Probing Dark Sectors

Felix Yu
Johannes Gutenberg University, Mainz

Based on JHEP **1706**, 077 (2017) [1704.00730], with Jia Liu, Xiao-Ping Wang

The 2018 International Workshop on the High Energy CEPC
IHEP, Beijing – November 13, 2018

CEPC as a Discovery Machine

In a nutshell:

Lack of confirmed signals from direct detection (failure of WIMP miracle?) and absence of MSSM at colliders invites *reappraisal of founding assumptions* underpinning DM phenomenology

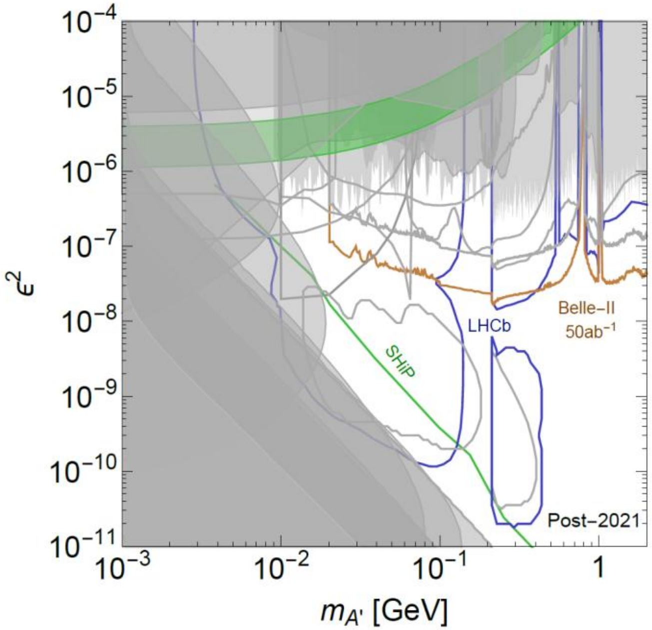
Resurgence of interest in general dark sectors and ALPs, from fuzzy DM to pBHs

- Dark sectors broadly characterized by mediators to SM particles and possible self-interactions
    - “WIMP-less” miracle still motivates EW-scale couplings and masses
  - – Renormalizability biases us to consider a prescribed set of “portal” couplings

Portal couplings

- Given direct probes at a given energy scale, sensitivity to UV scales follows NDA
  - Renormalizable, "portal" couplings are few (e.g. scalar Higgs portal, neutrino portal, vector portal, axion portal)

Alexander, et al. [1608.08632]



- Weakly-coupled new particles can be hidden or inaccessible at LHC or beam dumps
- Open opportunity for CEPC

*CEPC can produce new particles **directly** here*

Double Dark Portal model

Kinetic mixing of *K* with hypercharge gauge boson *B*

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W^{i\,\mu\nu} - \frac{1}{4}K_{\mu\nu}K^{\mu\nu} + \frac{\epsilon}{2\cos\theta_W}B_{\mu\nu}K^{\mu\nu}$$
$$+ |D_\mu H|^2 + |D_\mu \Phi|^2 + \mu_H^2|H|^2 - \lambda_H|H|^4 + \mu_D^2|\Phi|^2 - \lambda_D|\Phi|^4 - \lambda_{HP}|H|^2|\Phi|^2$$
$$+ \bar{\chi}(i\not{D} - m_\chi)\chi$$

Scalar Higgs portal between dark Higgs Φ and SM *H*

$U(1)_D$ charges $\Phi \sim +1\ ,\ \chi \sim +1$

- Two marginal operators: simultaneous vector portal and scalar portal couplings
  - Constraints driven by searches, magnitudes not known from first principles (possible in UV completions)

Double Dark Portal model

- Fermion bilinear currents modified

$$\begin{aligned}\mathcal{L} \supset\, & g Z_{\mu,\,\mathrm{SM}} J_Z^\mu + e A_{\mu,\,\mathrm{SM}} J_{\mathrm{em}}^\mu + g_D K_\mu J_D^\mu \\ =\, & \tilde{Z}_\mu \left(g J_Z^\mu - g_D \frac{m_{Z,\,\mathrm{SM}}^2 t_W}{m_{Z,\,\mathrm{SM}}^2 - m_K^2} \epsilon J_D^\mu \right) \\ & + \tilde{K}_\mu \left(g_D J_D^\mu + g \frac{m_K^2 t_W}{m_{Z,\,\mathrm{SM}}^2 - m_K^2} \epsilon J_Z^\mu + e\epsilon J_{\mathrm{em}}^\mu \right) \\ & + \tilde{A}_\mu e J_{\mathrm{em}}^\mu + \mathcal{O}(\epsilon^2)\end{aligned}$$

  - $U(1)_D$- charged fermions pick up ε weak charge mediated by *Z*
  - SM charged fermions pick up ε weak charge and ε electric charge mediated by dark photon
  - Photon remains massless, long-range
    - (Singular behavior at $m_K = m_{Z,\,SM}$ is maximal mixing limit)

Double Dark Portal model

- Higgs portal induces scalar mass mixing
  - Mixing angle

$$\tan 2\alpha = \frac{\lambda_{HP} v_H v_D}{\lambda_D v_D^2 - \lambda_H v_H^2}$$

  - Masses

$$m_{S,\, H_0}^2 = \lambda_H v_H^2 + \lambda_D v_D^2 \pm \sqrt{(\lambda_H v_H^2 - \lambda_D v_D^2)^2 + \lambda_{HP} v_H^2 v_D^2}$$

  - As usual, cos α and sin α suppression of scalar couplings to SM fermions (since S is a SM gauge singlet)

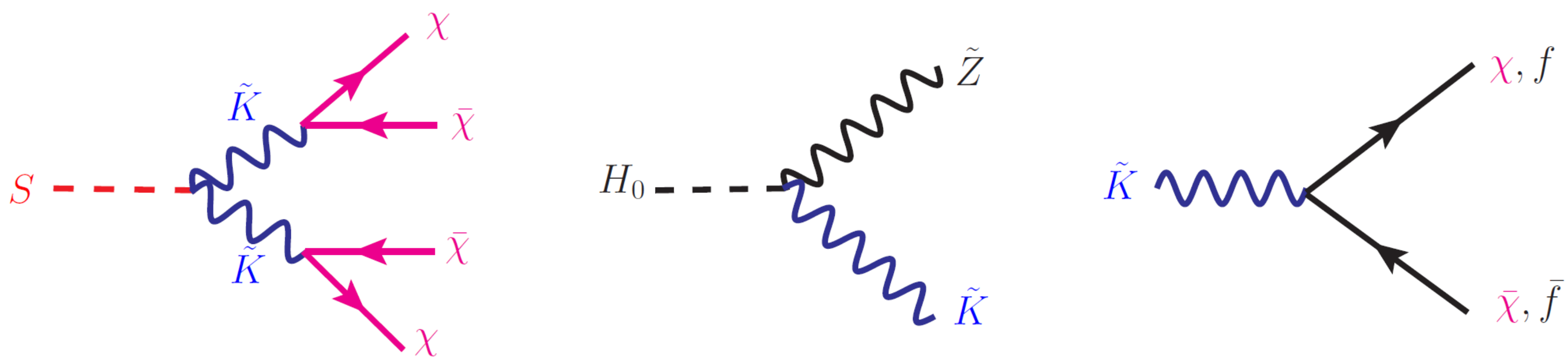
Double Dark Portal model

- Scalar-vector-vector interactions
  - Key role in e^+e^- Higgs studies

$$
\begin{aligned}
\mathcal{L} \supset\ & m_{Z,\mathrm{SM}}^2 \left(\frac{\cos\alpha}{v_H}\right) \tilde{Z}_\mu \tilde{Z}^\mu H_0 \\
& + 2\epsilon t_W \frac{m_K^2 m_{Z,\ \mathrm{SM}}^2}{(m_{Z,\ \mathrm{SM}}^2 - m_K^2)} \left(\frac{\cos\alpha}{v_H} + \frac{\sin\alpha}{v_D}\right) \tilde{Z}_\mu \tilde{K}^\mu H_0 \\
& + m_K^2 \left(-\frac{\sin\alpha}{v_D}\right) \tilde{K}_\mu \tilde{K}^\mu H_0 \\
& + m_{Z,\mathrm{SM}}^2 \left(\frac{\sin\alpha}{v_H}\right) \tilde{Z}_\mu \tilde{Z}^\mu S \\
& + 2\epsilon t_W \frac{m_K^2 m_{Z,\ \mathrm{SM}}^2}{(m_{Z,\ \mathrm{SM}}^2 - m_K^2)} \left(-\frac{\cos\alpha}{v_D} + \frac{\sin\alpha}{v_H}\right) \tilde{Z}_\mu \tilde{K}^\mu S \\
& + m_K^2 \left(\frac{\cos\alpha}{v_D}\right) \tilde{K}_\mu \tilde{K}^\mu S + \mathcal{O}(\epsilon^2)
\end{aligned}
$$

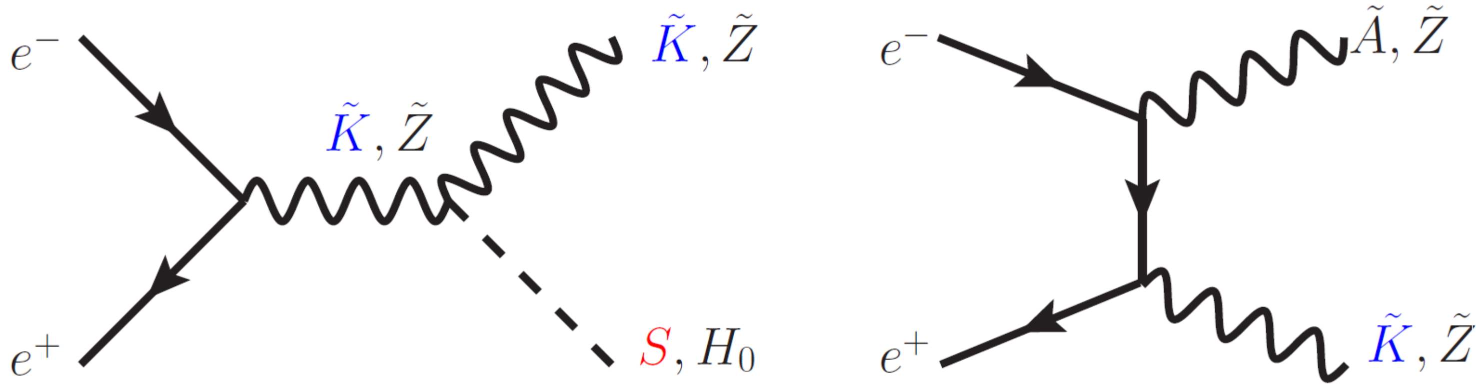
Collider phenomenology

- Precision EW observables for modifications to Z couplings
- Modifications to Higgs couplings
  - Also induce invisible and semi-visible exotic Higgs decays
- Will assume dark decays of S and K are on-shell
  - Ensured by kinematics and mild hierarchy for g_D and ε



Going beyond κ-framework, Higgs EFT

- Direct production of new light states



- Exploit radiative return process for hidden photon production
  - Recoil mass technique adapted to monophoton events and other SM candles as recoil taggers

Exploiting radiative return and recoil mass techniques at e^+e^- machines

- Radiative return – use ISR photon to make 2-2 production on-shell
    - At LHC, “radiative return” is better known as “mono-jet”
- Recoil mass method – use four-momentum conservation in 2-2 process
    - In case of invisible decay and radiative return, equivalent to searching for a monophoton peak
        - Design driver for e^+e^- EM calorimeter

$$E_{\text{vis}} = \frac{\sqrt{s}}{2} + \frac{m_{\text{vis}}^2 - m_X^2}{2\sqrt{s}}$$

$$m_{\text{recoil}} = m_X = \sqrt{s + m_{\text{vis}}^2 - 2E_{\text{vis}}\sqrt{s}}$$

Delphes CEPC card

$$\frac{\delta E}{E} = \sqrt{(0.5\%)^2 + \frac{1\,\text{GeV}}{E}(20\%)^2}$$

Exotic invisible decay of Higgs

- Familiar case: Higgs recoiling against Z for invisible Higgs decays
  - Invisible decay combines sensitivity to sin α and ε, overall rate driven by g_D

$$\Gamma(H_0 \to \text{inv}) \approx \Gamma(H_0 \to SS) + \Gamma(H_0 \to \tilde{K}\tilde{K}) + 0.2 \times \Gamma(H_0 \to \tilde{K}\tilde{Z})$$

- Individual rates are

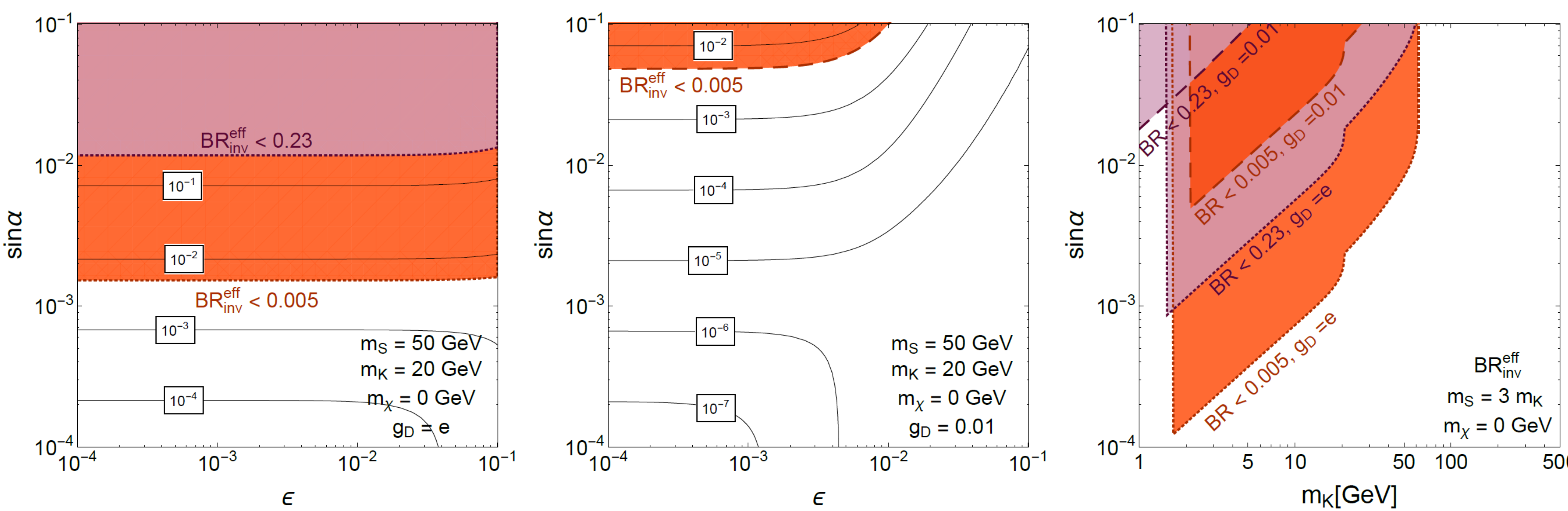
$$\Gamma(H_0 \to SS) = g_D^2 \sin^2\alpha \frac{m_{H_0}}{32\pi}\sqrt{1 - \frac{4m_S^2}{m_{H_0}^2}} \frac{(m_{H_0}^2 + 2m_S^2)^2}{m_{H_0}^2 m_K^2} \,,$$

$$\Gamma(H_0 \to \tilde{K}\tilde{K}) = g_D^2 \sin^2\alpha \frac{m_{H_0}}{32\pi}\sqrt{1 - \frac{4m_{\tilde{K}}^2}{m_{H_0}^2}} \frac{m_{H_0}^4 - 4m_{H_0}^2 m_{\tilde{K}}^2 + 12 m_{\tilde{K}}^4}{m_{H_0}^2 m_{\tilde{K}}^2} \frac{m_K^2}{m_{\tilde{K}}^2} \,,$$

$$\Gamma(H_0 \to \tilde{K}\tilde{Z}) = \frac{\epsilon^2 t_W^2 \left(\frac{\cos\alpha}{v_H} + \frac{\sin\alpha}{v_D}\right)^2}{16\pi m_{H_0}^3 \left(m_K^2 - m_{Z,\,\text{SM}}^2\right)^2} \frac{m_K^4 m_{Z,\,\text{SM}}^4}{m_{\tilde{K}}^2 m_{\tilde{Z}}^2} \sqrt{m_{H_0}^4 + \left(m_{\tilde{K}}^2 - m_{\tilde{Z}}^2\right)^2 - 2m_{H_0}^2\left(m_{\tilde{K}}^2 + m_{\tilde{Z}}^2\right)}$$
$$\times \left((m_{H_0}^2 - m_{\tilde{K}}^2 - m_{\tilde{Z}}^2)^2 + 8 m_{\tilde{K}}^2 m_{\tilde{Z}}^2\right)$$

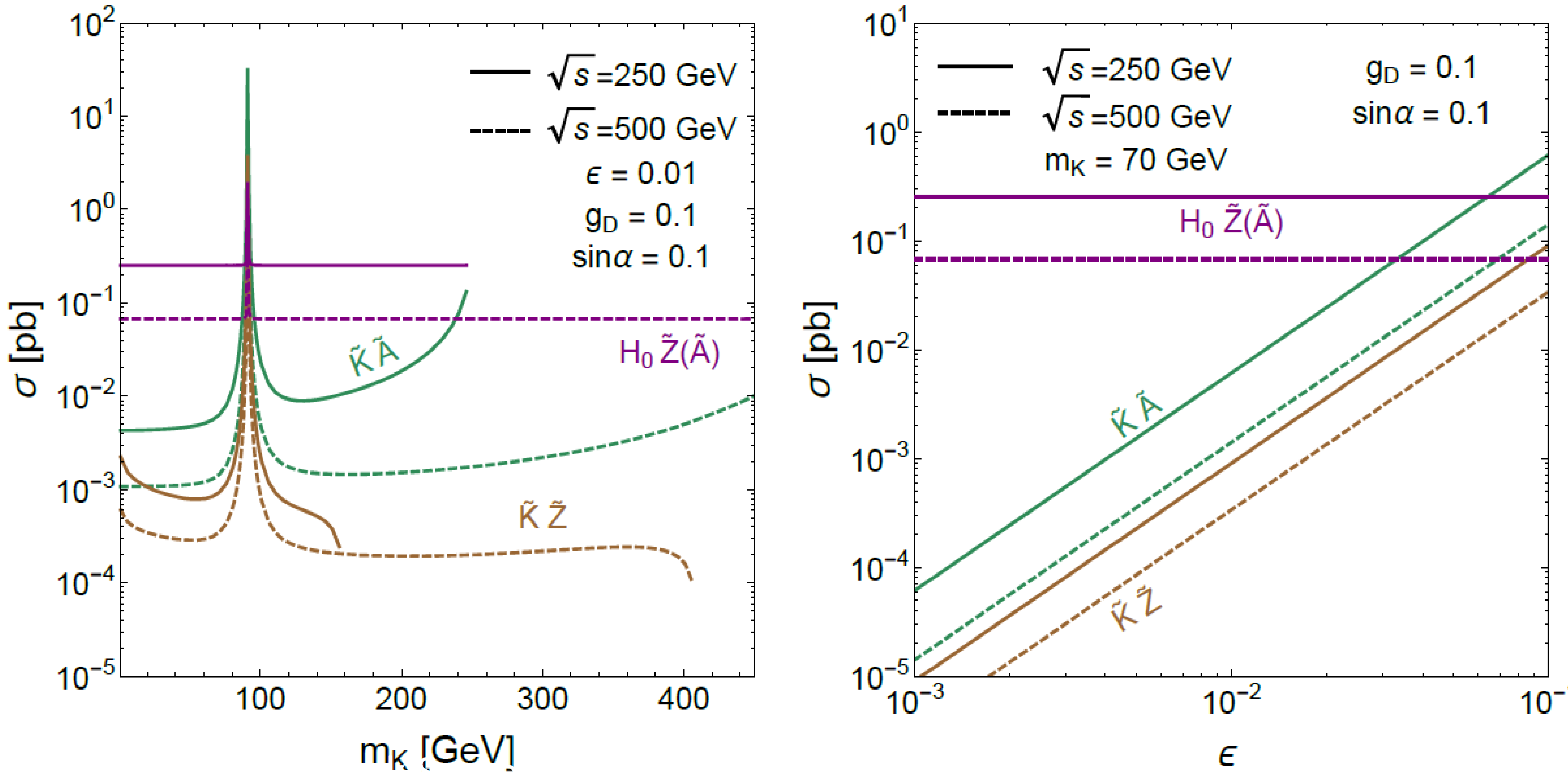
Exotic invisible decay of Higgs

- Familiar case: Higgs recoiling against Z for invisible Higgs decays
  – Invisible decay combines sensitivity to sin α and ε, overall rate driven by g_D



Direct production of new light states

- Possible new physics within kinematic reach
  - Signatures too difficult at LHC, exploit e^+e^- capabilities



Prospects for dark photon

- Many possible visible and invisible final states

$$e^+e^- \to \tilde{Z}H_0 \;\; \text{Study } \tilde{Z} \to \ell\ell \text{ and semi-visible } H_0 \to (\ell\ell)_Z\chi\chi$$

$$e^+e^- \to \tilde{Z}\tilde{K} \;\; \text{Study } \tilde{Z} \to \ell\ell \text{ and } \tilde{K} \to \bar{\chi}\chi \text{ or } \ell\ell$$

$$e^+e^- \to \gamma\tilde{K} \;\; \text{Study } \tilde{K} \text{ inclusive decays, and exclusive } \tilde{K} \to \bar{\chi}\chi \text{ or } \ell\ell$$

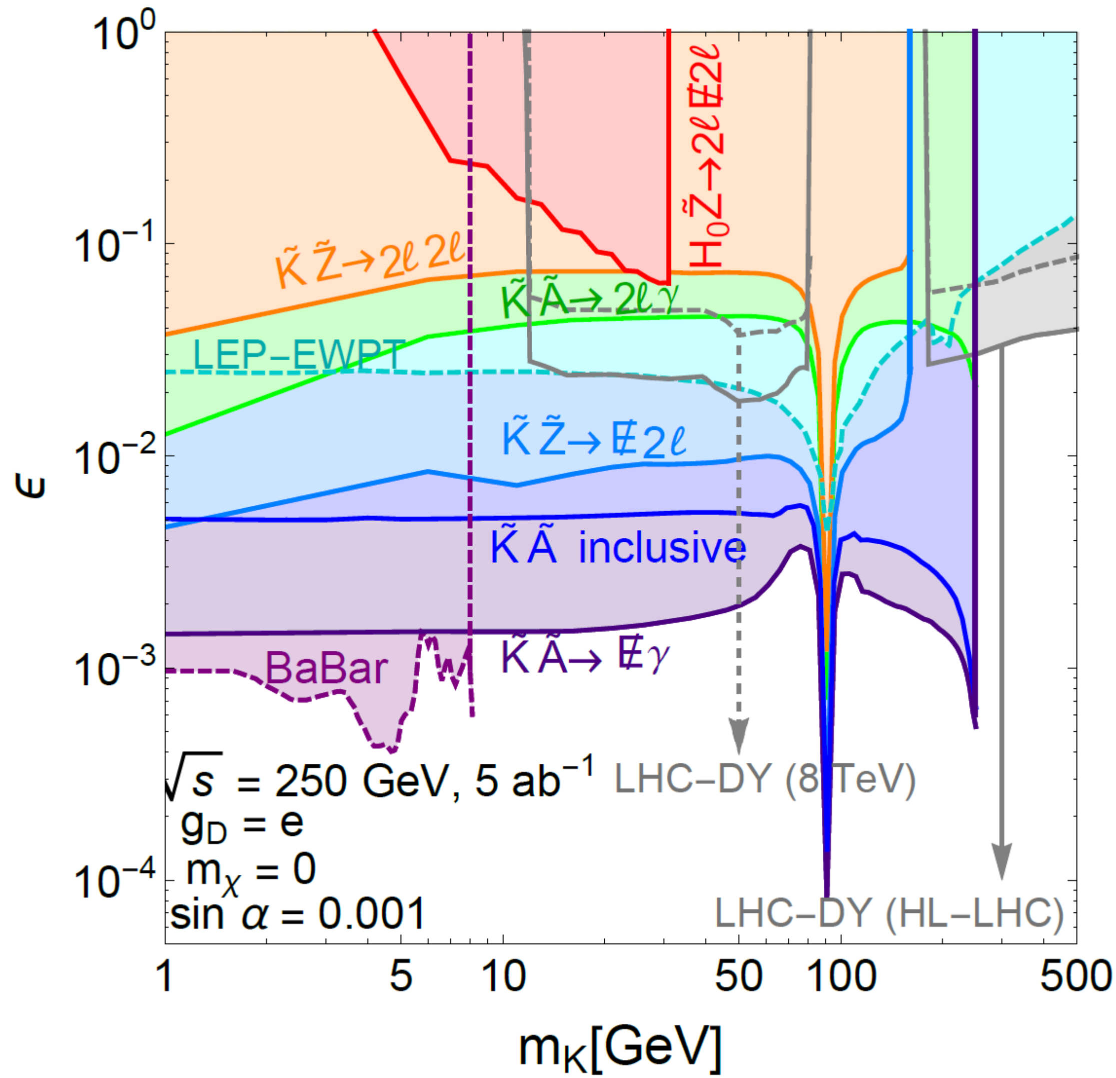
$$e^+e^- \to \tilde{Z}S \;\; \text{Study } \tilde{Z} \to \ell\ell \text{ and } S \to 4\chi$$

  – Event simulation using MG5+Pythia+Delphes
    - Use parametrized preliminary CEPC detector card
  – SM backgrounds and cuts driven by e^+e^- environment
- Rates for visible states are lower by $(\varepsilon/g_D)^2$, best sensitivity from requiring missing energy threshold
  – LEP direct constraints ($\varepsilon < 0.03$) not competitive

Collider study cuts

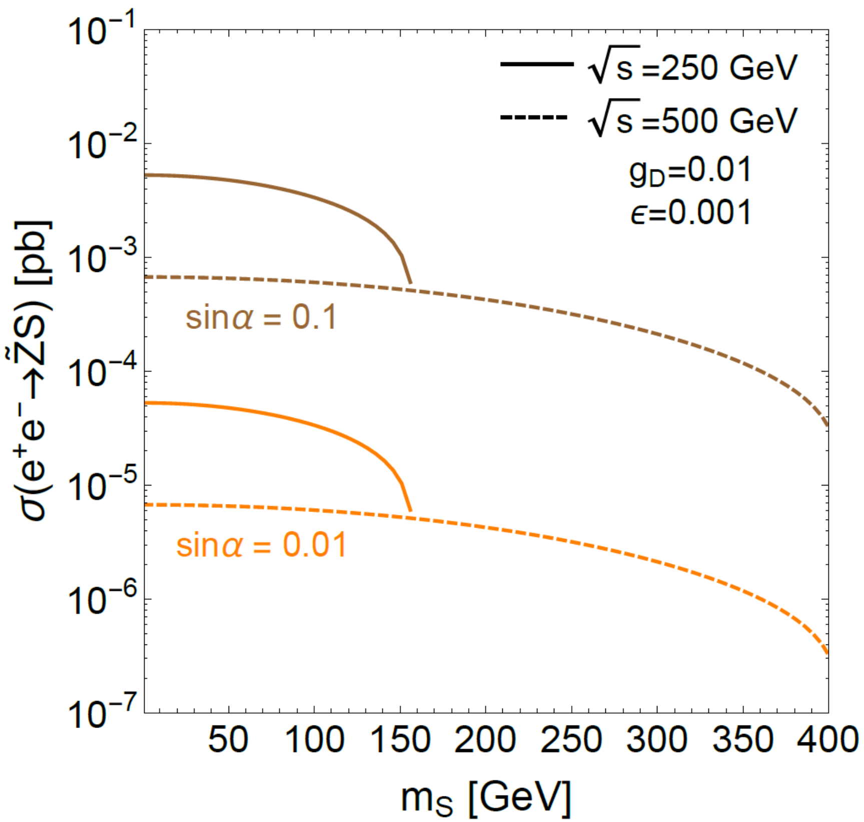
Parameter	Signal process		Background (pb)		Signal region
ϵ	$\tilde{Z}\tilde{K}$	$\tilde{Z} \to \bar{\ell}\ell$, $\tilde{K} \to \bar{\chi}\chi$	$\bar{\ell}\ell\bar{\nu}\nu$	0.929 (250 GeV)	$N_\ell \geq 2$, $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV,
				0.545 (500 GeV)	and $\lvert m_{\text{recoil}} - m_{\tilde{K}}\rvert < 2.5$ GeV
		$\tilde{Z} \to \bar{\ell}\ell$, $\tilde{K} \to \bar{\ell}\ell$	$\bar{\ell}\ell\bar{\ell}\ell$	0.055 (250 GeV)	$N_\ell \geq 4$, $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV,
				0.023 (500 GeV)	and $\lvert m_{\ell\ell} - m_{\tilde{K}}\rvert < 2.5$ GeV
	$\tilde{A}\tilde{K}$	$\tilde{K}$ inclusive decay	$\gamma\bar{f}f$	23.14 (250 GeV)	$N_\gamma \geq 1$, and
				8.88 (500 GeV)	$\lvert E_\gamma - (\frac{\sqrt{s}}{2} - \frac{m_{\tilde{K}}^2}{2\sqrt{s}})\rvert < 2.5$ GeV
		$\tilde{K} \to \bar{\ell}\ell$	$\gamma\bar{\ell}\ell$	12.67 (250 GeV)	$N_\gamma \geq 1$, $N_\ell \geq 2$, $\lvert E_\gamma - (\frac{\sqrt{s}}{2} - \frac{m_{\tilde{K}}^2}{2\sqrt{s}})\rvert < 2.5$ GeV,
				4.38 (500 GeV)	and $\lvert m_{\ell\ell} - m_{\tilde{K}}\rvert < 5$ GeV
		$\tilde{K} \to \bar{\chi}\chi$	$\gamma\bar{\nu}\nu$	3.45 (250 GeV)	$N_\gamma \geq 1$, $\lvert E_\gamma - (\frac{\sqrt{s}}{2} - \frac{m_{\tilde{K}}^2}{2\sqrt{s}})\rvert < 2.5$ GeV,
				2.92 (500 GeV)	and $\not{E} > 50$ GeV
	$\tilde{Z}H_0$	$H_0 \to \tilde{K}\tilde{Z}$ with	$\bar{\ell}\bar{\ell}\ell\ell\bar{\nu}\nu$	1.8×10^{-5} (250 GeV)	$N_\ell \geq 4$, $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV,
		$\tilde{K} \to \bar{\chi}\chi$, $\tilde{Z} \to \bar{\ell}\ell$		3.5×10^{-4} (500 GeV)	and $\lvert m_{\text{recoil}} - m_{\tilde{K}}\rvert < 2.5$ GeV
$\sin\alpha$	$\tilde{Z}S$	$\tilde{Z} \to \bar{\ell}\ell$	$\bar{\ell}\ell\bar{\nu}\nu$	0.87 (250 GeV)	$N_\ell \geq 2$, $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV,
		$S \to \tilde{K}\tilde{K} \to 4\chi$		0.505 (500 GeV)	and $\lvert m_{\text{recoil}} - m_S\rvert < 2.5$ GeV

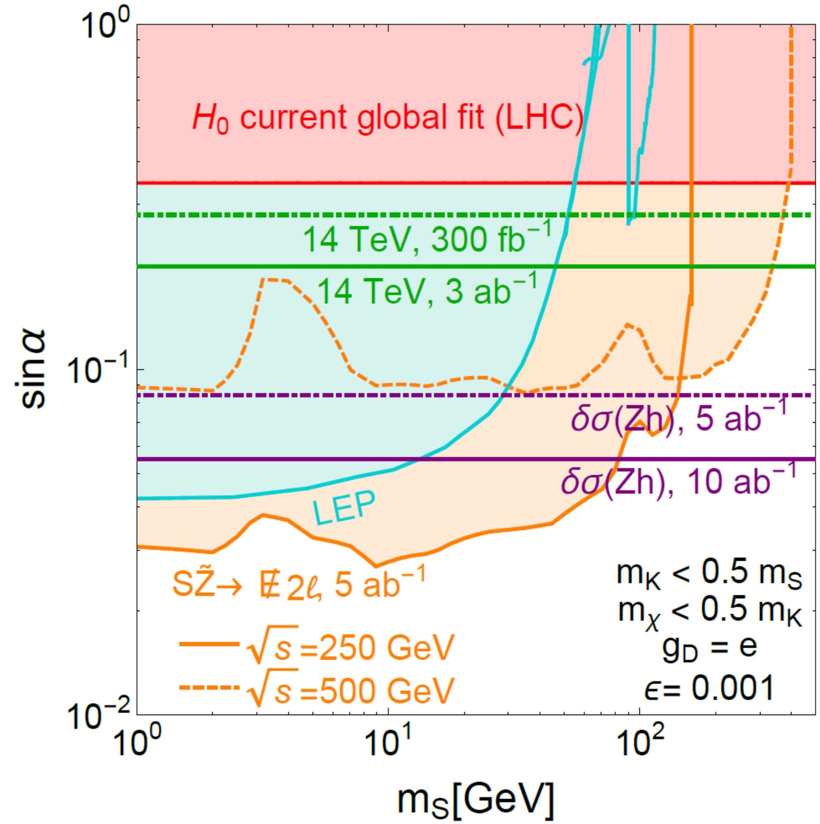
Dark photon sensitivity



Prospects for dark scalar

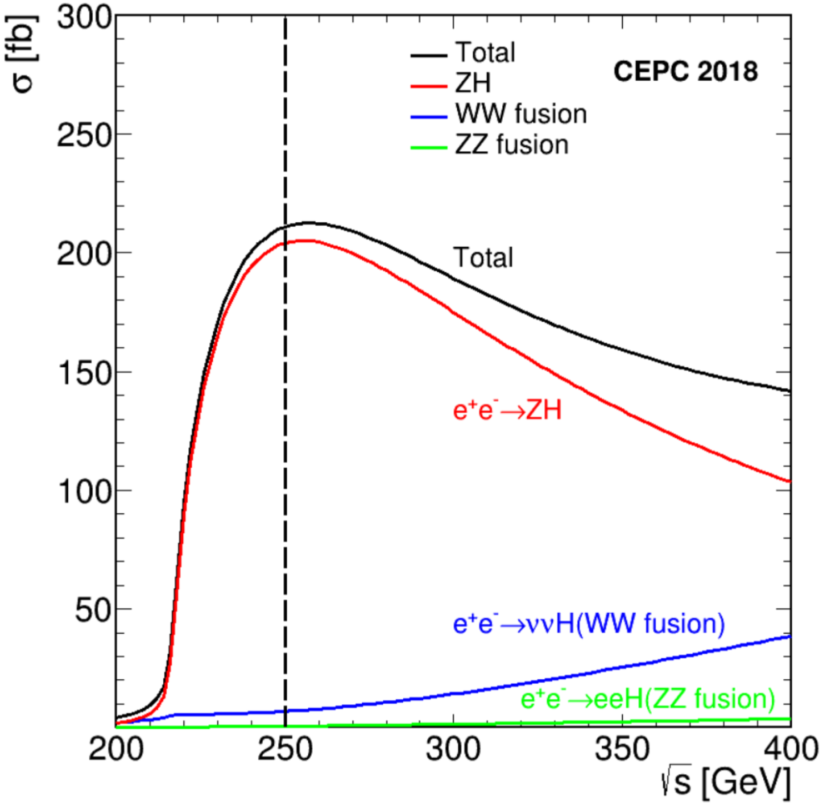
- Possibility to observe dark Higgstrahlung





Post-discovery plan

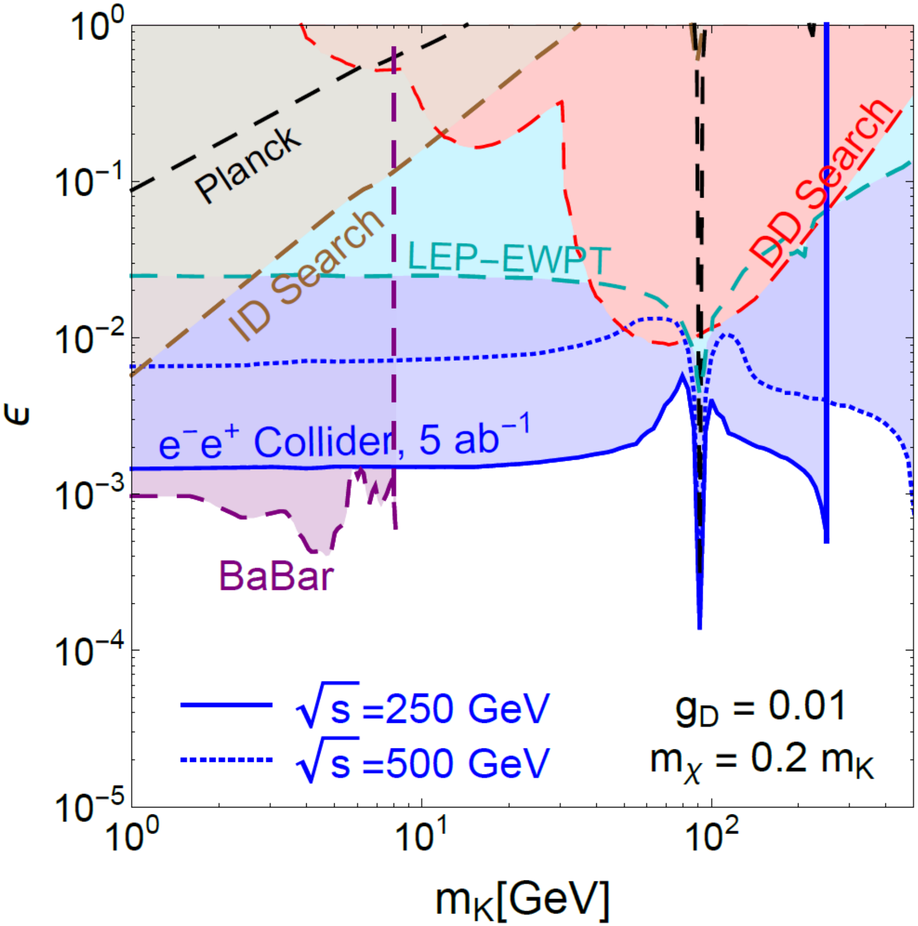
- Discovery of new, light particle (either K or S) immediately motivates dedicated run

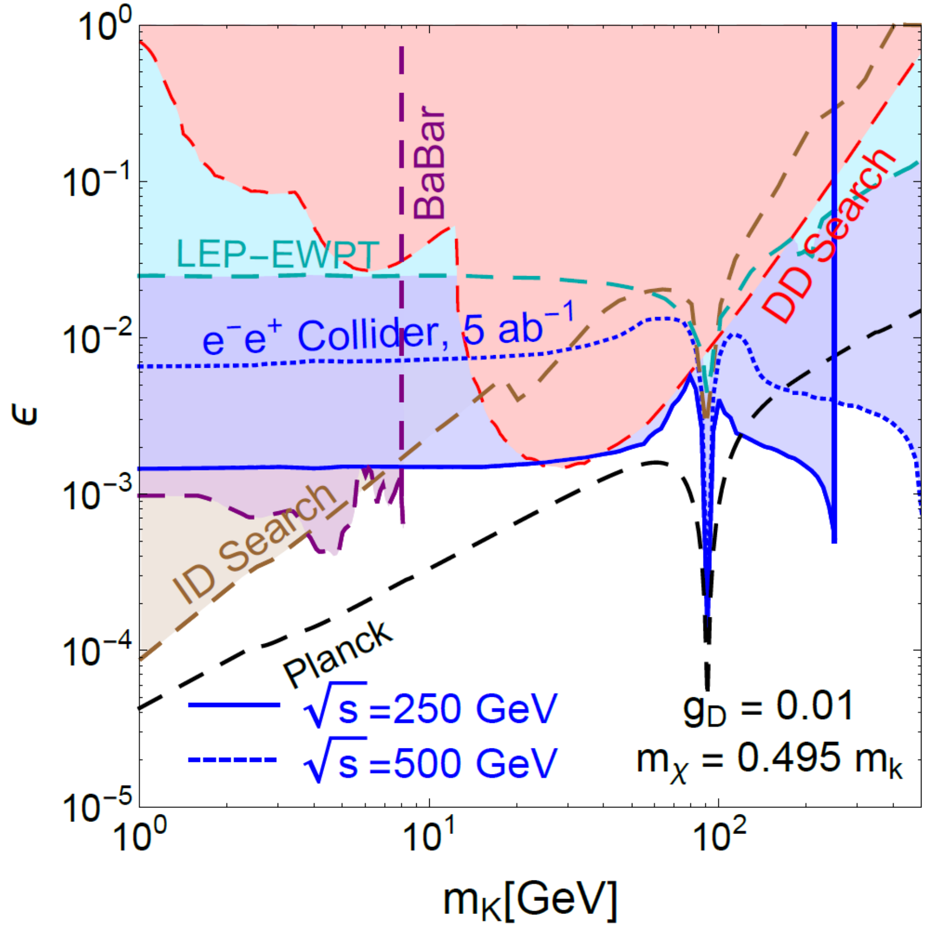


An, et. al. [1810.09037]

Comparing to complementary DM probes

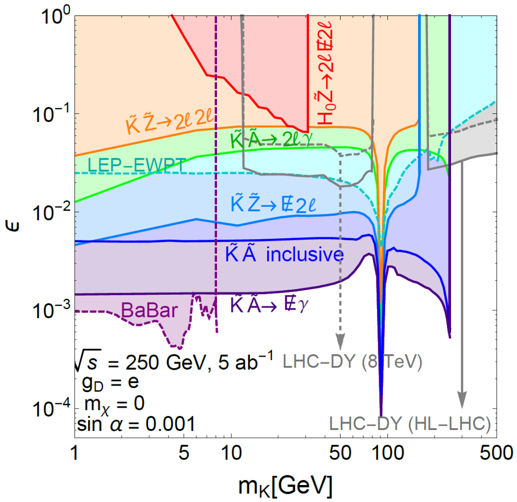
- Dark matter discovery possible at e^+e^- machines





Conclusions

- Physics potential of e^+e^- machine goes well beyond precision Z and Higgs program
- Direct production of new, light, very weakly-coupled hidden particles possible
- Comprehensive study of Higgsed, kinetically mixing dark sector and signals at CEPC



Phenomenology

- Three new particles $\tilde{K}$, S , χ and many interactions
  - Deviations in *Z* couplings
  - Deviations in Higgs couplings
  - Exotic Higgs decays (invisible, semi-visible, fully visible)
  - Interactions with dark matter mediated by dark photon
- Rich phenomenology for DM physics and colliders
  - Double Dark Portal model ties together two marginal couplings simultaneously
  - Attractive framework for marrying Higgs deviations and direct coupling to light, very-weakly coupled particles

Double Dark Portal model

- Steps for solving the neutral vector Lagrangian
  - Diagonalize gauge boson mass matrix
    - Usual $t_W = g'/g$ rotation corresponds to

$$\mathcal{L} \supset \frac{-1}{4} \begin{pmatrix} Z_{\rm SM}^{\mu\nu} & A_{\rm SM}^{\mu\nu} & K^{\mu\nu} \end{pmatrix} \begin{pmatrix} 1 & 0 & \epsilon t_W \\ 0 & 1 & -\epsilon \\ \epsilon t_W & -\epsilon & 1 \end{pmatrix} \begin{pmatrix} Z_{\mu\nu,\ \rm SM} \\ A_{\mu\nu,\ \rm SM} \\ K_{\mu\nu} \end{pmatrix}$$

$$+ \frac{1}{2} \begin{pmatrix} Z_{\rm SM}^{\mu} & A_{\rm SM}^{\mu} & K^{\mu} \end{pmatrix} \begin{pmatrix} m_{Z,\ \rm SM}^2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_K^2 \end{pmatrix} \begin{pmatrix} Z_{\mu,\ \rm SM} \\ A_{\mu,\ \rm SM} \\ K_{\mu} \end{pmatrix}$$

  - Require $|\varepsilon| < c_W$ for positive kinetic mixing determinant
  - Field strengths are Abelian kinetic terms, non-Abelian interactions inherited from transformations

Double Dark Portal model

- Steps for solving the neutral vector Lagrangian
  - Remove kinetic mixing and canonically normalize

$$U_1 = \begin{pmatrix} 1 & 0 & 0 \\ -\epsilon^2 t_W & 1 & \epsilon \\ -\epsilon t_W & 0 & 1 \end{pmatrix} \qquad U_2 = \begin{pmatrix} \sqrt{\dfrac{1-\epsilon^2}{1-\epsilon^2 c_W^{-2}}} & 0 & 0 \\ 0 & 1 & 0 \\ \dfrac{-\epsilon^3 t_W}{\sqrt{(1-\epsilon^2)(1-\epsilon^2 c_W^{-2})}} & 0 & \dfrac{1}{\sqrt{1-\epsilon^2}} \end{pmatrix}$$

$$\mathcal{L} \supset \frac{-1}{4} \begin{pmatrix} Z_{\rm SM}^{\mu\nu} & A_{\rm SM}^{\mu\nu} & K^{\mu\nu} \end{pmatrix} (U_1^T)^{-1} (U_2^T)^{-1} \mathbb{I}_3 U_2^{-1} U_1^{-1} \begin{pmatrix} Z_{\mu\nu,\ \rm SM} \\ A_{\mu\nu,\ \rm SM} \\ K_{\mu\nu} \end{pmatrix}$$

$$+ \frac{1}{2} \begin{pmatrix} Z_{\rm SM}^{\mu} & A_{\rm SM}^{\mu} & K^{\mu} \end{pmatrix} (U_1^T)^{-1} (U_2^T)^{-1} \begin{pmatrix} \dfrac{m_{Z,\ \rm SM}^2 (1-\epsilon^2)^2 + m_K^2 \epsilon^2 t_W^2}{(1-\epsilon^2)(1-\epsilon^2 c_W^{-2})} & 0 & \dfrac{-m_K^2 \epsilon t_W}{(1-\epsilon^2)\sqrt{1-\epsilon^2 c_W^{-2}}} \\ 0 & 0 & 0 \\ \dfrac{-m_K^2 \epsilon t_W}{(1-\epsilon^2)\sqrt{1-\epsilon^2 c_W^{-2}}} & 0 & \dfrac{m_K^2}{1-\epsilon^2} \end{pmatrix}$$

$$\times U_2^{-1} U_1^{-1} \begin{pmatrix} Z_{\mu,\ \rm SM} \\ A_{\mu,\ \rm SM} \\ K_{\mu} \end{pmatrix}$$

Double Dark Portal model

- Steps for solving the neutral vector Lagrangian
  - Rediagonalize mass matrix via Jacobi rotation (exact)
  - To O(ε^3), masses and fields are

$$m^2_{\tilde{K}} = m^2_K + \frac{m^2_K c_W^{-2} \epsilon^2 (m^2_{Z,\,\mathrm{SM}} c_W^2 - m^2_K)}{m^2_{Z,\,\mathrm{SM}} - m^2_K}\,, \qquad m^2_{\tilde{Z}} = m^2_{Z,\,\mathrm{SM}} + \frac{m^4_{Z,\,\mathrm{SM}} t_W^2 \epsilon^2}{m^2_{Z,\,\mathrm{SM}} - m^2_K}$$

$$\begin{pmatrix} \tilde{Z}_\mu \\ \tilde{A}_\mu \\ \tilde{K}_\mu \end{pmatrix} = \begin{pmatrix} Z_{\mu,\,\mathrm{SM}} - \dfrac{t_W m^2_K}{m^2_{Z,\,\mathrm{SM}} - m^2_K} \epsilon K_\mu - \dfrac{m^4_{Z,\,\mathrm{SM}} t_W^2}{2(m^2_{Z,\,\mathrm{SM}} - m^2_K)^2} \epsilon^2 Z_{\mu,\,\mathrm{SM}} \\ A_{\mu,\,\mathrm{SM}} - \epsilon K_\mu \\ K_\mu + \dfrac{t_W m^2_{Z,\,\mathrm{SM}}}{m^2_{Z,\,\mathrm{SM}} - m^2_K} \epsilon Z_{\mu,\,\mathrm{SM}} - \left(\dfrac{1}{2} + \dfrac{m^4_K t_W^2}{2(m^2_{Z,\,\mathrm{SM}} - m^2_K)^2} \right) \epsilon^2 K_\mu \end{pmatrix}$$

    - Singular behavior at $m_K = m_{Z,\,\mathrm{SM}}$ is maximal mixing limit
  - Effects from field redefinitions seen in dark, SM currents

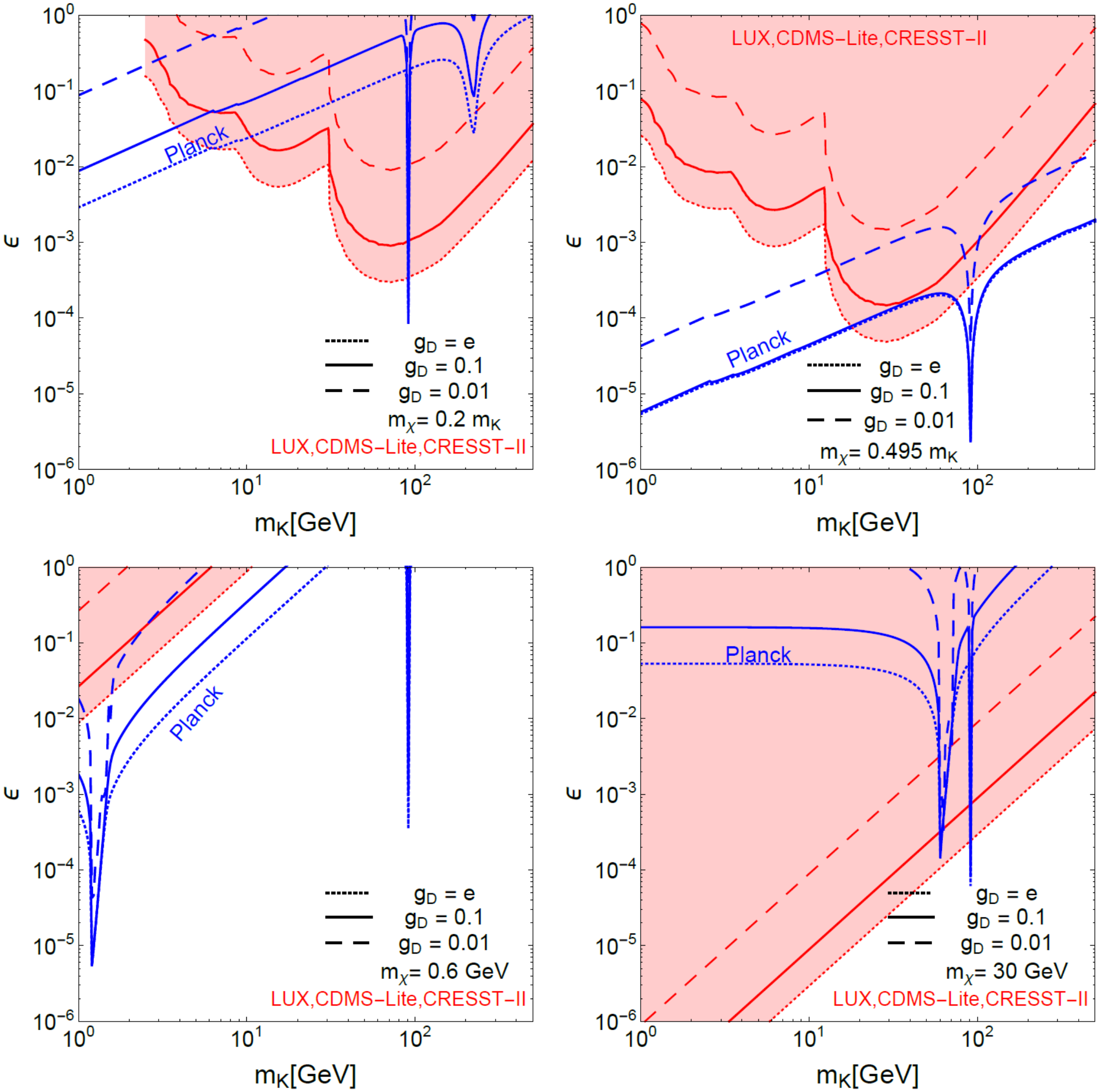
Dark matter direct detection

- Dark matter scattering off protons dominantly from dark photon exchange, suppressed by $(\varepsilon e)^2$
  - Intrinsic cancellation between weak charged currents mediated by massive Z and K vectors (at this order in ε)
  - Dark matter does not interact with photon, hence only protons contribute to direct detection

$$\sigma_p \simeq \frac{\epsilon^2 g_D^2 e^2}{\pi} \frac{\mu_{\chi p}^2}{m_{\tilde{K}}^4} \approx 10^{-44}\ \text{cm}^2 \left(\frac{g_D}{e}\right)^2 \left(\frac{\epsilon}{10^{-5}}\right)^2 \left(\frac{10\ \text{GeV}}{m_{\tilde{K}}}\right)^2$$

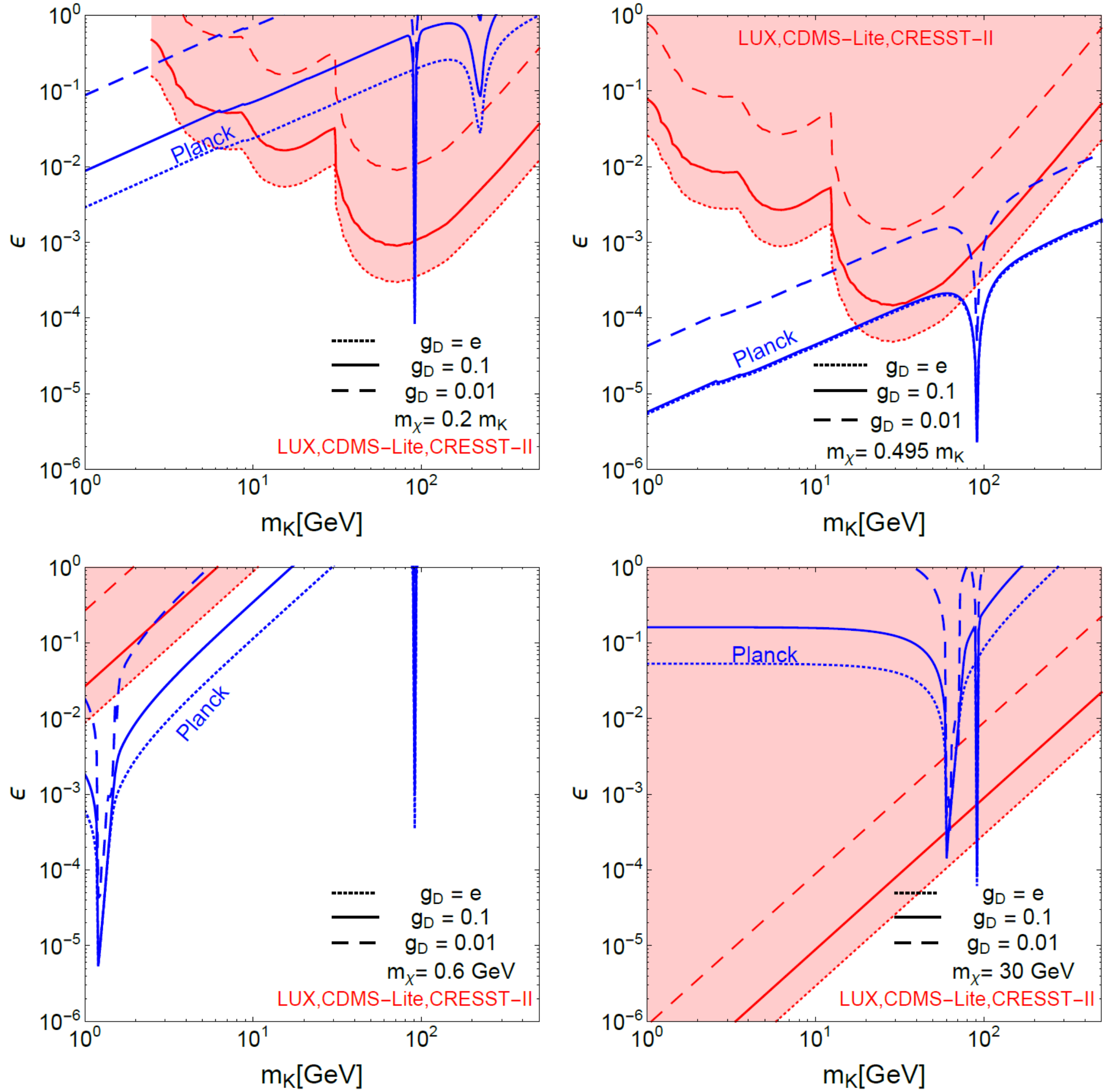
Dark matter direct detection

- Exclusion limits are highly sensitive to the dark matter mass
  - Nuclear recoil energy threshold becomes too soft for light dark matter (about 5 GeV)



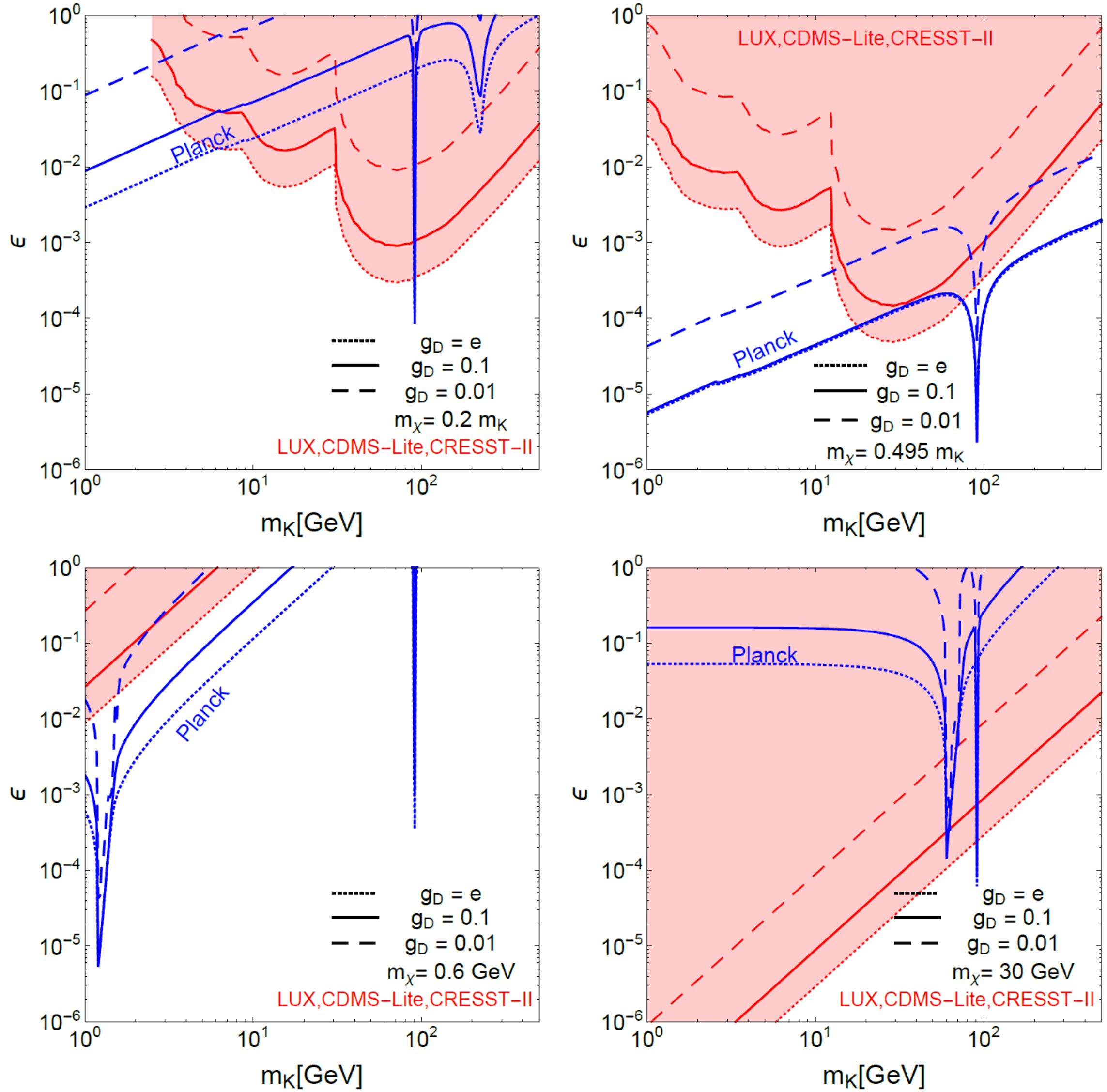
Dark matter direct detection

- Relic abundance (blue line) shows resonances at dark photon and *Z* masses
- DM is underabundant above blue line, overabundant below blue line



Dark matter direct detection

- Dark matter experiments fix the local relic abundance to 0.3 GeV/cm^3
  - On the other hand, the predicted dark matter relic abundance scales as ε^{-2}, while the scattering rate scales as ε^2
- Ratio of DD limits to relic abundance curve (for fixed m_K) gives the limit on local abundance



Dark matter indirect detection

- Present day annihilation constrained by observations of gamma ray spectra
- Early universe annihilation constrained by energy injection in CMB
- Strongest limits when DM mass is close to *Z* or dark photon resonance