# Dark Matter and Axion Like Particles

#### exposing dark sectors with future Z-factories

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Jan 9, 2019

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



. . .

## Probing dark sector with Z-factories

 Can the future e<sup>+</sup>e<sup>-</sup> 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<sup>9</sup>) 22.9 fb<sup>-1</sup> Tera Z (10<sup>12</sup>) 22.9 ab<sup>-1</sup>
- 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)<sub>Y</sub> 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  $\alpha$   
 $\begin{pmatrix} \tilde{h} \\ \tilde{s} \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$ 

• linking to dark matter 
$$\chi$$

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

 exotic Z decays (MET+l<sup>+</sup>l<sup>-</sup>, 1 resonance)



# Higgs portal + fermionic DM



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

A' and U(1)<sub>Y</sub> gauge field B mixing

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

A' mix with Z and photon

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

• linking to scalar dark matter

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



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



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

A' and U(1)<sub>Y</sub> gauge field B mixing

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



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

 $e^+$ 



dark photon searches BaBar and LHCb

 $e^{\dagger}$ 

 $e^+$ 

 $\$  S

 indirect detection (p-wave) direct detection (> 10 GeV)

 $\checkmark S$ 

 $\checkmark S$ 

 $\tilde{Z}$ 

 $\mathcal{L} = \bar{\chi}(i\partial \!\!\!/ - m_{\chi})\chi - \frac{1}{2} \delta m \bar{\chi}^c \chi + \psi(iD \!\!\!/ - M_{\psi})\psi + (D \!\!\!/ \mathcal{A}) \psi del_{\mathcal{M}} \partial \!\!\!/ \psi del_{\mathcal{M}}^2 \phi^{\dagger} \phi + \mathcal{M} \mathcal{A} \partial \!\!\!/ \psi \chi^{\dagger} \phi + \mathcal{M} \mathcal{A} \partial \!\!/ \psi \chi^{\dagger} \psi \chi^{\dagger} \phi + \mathcal{M} \partial \!\!/ \psi \chi^{\dagger} \psi \chi^{\dagger}$ 

The Legendry of this model is given by [6] is the provided by the provided by

 $\sum_{p_2} p_2 = \frac{1}{\Lambda_{\text{MIDM}}} \sum_{p_2} \sigma^{\mu\nu} \chi_1 B_{\mu\nu} \psi = \frac{1}{h.c.}, \quad O_{\text{RayDM}} = \frac{1}{\Lambda_{\text{RayDM}}^{3/\mu}} \sum_{p_2} \sigma^{\mu\nu} \chi_1 B_{\mu\nu} \psi = \frac{1}{h.c.}, \quad O_{\text{RayDM}} = \frac{1}{\Lambda_{\text{RayDM}}^{3/\mu}} \sum_{p_2} \sigma^{\mu\nu} \chi_1 B_{\mu\nu} \psi = \frac{1}{h.c.}, \quad O_{\text{RayDM}} = \frac{1}{\Lambda_{\text{RayDM}}^{3/\mu}} \sum_{p_2} \sigma^{\mu\nu} \chi_1 B_{\mu\nu} \psi = \frac{1}{h.c.}, \quad O_{\text{RayDM}} = \frac{1}{\Lambda_{\text{RayDM}}^{3/\mu}} \sum_{p_2} \sigma^{\mu\nu} \chi_1 B_{\mu\nu} \psi = \frac{1}{h.c.}, \quad O_{\text{RayDM}} = \frac{1}{\Lambda_{\text{RayDM}}^{3/\mu}} \sum_{p_2} \sigma^{\mu\nu} \chi_1 B_{\mu\nu} \psi = \frac{1}{h.c.}, \quad O_{\text{RayDM}} = \frac{1}{\Lambda_{\text{RayDM}}^{3/\mu}} \sum_{p_1} \sigma^{\mu\nu} B_{\mu\nu} \psi = \frac{1}{(3\mu\nu)} \sum_{p_1} \sigma^{\mu\nu} B_{\mu\nu} \psi =$ 

where will have oscillation and significantly in the specific value  $e^+$ ghat d note otto hi sign  $(-M_f)\psi$ In a 122 Minter  $\overline{32\pi^2 M_{\psi}}^{1}$   $\overline{32\pi^2 M_{\psi}}^{1}$ ton function to be where we have simply assumed  $\psi$  and  $\phi$  are singlet under  $SU(2)_{I}$ re charged under U(in eq. (36), we have assumed  $\phi$  mass is similar to  $M_{\psi}$  and we tak  $\mathcal{G}_{w}^{(12)}$  generone can Taid domainstan to the have successfully motivated decay topologies  $Z \to \chi_2 \chi_1 \to (e^{-1})$ and we want to motivate another cascade decay  $Z \to \chi_2 \chi_2 \stackrel{(b)}{\to} (\chi_1 \gamma) (\chi_1 \chi_1 \gamma) \chi_1 \chi_2 \chi_2 \stackrel{(b)}{\to} \chi_2 \chi_2 \stackrel{(b)}{\to} \chi_1 \chi_1 \chi_2 \chi_2 \stackrel{(b)}{\to} \chi_2 \chi_2 \stackrel{(b)}{\to} \chi_1 \chi_2 \chi_2 \stackrel{(b)}{\to} \chi_1 \chi_2 \chi_2 \stackrel{(b)}{\to} \chi_1 \chi_2 \chi_2 \stackrel{(b)}{\to} \chi_2 \chi_2 \stackrel{(b)}{\to} \chi_1 \chi_2 \chi_2 \stackrel{(b)}{\to} \chi_2 \chi_2 \stackrel{(b)}{\to} \chi_1 \stackrel{(b)}{\to} \chi_1 \stackrel{(b)}{\to} \chi_2 \stackrel{(b)}{\to} \chi_1 \stackrel{(b)}{\to} \chi_2 \stackrel{(b)}{\to} \chi_1 \stackrel{(b)}{\to} \chi_1 \stackrel{(b)}{\to} \chi_2 \stackrel{(b)}{\to} \chi_1 \stackrel{(b)}{\to} \chi_2 \stackrel{(b)}{\to} \chi_2 \stackrel{(b)}{\to} \chi_1 \stackrel{(b)}{\to} \chi_2 \stackrel{(b)}{\to} \chi_1 \stackrel{(b)}{\to} \chi_2 \stackrel{(b)}{\to} \chi_1 \stackrel{(b)}{\to} \chi_2 \stackrel{(b)}{\to} \chi_2 \stackrel{(b)}{\to} \chi_1 \stackrel{(b)}{\to} \chi_2 \stackrel{(b)}$ However,  $\delta i f_n \chi_2$  is Majorana fermion, the dipole term  $\bar{\chi}_2 \sigma_{\mu\nu} \chi_2$  will vanish. Finite range that the dipole term  $\bar{\chi}_2 \sigma_{\mu\nu} \chi_2$  will vanish. spiqies  $\rho_{i}$  becomes  $\lambda_{i}\psi\chi_{i}\phi_{i}$ , then the Yukawa term in eq. (34) becomes  $\bar{\chi}_{i}\psi\chi_{i}\phi_{i}$ , where  $\lambda_{i}\psi\chi_{i}\phi_{i}$ , where fields such a spicies [64]. In this case, one can have  $\bar{\chi}_i \sigma_{\mu\nu} \chi_j$  in MIDM operation of the property of the property



# Axion-like particles



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



#### Summary

starting from models



10<sup>5</sup>

10<sup>4</sup>

 $10^{3}$ 

10<sup>2</sup> M

10<sup>1</sup>

10

 $M_{\psi}[GeV]$ 

vector portal

Higgs portal



MiDM



10<sup>2</sup>

50

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

exotic decays	topologies	$n_{res}$	models		
	$Z \to \chi_1 \chi_2, \chi_2 \to \chi_1 \gamma$	0	1A: $\frac{1}{\Lambda_{1A}} \bar{\chi_2} \sigma^{\mu\nu} \chi_1 B_{\mu\nu}$ (MIDM)		
$Z \rightarrow E + \alpha$	$Z \to \chi \bar{\chi} \gamma$	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)		
	$Z \to \phi_d A', \phi_d \to (\gamma \gamma), A' \to (\bar{\chi} \chi)$	2	2A: Vector portal		
$Z \to E + \gamma \gamma$	$Z \to \phi_H \phi_A, \ \phi_H \to (\gamma \gamma), \ \phi_A \to (\bar{\chi} \chi)$	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		
$Z \rightarrow E + \ell + \ell -$	$ \begin{array}{ccc} Z \rightarrow \phi_d A', \ A' \rightarrow (\ell^+ \ell^-), \ \phi_d \rightarrow \\ (\bar{\chi} \chi) \end{array} $	2	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		
	$Z \to \chi_2 \chi_1 \to \chi_1 A' \chi_1 \to (\ell^+ \ell^-) \not\!$	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		
	$Z \to \overline{\phi_d A' \to (\bar{\chi}\chi)(jj)}$	2	4A: Vector portal		
$ Z \to \not\!\!\!E + JJ$	$Z \to \phi_d A' \to (bb)(\bar{\chi}\chi)$	2	4B: Vector portal + Higgs portal		
	$Z \to \chi_2 \chi_1 \to bb\chi_1 + \chi_1 \to bb \not\!$	0	4C: MIDM		

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

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$Z \to \not\!\!\!E + \gamma \gamma$	$Z \to \phi_H \phi_A, \ \phi_H \to (\gamma \gamma), \ \phi_A \to (\bar{\chi} \chi)$	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		
$Z \rightarrow E + \ell^+ \ell^-$	$Z \to \phi_d A', \ A' \to (\ell^+ \ell^-), \ \phi_d \to (\bar{\chi}\chi)$	2 3A: Vector portal			
Δ μ + ί ί	$Z \to A'SS \to (\ell\ell)SS$	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		
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	$Z \to \phi_d A' \to (\bar{\chi}\chi)(jj)$	2	4A: Vector portal		
$Z \to \not\!$	$Z \to \overline{\phi_d A' \to (bb)(\bar{\chi}\chi)}$	2	4B: Vector portal + Higgs portal		
	$Z \to \chi_2 \chi_1 \to bb\chi_1 + \chi_1 \to bb \not\!$	0	4C: MIDM		

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

exotic decays	topologies	$n_{res}$	models	
	$Z \to \chi_1 \chi_2, \chi_2 \to \chi_1 \gamma$	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)	
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	$Z \to \phi_d A', \phi_d \to (\gamma \gamma), A' \to (\bar{\chi} \chi)$	2	2A: Vector portal	
$Z \to E \!\!\!\!/ + \gamma \gamma$	$ \begin{array}{c} Z \to \phi_H \phi_A, \ \phi_H \to (\gamma \gamma), \ \phi_A \to \\ (\bar{\chi} \chi) \end{array} $	2	2B: 2HDM extension	
	$Z \to \chi_2 \chi_1,  \chi_2 \to \chi_1 \phi,  \phi \to (\gamma \gamma)$	$\cdot \chi_1 \phi, \phi \to (\gamma \gamma)$ 1 2C: Inelastic DM		
	$Z \to \chi_2 \chi_2,  \chi_2 \to \gamma \chi_1$	0 2D: MIDM		
$Z \rightarrow E + \ell^+ \ell^-$	$ \begin{array}{ccc} Z \rightarrow \phi_d A', \; A' \rightarrow (\ell^+ \ell^-), \; \phi_d \rightarrow \\ (\bar{\chi} \chi) \end{array} $	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		
	$Z \to \chi_2 \chi_1 \to \chi_1 A' \chi_1 \to (\ell^+ \ell^-) \not\!\!\!E$	7 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	
$Z \to E \!\!\!\!/  + JJ$	$Z \to \phi_d A' \to (\bar{\chi}\chi)(jj)$	2	4A: Vector portal	
	$Z \to \phi_d A' \to (bb)(\bar{\chi}\chi)$	2	4B: Vector portal + Higgs portal	
	$Z \to \chi_2 \chi_1 \to bb \chi_1 + \chi_1 \to bb \not\!$	0	4C: MIDM	

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

exotic decays	topologies	$n_{res}$	s models		
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$Z \rightarrow \psi + \phi$	$Z \to \chi \bar{\chi} \gamma$	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)		
	$Z \to \phi_d A', \phi_d \to (\gamma \gamma), A' \to (\bar{\chi} \chi)$	2	2A: Vector portal		
$Z \to \not\!$	$Z \to \phi_H \phi_A, \ \phi_H \to (\gamma \gamma), \ \phi_A \to (\bar{\chi} \chi)$	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		
$Z \to \not\!\!\!E + \ell^+ \ell^-$	$\begin{array}{l} Z \rightarrow \phi_d A', \; A' \rightarrow (\ell^+ \ell^-), \; \phi_d \rightarrow \\ (\bar{\chi} \chi) \end{array}$	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		
	$Z \to \chi_2 \chi_1 \to \chi_1 A' \chi_1 \to (\ell^+ \ell^-) \not\!$	$\not E$ 1 3D: Vector portal and Inelastic DM			
	$Z \to \chi_2 \chi_1,  \chi_2 \to \chi_1 \ell^+ \ell^-$	0	3E: MIDM, SUSY		
	$Z  o \bar{\chi} \chi \ell^+ \ell^-$	0	3F: RayDM, slepton, heavy lepton mixing		
$Z \to E + JJ$	$Z \to \phi_d A' \to (\bar{\chi}\chi)(jj)$	2	4A: Vector portal		
	$Z \to \phi_d A' \to (bb)(\bar{\chi}\chi)$	2	4B: Vector portal + Higgs portal		
	$Z \to \chi_2 \chi_1 \to bb\chi_1 + \chi_1 \to bb \not\!$	0	4C: MIDM		

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

exotic decays	topologies	$n_{res}$	models	
	$Z \to \chi_1 \chi_2, \chi_2 \to \chi_1 \gamma$	0	1A: $\frac{1}{\Lambda_{1A}} \bar{\chi_2} \sigma^{\mu\nu} \chi_1 B_{\mu\nu}$ (MIDM)	
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	$Z \to \phi_d A', \phi_d \to (\gamma \gamma), A' \to (\bar{\chi} \chi)$	2	2A: Vector portal	
$Z \to E \!\!\!\!/ + \gamma \gamma$	$ \begin{array}{c} Z \to \phi_H \phi_A, \ \phi_H \to (\gamma \gamma), \ \phi_A \to \\ (\bar{\chi} \chi) \end{array} $	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	
$7 \rightarrow \overline{\psi} + \theta + \theta -$	$ \begin{array}{cccc} Z \rightarrow \phi_d A', \ A' \rightarrow (\ell^+ \ell^-), \ \phi_d \rightarrow \\ (\bar{\chi} \chi) \end{array} $	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	
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$Z \to E \!\!\!\!/  + JJ$	$Z \to \overline{\phi_d A' \to (\bar{\chi}\chi)(jj)}$	2	4A: Vector portal	
	$Z \to \phi_d A' \to (bb)(\bar{\chi}\chi)$	2	4B: Vector portal + Higgs portal	
	$Z \to \chi_2 \chi_1 \to bb\chi_1 + \chi_1 \to bb \not\!$	0	4C: MIDM	

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

exotic decay	topologies	$n_{res}$	models	
	$Z \to \chi_1 \chi_2, \chi_2 \to \chi_1 \gamma$	0	$2\mathbf{A}: \frac{1}{\Lambda} \bar{\chi_2} \sigma^{\mu\nu} \chi_1 B_{\mu\nu} \text{ (MIDM)}$	
$Z \to \mathbb{E} + \gamma$	$Z \to \chi \bar{\chi} \gamma$	$\rightarrow \phi_{d}$	$\begin{array}{c c} 2B: \frac{1}{\Lambda^3} \bar{\chi} \chi B_{\mu\nu} B^{\mu\nu} \text{ (Ray DM)} \\ A', \phi_d \rightarrow jj, A' \rightarrow jj & 2 & 5A: \text{ Vec} \end{array}$	ctor portal + Higgs portal
	$ \begin{array}{ccc} Z & \to a\gamma \to (I & \gamma) \\ Z & \to (JJ)(JJ) \\ Z \end{array} $	$\rightarrow \phi_{d}$	$\begin{array}{c c} 2C: & \frac{1}{\Lambda_{2C}} aB_{\mu\nu} \tilde{B}^{\mu\nu} \text{ (long-lived ALP)} \\ A', \phi_d  b\bar{b}, A'  jj & 2 & 5B: \text{ vec} \end{array}$	tor portal + Higgs portal
	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$ ightarrow \phi_{d}$	$\begin{array}{cccc} {}^{2}\mathrm{D:} & \epsilon^{\mu\nu\rho\sigma}A'_{\mu}B_{\nu}\partial_{\sigma}B_{\sigma} & (\mathrm{WZ\ terms})\\ {}^{4}\!$	tor portal + Higgs portal
	$ \begin{array}{c} Z \to \phi_d A' , \phi_d \end{array} \xrightarrow{\rightarrow} (\gamma \gamma), A' \to (\chi \chi) \\ Z \to \gamma \gamma \gamma \end{array} $	$\rightarrow \frac{2}{\phi \gamma}$	$\begin{array}{c c} 3A: \text{ Vector portal} \\ \rightarrow (\gamma\gamma)\gamma & 1 & 6A: \text{ AL} \end{array}$	P, Higgs portal
$Z \to \mathbb{E} + \gamma \gamma$	$Z \to \phi_H \phi_A, \qquad \qquad$	-		
	$Z \to \chi_2 \chi_1,  \chi_2 \to \chi_1 \phi,  \phi \to (\gamma \gamma)$	1	3C: Inelastic DM	
	$Z \to \chi_2 \chi_2,  \chi_2 \to \gamma \chi_1$		3D: MIDM	
$7 \rightarrow t + 0 + 0 -$	$ \begin{array}{c} Z \rightarrow \phi_d A', \ A' \rightarrow (\ell^+ \ell^-), \ \phi_d \rightarrow \\ (\bar{\chi}\chi) \end{array} $	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 mi	xing
$Z \to \not\!$	si			

# $Z \rightarrow MET + \gamma$





- box shape of photon spectrum
- Luminosity scale

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

#### $Z \rightarrow MET + \gamma$



# 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<sup>-6</sup> - 10<sup>-8.5</sup> Tera Z limits BR 10<sup>-7.5</sup> - 10<sup>-11</sup>



# Axion-like particies



 $\gamma$