

Exposing Dark Sector with Z Factory

(Based on the preliminary result)

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Motivation: dark sector probes at CEPC

- How to related with new physics
 - LEP Shines Light on DM (Fox et al 1103.0240)
 - Electroweak Precision Observable (Linear collider report 1504.01726)
 - Z invisible width (Carena et al hep-ph/0308053)
 - DM physics (many...)
 - Lepton flavor violation (see Qin Qin's talk)
- Dark sector at low energy ee collider e.g. BES-III, BaBar
 - Dark Higgstrahlung to multi-leptons (Shuve et al 1710.07635)

Motivation: dark sector probes at CEPC

- LEP at Z pole
 - $Z \rightarrow \gamma\gamma\gamma$ by L3
 - $Z \rightarrow \gamma + \text{inv}$ by L3, OPAL
 - $Z \rightarrow hZ^*$ by L3
 - $Z \rightarrow H_1H_2$ by L3
- LEP at higher energy
 - MSSM by LEP-II
 - Multiple photon + MET
 - Hadronic event with MET
 - Invisible Higgs
 - ...
- How to related with new physics
 - LEP Shines Light on DM (Fox et al 1103.0240)
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Motivation: dark sector probes at CEPC

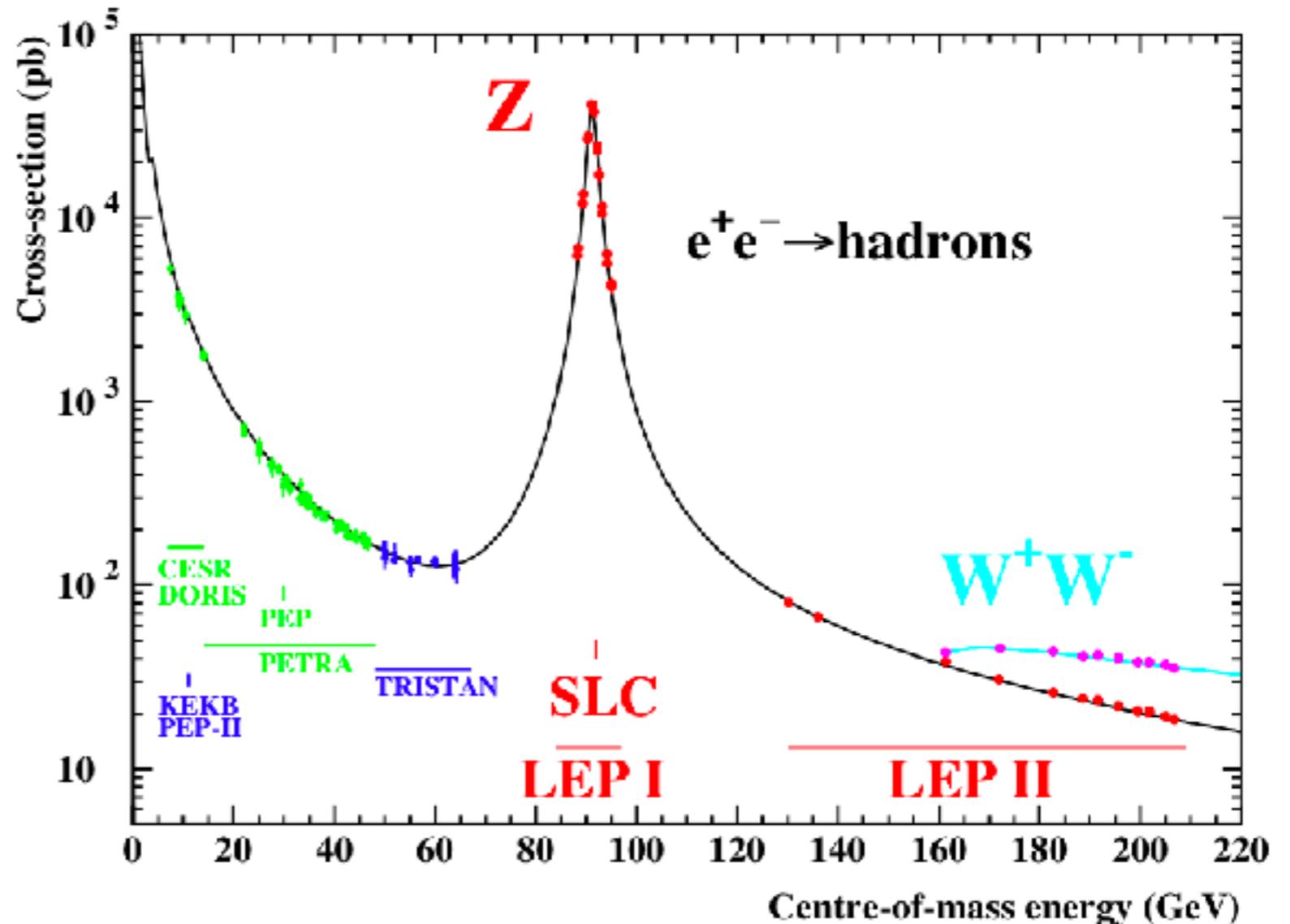
- Future Z factory (Giga/Tera)
 - Resonant prod $\sim 59000\text{pb}$, $10^9/10^{12}$ Z
 - Direct search on dark sector via exotic Z decay

- LEP at Z pole

- $Z \rightarrow \gamma\gamma\gamma$ by L3
- $Z \rightarrow \gamma + \text{inv}$ by L3, OPAL
- $Z \rightarrow hZ^*$ by L3
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- LEP at higher energy

- MSSM by LEP-II
- Multiple photon + MET
- Hadronic event with MET
- Invisible Higgs
- ...



Exotic Z decay at CEPC

Dark Sectors 2016 Workshop: Community Report

1. Dark sector models

- Higgs portal + DM
- Vector portal + DM
- Axion-like particle
- Higher dimensional Operator
 - Comparing with existing collider and DM limits

$$\mathcal{L} \supset \begin{cases} -\frac{\epsilon}{2 \cos \theta_W} B_{\mu\nu} F'^{\mu\nu}, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H, & \text{Higgs portal} \\ y_n L H N, & \text{neutrino portal} \\ \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, & \text{axion portal.} \end{cases}$$

Marco's talk

2. Exotic Z decay topologies

- Motivating topologies
- Classifying by final state and resonances
 - Limits on BR

3. CEPC specialty: focus on invisible final state

Higgs portal + DM

- Lagrangian

$$\mathcal{L} = \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{\mu_S^2}{2} S^2 - \frac{\lambda_3}{6} S^3 - \frac{\lambda_4}{24} S^4 - \lambda_1 (H^\dagger H) S - \lambda_2 (H^\dagger H) S^2 + \bar{\chi} (i\not{\partial} - m_\chi^0) \chi - y_\chi S \bar{\chi} \chi + |D_\mu H|^2 - \mu_H^2 (H^\dagger H) - \lambda_H (H^\dagger H)^2.$$

- Scalar mixing

$$H = \frac{1}{\sqrt{2}} (v_H + h), \quad S = v_S + s \quad \begin{pmatrix} \tilde{h} \\ \tilde{s} \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

- Interactions and decays

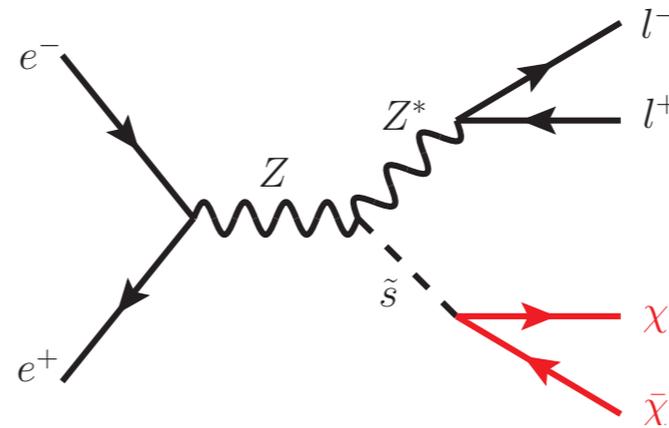
- s interacts with SM from scalar mixing

$$\Gamma(\tilde{s} \rightarrow \bar{\chi} \chi) = \frac{y_\chi^2 \cos^2 \alpha}{8\pi} m_{\tilde{s}} \left(1 - \frac{4m_\chi^2}{m_{\tilde{s}}^2}\right)^{3/2}$$

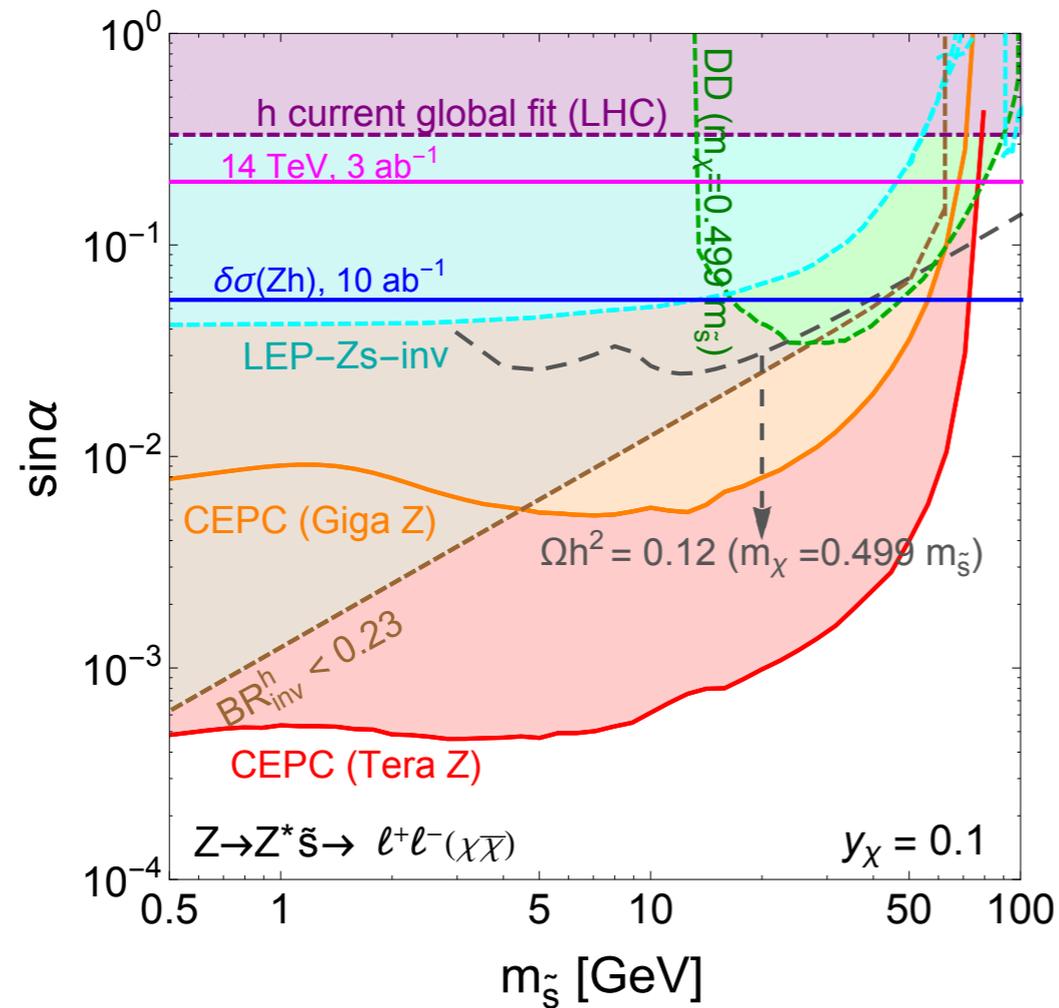
$$\Gamma(\tilde{h} \rightarrow \tilde{s} \tilde{s}) = \frac{\sin^2 \alpha \cos^2 \alpha}{32\pi} \sqrt{1 - \frac{4m_{\tilde{s}}^2}{m_{\tilde{h}}^2}} \left(1 + 2 \frac{m_{\tilde{s}}^2}{m_{\tilde{h}}^2}\right)^2 \frac{m_{\tilde{h}}^3 (\cos \alpha v_H - \sin \alpha v_S)^2}{v_H^2 v_S^2}$$

Higgs portal + DM

- Limit from exotic Z decay $Z \rightarrow \tilde{s}Z^* \rightarrow (\bar{\chi}\chi) + l^+l^-$

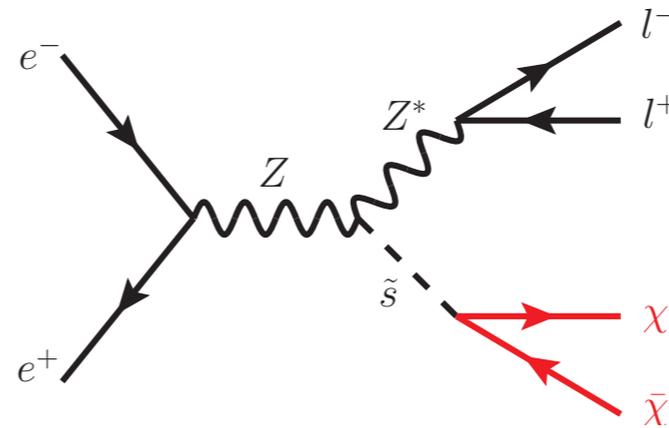


- Various constraints

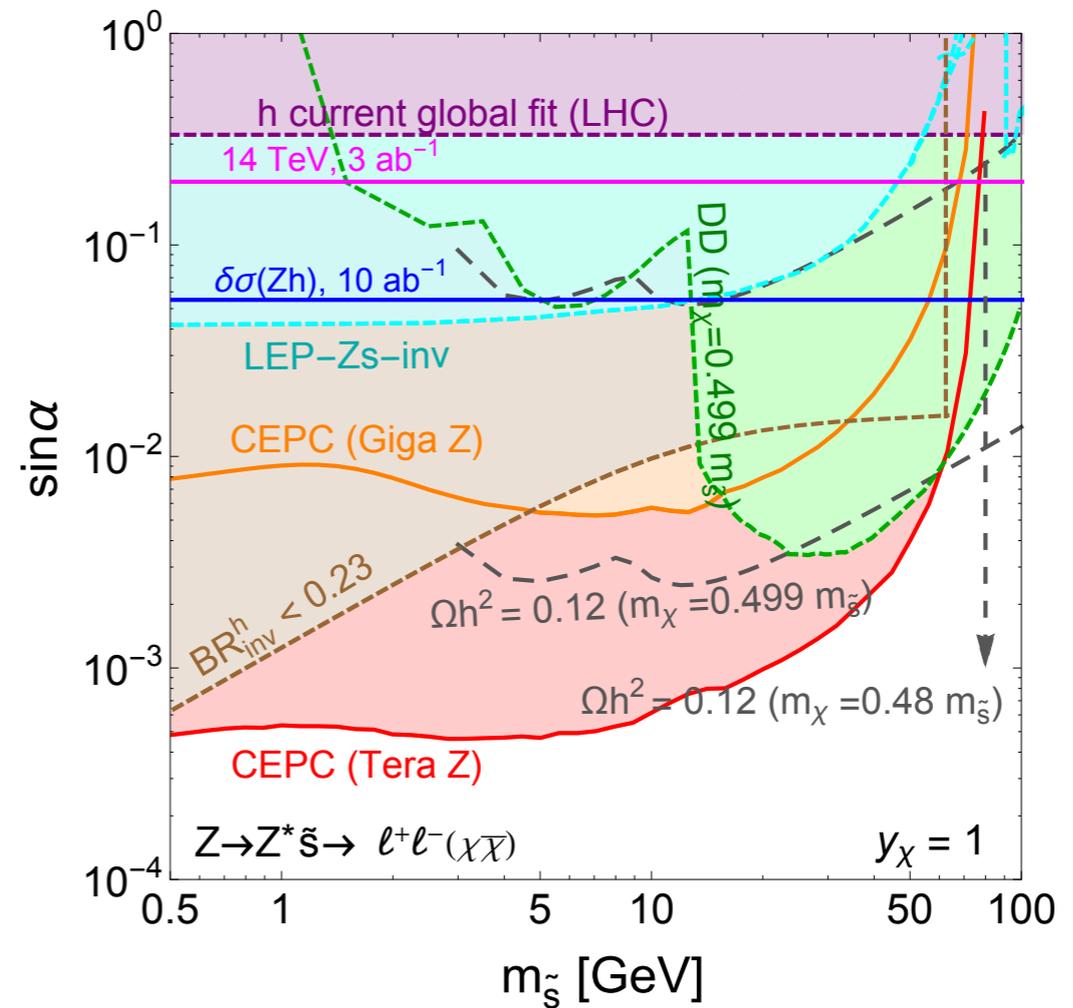
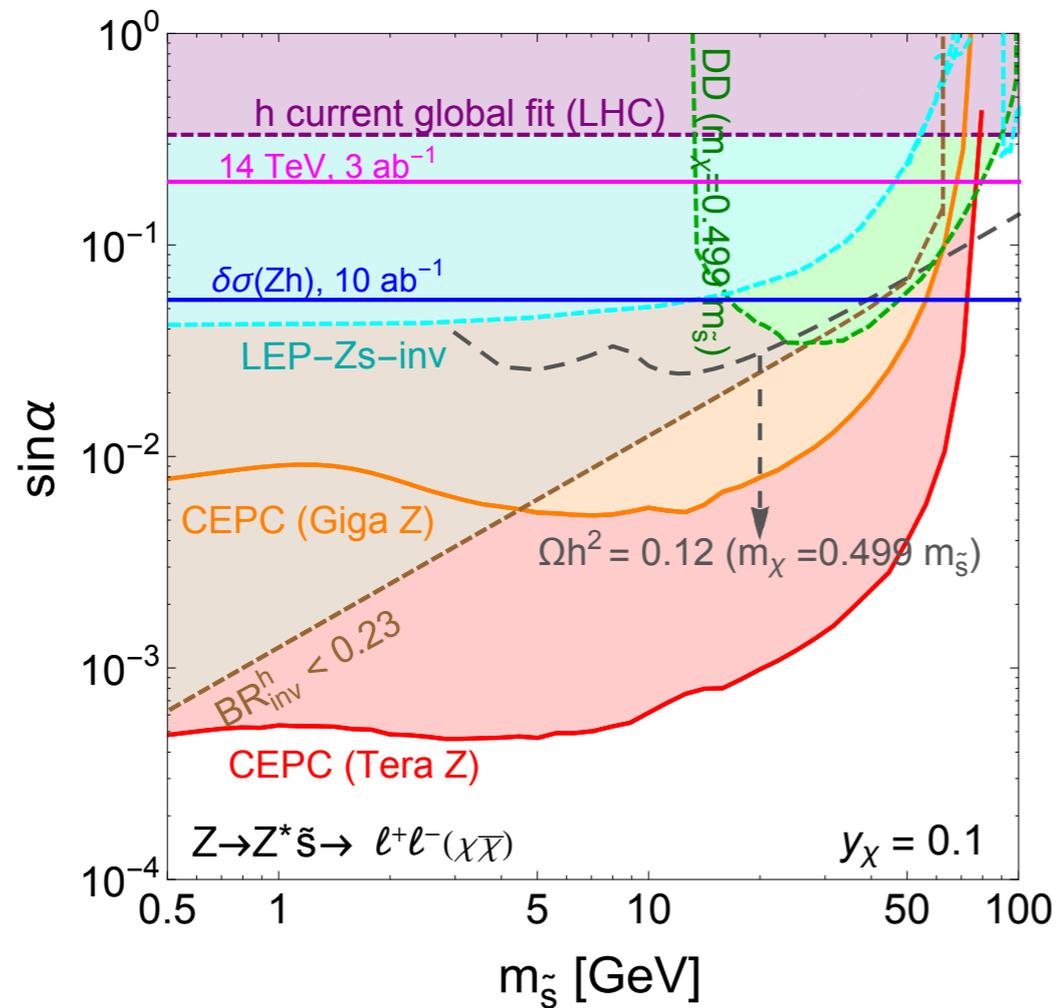


Higgs portal + DM

- Limit from exotic Z decay $Z \rightarrow \tilde{s} Z^* \rightarrow (\bar{\chi}\chi) + l^+ l^-$



- Various constraints



Vector portal + DM

- Vector Lagrangian

$$\mathcal{L}_{\text{boson}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W_{\mu\nu}^i W^{i\mu\nu} - \frac{1}{4}K_{\mu\nu}K^{\mu\nu} + \frac{\epsilon}{2c_W}B_{\mu\nu}K^{\mu\nu}$$

- Vector mixing

$$\begin{pmatrix} Z_{\mu, \text{SM}} \\ A_{\mu, \text{SM}} \\ K_{\mu} \end{pmatrix} = \begin{pmatrix} 1 + \frac{\epsilon^2 t_W^2}{2} \frac{m_{Z, \text{SM}}^2 (m_{Z, \text{SM}}^2 - 2m_K^2)}{(m_K^2 - m_{Z, \text{SM}}^2)^2} & 0 & \frac{m_K^2}{-m_K^2 + m_{Z, \text{SM}}^2} \epsilon t_W \\ \epsilon^2 t_W \frac{m_{Z, \text{SM}}^2}{m_K^2 - m_{Z, \text{SM}}^2} & 1 & \epsilon \\ \frac{m_{Z, \text{SM}}^2}{m_K^2 - m_{Z, \text{SM}}^2} \epsilon t_W & 0 & 1 + \frac{\epsilon^2}{2c_W^2} \frac{(m_{Z, \text{SM}}^4 c_W^2 - 2m_K^2 m_{Z, \text{SM}}^2 + m_K^4)}{(m_K^2 - m_{Z, \text{SM}}^2)^2} \end{pmatrix} \begin{pmatrix} \tilde{Z}_{\mu} \\ \tilde{A}_{\mu} \\ \tilde{K}_{\mu} \end{pmatrix}$$

- Interactions and decays

$$\mathcal{L}_{\text{int}} = \tilde{Z}_{\mu} \left(g J_Z^{\mu} - g_D \frac{m_{Z, \text{SM}}^2 t_W}{m_{Z, \text{SM}}^2 - m_K^2} \epsilon J_D^{\mu} + g \frac{m_{Z, \text{SM}}^2 (m_{Z, \text{SM}}^2 - 2m_K^2) t_W^2}{2(m_K^2 - m_{Z, \text{SM}}^2)^2} \epsilon^2 J_Z^{\mu} - e \frac{m_{Z, \text{SM}}^2 t_W}{m_{Z, \text{SM}}^2 - m_K^2} \epsilon^2 J_{\text{em}}^{\mu} \right) \\ + \tilde{K}_{\mu} \left(g_D J_D^{\mu} + g \frac{m_K^2 t_W}{m_{Z, \text{SM}}^2 - m_K^2} \epsilon J_Z^{\mu} + e \epsilon J_{\text{em}}^{\mu} + g_D \frac{(m_{Z, \text{SM}}^4 c_W^2 - 2m_K^2 m_{Z, \text{SM}}^2 + m_K^4) c_W^{-2}}{2(m_{Z, \text{SM}}^2 - m_K^2)^2} \epsilon^2 J_D^{\mu} \right)$$

Vector portal + DM

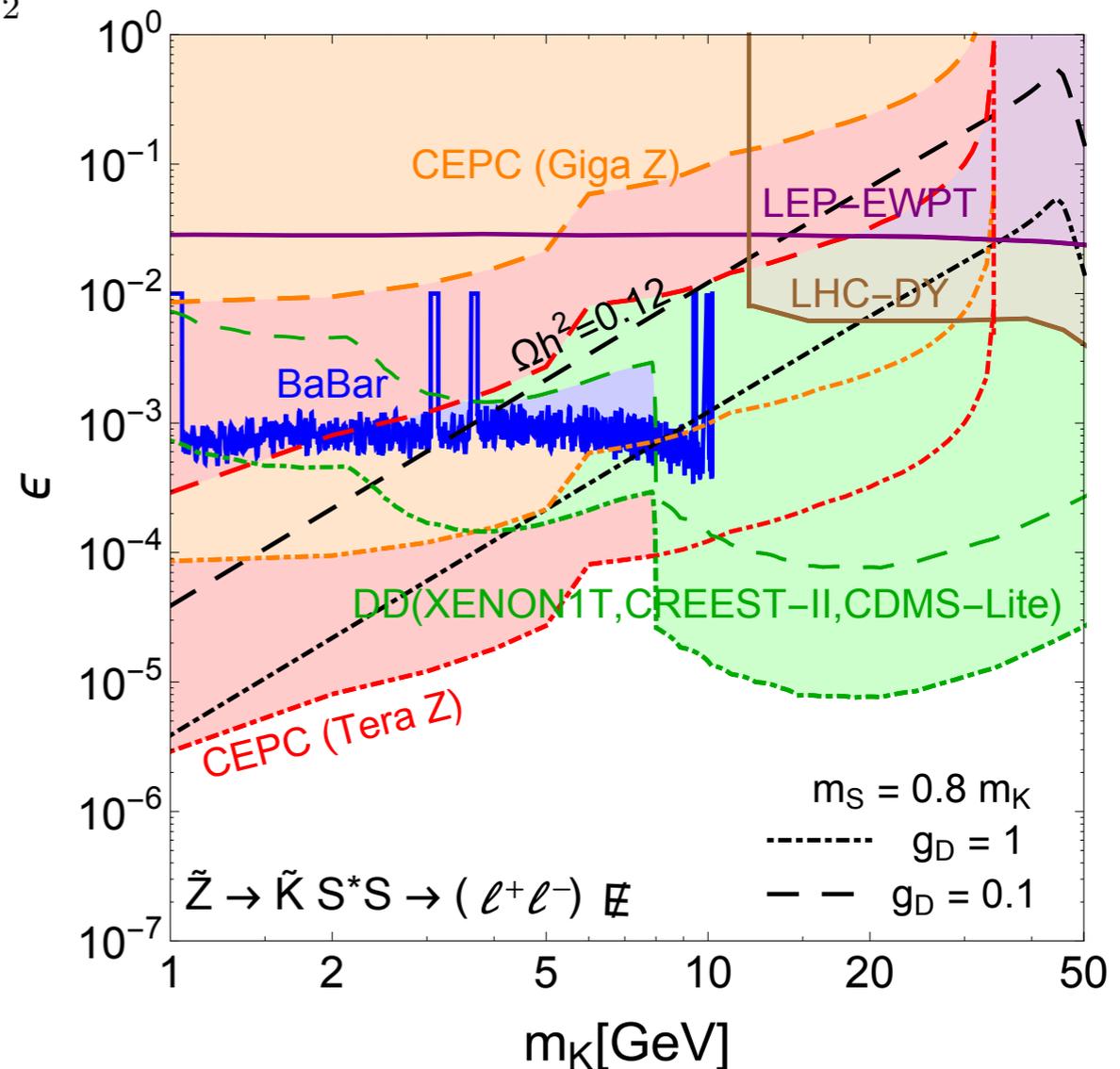
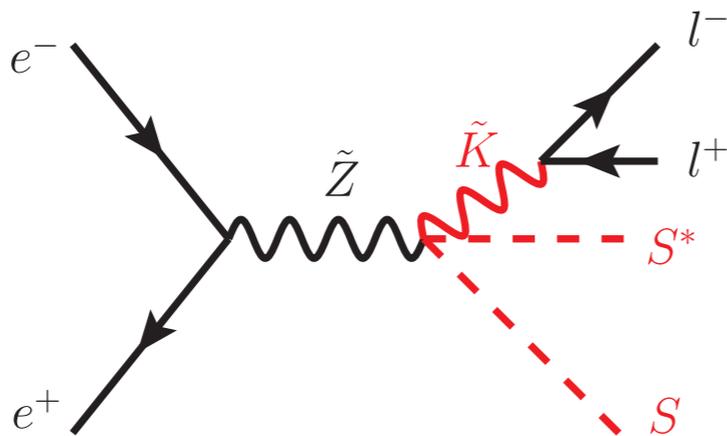
- Complex Scalar DM Lagrangian

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

- Connection to Z

$$\mathcal{L}_S \supset g_D^2 S^* S \left(\tilde{K}_\mu + t_W \epsilon \frac{m_{Z, \text{SM}}^2}{(m_K^2 - m_{Z, \text{SM}}^2)} \tilde{Z}_\mu \right)^2$$

- Various constraints



Vector portal + DM

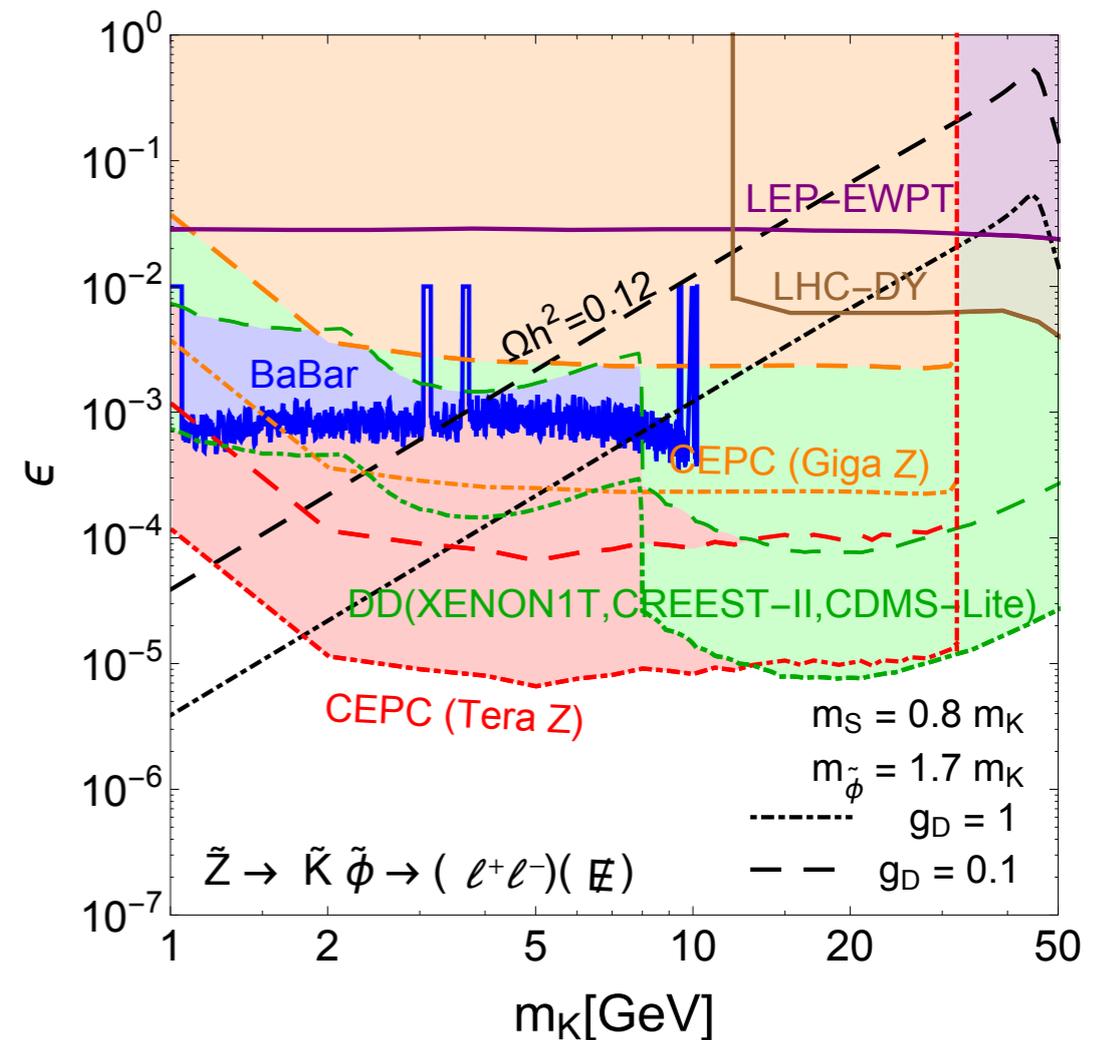
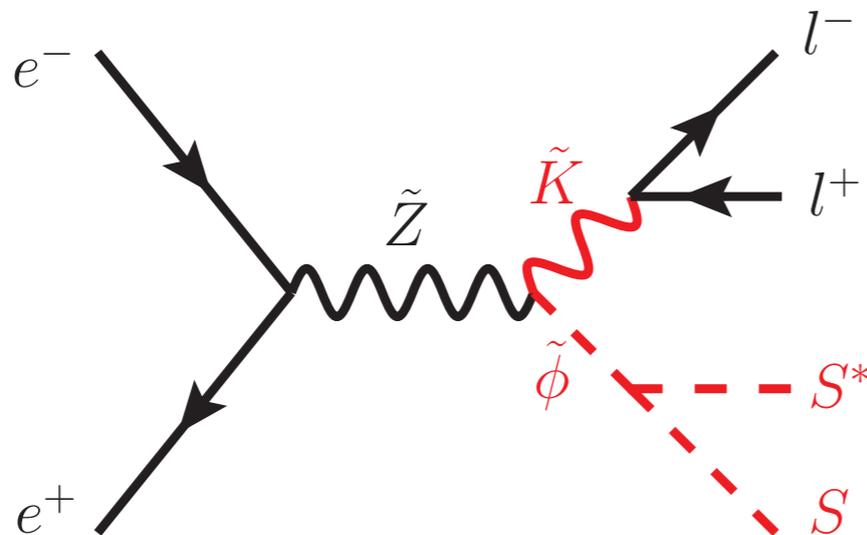
- Complex Scalar DM Lagrangian

$$\mathcal{L}_S = (\partial_\mu S + ig_D K_\mu S)^* (\partial^\mu S + ig_D K^\mu S) - m_S^2 S^* S + \lambda_1 S^* S \Phi^* \Phi + \lambda_2 S^* S H^\dagger H + (\mu_1 \Phi^* S S + h.c.) .$$

- Connection to Z

$$\mathcal{L}_S \supset g_D^2 S^* S \left(\tilde{K}_\mu + t_W \epsilon \frac{m_{Z, SM}^2}{(m_K^2 - m_{Z, SM}^2)} \tilde{Z}_\mu \right)^2$$

- Various constraints



Axion-like particle

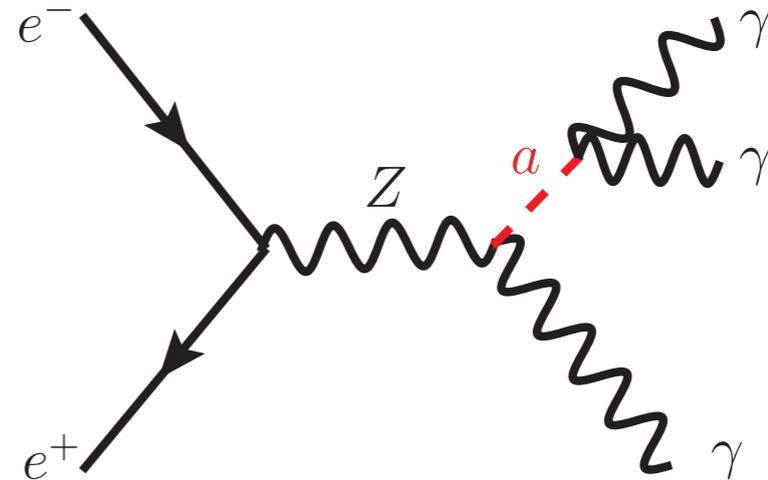
- Lagrangian

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

- Interactions and decays

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

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



Axion-like particle

- Lagrangian

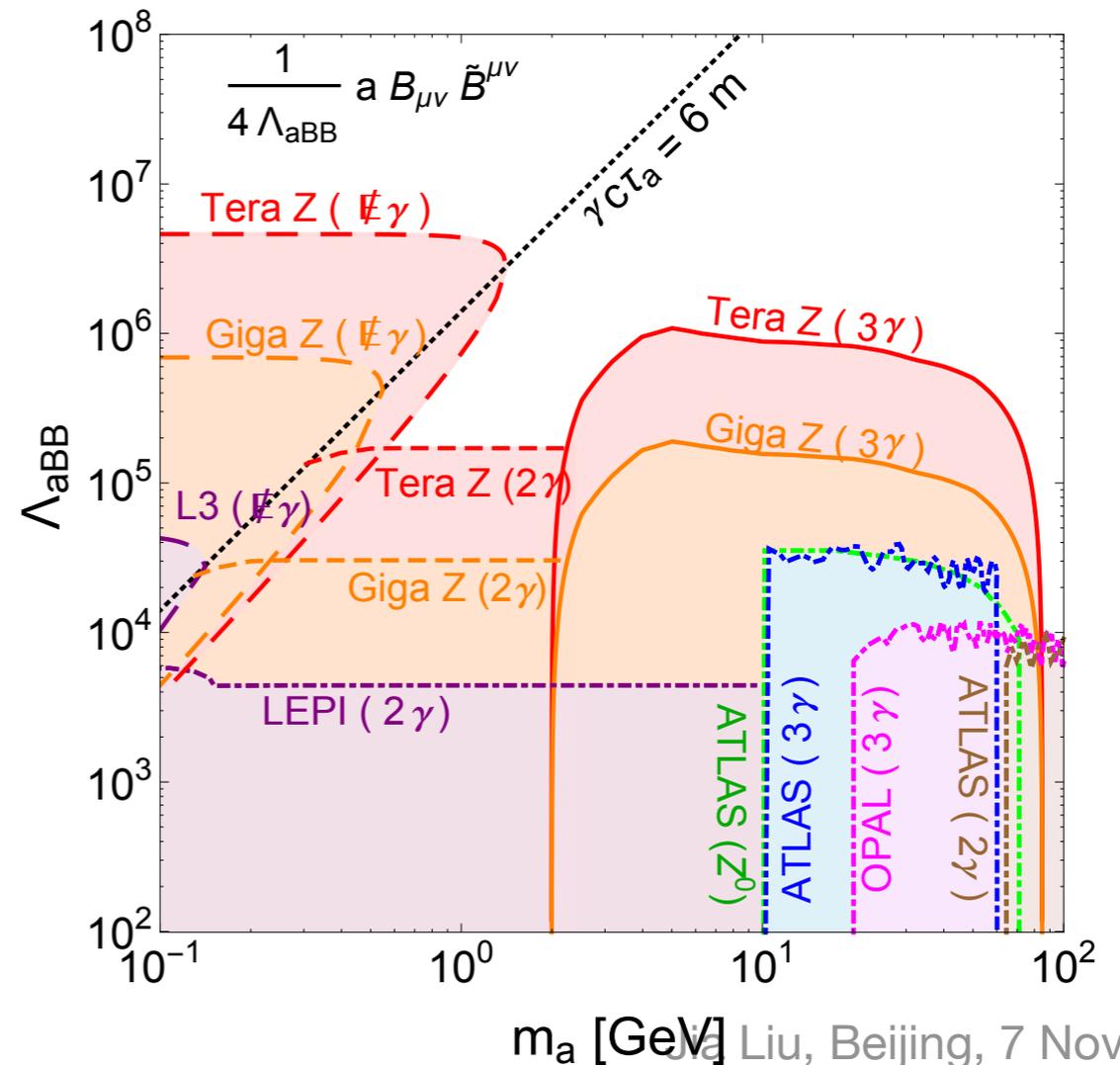
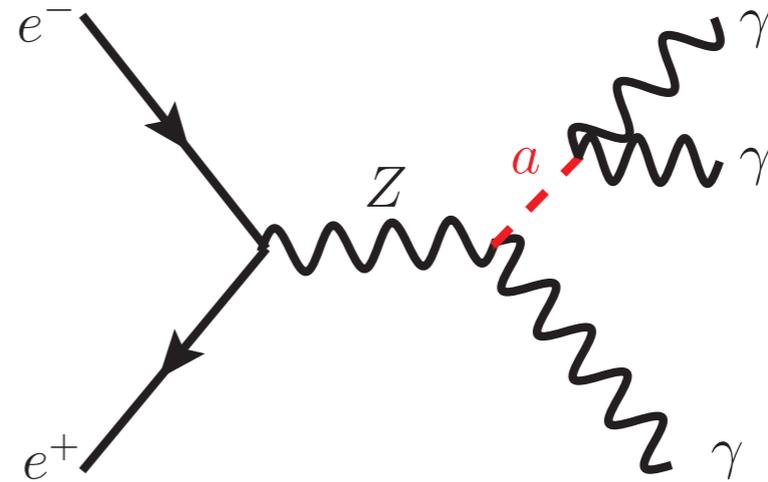
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- Interactions and decays

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- Various constraints



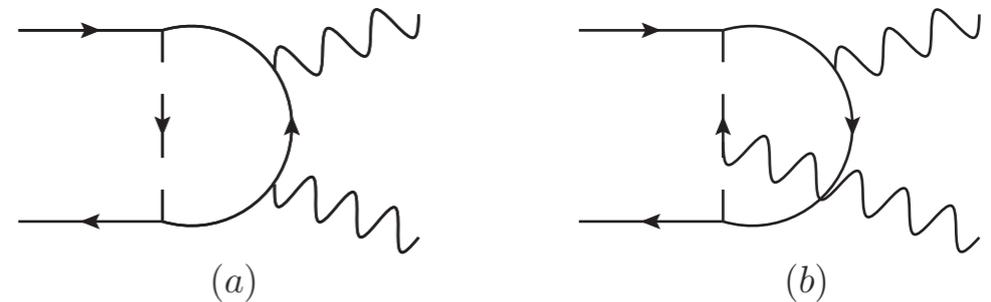
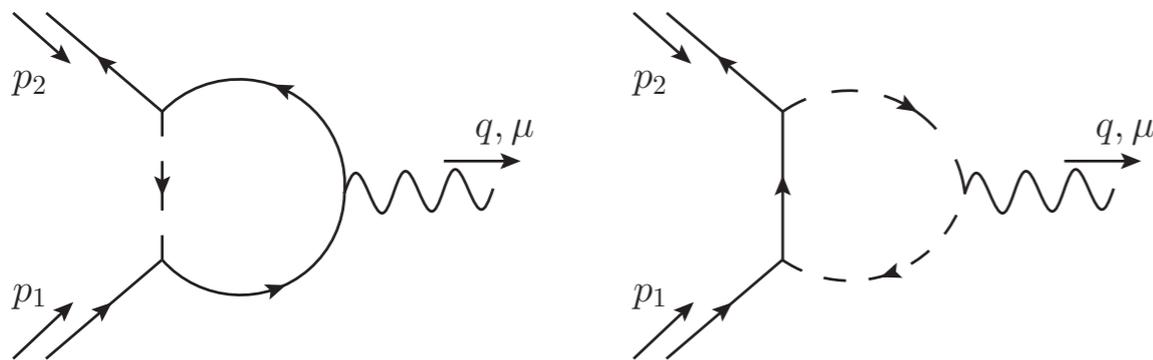
Higher dimensional operator

- UV model

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

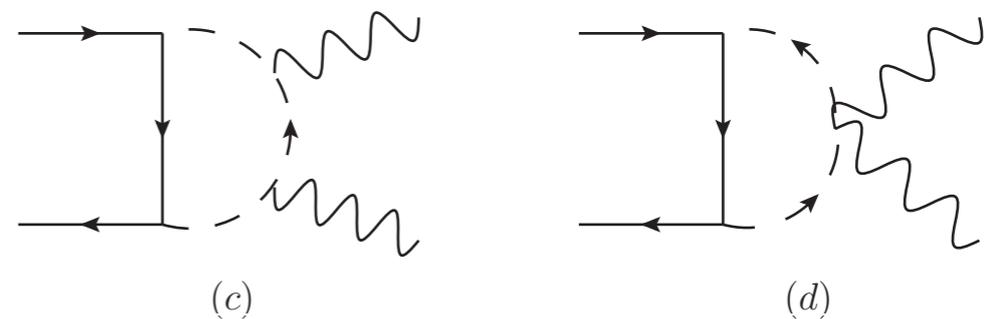
- Interactions: **Magnetic inelastic DM and Rayleigh DM** (Weiner, Yavin)

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



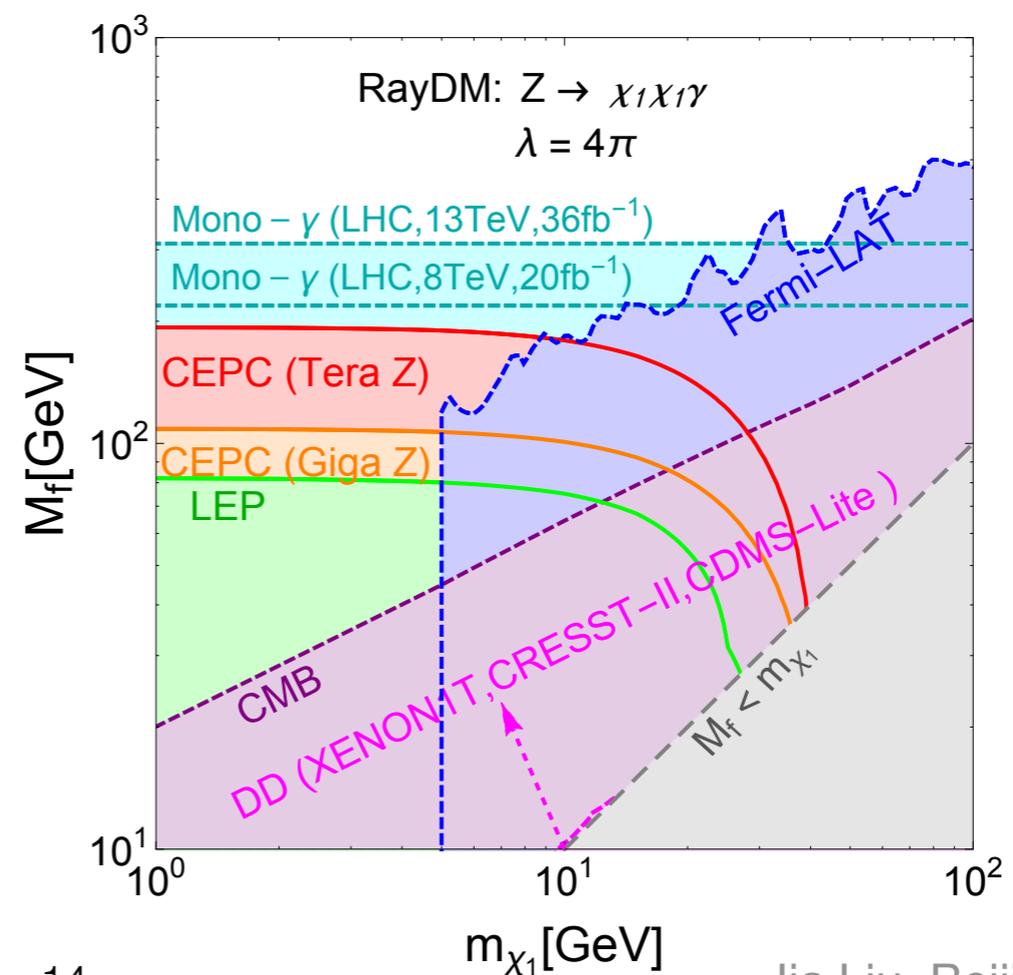
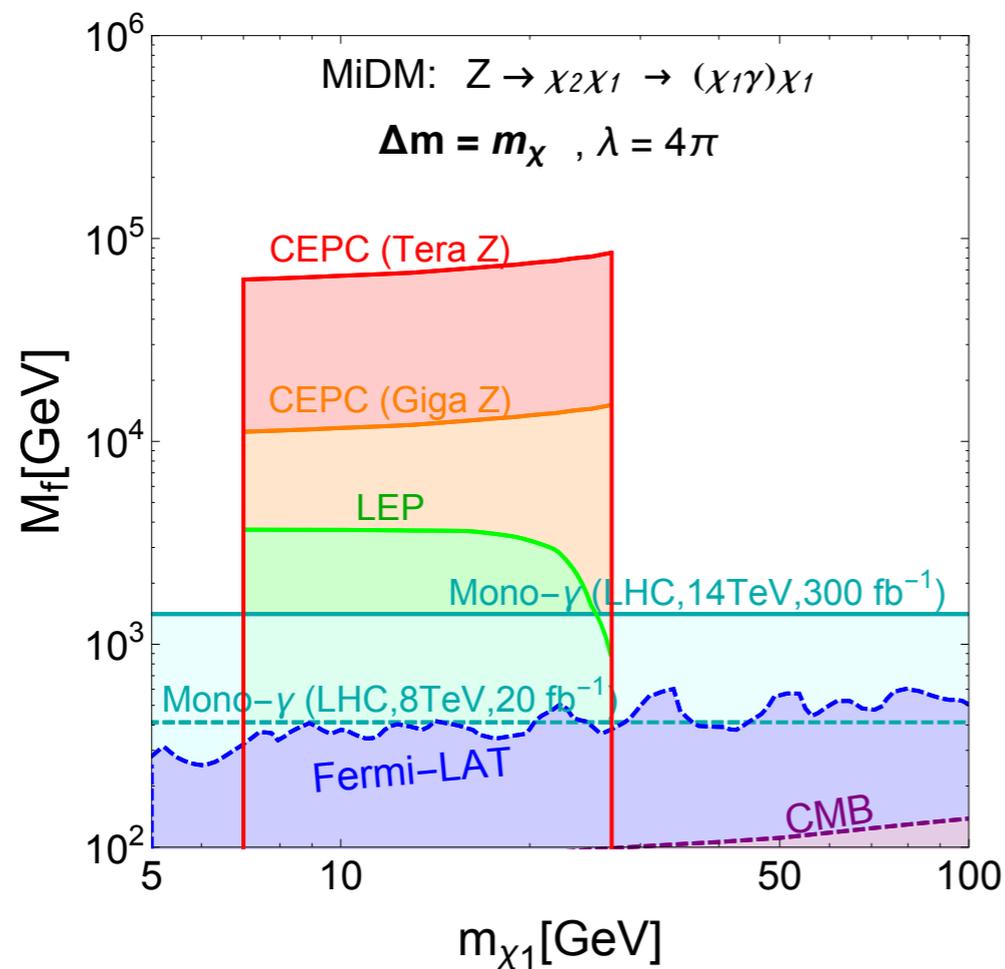
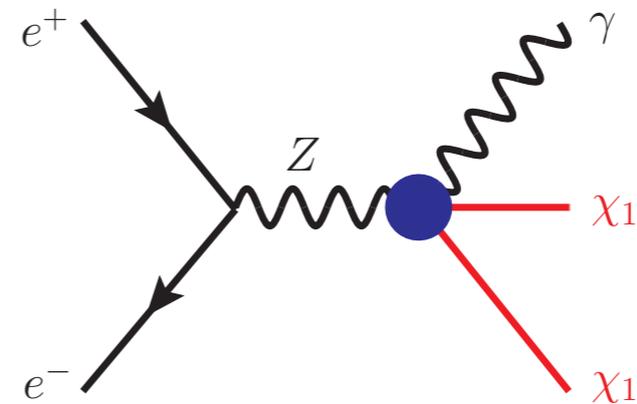
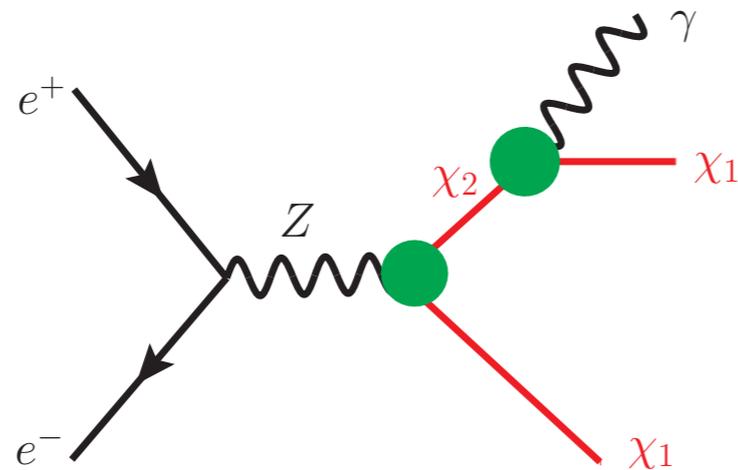
- Scale from mass in the loop

$$\frac{1}{\Lambda_{\text{MIDM}}} \approx \frac{\lambda^2 g_Y}{32\pi^2 M_\psi}, \quad \frac{1}{\Lambda_{\text{RayDM}}^3} \approx \frac{\lambda^2 g_Y^2}{24\pi^2 M_\psi^3},$$



Higher dimensional operator

- Magnetic inelastic DM and Rayleigh DM



Exotic Z decay topologies

- Exotic Z decay final states

$$Z \rightarrow n_{\cancel{E}} \cancel{E} + n_{\gamma} \gamma + n_{\ell^+ \ell^-} \ell^+ \ell^- + n_{\bar{q}q} \bar{q}q$$

exotic decay	topologies	n_{res}	models
$Z \rightarrow \cancel{E} + \gamma$	$Z \rightarrow \chi_1 \chi_2, \chi_2 \rightarrow \chi_1 \gamma$	0	2A: $\frac{1}{\Lambda} \bar{\chi}_2 \sigma^{\mu\nu} \chi_1 B_{\mu\nu}$ (MIDM)
	$Z \rightarrow \chi \bar{\chi} \gamma$	0	2B: $\frac{1}{\Lambda^3} \bar{\chi} \chi B_{\mu\nu} B^{\mu\nu}$ (RayDM)
	$Z \rightarrow a \gamma \rightarrow (\cancel{E}) \gamma$	1	2C: $\frac{1}{\Lambda_{2C}} a B_{\mu\nu} \tilde{B}^{\mu\nu}$ (long-lived ALP)
	$Z \rightarrow A' \gamma \rightarrow (\bar{\chi} \chi) \gamma$	1	2D: $\epsilon^{\mu\nu\rho\sigma} A'_\mu B_\nu \partial_\rho B_\sigma$ (WZ terms)
$Z \rightarrow \cancel{E} + \gamma\gamma$	$Z \rightarrow \phi_d A', \phi_d \rightarrow (\gamma\gamma), A' \rightarrow (\bar{\chi} \chi)$	2	3A: Vector portal
	$Z \rightarrow \phi_H \phi_A, \phi_H \rightarrow (\gamma\gamma), \phi_A \rightarrow (\bar{\chi} \chi)$	2	3B: 2HDM extension
	$Z \rightarrow \chi_2 \chi_1, \chi_2 \rightarrow \chi_1 \phi, \phi \rightarrow (\gamma\gamma)$	1	3C: Inelastic DM
	$Z \rightarrow \chi_2 \chi_2, \chi_2 \rightarrow \gamma \chi_1$	0	3D: MIDM
$Z \rightarrow \cancel{E} + \ell^+ \ell^-$	$Z \rightarrow \phi_d A', A' \rightarrow (\ell^+ \ell^-), \phi_d \rightarrow (\bar{\chi} \chi)$	2	4A: Vector portal
	$Z \rightarrow A' S S \rightarrow (\ell\ell) S S$	1	4B: Vector portal
	$Z \rightarrow \phi(Z^*/\gamma^*) \rightarrow \phi \ell^+ \ell^-$	1	4C: Long-lived ALP, Higgs portal
	$Z \rightarrow \chi_2 \chi_1 \rightarrow \chi_1 A' \chi_1 \rightarrow (\ell^+ \ell^-) \cancel{E}$	1	4D: Vector portal and Inelastic DM
	$Z \rightarrow \chi_2 \chi_1, \chi_2 \rightarrow \chi_1 \ell^+ \ell^-$	0	4E: MIDM, SUSY
	$Z \rightarrow \bar{\chi} \chi \ell^+ \ell^-$	0	4F: RayDM, slepton, heavy lepton mixing
$Z \rightarrow \cancel{E} + J J$	similar to $\cancel{E} + \ell^+ \ell^-$		15

Exotic Z decay topologies

- Exotic Z decay final states

$$Z \rightarrow n_{\cancel{E}} \cancel{E} + n_{\gamma} \gamma + n_{\ell^+ \ell^-} \ell^+ \ell^- + n_{\bar{q}q} \bar{q}q$$

exotic decay	topologies	n_{res}	models
$Z \rightarrow \cancel{E} + \gamma$	$Z \rightarrow \chi_1 \chi_2, \chi_2 \rightarrow \chi_1 \gamma$	0	2A: $\frac{1}{\Lambda} \bar{\chi}_2 \sigma^{\mu\nu} \chi_1 B_{\mu\nu}$ (MIDM)
	$Z \rightarrow \chi \bar{\chi} \gamma$	0	2B: $\frac{1}{\Lambda^3} \bar{\chi} \chi B_{\mu\nu} B^{\mu\nu}$ (RayDM)
	$Z \rightarrow a \gamma \rightarrow (\cancel{E}) \gamma$	1	2C: $\frac{1}{\Lambda_{2C}} a B_{\mu\nu} \tilde{B}^{\mu\nu}$ (long-lived ALP)
	$Z \rightarrow A' \gamma \rightarrow (\bar{\chi} \chi) \gamma$	1	2D: $\frac{1}{\Lambda} \bar{\chi} \chi B_{\mu\nu} B^{\mu\nu}$ (MIDM)
$Z \rightarrow \cancel{E} + \gamma\gamma$	$Z \rightarrow \phi_d A', \phi_d \rightarrow (\gamma\gamma), A' \rightarrow (\bar{\chi} \chi)$	2	3A: Vector portal $Z \rightarrow \phi_d A' \rightarrow (JJ)(JJ)$
	$Z \rightarrow \phi_H \phi_A, \phi_H \rightarrow (\gamma\gamma), \phi_A \rightarrow (\bar{\chi} \chi)$	2	3B: 2HDM extension $Z \rightarrow \phi_H \phi_A \rightarrow (JJ)(JJ)$
	$Z \rightarrow \chi_2 \chi_1, \chi_2 \rightarrow \chi_1 \phi, \phi \rightarrow (\gamma\gamma)$	1	3C: Inelastic RayDM $Z \rightarrow G_0 G_0, G_0 \rightarrow (bb)$
	$Z \rightarrow \chi_2 \chi_2, \chi_2 \rightarrow \gamma \chi_1$	0	3D: MIDM
	$Z \rightarrow \phi \gamma \rightarrow (\gamma\gamma) \gamma$	1	7A: ALP, Higgs portal
$Z \rightarrow \cancel{E} + \ell^+ \ell^-$	$Z \rightarrow \phi_d A', A' \rightarrow (\ell^+ \ell^-), \phi_d \rightarrow (\bar{\chi} \chi)$	2	4A: Vector portal
	$Z \rightarrow A' S S \rightarrow (\ell\ell) S S$	1	4B: Vector portal
	$Z \rightarrow \phi (Z^*/\gamma^*) \rightarrow \phi \ell^+ \ell^-$	1	4C: Long-lived ALP, Higgs portal
	$Z \rightarrow \chi_2 \chi_1 \rightarrow \chi_1 A' \chi_1 \rightarrow (\ell^+ \ell^-) \cancel{E}$	1	4D: Vector portal and Inelastic DM
	$Z \rightarrow \chi_2 \chi_1, \chi_2 \rightarrow \chi_1 \ell^+ \ell^-$	0	4E: MIDM, SUSY
	$Z \rightarrow \bar{\chi} \chi \ell^+ \ell^-$	0	4F: RayDM, slepton, heavy lepton mixing
$Z \rightarrow \cancel{E} + JJ$	similar to $\cancel{E} + \ell^+ \ell^-$		

CEPC collider setup

- Detector performance

$$\text{Photon energy resolution: } \frac{\delta E_\gamma}{E_\gamma} = \frac{0.16}{\sqrt{E_\gamma/\text{GeV}}} \oplus 0.01,$$

$$\text{Lepton momentum resolution: } \Delta \frac{\text{GeV}}{p_T^\ell} = 2 \times 10^{-5} \oplus \frac{10^{-3} \text{GeV}}{p_T^\ell \sin \theta},$$

$$\text{Jet energy resolution: } \frac{\delta E_j}{E_j} = \frac{0.3}{\sqrt{E_j/\text{GeV}}} \oplus 0.02.$$

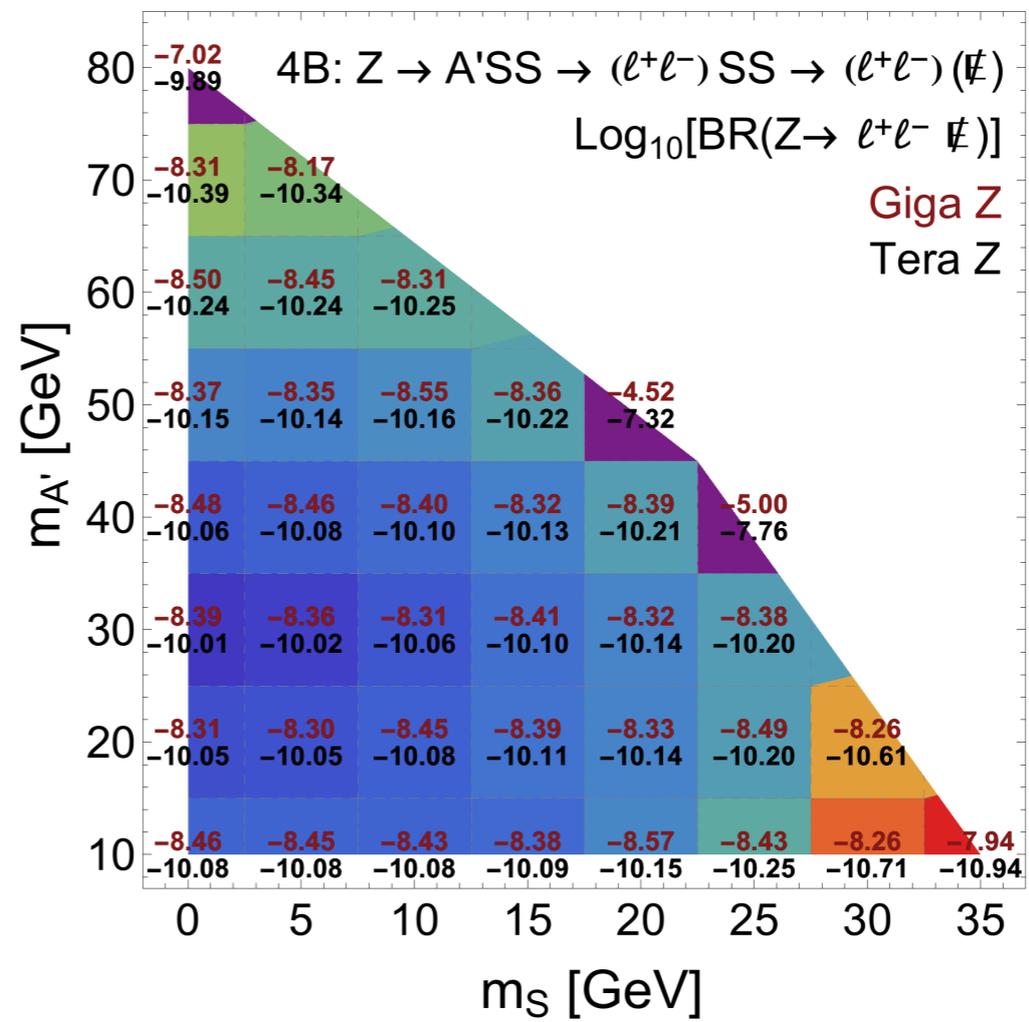
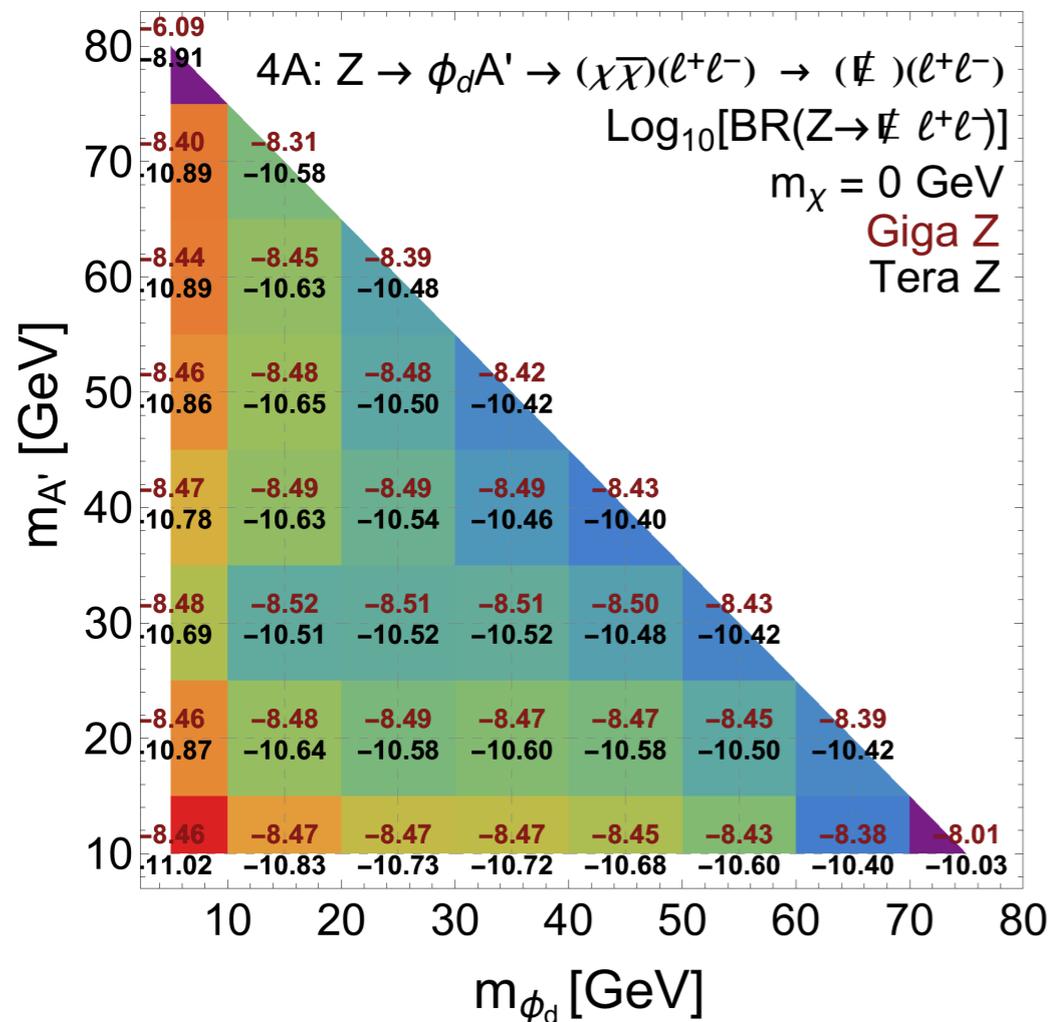
- Preliminary cuts

$$|\eta| < 2.3, E_\gamma > 10\text{GeV}, E_\ell > 5\text{GeV}, E_j > 10\text{GeV}, E_{(\text{MET})} > 10\text{GeV},$$
$$y_{ij} \equiv \frac{2\text{Min}(E_i^2, E_j^2) (1 - \cos \theta_{ij})}{E_{vis}^2} \geq 0.001$$

- SM background including one photon from ISR

Limits on exotic Z decay BR

• Di-Lepton + MET	$Z \rightarrow \phi_d A', A' \rightarrow (\ell^+ \ell^-), \phi_d \rightarrow (\bar{\chi} \chi)$	2	4A: Vector portal
	$Z \rightarrow A' S S \rightarrow (\ell \ell) S S$	1	4B: Vector portal
	$Z \rightarrow \phi(Z^*/\gamma^*) \rightarrow \phi \ell^+ \ell^-$	1	4C: Long-lived ALP, Higgs portal
	$Z \rightarrow \chi_2 \chi_1 \rightarrow \chi_1 A' \chi_1 \rightarrow (\ell^+ \ell^-) \cancel{E}$	1	4D: Vector portal and Inelastic DM
	$Z \rightarrow \chi_2 \chi_1, \chi_2 \rightarrow \chi_1 \ell^+ \ell^-$	0	4E: MIDM, SUSY
	$Z \rightarrow \bar{\chi} \chi \ell^+ \ell^-$	0	4F: RayDM, slepton, heavy lepton mixing



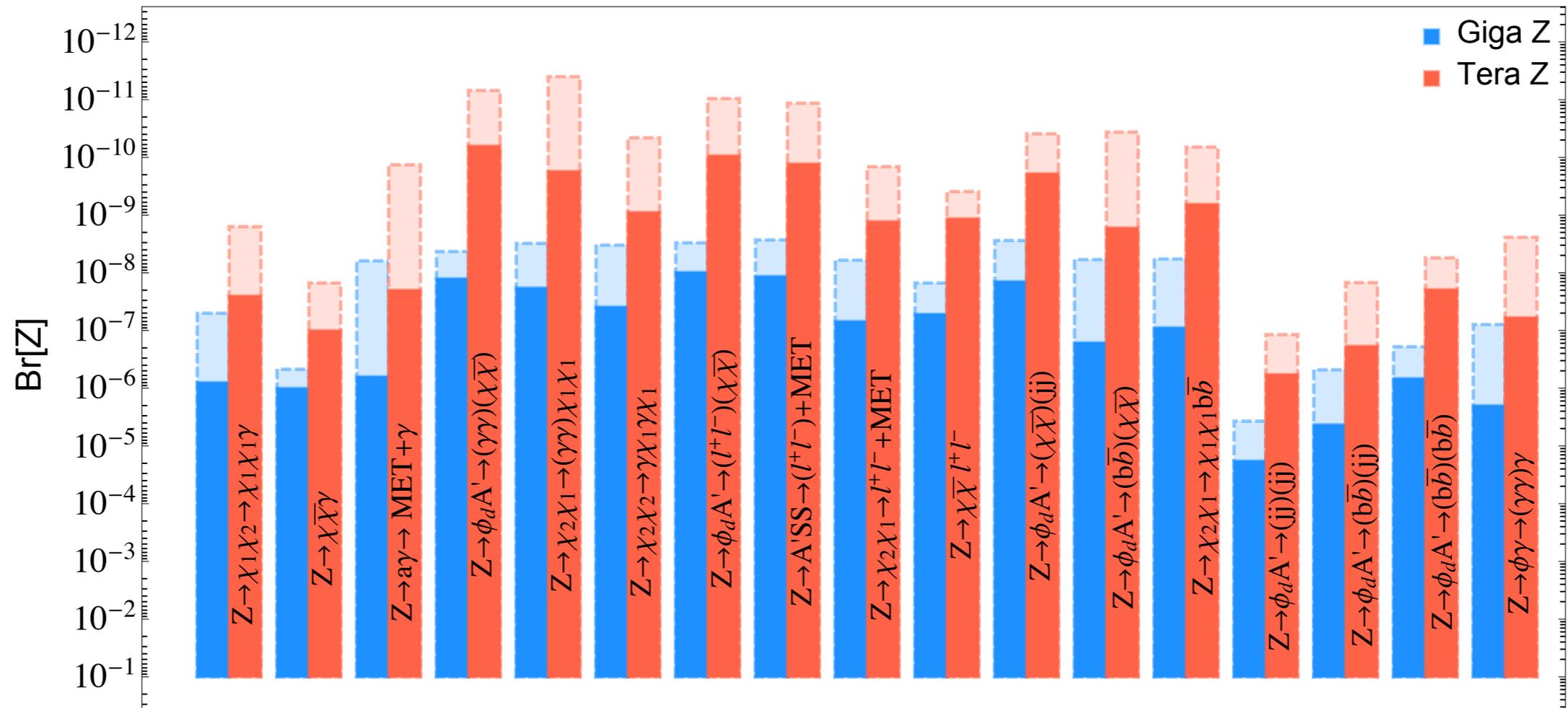
Summary

- Dark sector models
 - Higgs portal, Vector portal,
 - Axion-like Particle, Higher dimension Operator
- Can provide **leading and complementary** constraints comparing to current collider limits and DM limits

Summary

- Exotic Z decay topologies
- Sensitivities on BR

$$\ell^+ \ell^- + \text{MET} > \gamma\gamma + \text{MET} > \text{JJ} + \text{MET} > \gamma + \text{MET}$$



Thank you!