Dark matter probes with FCC-ee

(based on preliminary results from two on-going projects)
with Lian-Tao Wang, Xiao-Ping Wang, Wei Xue, Felix Yu

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Motivation for first project

- Dark matter with two portals at FCC-ee (Xiao-Ping Wang, Felix Yu)
  - we consider $U(1)'$ dark photon UV model, with kinetic mixing portal ($\epsilon B_{\mu\nu} F'^{\mu\nu}$) and Higgs portal ($\Phi^\dagger \Phi H^\dagger H$)
    - LEP limits on Z': for $m_{Z'} < 90\mathrm{GeV}$, coupling $(\epsilon e) \lesssim 10^{-2}$
    - $A'\gamma$ searches (P.F. Yin et al 0904.4644; H.B Li et al 0911.2067; V. Prasad et al 1508.07659; D. Curtin et al 1412.0018; BABAR 1406.2980; M. Karliner et al 1503.07209; Y. Hochberg et al 1512.07917; Belle 1609.05599;)

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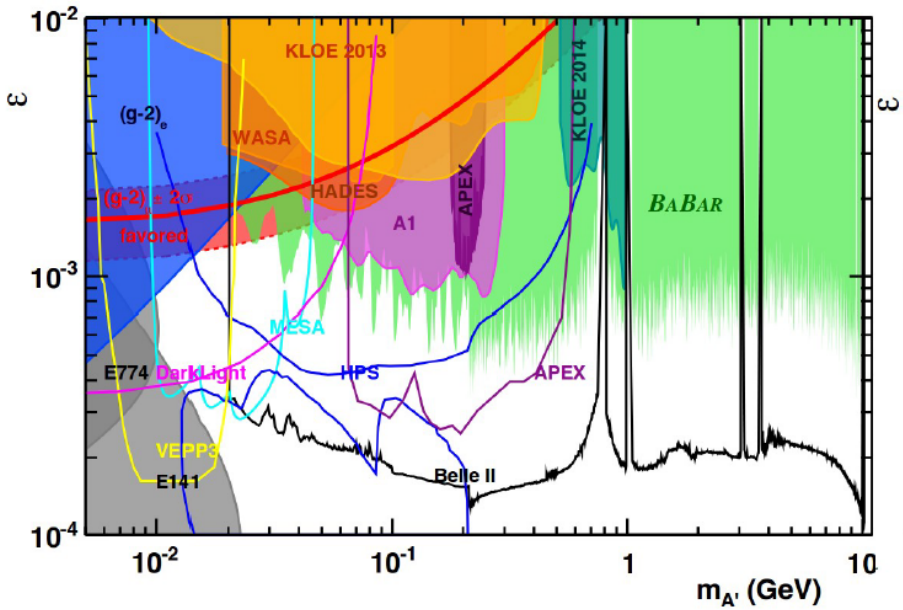
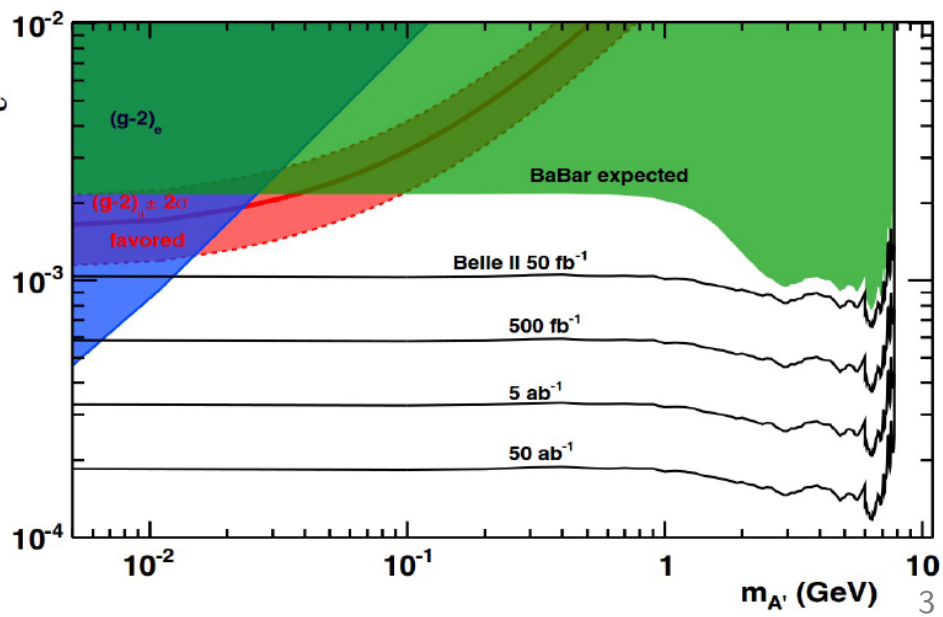
    - $A'\gamma$ Belle projection ($< 10\mathrm{GeV}$) (from Inguglia ICHEP2016)

$e^+e^- \to \gamma A' \to \gamma e^+e^-, \gamma \mu^+\mu^-,$ *prompt*



$e^+e^- \to \gamma A' \to \gamma \chi \bar{\chi}$



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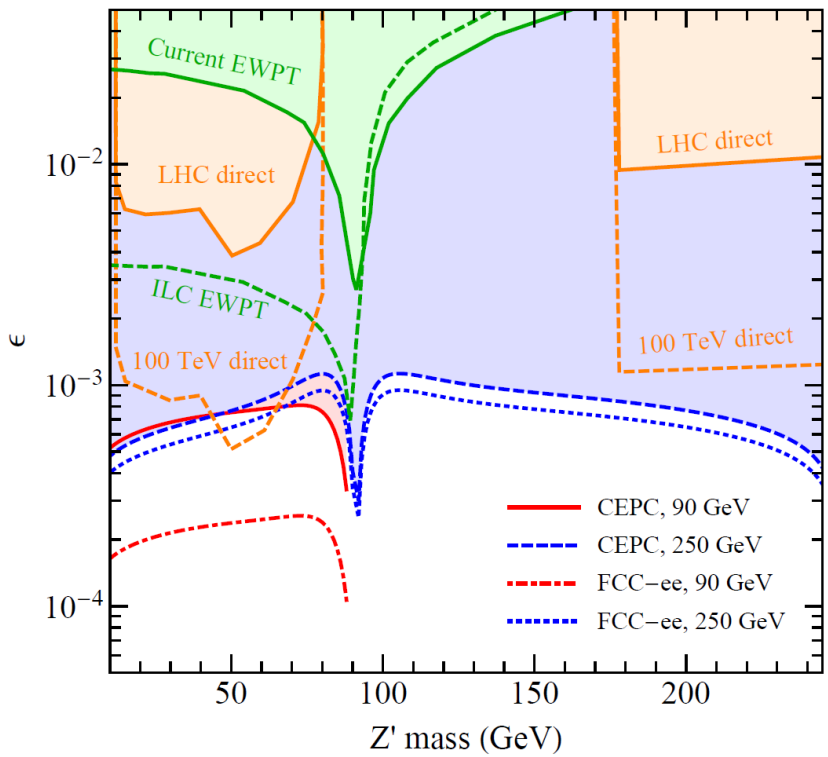
    - $A'\gamma$ FCC-ee projection ($> 10\mathrm{GeV}$, $A' \to \ell^+\ell^-$) (M. Karliner et al 1503.07209)



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    - Electroweak precision observables at Giga Z $\Rightarrow \epsilon \sim 3 \times 10^{-3}$ Curtin et al 1412.0018
    - Higgs precision measurement FCC-ee projection $\frac{\Delta\sigma(ZH)}{\sigma(ZH)} \sim 0.5\%$ $\Longrightarrow \sin^2\alpha \lesssim 0.005$
  - New combinations: explore all VV and VS possibilities, $V = \gamma, Z, A'$ and $S = H, H_d$ (HA', SA' and ZS search by Gilad's talk and ; S. Biswas et al 1503.05836; Belle 1502.00084;)
    - $hZ \to (\bar{b}b/\tau^+\tau^-) + Z$ search at LEP hep-ph/0602042
      for $m_h < 112\mathrm{GeV}$, $\sigma/\sigma_{\mathrm{SM}} \sim \sin^2\alpha \in [10^{-2}, 10^{-1}]$
  - $A', H_d \to$ invisible

Dark matter with two portals

- Lagrangian

$$\mathcal{L}_{\mathrm{DP}} \equiv \bar{\chi}(i\partial\!\!\!/ - m_\chi + i g_d A\!\!\!/')\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2c_w}F'_{\mu\nu}B^{\mu\nu}$$
$$+ (D_\mu\Phi)^\dagger (D_\mu\Phi) - \mu_d^2\Phi^\dagger\Phi + \frac{\lambda_d}{2}(\Phi^\dagger\Phi)^2 + \lambda_{HS}(\Phi^\dagger\Phi)(H^\dagger H)$$

- Mixing between $A' - Z$ and $\phi - H$

$$\begin{pmatrix} Z_{\mathrm{SM}} \\ A_{\mathrm{SM}} \\ A' \end{pmatrix} = \begin{pmatrix} 1+\mathcal{O}(\varepsilon^2) & 0 & -\varepsilon t_w \frac{m_{A'}^2}{m_{A'}^2 - m_Z^2} \\ \mathcal{O}(\varepsilon^2) & 1 & \varepsilon \\ \varepsilon t_w \frac{m_Z^2}{m_{A'}^2 - m_Z^2} & 0 & 1+\mathcal{O}(\varepsilon^2) \end{pmatrix} \cdot \begin{pmatrix} \tilde{Z} \\ \tilde{A} \\ \tilde{A}' \end{pmatrix}$$

A' search

$$\begin{pmatrix} S \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \Phi \\ h_0 \end{pmatrix}$$

Higgs precision measurement

$$\tan 2\alpha = \frac{\lambda_{HS} v_h v_s}{\lambda_d v_s^2 - \lambda v_h^2}$$

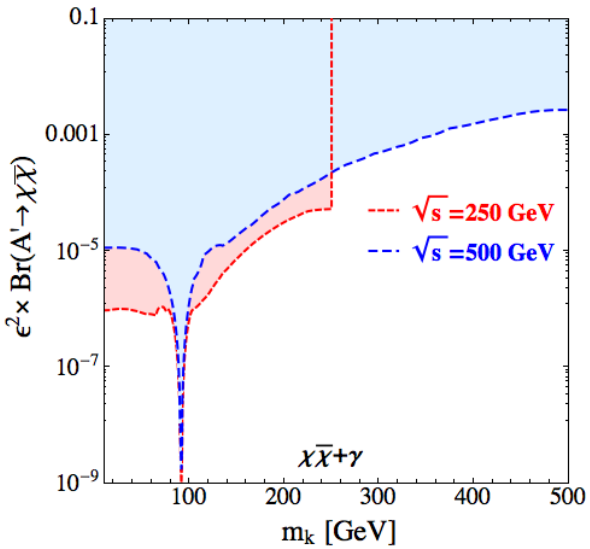
Phenomenology

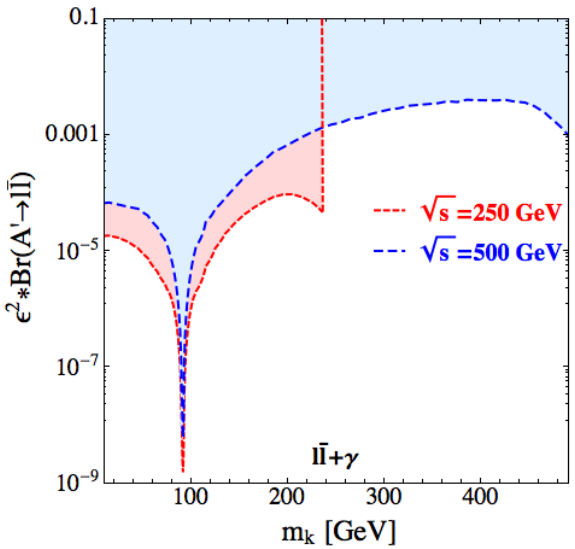
- $A' \to \bar{\chi}\chi \quad \mathcal{O}(1), \quad A' \to \bar{f}f \quad \mathcal{O}(\epsilon^2)$
- $S \to A'A' \quad \mathcal{O}(1), \quad S \to \bar{b}b \quad \mathcal{O}(\sin^2\alpha)$

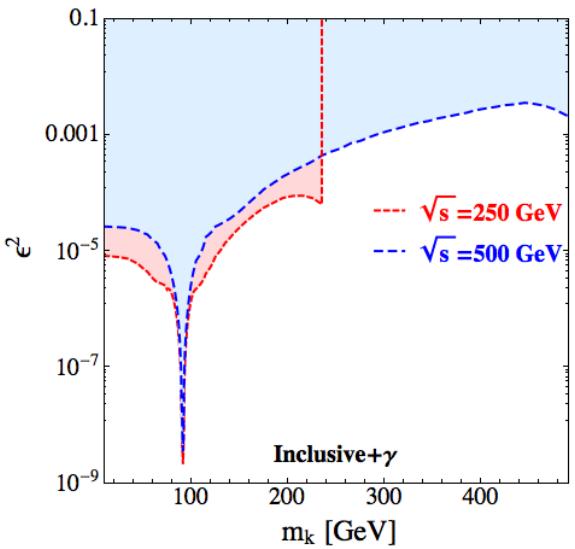
	process	suppression	BKG
V+V	$A'\gamma \to (\chi\bar{\chi})\gamma$	ϵ^2	$\nu\bar{\nu}\gamma$
	$Z\gamma \to (SA')\gamma \to 3A'\gamma \to 3(\bar{\chi}\chi)\gamma$		
	$ZA' \to Z(\chi\bar{\chi})$		$\ell^+\ell^-\nu\bar{\nu}$
V+S	$Zh \to Z(2S) \to Z(4A') \to Z4(\bar{\chi}\chi)$	$\sin^2\alpha$	$\ell^+\ell^-\nu\bar{\nu}$
	$ZS \to Z(2A') \to Z2(\bar{\chi}\chi)$		
	$A'h \to (\chi\bar{\chi})(\bar{b}b)$	ϵ^2	$\nu\bar{\nu}\bar{b}b$
	$Zh \to Z(A'Z) \to 2Z(\chi\bar{\chi})$		$2(\ell^+\ell^-)\nu\bar{\nu}$
	$A'S \to (\chi\bar{\chi})(SM\overline{SM})$	$\epsilon^2\sin^2\alpha$	$\nu\bar{\nu}SM\overline{SM}$

$A'\gamma$ sensitivity to ϵ

- $A' \to \bar{\chi}\chi \quad \mathcal{O}(1), \quad \ell^+\ell^- \quad \mathcal{O}(\epsilon^2)$
- Cuts: $E_\gamma^{\text{recoil}} = \frac{s - m_{A'}^2}{2\sqrt{s}}$, $|E_\gamma - E_\gamma^{\text{recoil}}| < 2.5\text{GeV}$ $(\frac{\delta E_\gamma}{E_\gamma} = \frac{0.16}{\sqrt{E/\text{GeV}}} \oplus 0.01)$
- preliminary results







- $m_{A'} = m_k(1 + \mathcal{O}(\epsilon^2))$
- for visible $A' \to \ell^+\ell^-$: adding $m_{\ell^+\ell^-}$ cut can improve $\epsilon \sim [10^{-4}, 10^{-3}]$ (see M. Karliner et al 1503.07209)

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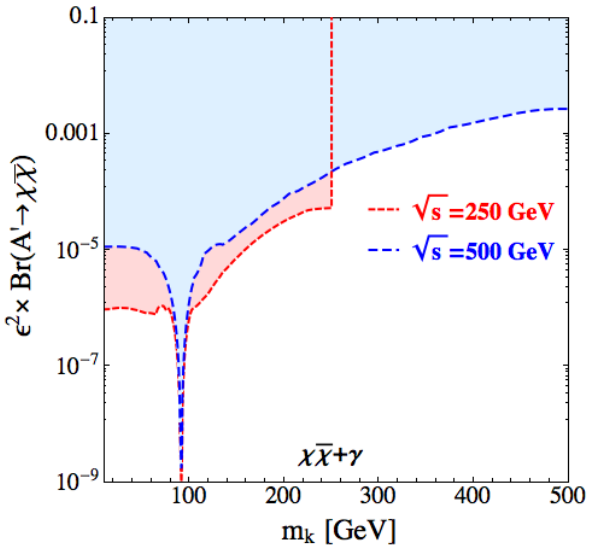
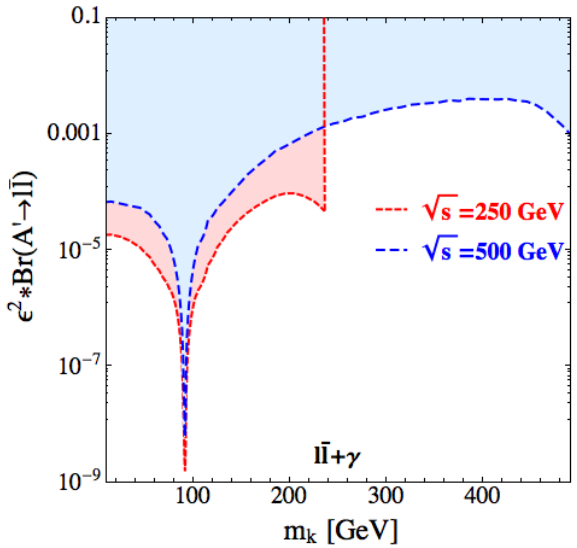
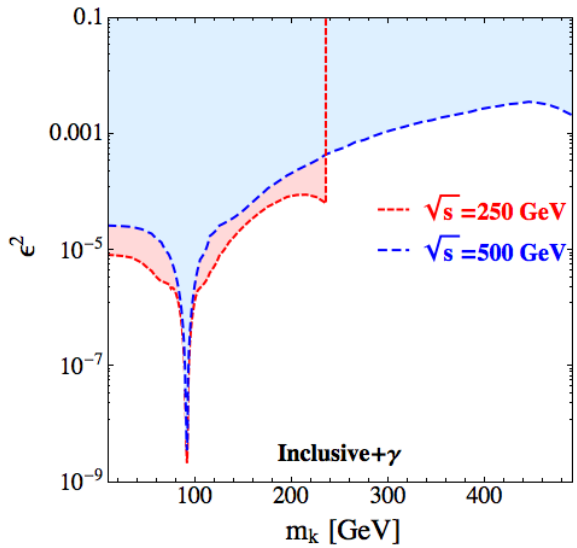


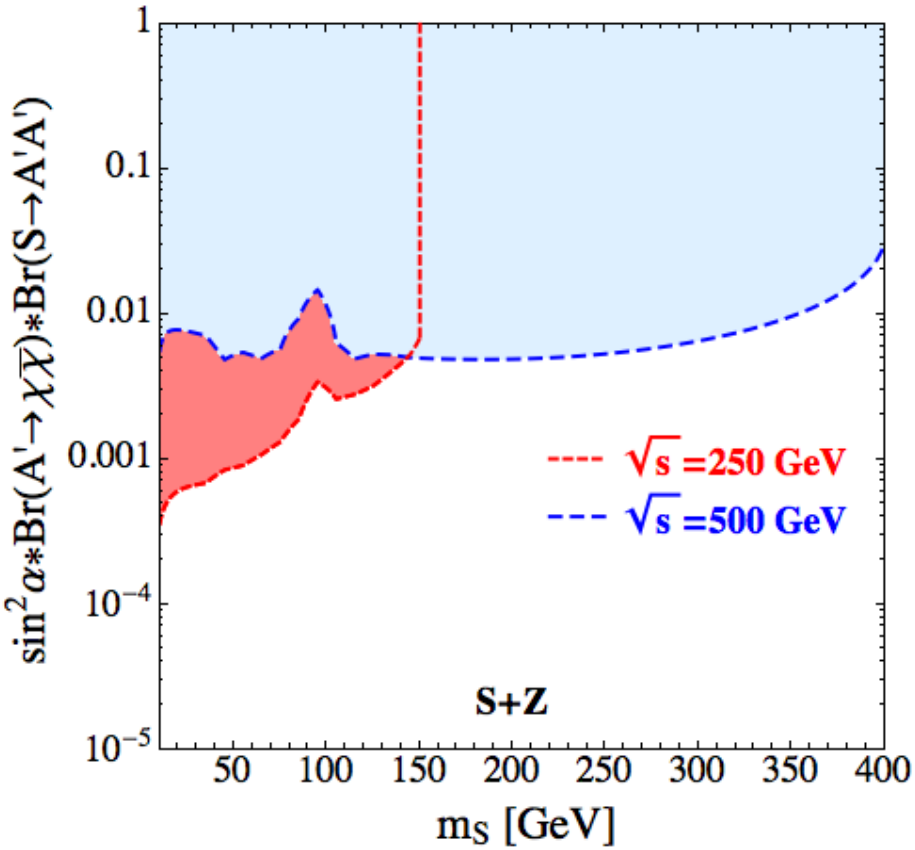




- Comparing with DM relic abundance requirement:
  - DM relic abundance: $\sigma(\bar{\chi}\chi \to A'^*/Z^* \to \bar{f}f) \sim \epsilon^2 \alpha_{\text{EM}} \alpha_d \frac{1}{m_{A'}^2}$
  - Assuming $\alpha_d \sim \alpha_{\text{EM}}$, $m_{A'} \sim \mathcal{O}(10)\text{GeV}$, $\epsilon \sim \mathcal{O}(0.1 \sim 1)$

ZS sensitivity to $\sin\alpha$

- $Z \to \ell^+\ell^-$, $S \to A'A'$ $\mathcal{O}(1)$ and $A' \to \bar{\chi}\chi$ $\mathcal{O}(1)$
- $|m_{\ell^+\ell^-} - m_Z| < 10\text{GeV}$ with $|m_{\text{inv}} - m_S| < 2\text{GeV}$
- preliminary results



- Higgs precision measurement $\frac{\Delta\sigma(ZH)}{\sigma(ZH)} \sim 0.5\% \Longrightarrow \sin^2\alpha \lesssim 0.005$

Summary for the first project

- Dark matter with two portals
  - ϵ sensitivity
    - $A'\gamma$ channel sensitivity $\epsilon \sim \mathcal{O}(10^{-3})$
    - DM relic abundance: $\sigma(\bar{\chi}\chi \to \bar{f}f) \sim \epsilon^2 \alpha_{\mathrm{EM}} \alpha_d \frac{1}{m_{A'}^2}$
    - Assuming $\alpha_d \sim \alpha_{\mathrm{EM}}$, $m_{A'} \sim \mathcal{O}(10)\mathrm{GeV}$, $\epsilon \sim \mathcal{O}(0.1 \sim 1)$
    - DM relic abundance region well explored
  - $\sin\alpha$ sensitivity
    - ZS channel sensitivity $\sin^2\alpha \sim \mathcal{O}(10^{-3} \sim 10^{-2})$
    - Higgs precision measurement $\frac{\Delta\sigma(ZH)}{\sigma(ZH)} \sim 0.5\% \Longrightarrow \sin^2\alpha \lesssim 0.005$
    - New combinations of VV and VS can give better sensitivity

Motivation for the second project

- What can we do for dark matter probes at FCC-ee?
  - LEP Shines Light on Dark Matter Fox et al 1103.0240
  - missing energy + X

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- What can we do for dark matter probes at FCC-ee?
  - LEP Shines Light on Dark Matter Fox et al 1103.0240
  - missing energy + X
- Giga(Tera) Z as intensity frontier (Lian-Tao Wang, Xiao-Ping Wang, Wei Xue)
  - We consider exotic Z decay via dark matter or dark mediators
    - indirectly constrain the model via Electroweak Precision Observables e.g. CMSSM O. Buchmueller et al 1505.04702; Linear Collider report 1504.01726;
    - Z invisible width M. Carena et al hep-ph/0308053;
    - sterile neutrino from Z pole Blondel's talk and 1411.5230;
    - $Z \to \phi \bar{f} f$ Gilad's talk ;
    - Z decay to hidden valley Verhaaren's talk
    - $e^+e^- \to Z \to Z^* h$ from LEP PLB 385, 454;also see Flacke et al 1610.02025
      $m_h < 60.2\mathrm{GeV}$ from visible, $m_h < 66.7\mathrm{GeV}$ from invisible
    - $Z \to H_1 H_2$ from LEP hep-ph/0602042
    - rare Z decays Durieux's talk 1512.03071
    - Z lepton flavor violating decay Dam's talk
  - Emphasize on channels with missing energy

Exotic Z decay at FCC-ee (Giga Z)

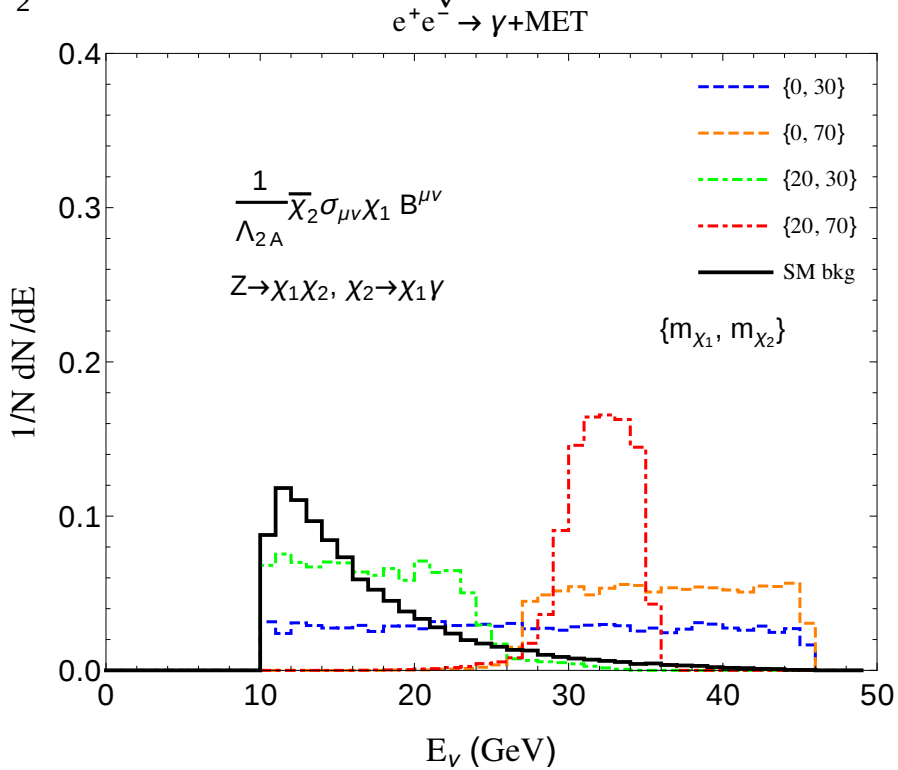
- Exotic Z decay classification by final state
  - FCC-ee speciality: missing energy and clean environment
  - final state
    - $\gamma + \not{E}$
    - $2\gamma + \not{E}$
    - $\ell^+\ell^- + \not{E}$
    - $JJ + \not{E}$
    - JJJ
    - 3γ
    - ...
  - motivation for event topologies
    - dark matter UV models
    - higher dimensional operators

Exotic decay final states and topologies

exotic Z decay	topology	SM bkg (pb)
$\gamma + \not{E}$	$Z \to \chi_1\chi_2, \chi_2 \to \chi_1\gamma$ $Z \to \chi\bar{\chi}\gamma$, $aB_{\mu\nu}\tilde{B}^{\mu\nu}$, $aW_{\mu\nu}\tilde{W}^{\mu\nu}$	0.243
$2\gamma + \not{E}$	$Z \to \phi_d A'$,$\phi_d \to (\gamma\gamma)$, $A' \to (\bar{\chi}\chi)$ $Z \to \chi_2\chi_2$,$\chi_2 \to \gamma\chi_1$ $Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\phi$, $\phi \to (\gamma\gamma)$	1.5×10^{-4}
$\ell^+\ell^- + \not{E}$	$Z \to \phi_d A'$,$A' \to (\ell^+\ell^-)$,$\phi_d \to (\bar{\chi}\chi)$ $Z \to \chi_2\chi_1$,$\chi_2 \to \ell^+\ell^-\chi_1$ $Z \to \bar{\chi}\chi\ell^+\ell^-$ vector-like heavy lepton	1.7×10^{-3}
$JJ + \not{E}$	$Z \to \phi_d A'$,$A' \to (jj)$,$\phi_d \to (\bar{\chi}\chi)$ $Z \to \phi_d A'$,$\phi_d \to (\bar{b}b)$,$A' \to (\bar{\chi}\chi)$ $Z \to \chi_1\chi_2$,$\chi_2 \to \bar{b}b\chi_1$	9.5×10^{-3}
$Z \to JJ + JJ$	$Z \to \phi_d A'$,$\phi_d \to jj$,$A' \to jj$ $Z \to \phi_d A'$,$\phi_d \to bb$,$A' \to jj$ $Z \to \phi_d A'$,$\phi_d \to bb$,$A' \to bb$ $(H_1H_2,\ G_0G_0)$	5450
$Z \to 3\gamma$	$aB_{\mu\nu}\tilde{B}^{\mu\nu}$, $aW_{\mu\nu}\tilde{W}^{\mu\nu}$	

Background for $Z \to \chi_1\chi_2, \chi_2 \to \chi_1\gamma$

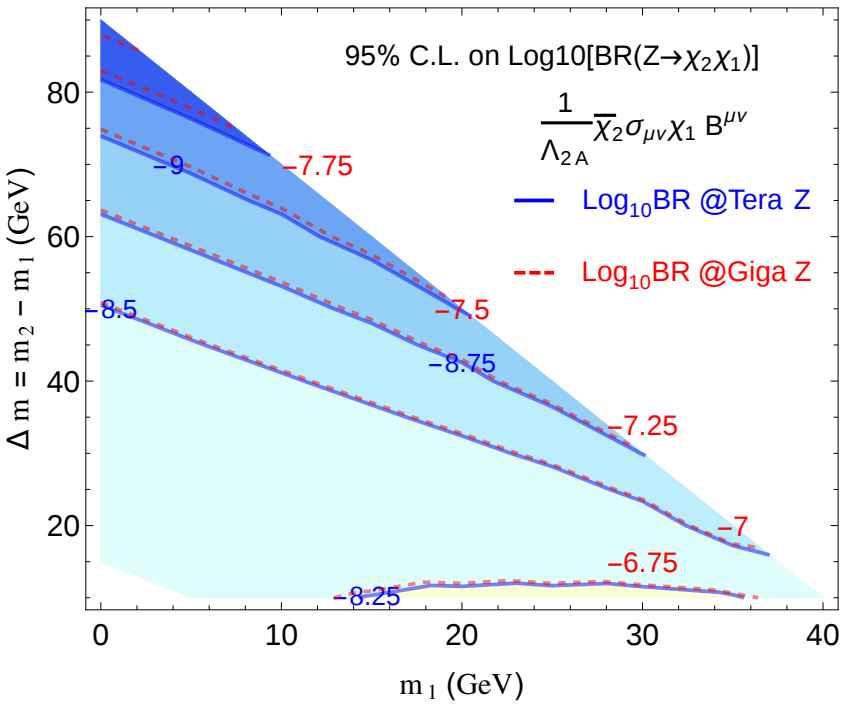
- SM background from γZ^*, for $\bar{\nu}_e\nu_e$ W^* also contributes
  - γ dominates at small energy due to radiative nature
- Signal topology from: $\frac{1}{\Lambda}\bar{\chi}_2\sigma^{\mu\nu}\chi_1 B_{\mu\nu}$
  - E_γ has a box shape due to boost of χ_2
  - $E_\gamma^{max} = \frac{m_2^2-m_1^2}{4m_2^2}\frac{s+m_2^2-m_1^2+\sqrt{s^2+(m_2^2-m_1^2)^2-2s(m_2^2+m_1^2)}}{\sqrt{s}}$
  - $E_\gamma^{min} = \frac{m_2^2-m_1^2}{4m_2^2}\frac{s+m_2^2-m_1^2-\sqrt{s^2+(m_2^2-m_1^2)^2-2s(m_2^2+m_1^2)}}{\sqrt{s}}$



Sensitivity for $Z \to \chi_1\chi_2, \chi_2 \to \chi_1\gamma$

- pre-cuts: $E_\gamma > 10\text{GeV}$, $\eta < 2.3$
- cuts: $E_\gamma^{max} > E_\gamma > E_\gamma^{min}$, $m_{inv} > 2m_{\chi_1}$
  - BR sensitivity $\propto \sqrt{L}$, $BR \sim 10^{-7}$, $10^{-8.5}$
  - Λ sensitivity $\propto L^{1/4}$, $\Lambda \sim 10^{5.5}\text{GeV}$, $10^{6.25}\text{GeV}$
  - DM relic requires: $\Lambda \sim \mathcal{O}(10^2 \sim 10^3)\text{GeV}$
  - preliminary results

$e^+e^- \to \gamma$+inv @$\sqrt{s}$=m_Z @2A



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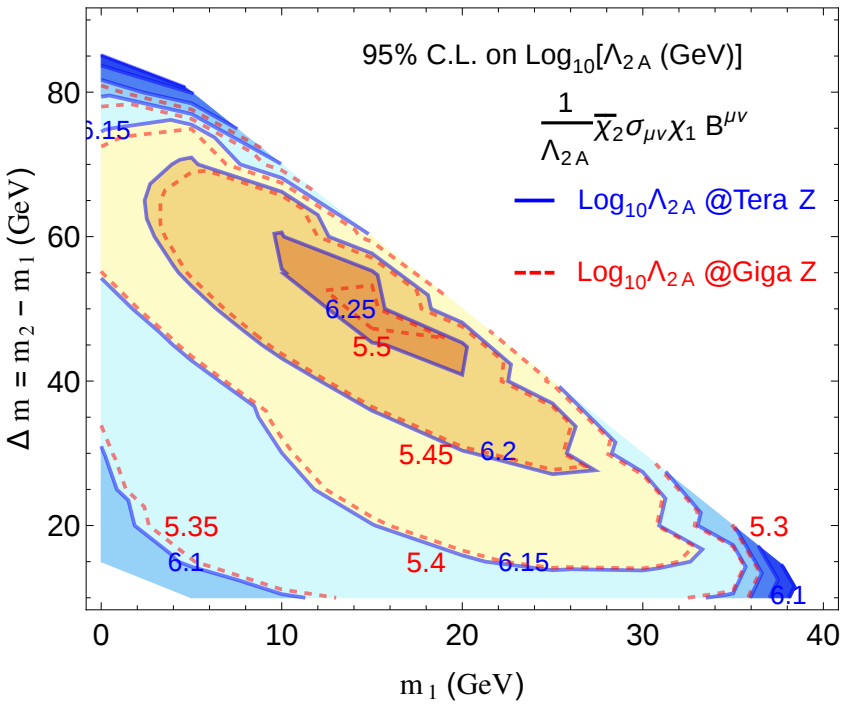
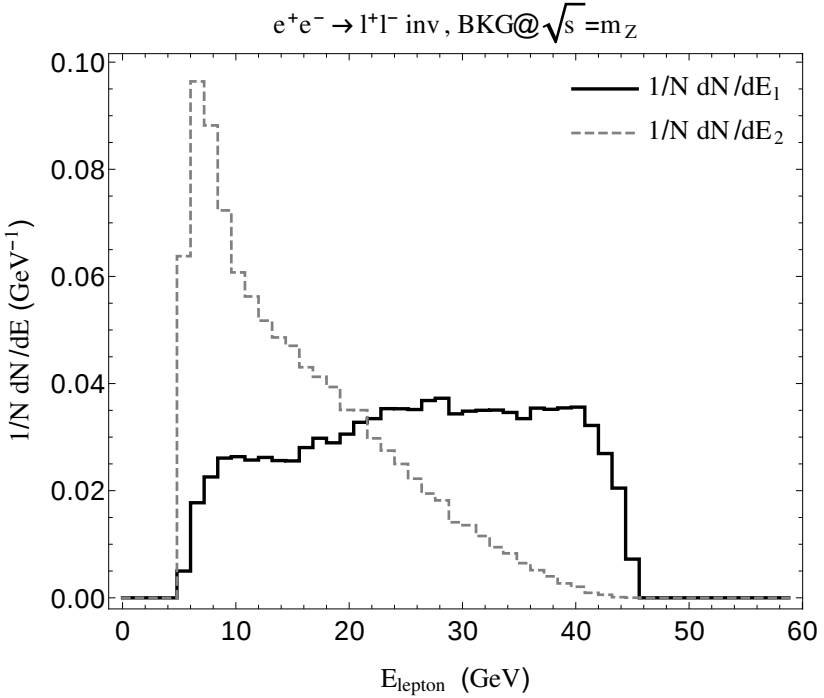
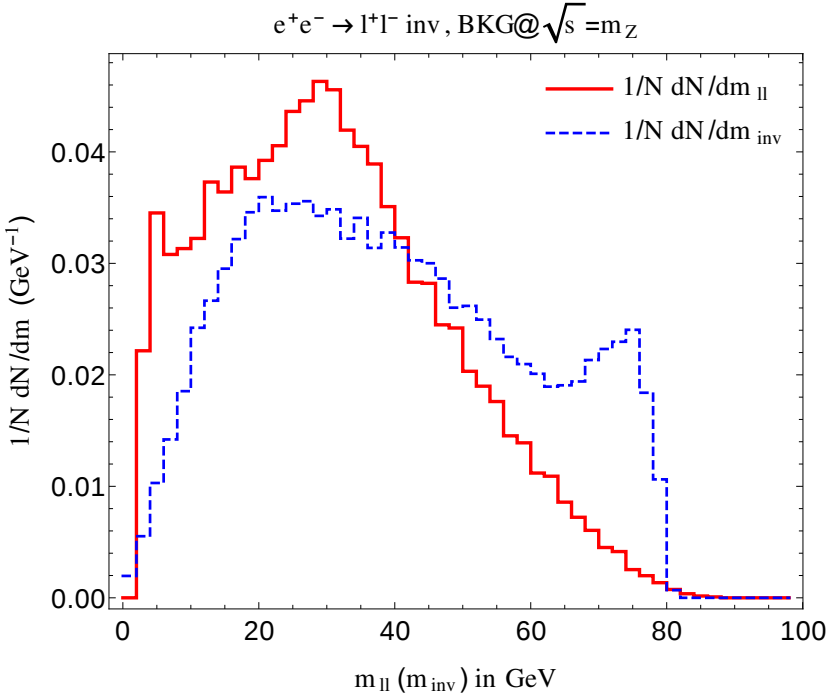


Background for $Z \to \bar{\chi}\chi Z^*/\gamma^*, Z^*/\gamma^* \to \ell^+\ell^-$

- SM background from γ^* , $W^*$and Z^*
- Signal topology from: $\frac{1}{\Lambda^3}\bar{\chi}\chi B_{\mu\nu}B^{\mu\nu}$

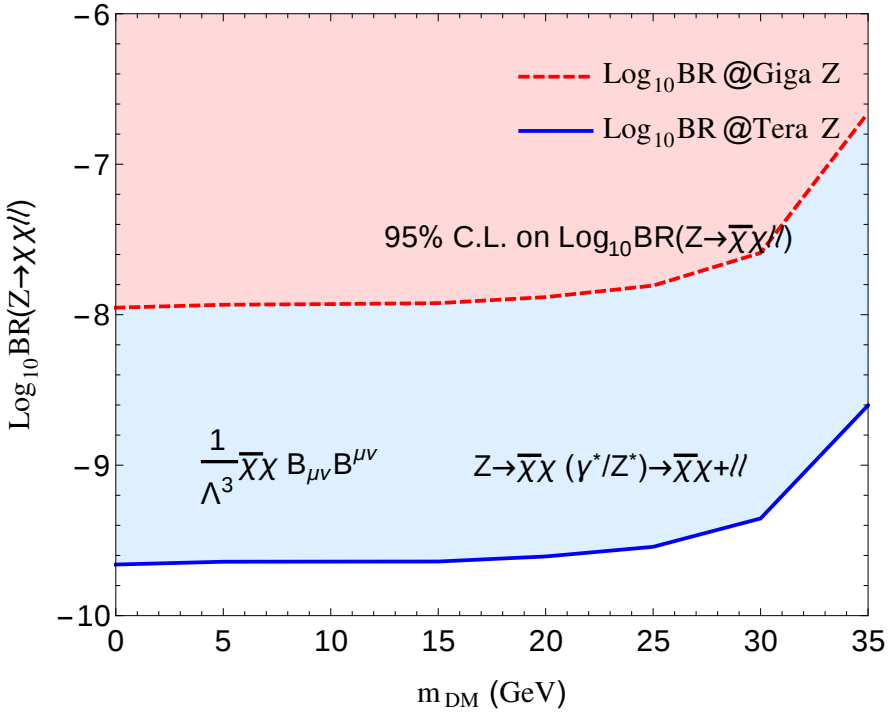




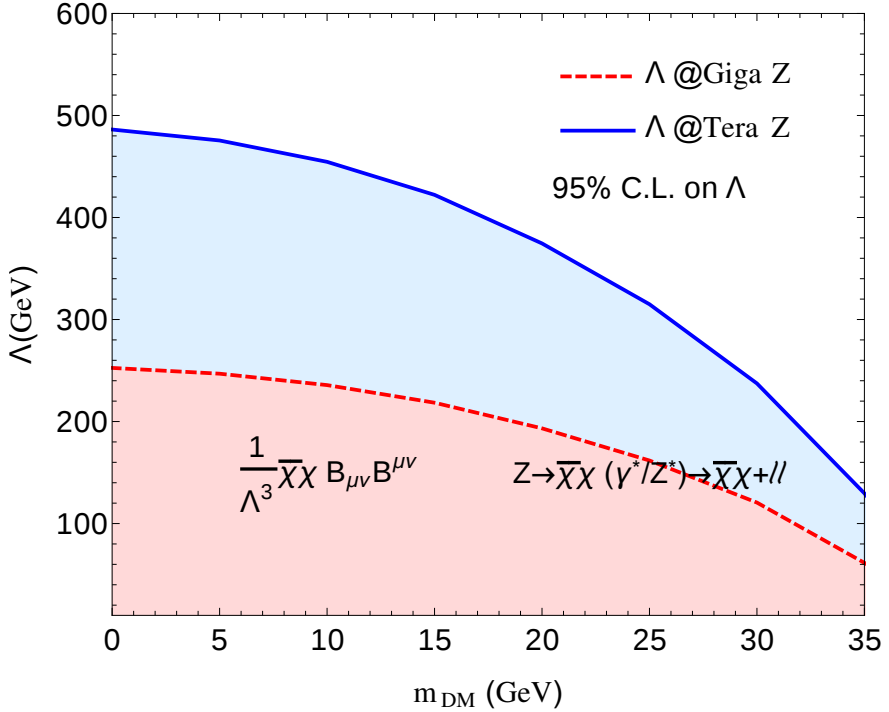
Sensitivity for $Z \to \bar{\chi}\chi Z^*/\gamma^*, Z^*/\gamma^* \to \ell^+\ell^-$

- pre-cuts: pre-cuts: $E_{\ell_1} > 10\text{GeV}$, $E_{\ell_2} > 5\text{GeV}$, $\eta < 2.3$
- cuts: $m_{\ell^+\ell^-} < 10\text{GeV}$, $2m_1 < m_{inv}$
  - BR sensitivity $\propto \sqrt{L}$, $BR \sim 10^{-8}$, $10^{-9.5}$
  - Λ sensitivity $\propto L^{1/6}$, $\Lambda \sim [50, 250]\text{GeV}$, $[100, 500]\text{GeV}$
  - DM relic requires: $\Lambda \sim \mathcal{O}(100 \sim 300)\text{GeV}$
  - preliminary results

95% C.L. on $\text{Log}_{10}\text{BR}(Z\to\bar{\chi}\chi l^+l^-)$



95% C.L. on Λ



Exotic decay final states and preliminary results

exotic Z decay	topology	preliminary BR at Giga(Tera)Z
$\gamma + \not{E}$	$Z \to \chi_1\chi_2, \chi_2 \to \chi_1\gamma$	$10^{-6.5} \sim 10^{-7.5}\left(10^{-8} \sim 10^{-9}\right)$
	$Z \to \chi\bar{\chi}\gamma$	$10^{-6.5} \sim 10^{-7.5}\left(10^{-8} \sim 10^{-9}\right)$
$2\gamma + \not{E}$	$Z \to \phi_d A'$,$\phi_d \to (\gamma\gamma)$, $A' \to (\bar{\chi}\chi)$	$10^{-8.1} \sim 10^{-8.4}\left(10^{-10.5} \sim 10^{-11.5}\right)$
	$Z \to \chi_2\chi_2, \chi_2 \to \gamma\chi_1$	$10^{-7.5} \sim 10^{-8.5}\left(10^{-9} \sim 10^{-10}\right)$
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\phi$, $\phi \to (\gamma\gamma)$	$10^{-8.1} \sim 10^{-8.4}\left(10^{-10} \sim 10^{-11}\right)$
$\ell^+\ell^- + \not{E}$	$Z \to \phi_d A', A' \to (\ell^+\ell^-), \phi_d \to (\bar{\chi}\chi)$	$\sim 10^{-8.3}\left(\sim 10^{-10}\right)$
	$Z \to \chi_2\chi_1, \chi_2 \to \ell^+\ell^-\chi_1$	$\sim 10^{-8}\left(\sim 10^{-9.5}\right)$
	$Z \to \bar{\chi}\chi\ell^+\ell^-$	$\sim 10^{-8}\left(\sim 10^{-9.5}\right)$
$JJ + \not{E}$	$Z \to \phi_d A', A' \to (jj), \phi_d \to (\bar{\chi}\chi)$	$\sim 10^{-8.5}\left(\sim 10^{-10}\right)$
	$Z \to \phi_d A', \phi_d \to (\bar{b}b), A' \to (\bar{\chi}\chi)$	
	$Z \to \chi_1\chi_2, \chi_2 \to \bar{b}b\chi_1$	$\sim 10^{-8.5}\left(\sim 10^{-9.6}\right)$

Summary for the second project

- Exotic Z decay
  - BR sensitivity
    - $10^{-6.5} \sim 10^{-9.5}(10^{-8} \sim 10^{-11})$ for Giga(Tera) Z
    - usually scale with $\sqrt{L}$
  - scale sensitivity
    - extremely good $10^5 \sim 10^6 \mathrm{GeV}$ for $\frac{1}{\Lambda}\bar{\chi_2}\sigma^{\mu\nu}\chi_1 B_{\mu\nu}$
    - $100 \sim 500 \mathrm{GeV}$ for $\frac{1}{\Lambda^3}\bar{\chi}\chi B^{\mu\nu}B_{\mu\nu}$
  - Giga Z already provides great sensitivity on exotic Z decay
  - Tera Z might be helpful for high dimensional operators to explore relic abundance parameter region

Thank you!

Pre-selection and smearing

- Pre-selection
  - $E_\gamma > 10\text{GeV}$, $|\eta| < 2.3$
  - $E_\ell > 5\text{GeV}$, $|\eta| < 2.3$
  - $E_j > 5\text{GeV}$, $|\eta| < 2.3$
- Detector resolution by Gaussian smearing
  - $\frac{\delta E_\gamma}{E_\gamma} = \frac{0.16}{\sqrt{E/\text{GeV}}} \oplus 0.01$
  - $\frac{\delta E_j}{E_j} = \frac{0.3}{\sqrt{E/\text{GeV}}} \oplus 0.02$
  - $\Delta\left(\frac{1}{p_T^\ell/\text{GeV}}\right) = \frac{10^{-3}\text{GeV}}{p_T \sin\theta} \oplus 2 \times 10^{-5}$