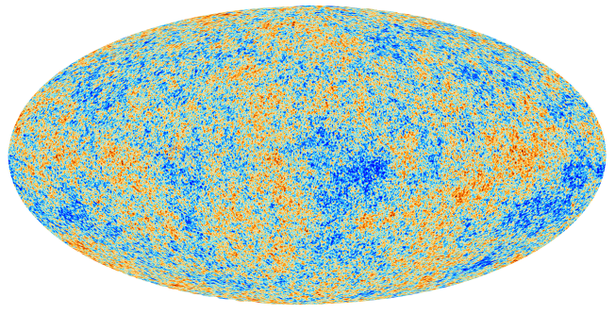


Dark Sectors

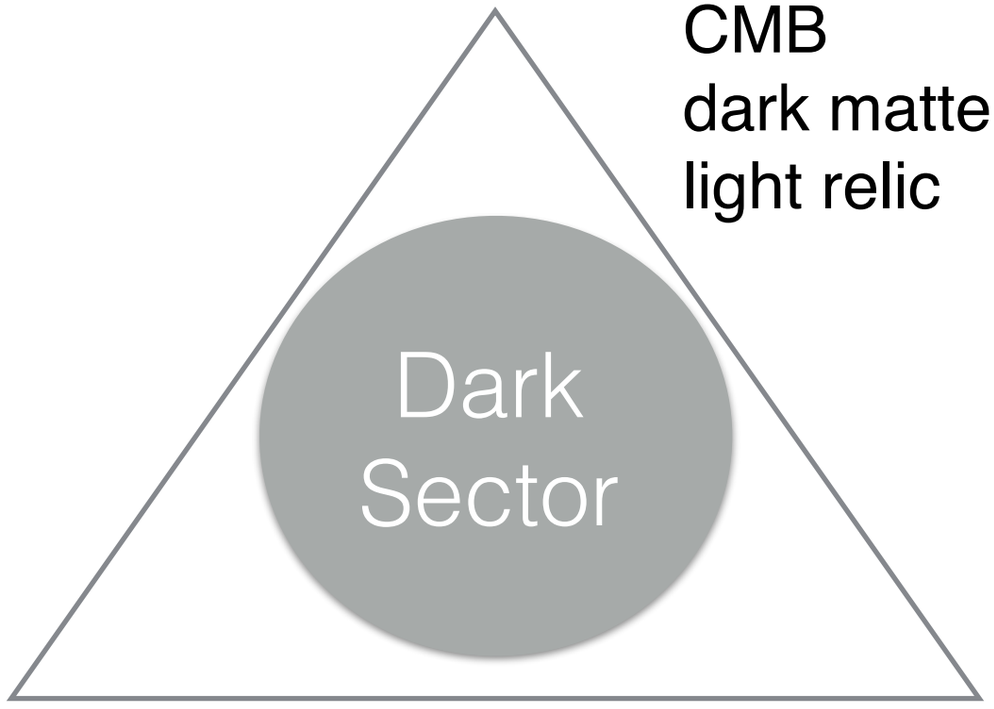


Probing dark sector in all the directions

Cosmology



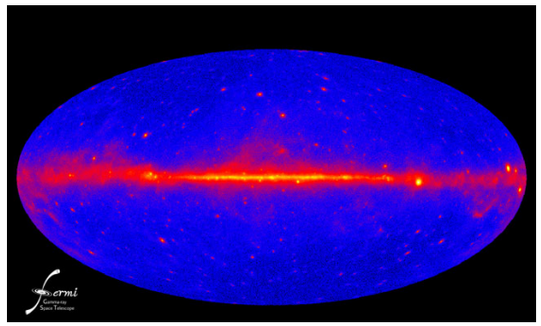
CMB
dark matter annihilation
light relic



Particle Physics

LHC
future colliders
XENONnT, LZ
SuperCDMS, …
SHiP, …

Astrophysics



FermiLAT
AMS
LISA
…

Probing dark sector with Z-factories

- Can the future e^+e^- colliders (exotic Z decay) search for dark sector?

  Is it better than other searches?

  dark matter direct and indirect detection experiments

  colliders

- How many Z will be produced?
  Giga Z (10^9) 22.9 fb^{-1}
  Tera Z (10^{12}) 22.9 ab^{-1}

- the existing LEP searches
  $Z \rightarrow 3\,\gamma$
  $Z \rightarrow \ell^+\ell^-$ + invisible
  …

Plan

- starting from models
  - Higgs portal
    mixing with Higgs
    vector portal
    mixing with $U(1)_Y$ gauge fields
  - axion-like particles
    higher dimensional operators

- model independent
  classified by final states, topologies and resonances

Higgs portal + fermionic DM

- S and higgs mixing

$$\mathcal{L} = -\lambda_1 \left(H^\dagger H\right) S - \lambda_2 \left(H^\dagger H\right) S^2 + \cdots$$

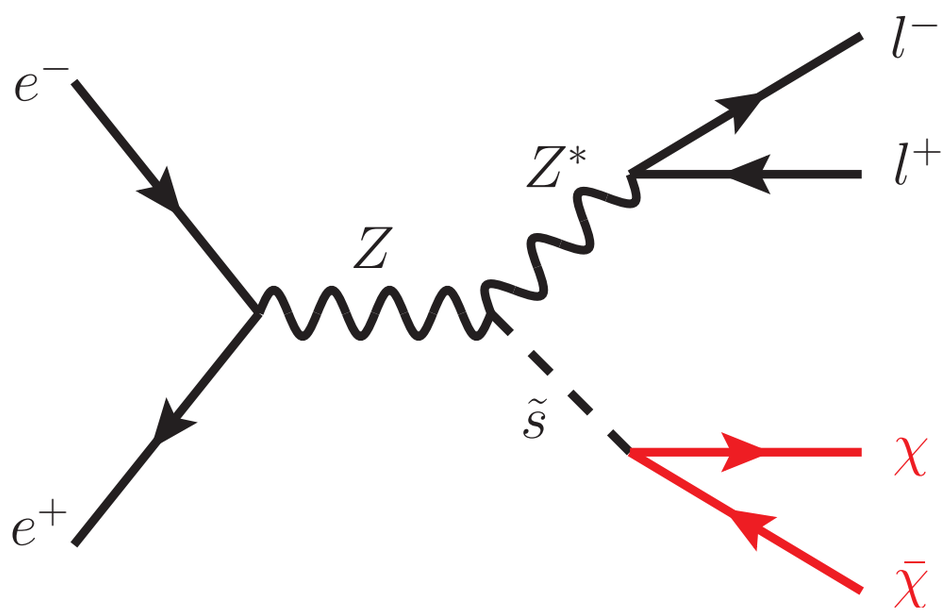
mixing angle α

$$\begin{pmatrix} \tilde{h} \\ \tilde{s} \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

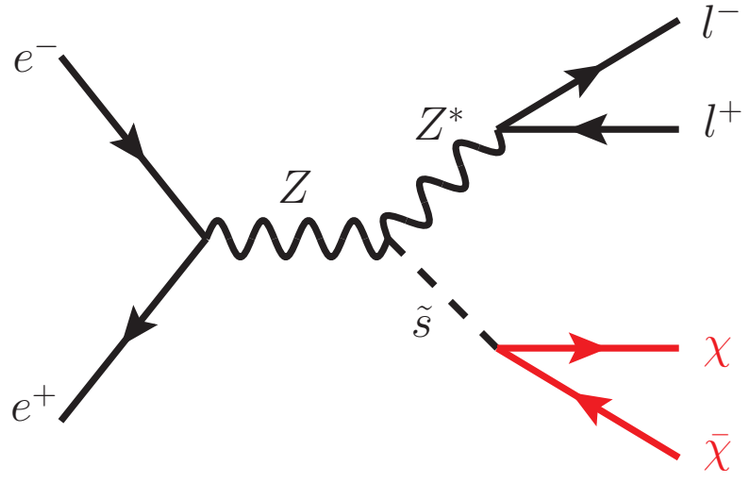
- linking to dark matter χ

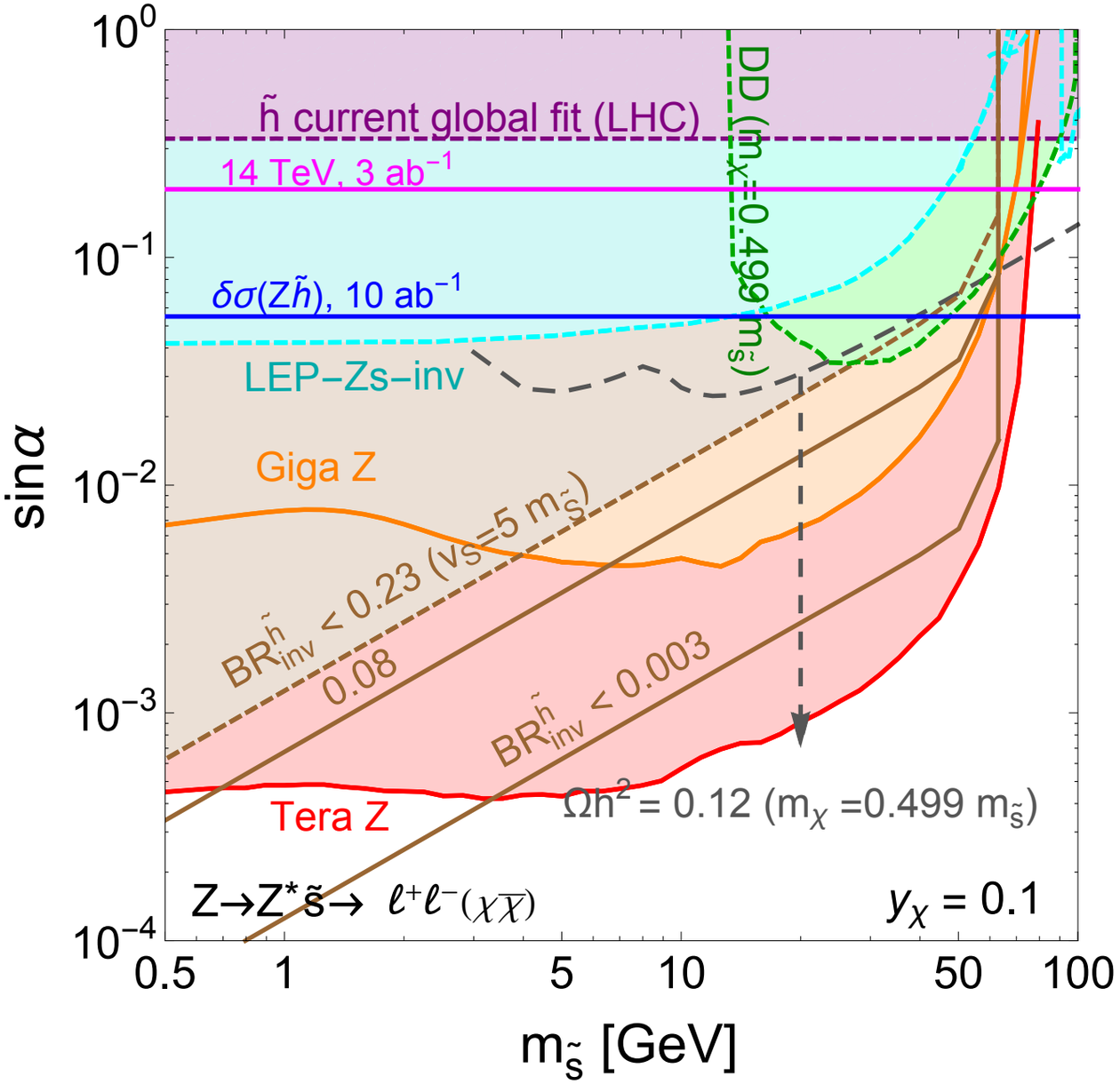
$$\mathcal{L} = -y_\chi S \bar{\chi}\chi$$

- exotic Z decays
  (MET+$\ell^+\ell^-$, 1 resonance)



Higgs portal + fermionic DM





- higgs invisible decay (h→ss)
- indirect detection (p-wave)
  direct detection (> 10 GeV)

Vector portal + scalar DM

- A′ and U(1)$_Y$ gauge field B mixing

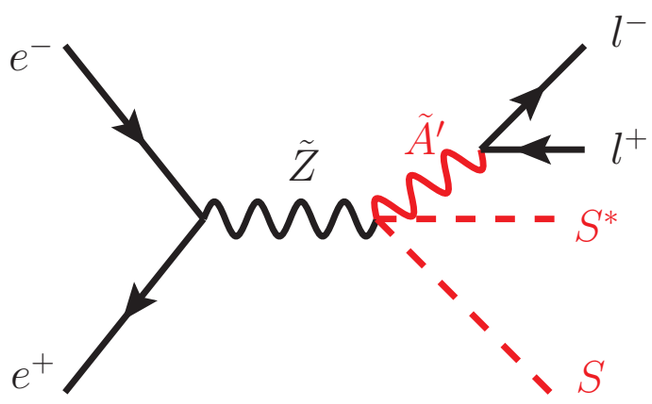
$$\mathcal{L} = \frac{\epsilon}{2c_W} B^{\mu\nu} A'_{\mu\nu} + \cdots$$

A′ mix with Z and photon

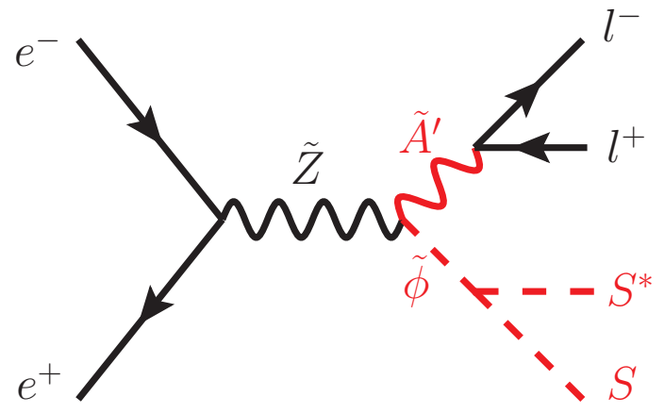
$$\begin{pmatrix} Z_\mu \\ A_\mu \\ A'_\mu \end{pmatrix} = \begin{pmatrix} 1 & 0 & \frac{m^2_{A'} t_W}{-m^2_{A'} + m^2_Z}\epsilon \\ 0 & 1 & \epsilon \\ \frac{m^2_Z t_W}{m^2_{A'} - m^2_Z}\epsilon & 0 & 1 \end{pmatrix} \begin{pmatrix} \tilde{Z}_\mu \\ \tilde{A}_\mu \\ \tilde{A'}_\mu \end{pmatrix}$$

- linking to scalar dark matter

$$\mathcal{L}_S = (\partial_\mu S + i g_D A'_\mu S)^* (\partial^\mu S + i g_D A'^\mu S) - m_S^2 S^* S$$



(MET+$\ell^+\ell^-$, 1 resonance)



ϕ gives mass to S and A′
(MET+$\ell^+\ell^-$, 2 resonances)

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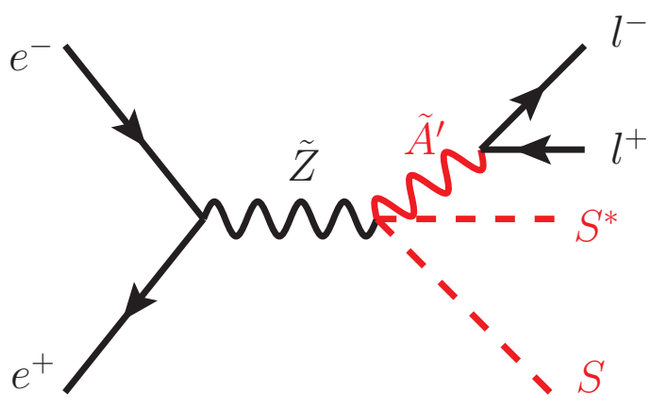

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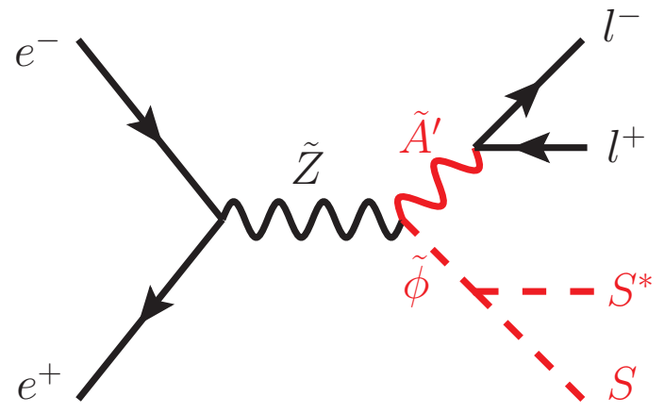

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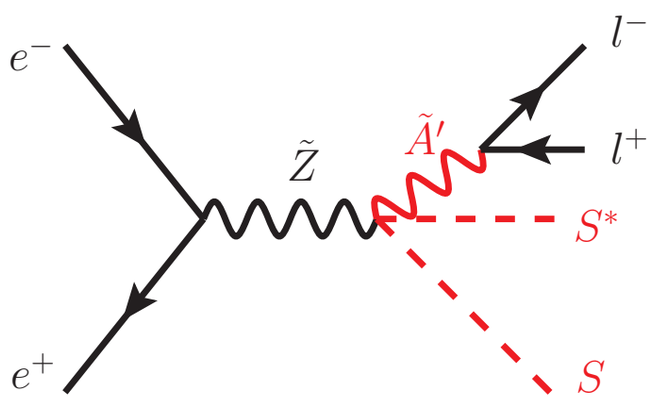
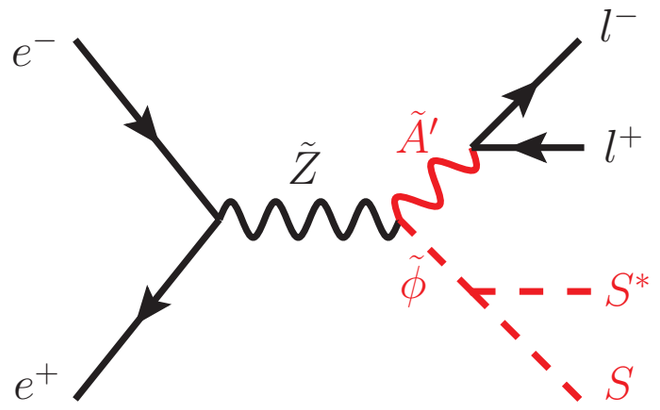


(MET+$\ell^+\ell^-$, 1 resonance)



ϕ gives mass to S and A′
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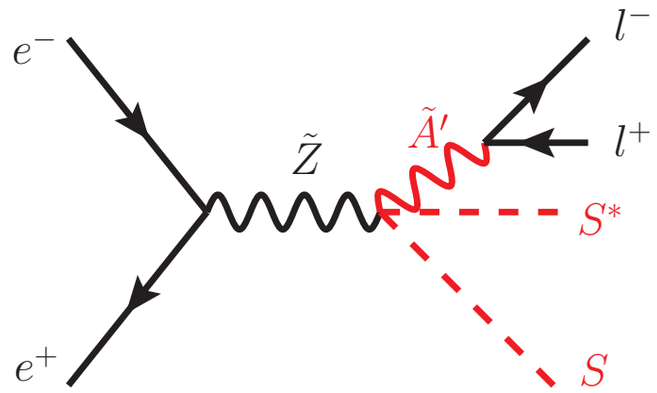
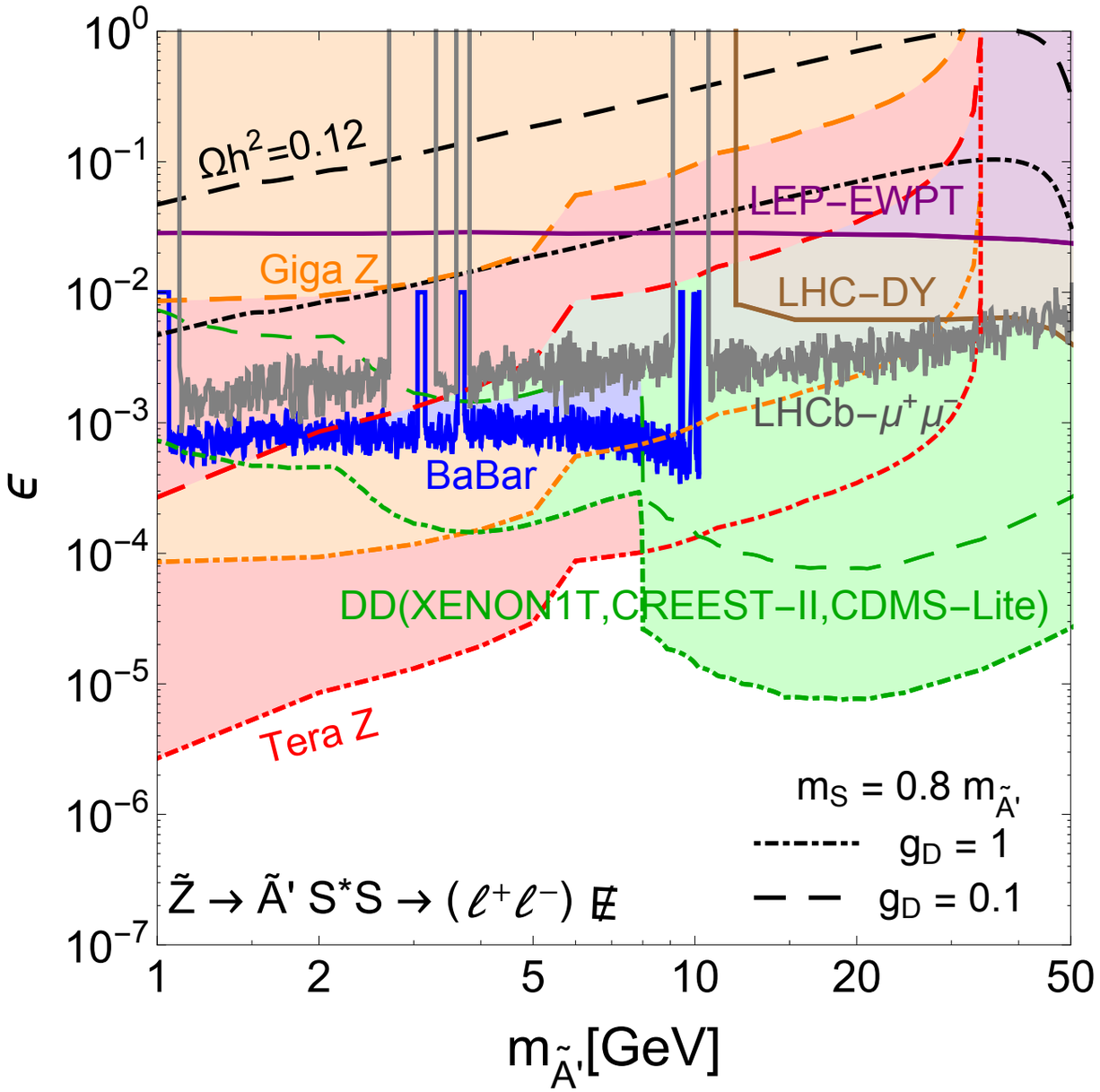
Vector portal + scalar DM





- dark photon searches BaBar and LHCb
- indirect detection (p-wave) direct detection (> 10 GeV)

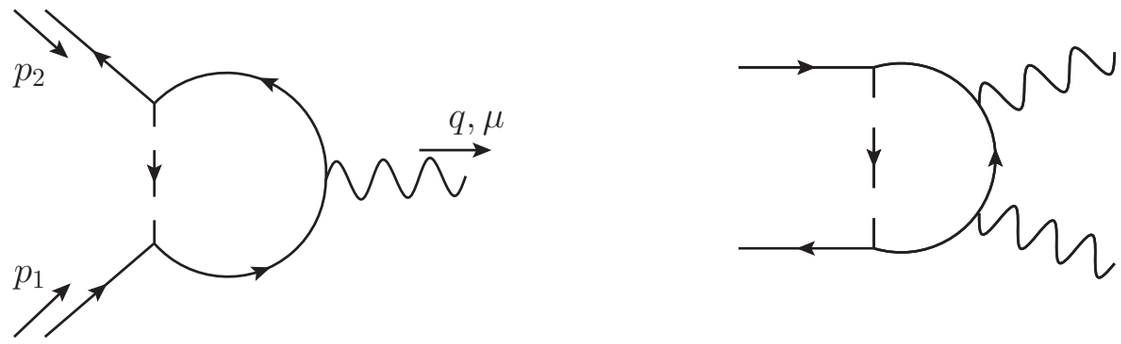
Higher dimensional Operators

- Magnetic inelastic DM (MIDM) and Rayleigh DM (RayDM)

$$O_{\mathrm{MIDM}} = \frac{1}{\Lambda_{\mathrm{MIDM}}} \bar{\chi}_2 \sigma^{\mu\nu} \chi_1 B_{\mu\nu} + h.c., \quad O_{\mathrm{RayDM}} = \frac{1}{\Lambda^3_{\mathrm{RayDM}}} \bar{\chi}_1 \chi_1 B^{\mu\nu} B_{\mu\nu}$$

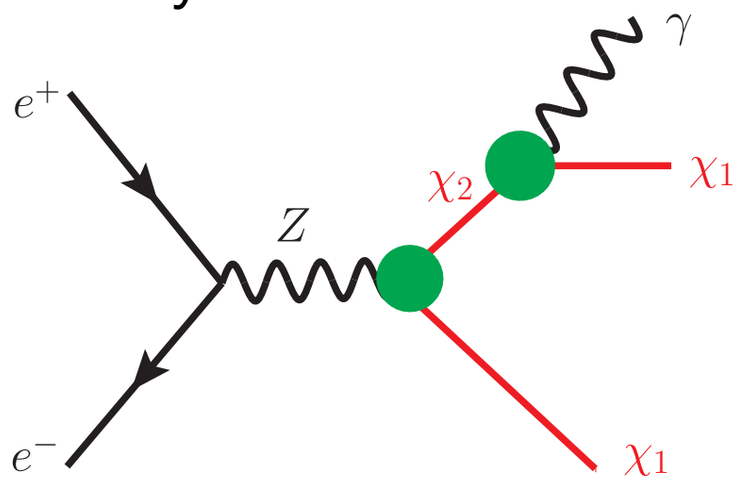
- from the same UV theory (χ has Dirac and Majorana mass)

$$(\lambda \bar{\psi} \chi \phi + h.c.)$$

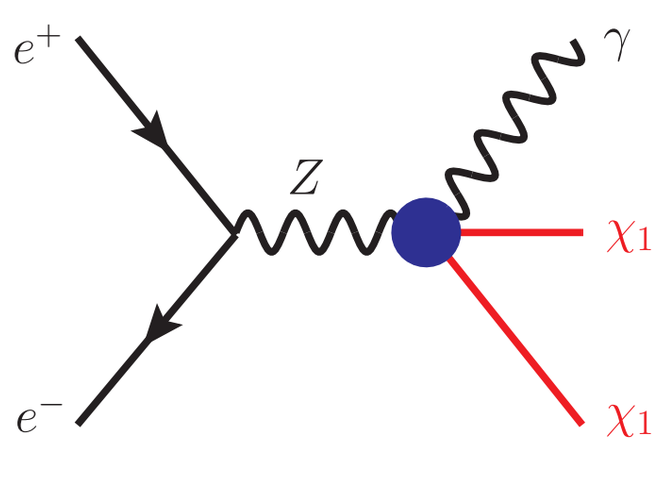


[N. Weiner, I. Yavin arXiv : 1206.2910]

- exotic Z decays

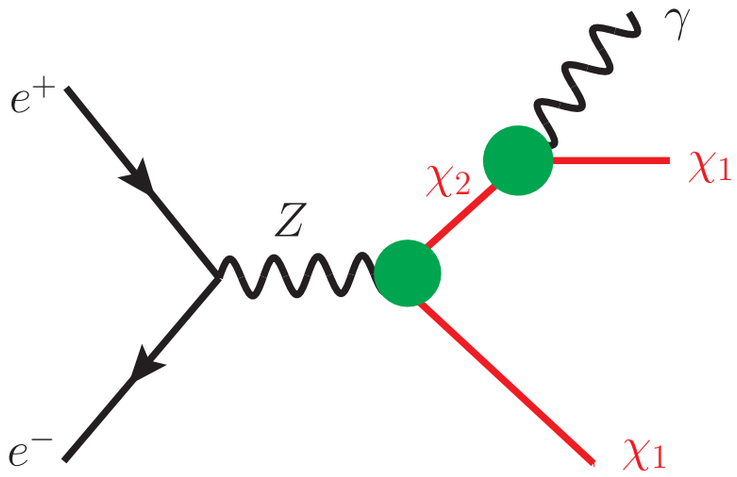


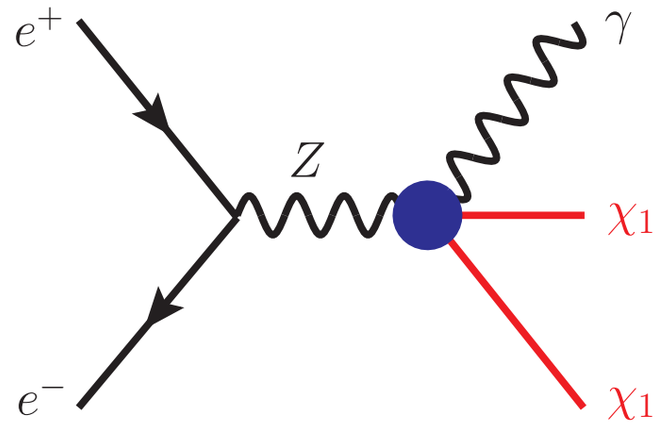
(MET + γ, 0 res)

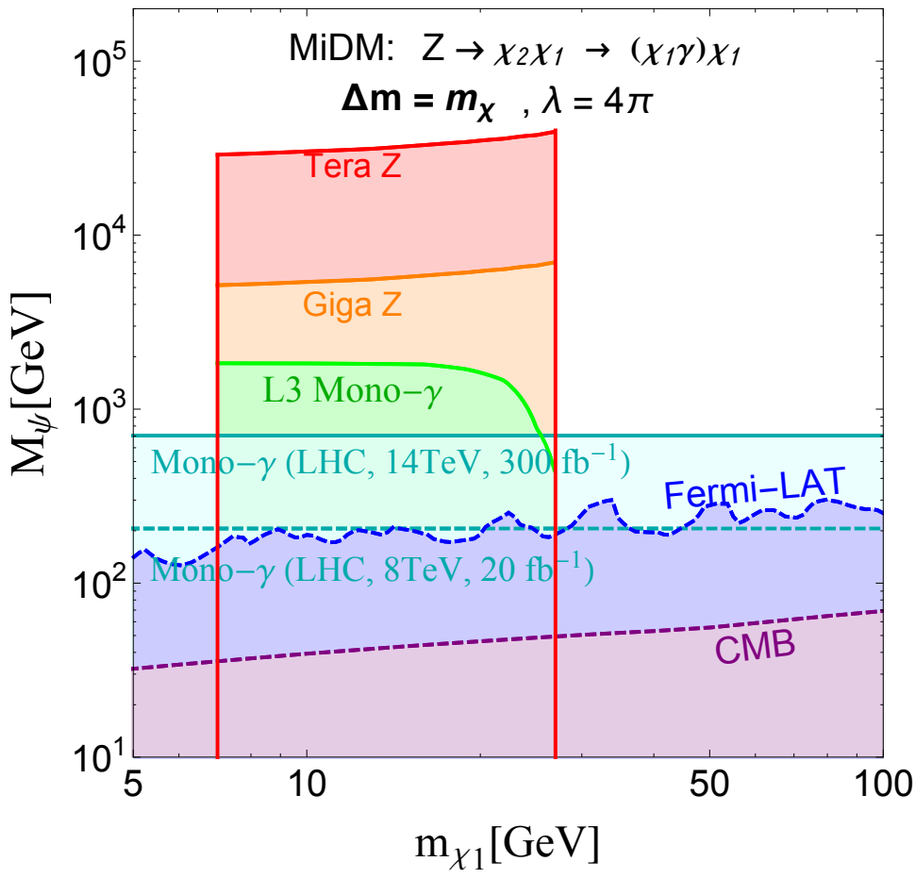


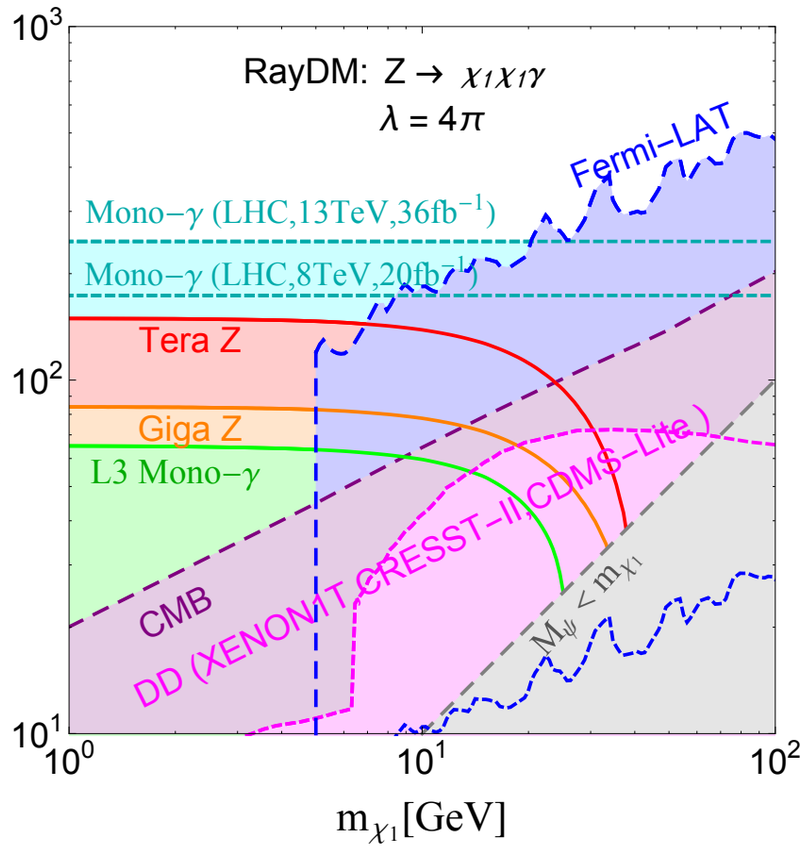
(MET + γ, 0 res)

Magnetic inelastic DM and Rayleigh DM







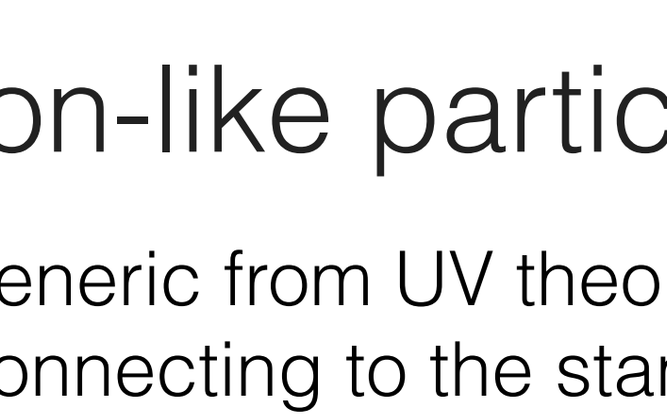


Axion-like particles

- generic from UV theories
  connecting to the standard model and dark sector

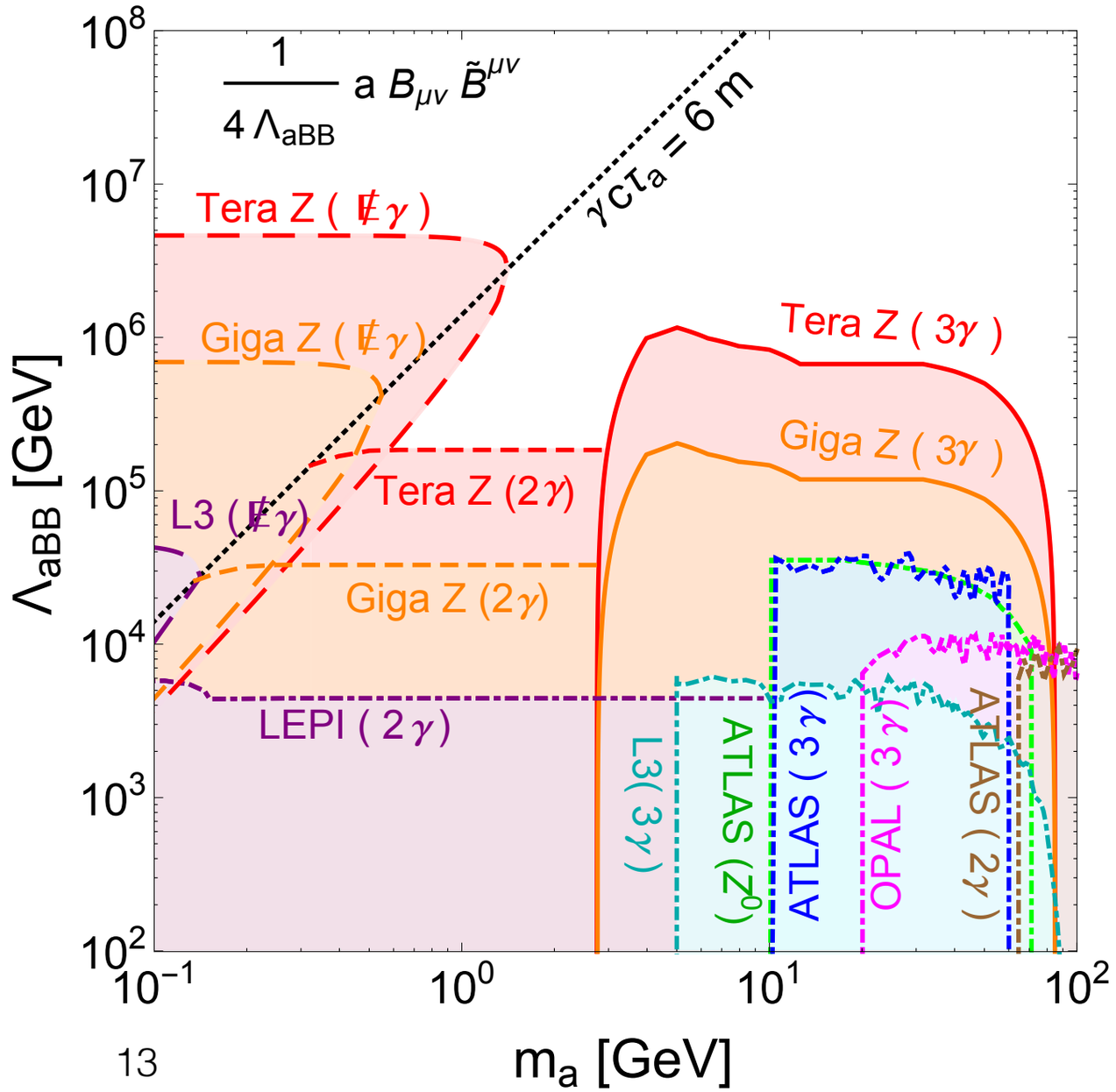
$$\mathcal{L}_{\rm ALP} = \frac{1}{4\Lambda_{aBB}} a B_{\mu\nu} \tilde{B}^{\mu\nu}$$

- exotic Z decays



(2 or 3 γ, 1 resonance)

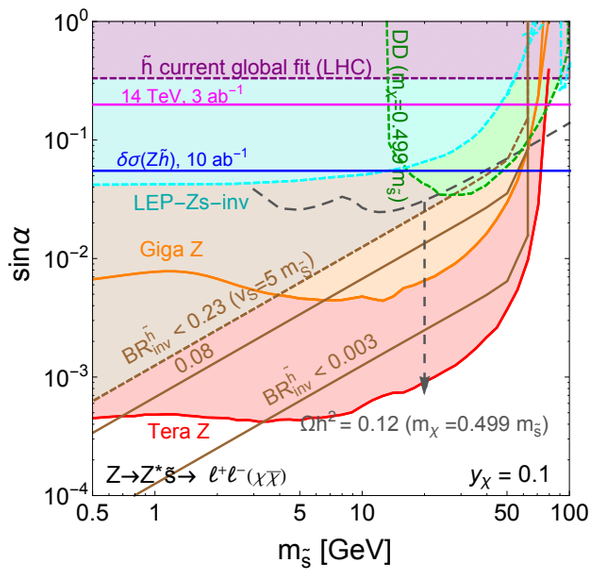
(MET+γ, 1 resonance)



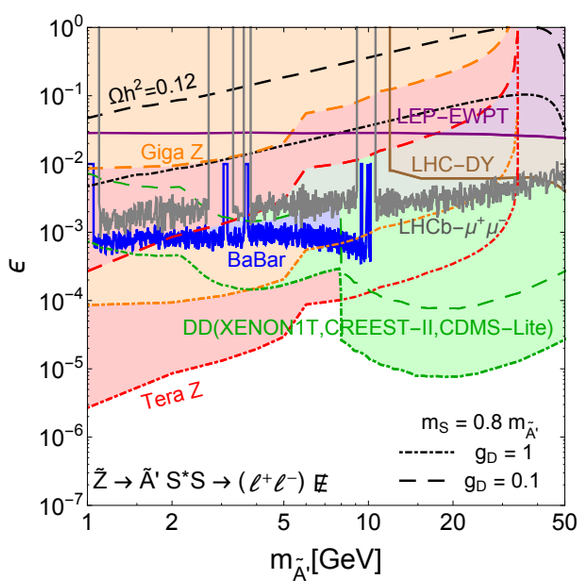
Summary

- starting from models
  - Higgs portal + fermionic DM
    mixing with Higgs
    vector portal + scalar DM
    mixing with $U(1)_Y$ gauge fields
- axion-like particles
  higher dimensional operators MiDM and Rayleigh DM

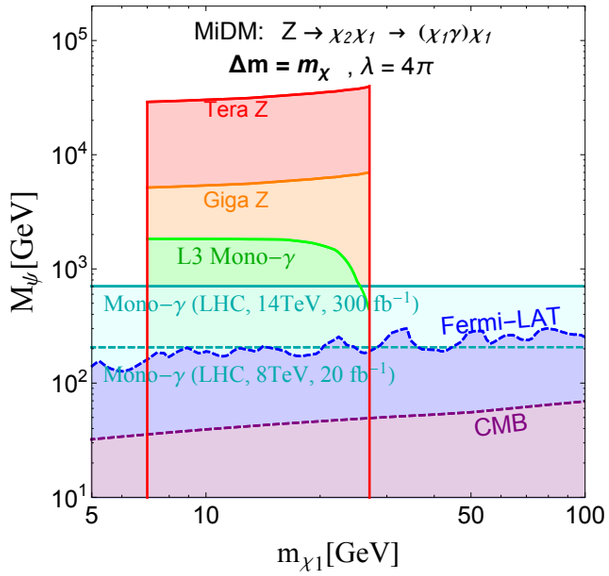
Higgs portal



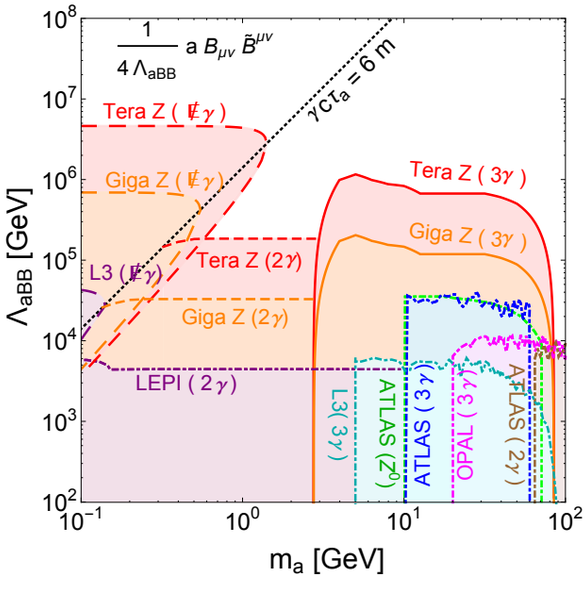
vector portal



MiDM



ALPs



Exotic Z decay topologies

$$Z \to \not{E} + n_\gamma \gamma + n_{\ell^+\ell^-} \ell^+\ell^- + n_{\bar{q}q} \bar{q} q$$

exotic decays	topologies	n_{res}	models
$Z \to \not{E} + \gamma$	$Z \to \chi_1\chi_2, \chi_2 \to \chi_1\gamma$	0	1A: $\frac{1}{\Lambda_{1A}} \bar{\chi_2} \sigma^{\mu\nu} \chi_1 B_{\mu\nu}$ (MIDM)
	$Z \to \chi\bar{\chi}\gamma$	0	1B: $\frac{1}{\Lambda_{1B}^3} \bar{\chi}\chi B_{\mu\nu} B^{\mu\nu}$ (RayDM)
	$Z \to a\gamma \to (\not{E})\gamma$	1	1C: $\frac{1}{4\Lambda_{1C}} a B_{\mu\nu} \tilde{B}^{\mu\nu}$ (long-lived ALP)
	$Z \to A'\gamma \to (\bar{\chi}\chi)\gamma$	1	1D: $\epsilon^{\mu\nu\rho\sigma} A'_\mu B_\nu \partial_\rho B_\sigma$ (WZ terms)
$Z \to \not{E} + \gamma\gamma$	$Z \to \phi_d A'$,$\phi_d \to (\gamma\gamma)$, $A' \to (\bar{\chi}\chi)$	2	2A: Vector portal
	$Z \to \phi_H \phi_A$, $\phi_H \to (\gamma\gamma)$, $\phi_A \to (\bar{\chi}\chi)$	2	2B: 2HDM extension
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\phi$, $\phi \to (\gamma\gamma)$	1	2C: Inelastic DM
	$Z \to \chi_2\chi_2$, $\chi_2 \to \gamma\chi_1$	0	2D: MIDM
$Z \to \not{E} + \ell^+\ell^-$	$Z \to \phi_d A'$, $A' \to (\ell^+\ell^-)$, $\phi_d \to (\bar{\chi}\chi)$	2	3A: Vector portal
	$Z \to A'SS \to (\ell\ell)SS$	1	3B: Vector portal
	$Z \to \phi(Z^*/\gamma^*) \to \phi\ell^+\ell^-$	1	3C: Long-lived ALP, Higgs portal
	$Z \to \chi_2\chi_1 \to \chi_1 A'\chi_1 \to (\ell^+\ell^-)\not{E}$	1	3D: Vector portal and Inelastic DM
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\ell^+\ell^-$	0	3E: MIDM, SUSY
	$Z \to \bar{\chi}\chi\ell^+\ell^-$	0	3F: RayDM, slepton, heavy lepton mixing
$Z \to \not{E} + JJ$	$Z \to \phi_d A' \to (\bar{\chi}\chi)(jj)$	2	4A: Vector portal
	$Z \to \phi_d A' \to (bb)(\bar{\chi}\chi)$	2	4B: Vector portal + Higgs portal
	$Z \to \chi_2\chi_1 \to bb\chi_1 + \chi_1 \to bb\not{E}$	0	4C: MIDM

Exotic Z decay topologies

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	$Z \to \chi_2\chi_1 \to bb\chi_1 + \chi_1 \to bb\not{E}$	0	4C: MIDM

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	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\phi$, $\phi \to (\gamma\gamma)$	1	2C: Inelastic DM
	$Z \to \chi_2\chi_2$, $\chi_2 \to \gamma\chi_1$	0	2D: MIDM
$Z \to \not{E} + \ell^+\ell^-$	$Z \to \phi_d A'$, $A' \to (\ell^+\ell^-)$, $\phi_d \to (\bar{\chi}\chi)$	2	3A: Vector portal
	$Z \to A'SS \to (\ell\ell)SS$	1	3B: Vector portal
	$Z \to \phi(Z^*/\gamma^*) \to \phi\ell^+\ell^-$	1	3C: Long-lived ALP, Higgs portal
	$Z \to \chi_2\chi_1 \to \chi_1 A'\chi_1 \to (\ell^+\ell^-)\not{E}$	1	3D: Vector portal and Inelastic DM
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\ell^+\ell^-$	0	3E: MIDM, SUSY
	$Z \to \bar{\chi}\chi\ell^+\ell^-$	0	3F: RayDM, slepton, heavy lepton mixing
$Z \to \not{E} + JJ$	$Z \to \phi_d A' \to (\bar{\chi}\chi)(jj)$	2	4A: Vector portal
	$Z \to \phi_d A' \to (bb)(\bar{\chi}\chi)$	2	4B: Vector portal + Higgs portal
	$Z \to \chi_2\chi_1 \to bb\chi_1 + \chi_1 \to bb\not{E}$	0	4C: MIDM

Exotic Z decay topologies

$$Z \to \not{E} + n_\gamma \gamma + n_{\ell^+\ell^-} \ell^+\ell^- + n_{\bar{q}q} \bar{q}q$$

exotic decays	topologies	n_{res}	models
$Z \to \not{E} + \gamma$	$Z \to \chi_1\chi_2, \chi_2 \to \chi_1\gamma$	0	1A: $\frac{1}{\Lambda_{1A}} \bar{\chi_2} \sigma^{\mu\nu} \chi_1 B_{\mu\nu}$ (MIDM)
	$Z \to \chi\bar{\chi}\gamma$	0	1B: $\frac{1}{\Lambda_{1B}^3} \bar{\chi}\chi B_{\mu\nu} B^{\mu\nu}$ (RayDM)
	$Z \to a\gamma \to (\not{E})\gamma$	1	1C: $\frac{1}{4\Lambda_{1C}} a B_{\mu\nu} \tilde{B}^{\mu\nu}$ (long-lived ALP)
	$Z \to A'\gamma \to (\bar{\chi}\chi)\gamma$	1	1D: $\epsilon^{\mu\nu\rho\sigma} A'_\mu B_\nu \partial_\rho B_\sigma$ (WZ terms)
$Z \to \not{E} + \gamma\gamma$	$Z \to \phi_d A'$,$\phi_d \to (\gamma\gamma)$, $A' \to (\bar{\chi}\chi)$	2	2A: Vector portal
	$Z \to \phi_H \phi_A$, $\phi_H \to (\gamma\gamma)$, $\phi_A \to (\bar{\chi}\chi)$	2	2B: 2HDM extension
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\phi$, $\phi \to (\gamma\gamma)$	1	2C: Inelastic DM
	$Z \to \chi_2\chi_2$, $\chi_2 \to \gamma\chi_1$	0	2D: MIDM
$Z \to \not{E} + \ell^+\ell^-$	$Z \to \phi_d A'$, $A' \to (\ell^+\ell^-)$, $\phi_d \to (\bar{\chi}\chi)$	2	3A: Vector portal
	$Z \to A'SS \to (\ell\ell)SS$	1	3B: Vector portal
	$Z \to \phi(Z^*/\gamma^*) \to \phi\ell^+\ell^-$	1	3C: Long-lived ALP, Higgs portal
	$Z \to \chi_2\chi_1 \to \chi_1 A'\chi_1 \to (\ell^+\ell^-)\not{E}$	1	3D: Vector portal and Inelastic DM
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\ell^+\ell^-$	0	3E: MIDM, SUSY
	$Z \to \bar{\chi}\chi\ell^+\ell^-$	0	3F: RayDM, slepton, heavy lepton mixing
$Z \to \not{E} + JJ$	$Z \to \phi_d A' \to (\bar{\chi}\chi)(jj)$	2	4A: Vector portal
	$Z \to \phi_d A' \to (bb)(\bar{\chi}\chi)$	2	4B: Vector portal + Higgs portal
	$Z \to \chi_2\chi_1 \to bb\chi_1 + \chi_1 \to bb\not{E}$	0	4C: MIDM

Exotic Z decay topologies

$$Z \to \not{E} + n_\gamma \gamma + n_{\ell^+\ell^-} \ell^+\ell^- + n_{\bar{q}q} \bar{q}q$$

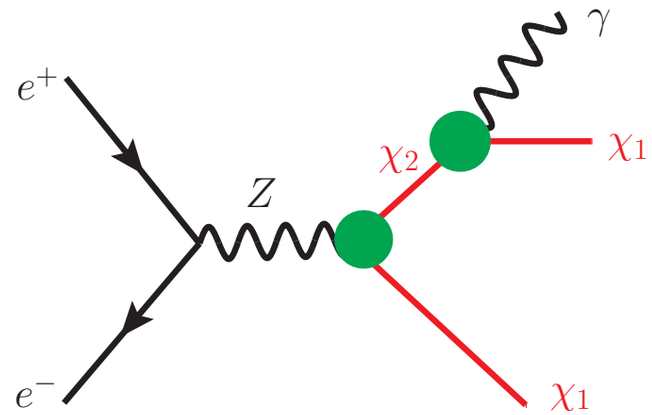
exotic decays	topologies	n_{res}	models
$Z \to \not{E} + \gamma$	$Z \to \chi_1\chi_2, \chi_2 \to \chi_1\gamma$	0	1A: $\frac{1}{\Lambda_{1A}} \bar{\chi_2} \sigma^{\mu\nu} \chi_1 B_{\mu\nu}$ (MIDM)
	$Z \to \chi\bar{\chi}\gamma$	0	1B: $\frac{1}{\Lambda_{1B}^3} \bar{\chi}\chi B_{\mu\nu} B^{\mu\nu}$ (RayDM)
	$Z \to a\gamma \to (\not{E})\gamma$	1	1C: $\frac{1}{4\Lambda_{1C}} a B_{\mu\nu} \tilde{B}^{\mu\nu}$ (long-lived ALP)
	$Z \to A'\gamma \to (\bar{\chi}\chi)\gamma$	1	1D: $\epsilon^{\mu\nu\rho\sigma} A'_\mu B_\nu \partial_\rho B_\sigma$ (WZ terms)
$Z \to \not{E} + \gamma\gamma$	$Z \to \phi_d A'$,$\phi_d \to (\gamma\gamma)$, $A' \to (\bar{\chi}\chi)$	2	2A: Vector portal
	$Z \to \phi_H \phi_A$, $\phi_H \to (\gamma\gamma)$, $\phi_A \to (\bar{\chi}\chi)$	2	2B: 2HDM extension
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\phi$, $\phi \to (\gamma\gamma)$	1	2C: Inelastic DM
	$Z \to \chi_2\chi_2$, $\chi_2 \to \gamma\chi_1$	0	2D: MIDM
$Z \to \not{E} + \ell^+\ell^-$	$Z \to \phi_d A'$, $A' \to (\ell^+\ell^-)$, $\phi_d \to (\bar{\chi}\chi)$	2	3A: Vector portal
	$Z \to A'SS \to (\ell\ell)SS$	1	3B: Vector portal
	$Z \to \phi(Z^*/\gamma^*) \to \phi\ell^+\ell^-$	1	3C: Long-lived ALP, Higgs portal
	$Z \to \chi_2\chi_1 \to \chi_1 A'\chi_1 \to (\ell^+\ell^-)\not{E}$	1	3D: Vector portal and Inelastic DM
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\ell^+\ell^-$	0	3E: MIDM, SUSY
	$Z \to \bar{\chi}\chi\ell^+\ell^-$	0	3F: RayDM, slepton, heavy lepton mixing
$Z \to \not{E} + JJ$	$Z \to \phi_d A' \to (\bar{\chi}\chi)(jj)$	2	4A: Vector portal
	$Z \to \phi_d A' \to (bb)(\bar{\chi}\chi)$	2	4B: Vector portal + Higgs portal
	$Z \to \chi_2\chi_1 \to bb\chi_1 + \chi_1 \to bb\not{E}$	0	4C: MIDM

Exotic Z decay topologies

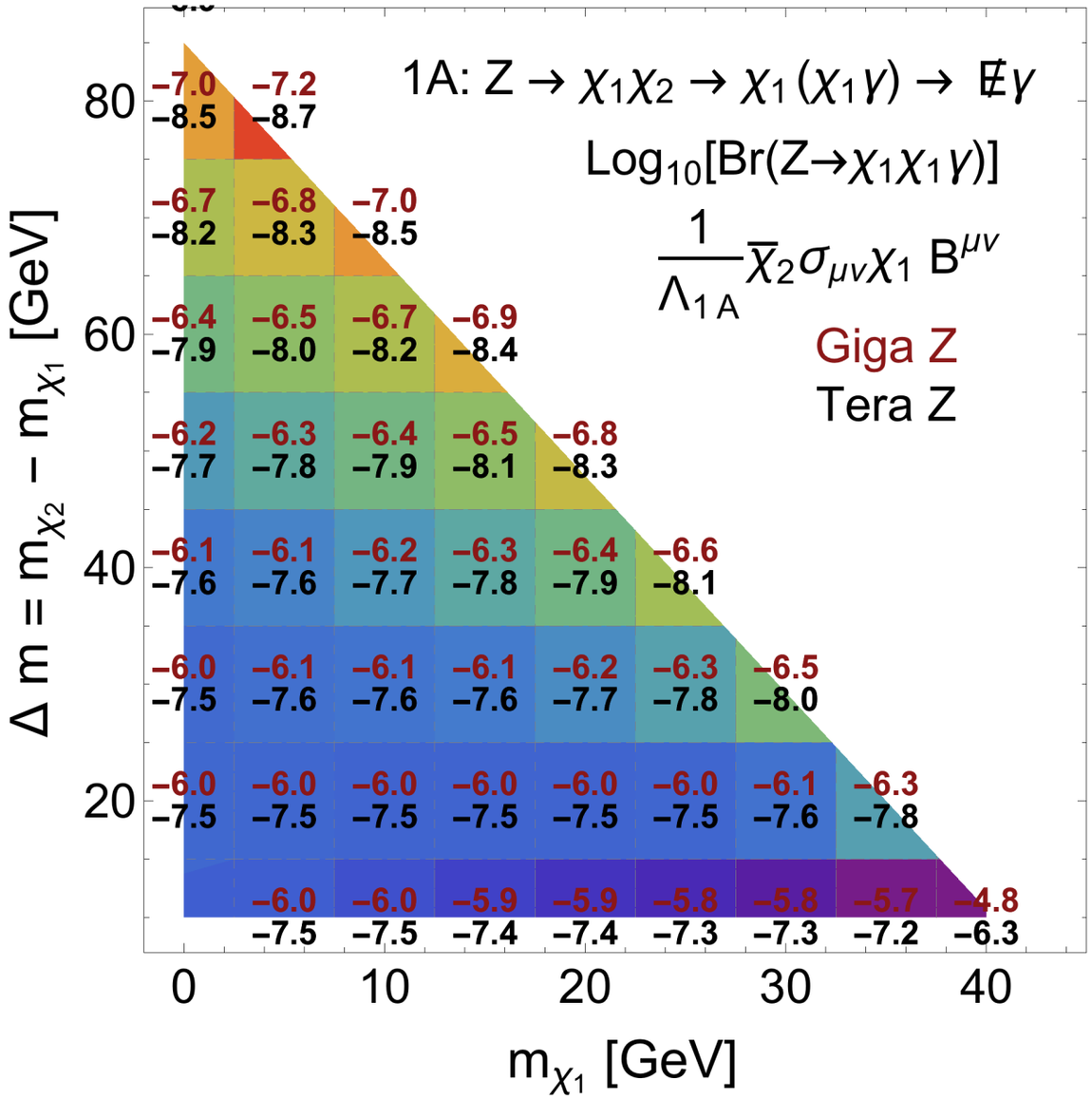
$$Z \to \not{E} + n_\gamma \gamma + n_{\ell^+\ell^-} \ell^+\ell^- + n_{\bar{q}q} \bar{q}q$$

exotic decay	topologies	n_{res}	models
$Z \to \not{E} + \gamma$	$Z \to \chi_1\chi_2, \chi_2 \to \chi_1\gamma$	0	2A: $\frac{1}{\Lambda}\bar{\chi}_2\sigma^{\mu\nu}\chi_1 B_{\mu\nu}$ (MIDM)
	$Z \to \chi\bar{\chi}\gamma$	0	2B: $\frac{1}{\Lambda^3}\bar{\chi}\chi B_{\mu\nu}B^{\mu\nu}$ (RayDM)
	$Z \to a\gamma \to (JJ)\gamma$	1	2C: $\frac{1}{\Lambda_{2C}}aB_{\mu\nu}\tilde{B}^{\mu\nu}$ (long-lived ALP)
	$Z \to A'\gamma \to (\bar{\chi}\chi)\gamma$	1	2D: $\epsilon^{\mu\nu\rho\sigma}A'_\mu B_\nu \partial_\rho B_\sigma$ (WZ terms)
$Z \to \not{E} + \gamma\gamma$	$Z \to \phi_d A'$,$\phi_d \to (\gamma\gamma)$, $A' \to (\bar{\chi}\chi)$	2	3A: Vector portal
	$Z \to \phi_H\phi_A$, $\phi_H \to (\gamma\gamma)$, $\phi_A \to (\bar{\chi}\chi)$	2	3B: Higgs portal
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\phi$, $\phi \to (\gamma\gamma)$	1	3C: Inelastic DM
	$Z \to \chi_2\chi_2$, $\chi_2 \to \gamma\chi_1$	0	3D: MIDM
$Z \to \not{E} + \ell^+\ell^-$	$Z \to \phi_d A'$, $A' \to (\ell^+\ell^-)$, $\phi_d \to (\bar{\chi}\chi)$	2	4A: Vector portal
	$Z \to A'SS \to (\ell\ell)SS$	1	4B: Vector portal
	$Z \to \phi(Z^*/\gamma^*) \to \phi\ell^+\ell^-$	1	4C: Long-lived ALP, Higgs portal
	$Z \to \chi_2\chi_1 \to \chi_1 A'\chi_1 \to (\ell^+\ell^-)\not{E}$	1	4D: Vector portal and Inelastic DM
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\ell^+\ell^-$	0	4E: MIDM, SUSY
	$Z \to \bar{\chi}\chi\ell^+\ell^-$	0	4F: RayDM, slepton, heavy lepton mixing
$Z \to \not{E} + JJ$	similar to $\not{E} + \ell^+\ell^-$		
$Z \to (JJ)(JJ)$	$Z \to \phi_d A', \phi_d \to jj, A' \to jj$	2	5A: Vector portal + Higgs portal
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to jj$	2	5B: vector portal + Higgs portal
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to b\bar{b}$	2	5C: vector portal + Higgs portal
$Z \to \gamma\gamma\gamma$	$Z \to \phi\gamma \to (\gamma\gamma)\gamma$	1	6A: ALP, Higgs portal

$Z \rightarrow \text{MET} + \gamma$



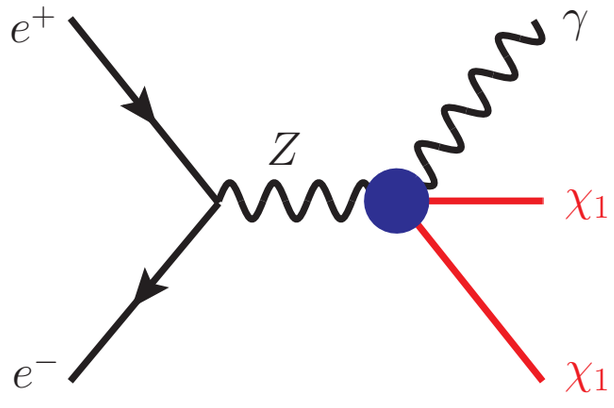
MiDM, 0 resonance



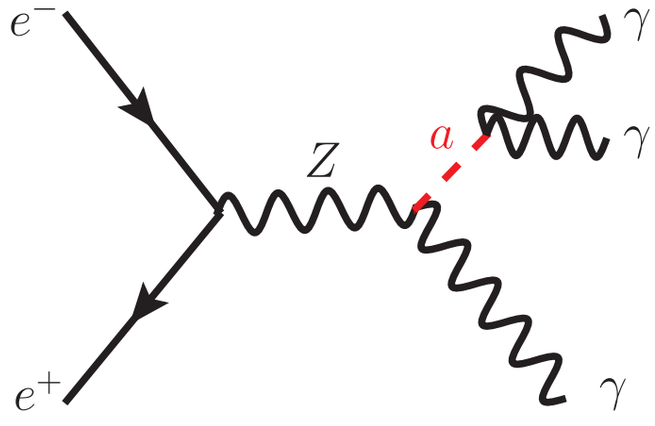
- box shape of photon spectrum
- Luminosity scale

$$\frac{S}{\sqrt{B}} \sim \sqrt{L} = 10^{1.5}$$

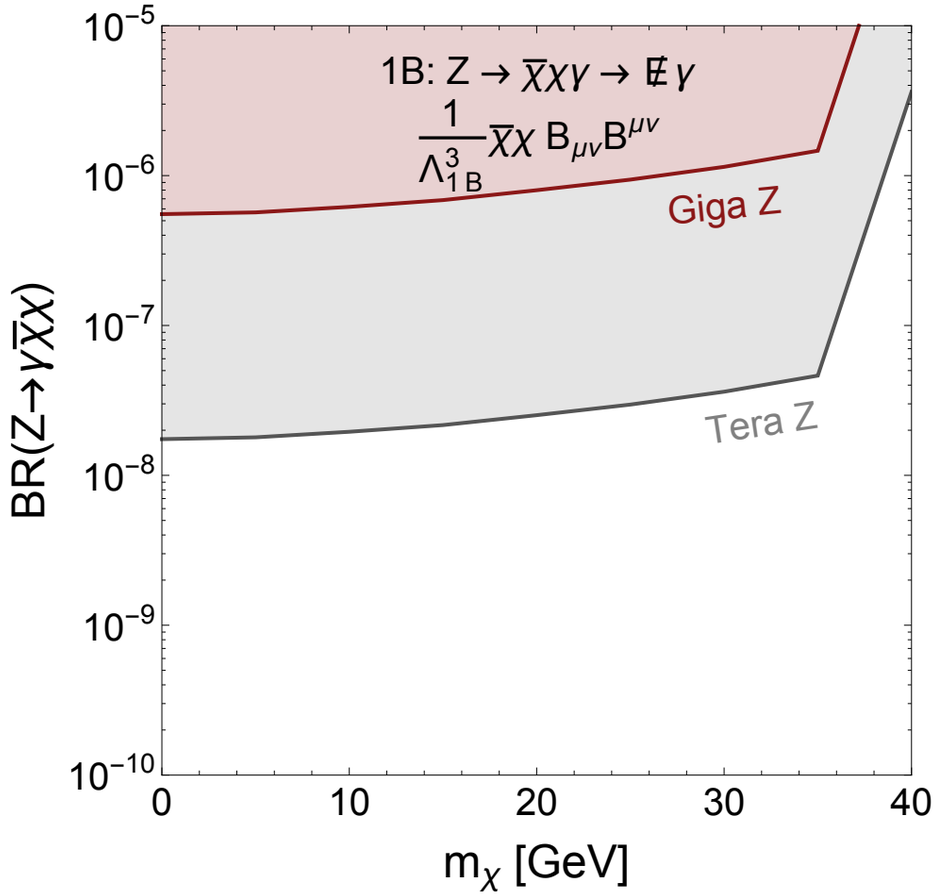
Z → MET + γ

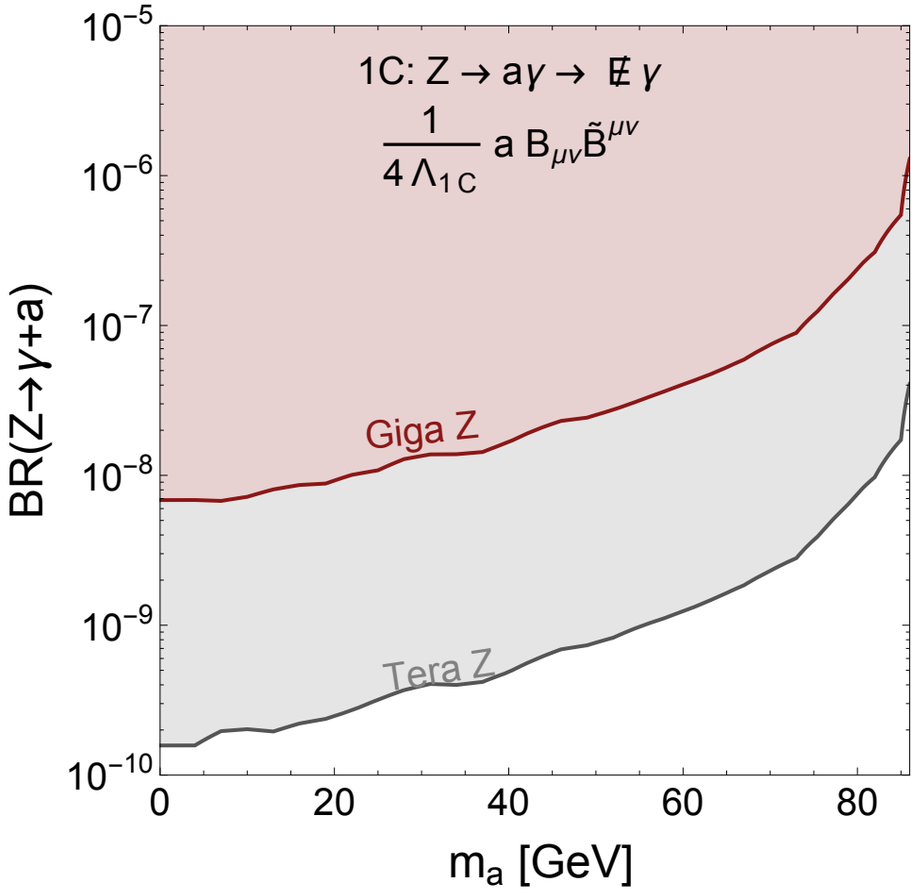


RayDM, 0 resonance

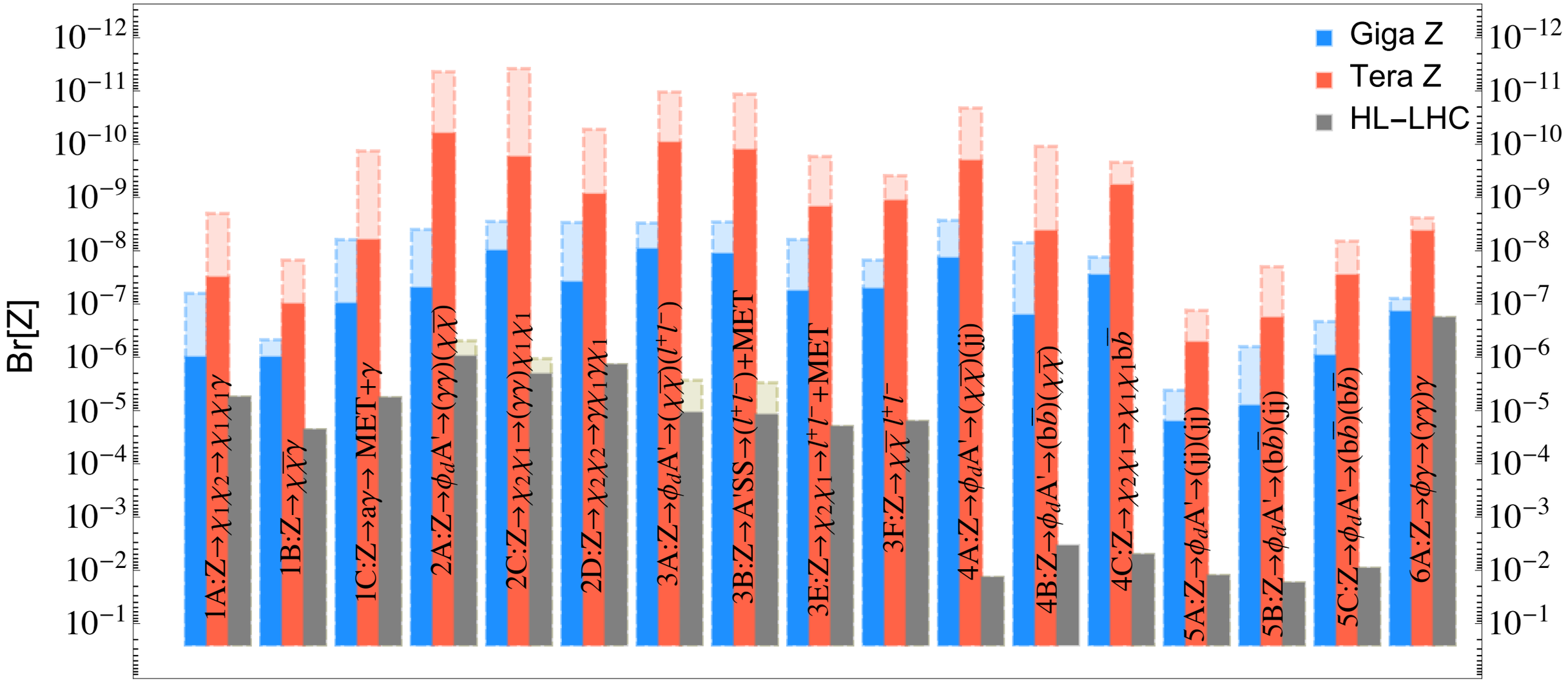


ALPs,1 resonance



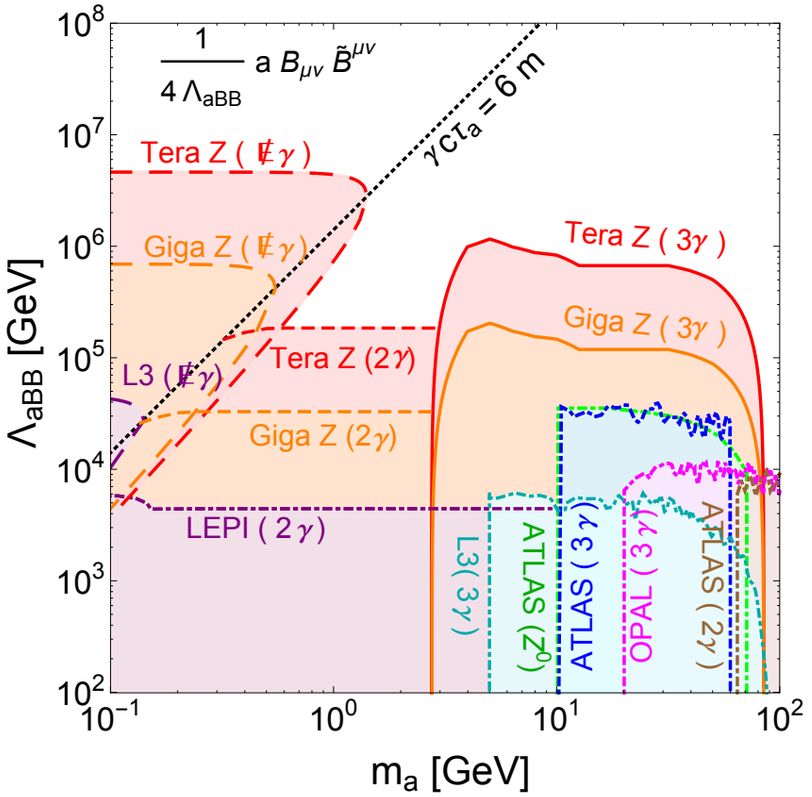


Comparing with HL-LHC

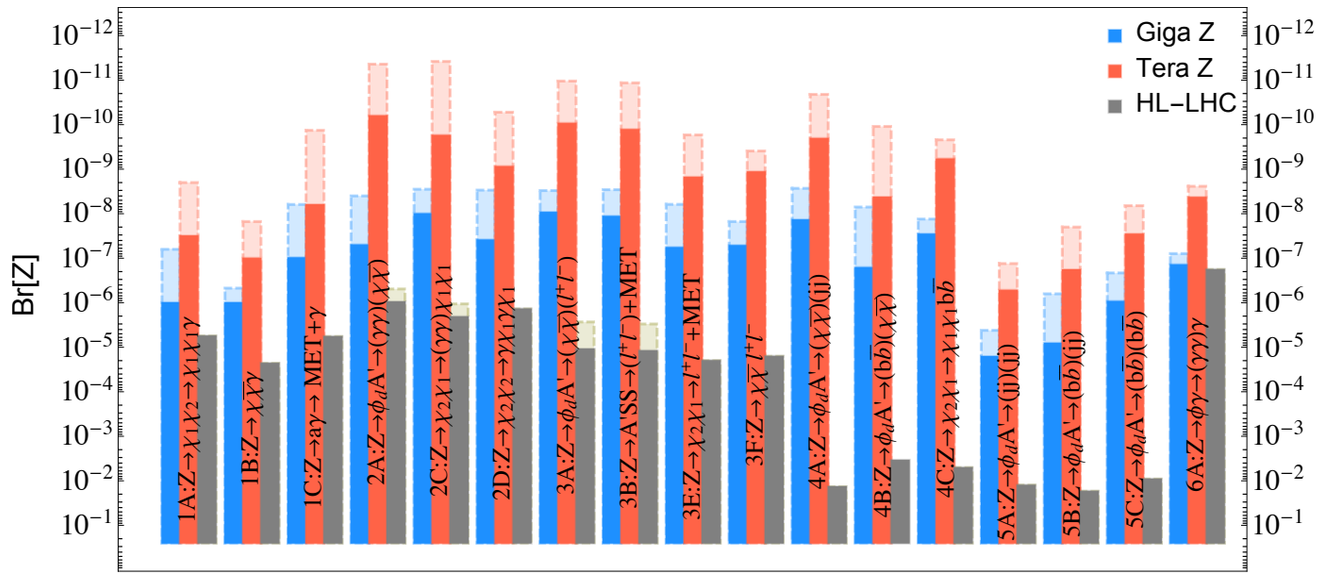


Conclusion

- from well-motivated models
  Higgs portal ,vector portal,
  high dimensional operators, ALPs
  give leading and complementary reaches



- from model-independent method (classified by topologies)
  Giga Z limits BR 10^{-6} - $10^{-8.5}$
  Tera Z limits BR $10^{-7.5}$ - 10^{-11}



Axion-like particles