Dark Matter & Dark Sector at CEPC

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The 2023 International Workshop on the High Energy Circular Electron Positron Collider

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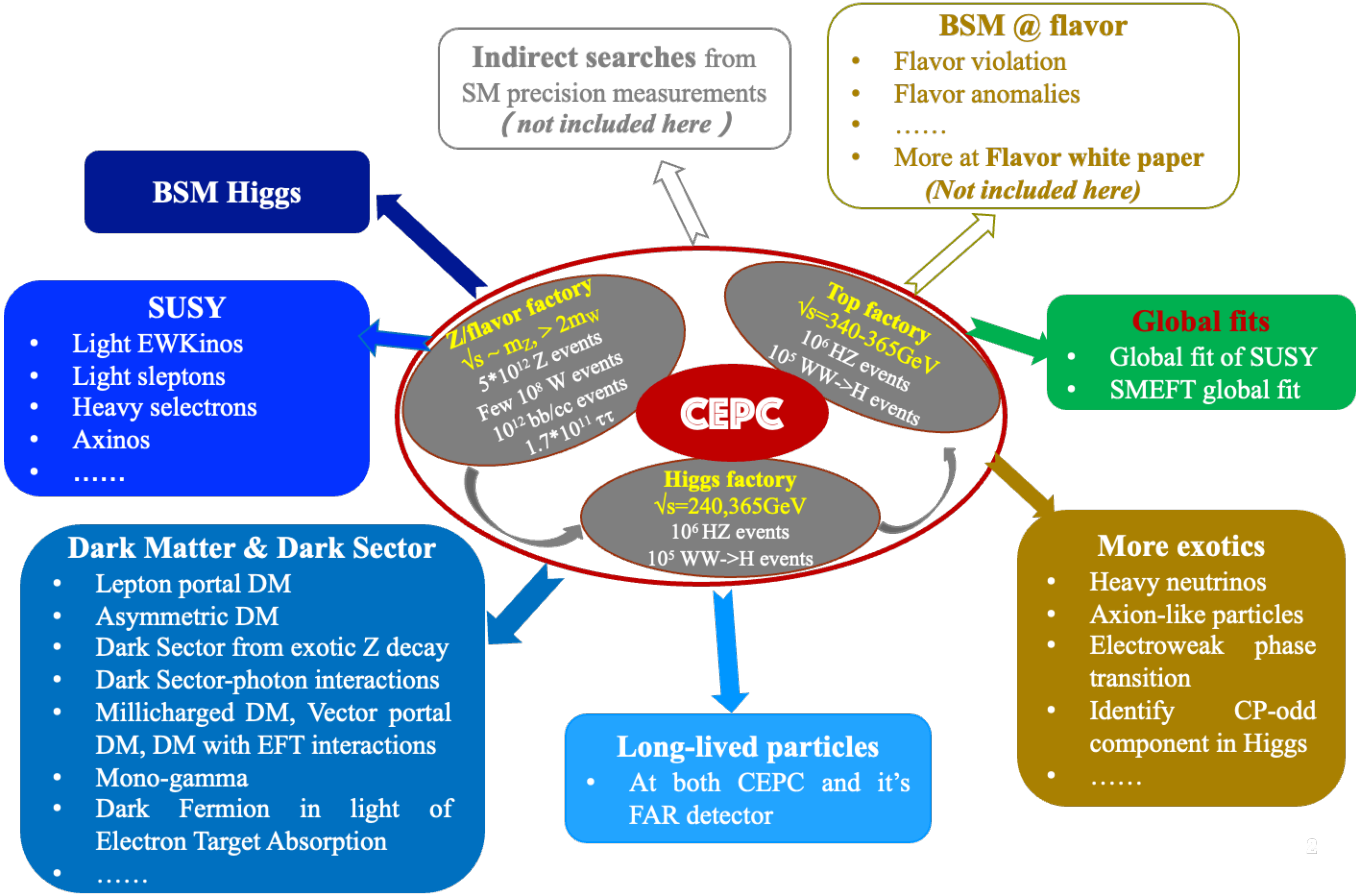
CEPC BSM Physics Program

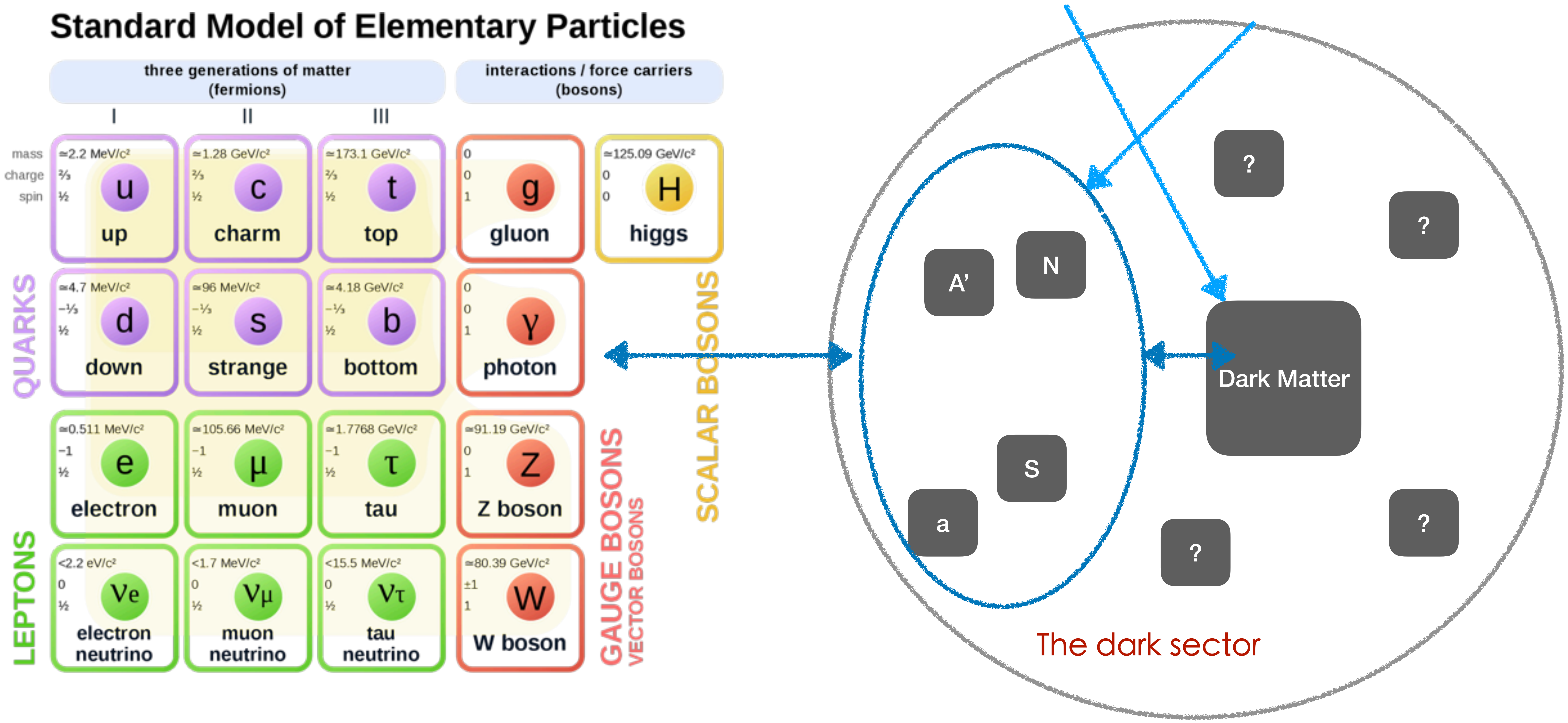


My topic

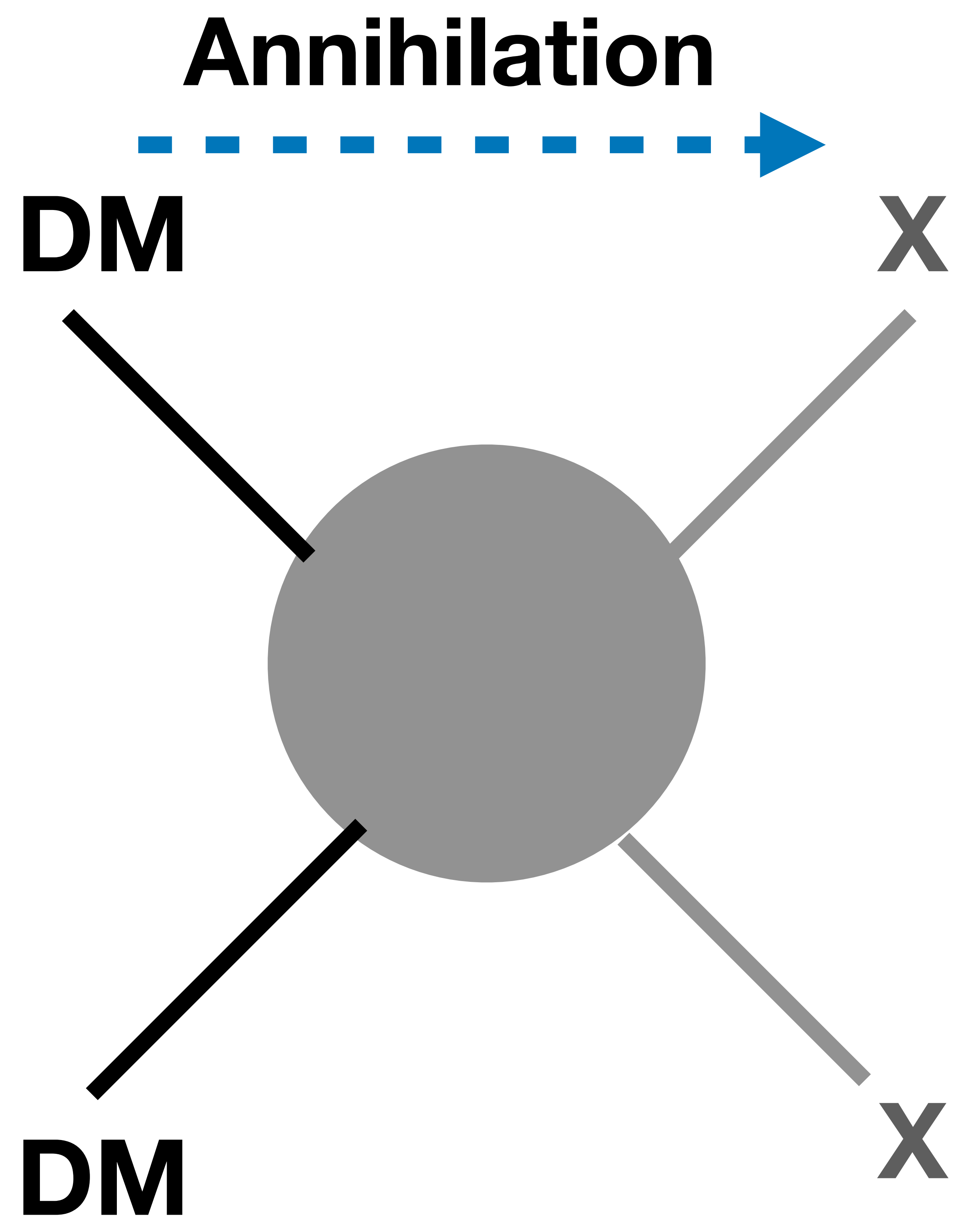
Courtesy of Xuai Zhuang

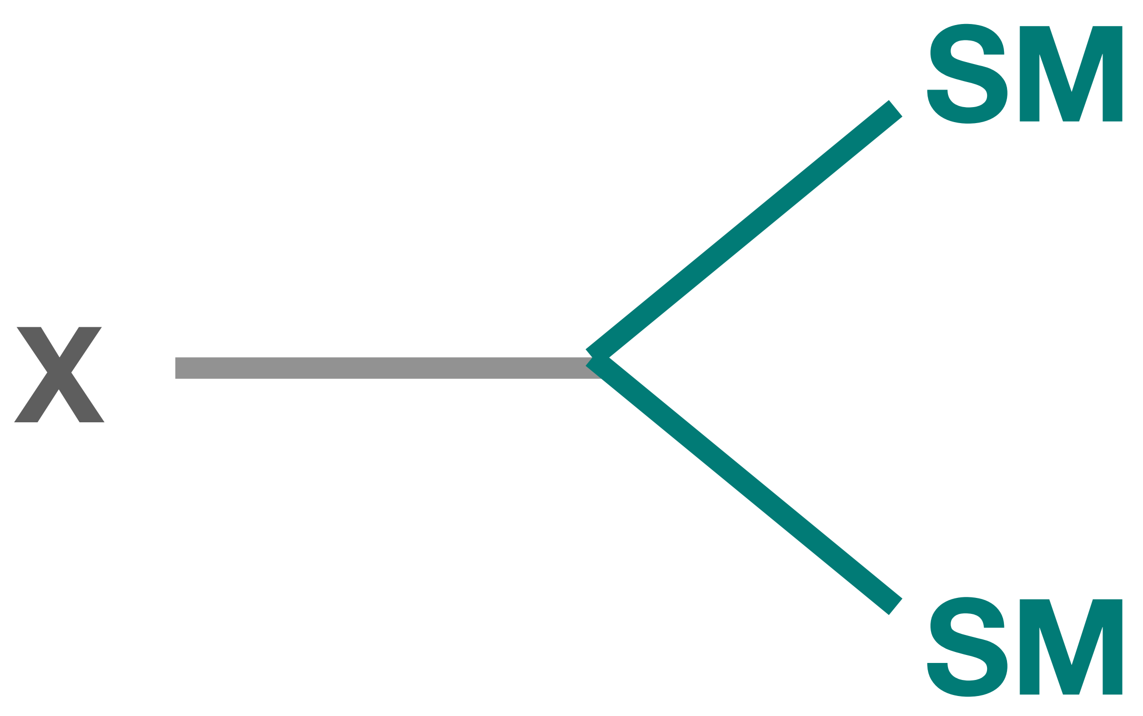
Dark Matter and Dark Sector

- Standard Model =fermions+force mediators
- Dark sector =DM+dark mediators



Dark Matter and Dark Sector





Dark mediator X
with small coupling to SM

Outline

- Dark Matter and Dark Sector
  - Fermion portal — lepton portal
  - Higgs portal
  - Vector portal
  - EFT models
- Summary

Fermion Portal

JL, S. Brian, N. Weiner, I. Yavin, 1303.4404 (JHEP)
Y. Bai, J. Berger, 1308.0612 (JHEP)

- The Fermion portal to DM
  - The Interaction: $\lambda\bar{\psi}\phi f_{\mathrm{SM}}$
  - Dark Matter and Dark Sector
    - Fermion portal — lepton portal
    - f can be quark/lepton, L/R-handed

	DM	SM charge	Z_2
	Yes	No	-1
	No	Yes	-1
	No	Yes	1

ϕ can be DM as well!

Searching lepton portal dark sector at CEPC

$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi} i \partial\!\!\!/ \chi - \frac{1}{2} m_\chi \bar{\chi}\chi + y_\ell \left(\bar{\chi}_L S^\dagger \ell_R + \text{h.c.} \right),$$

$$\mathcal{L}_S = \left(D^\mu S\right)^\dagger D_\mu S - V(H,S),$$

$$V(H,S) = \mu_H^2 |H|^2 + \mu_S^2 |S|^2 + \lambda_H |H|^4 + \lambda_S |S|^4 + 2\lambda_{HS} |H|^2 |S|^2$$

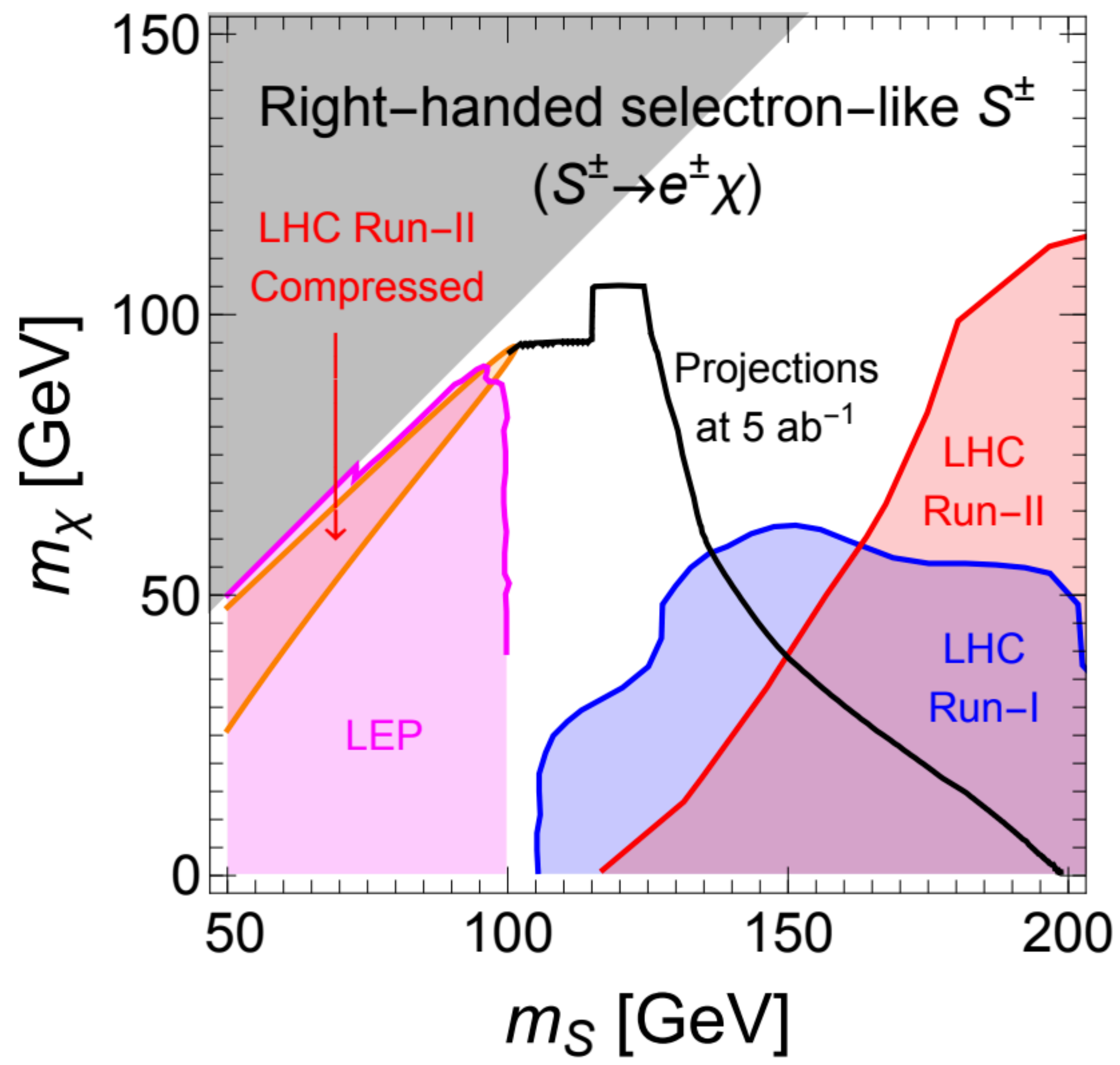
JL, XP Wang, KP Xie, 2104.06421 (JHEP)

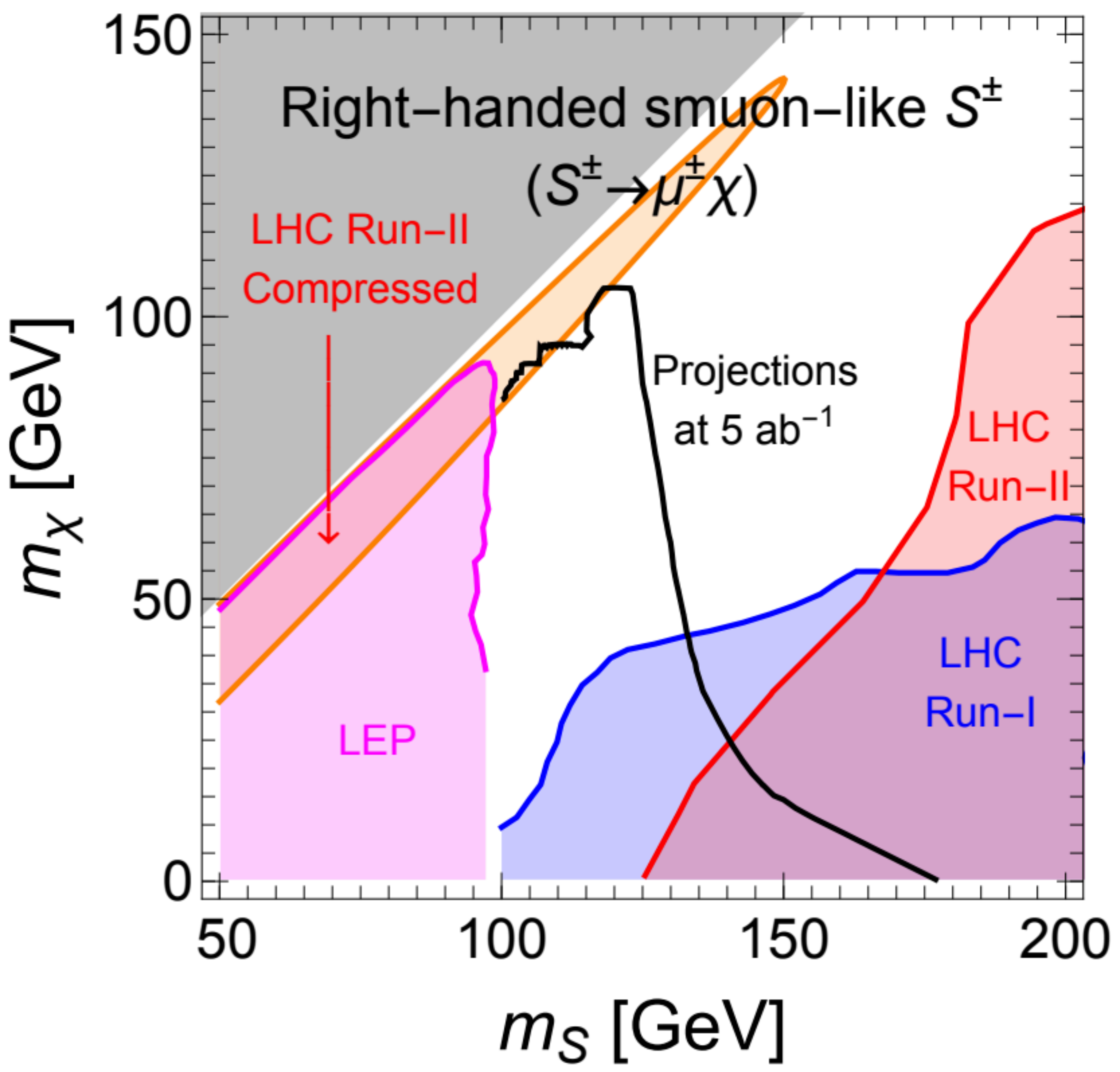
- DM (χ) couples to SM via the lepton portal
- Mediated by charged particle (S), similar to slepton
  - DM thermal relic requirements
  - Lepton collider production of dark sector particle S
  - Higgs precision test on the model
  - Gravitational Wave signal and its complementary with ee collider

Dark sector particle production in 3-body final state

JL, XP Wang, KP Xie, 2104.06421 (JHEP)

- 3-body final state: $e^+e^- \to S^+S^{-*} \to S^+\ell^-\chi \to (\ell^+\chi)\ell^-\chi$
  - Reaching higher mass: $m_S \gtrsim \sqrt{s}/2 = 120$ GeV

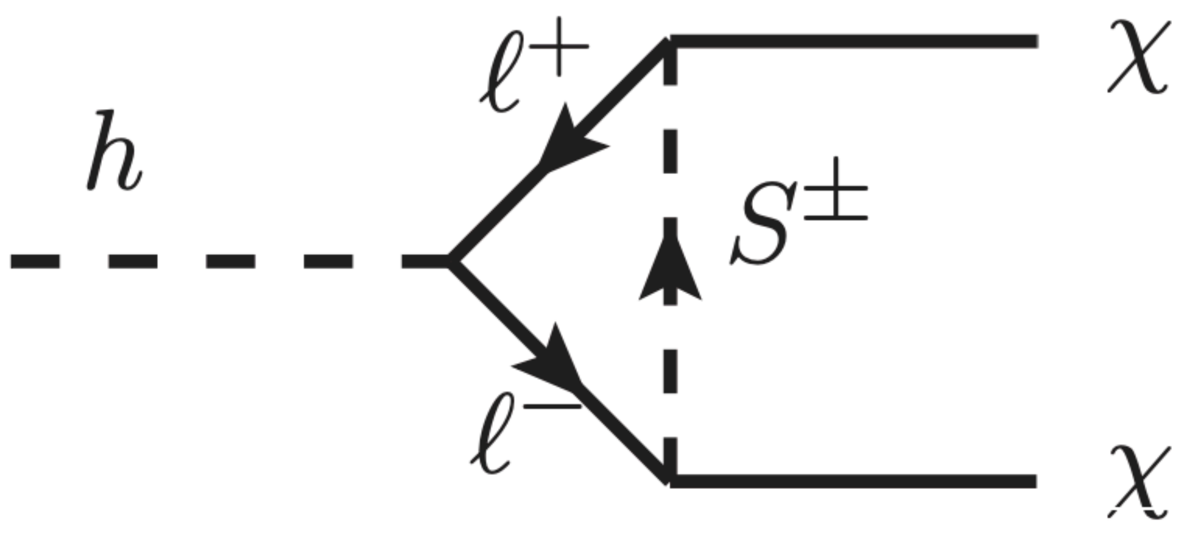


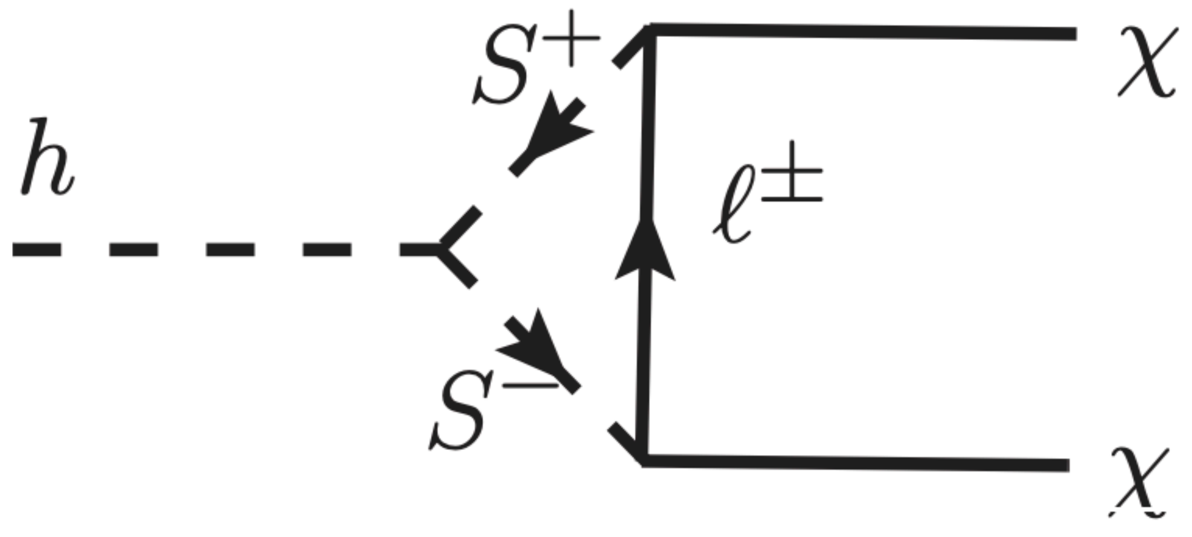


Exotic Higgs decay constraints

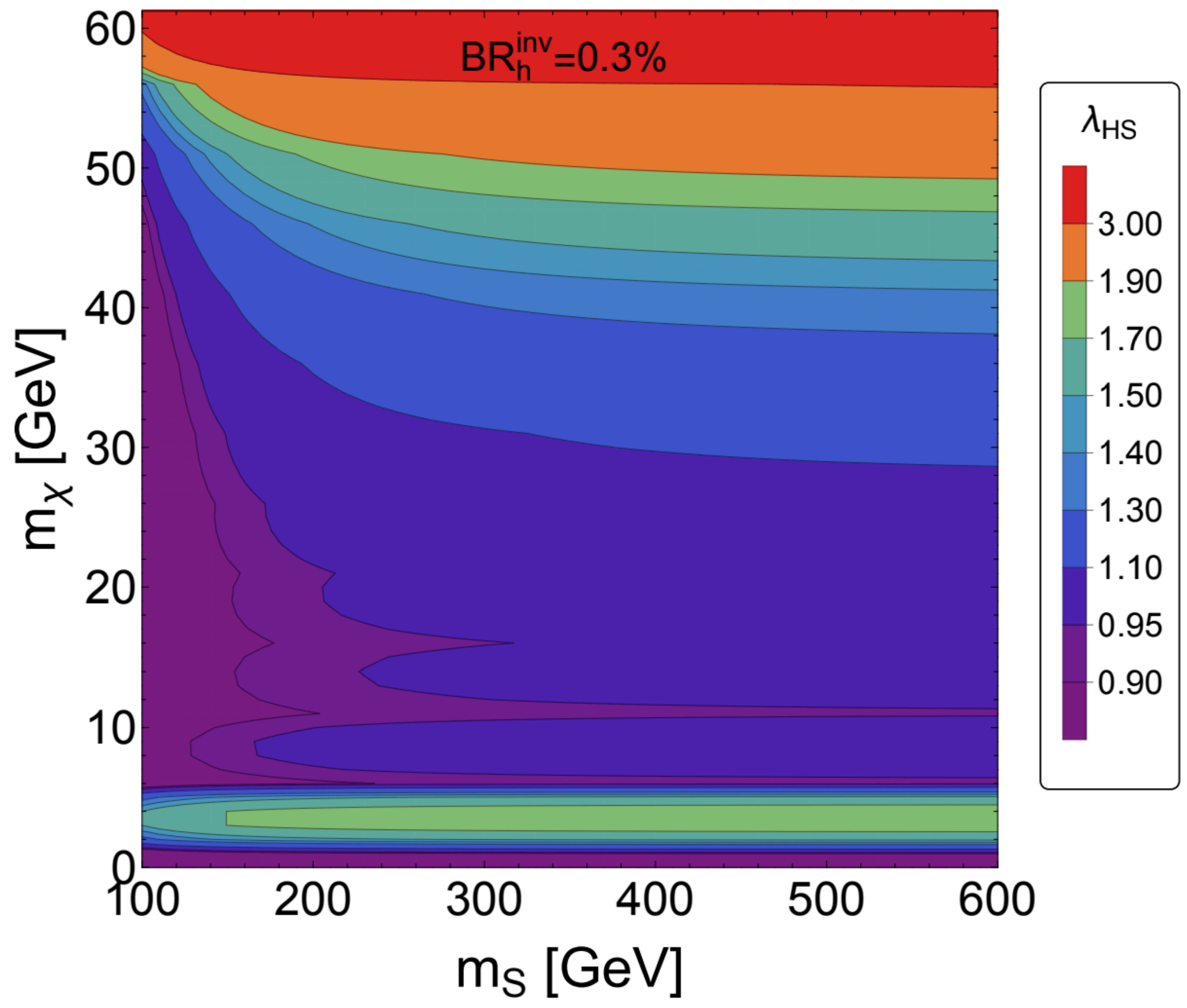
JL, XP Wang, KP Xie, 2104.06421 (JHEP)

- Invisible Higgs decay at 1-loop





- The Higgs-dark sector coupling is constrained



Future ee collider search and GW complementarity

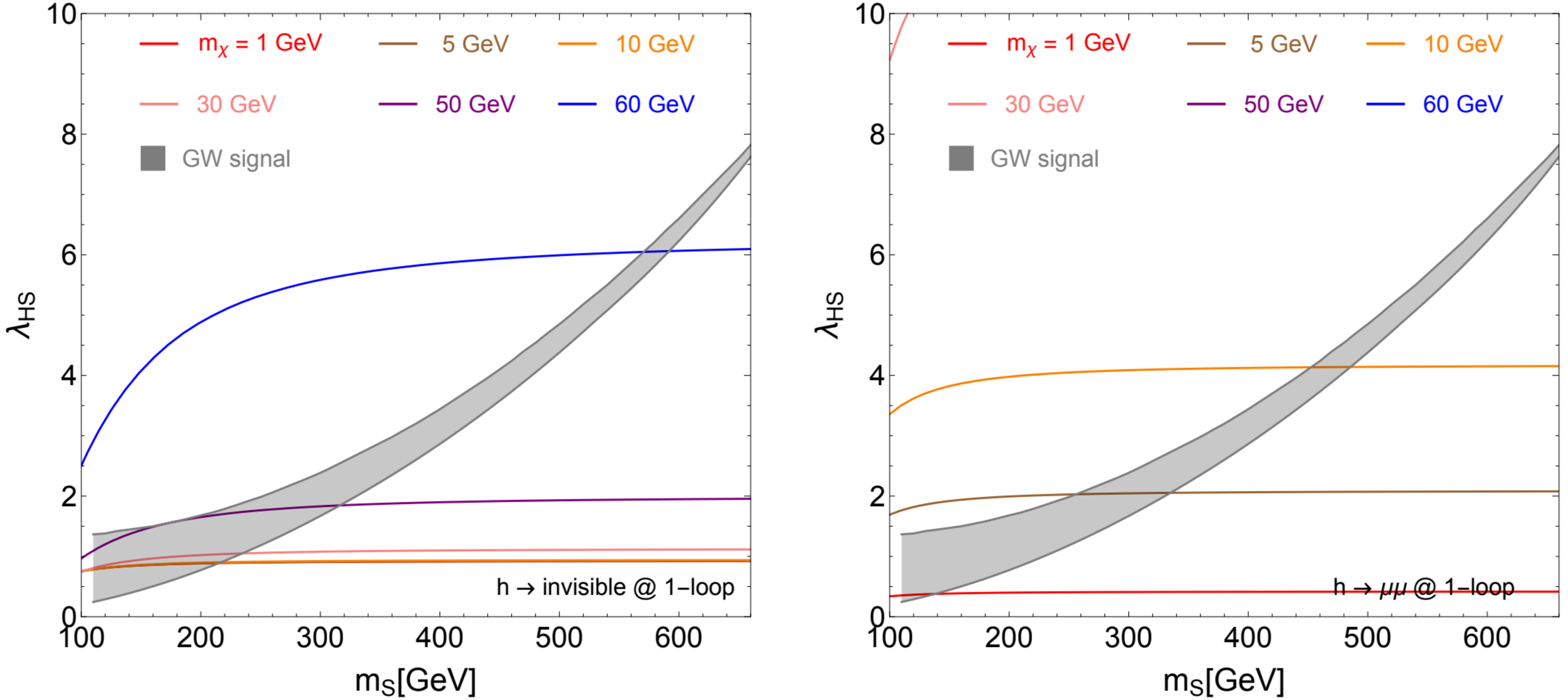
JL, XP Wang, KP Xie, 2104.06421 (JHEP)

- Higgs precision measurement can cover 1st order phase transition region, m_S, up to hundred of GeV

$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}i\partial\!\!\!/\chi - \frac{1}{2}m_\chi\bar{\chi}\chi + y_\ell\left(\bar{\chi}_L S^\dagger \ell_R + \text{h.c.}\right),$$

$$\mathcal{L}_S = (D^\mu S)^\dagger D_\mu S - V(H,S),$$

$$V(H,S) = \mu_H^2|H|^2 + \mu_S^2|S|^2 + \lambda_H|H|^4 + \lambda_S|S|^4 + 2\lambda_{HS}|H|^2|S|^2$$



Asymmetric dark matter connecting to lepton portal

Mengchao Zhang, 2104.06988 (PRD)

- A model for (dark) baryogengesis via leptogenesis
- The dark matter is dark baryon and asymmetric

Right-handed nu/Leptogenesis

Dark mediators/ Fermion-portal type

Dark quark/ DM is dark baryon

	$SU(3)'$	$SU(3)$	$U_Y(1)$	Spin	L	B	B'
N_1/N_2	1	1	0	1/2	0	0	0
Φ	3	1	1	0	-1	0	1/3
χ	3	1	1	1/2	-1	0	1/3
q'	3	1	0	1/2	0	0	1/3
l_R	1	1	-1	1/2	1	0	0
d_R	1	3	-1/3	1/2	0	1/3	0
u_R	1	3	2/3	1/2	0	1/3	0

$$
\begin{aligned}
\mathcal{L} =& \mathcal{L}_{\rm SM} - \frac{1}{2}\sum_{i=1,2} M_{N_i}\overline{N}_i N_i^C - m_\Phi^2 \Phi^\dagger\Phi - m_\chi \bar{\chi}\chi - m_{q'}\bar{q}'q' + \mathcal{L}_{\rm kinetic} \\
& - \sum_{i=1,2}\lambda_i \overline{N}_i \chi \Phi^\dagger - \kappa\Phi\bar{q}'_L l_R - \frac{1}{\Lambda_1^2}\left(\bar{q}'^C\chi\right)\left(\bar{q}'^C_L l_R\right) - \frac{1}{\Lambda_2^2}\left(\bar{\chi}\gamma^\mu q'\right)\left(\bar{d}_R\gamma_\mu u_R\right) + h.c.
\end{aligned}
$$

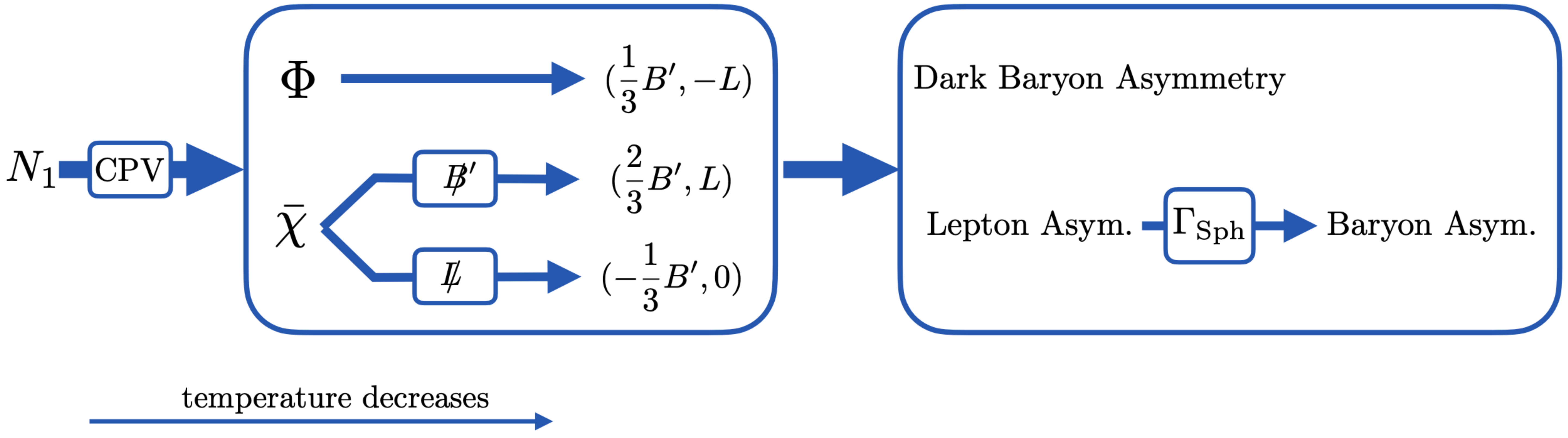
Dark matter and Baryon asymmetry

Mengchao Zhang, 2104.06988 (PRD)

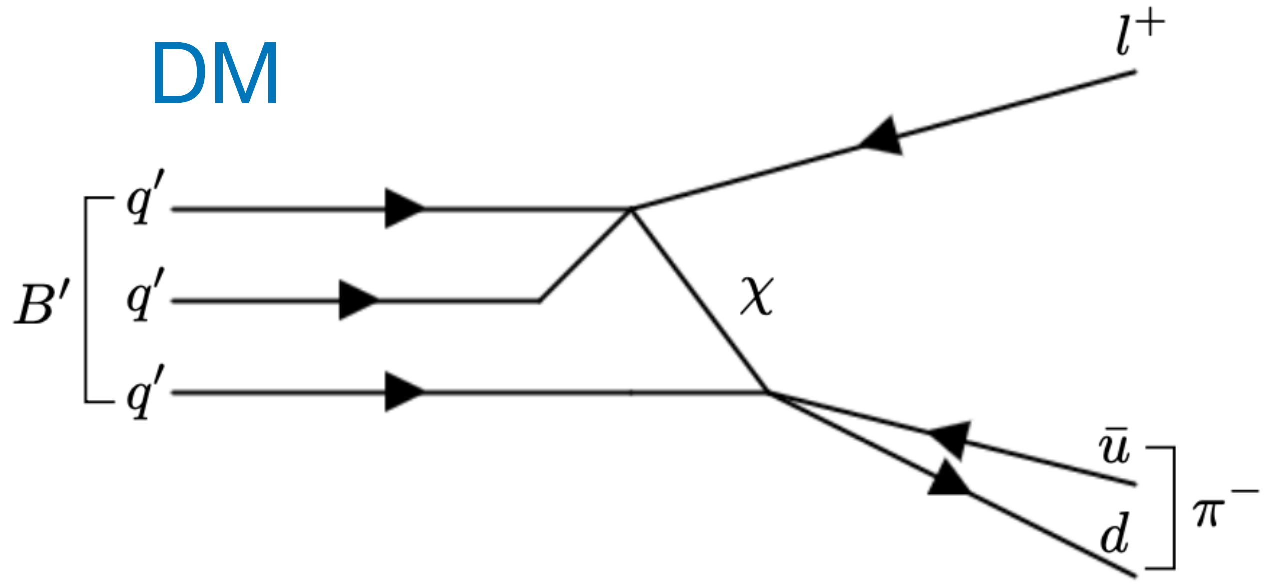
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{2}\sum_{i=1,2} M_{N_i}\overline{N}_i N_i^C - m_\Phi^2 \Phi^\dagger\Phi - m_\chi \bar{\chi}\chi - m_{q'}\bar{q}'q' + \mathcal{L}_{\rm kinetic}$$
$$- \sum_{i=1,2}\lambda_i \overline{N}_i \chi \Phi^\dagger - \kappa\Phi\bar{q}'_L l_R - \frac{1}{\Lambda_1^2}\left(\bar{q}'^C\chi\right)\left(\bar{q}'^C_L l_R\right) - \frac{1}{\Lambda_2^2}\left(\bar{\chi}\gamma^\mu q'\right)\left(\bar{d}_R\gamma_\mu u_R\right) + h.c.$$

$\Delta B' \neq 0$ $\qquad$ $\Delta L \neq 0$

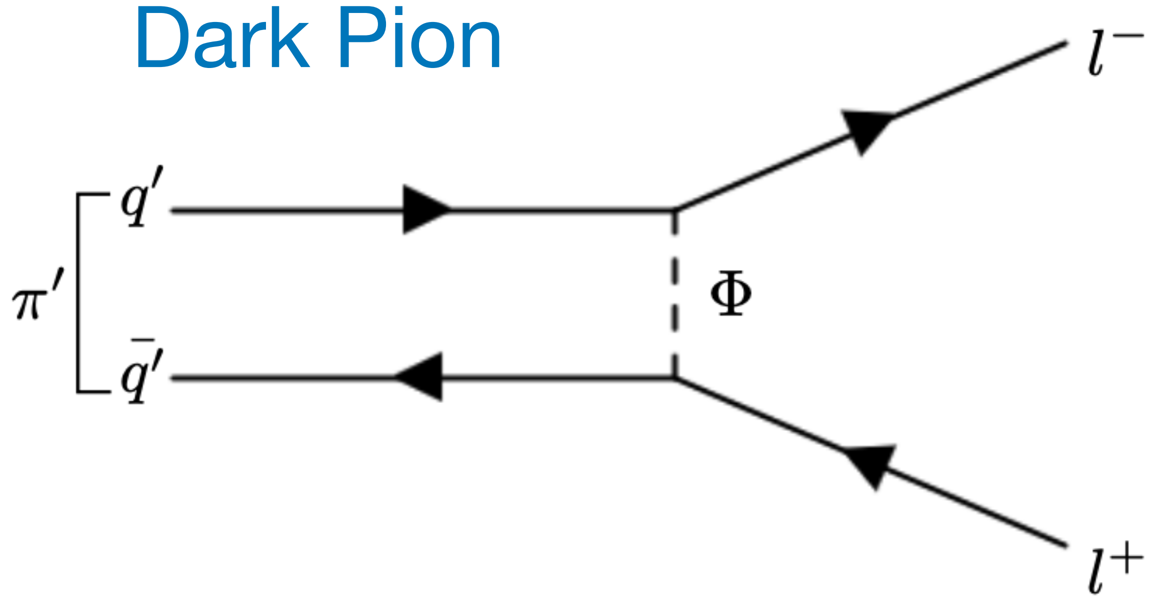
	$SU(3)'$	$SU(3)$	$U_Y(1)$	Spin	L	B	B'
N_1/N_2	1	1	0	1/2	0	0	0
Φ	3	1	1	0	-1	0	1/3
χ	3	1	1	1/2	-1	0	1/3
q'	3	1	0	1/2	0	0	1/3
l_R	1	1	-1	1/2	1	0	0
d_R	1	3	-1/3	1/2	0	1/3	0
u_R	1	3	2/3	1/2	0	1/3	0



DM



Dark Pion



Dark jets at ee collider

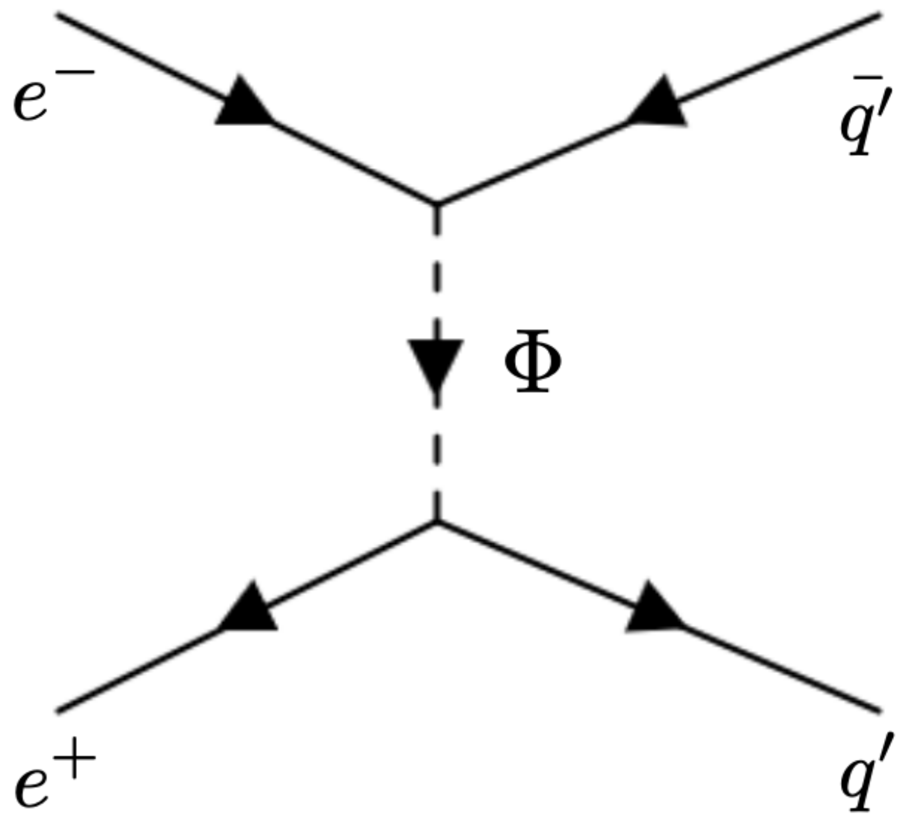
Mengchao Zhang, 2104.06988 (PRD)

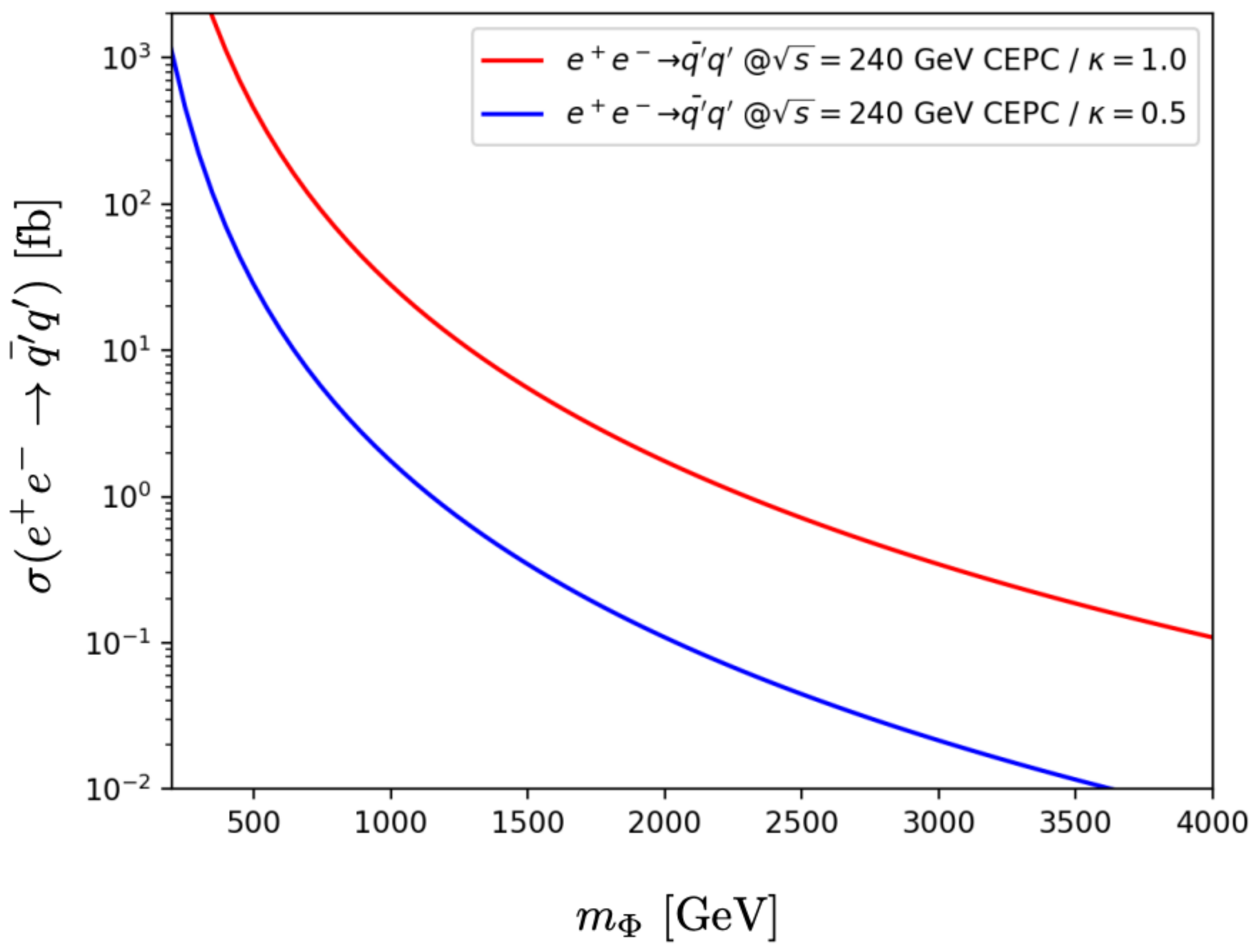
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{2}\sum_{i=1,2} M_{N_i}\overline{N}_i N_i^C - m_\Phi^2 \Phi^\dagger\Phi - m_\chi\bar{\chi}\chi - m_{q'}\bar{q}'q' + \mathcal{L}_{\rm kinetic}$$
$$- \sum_{i=1,2}\lambda_i \overline{N}_i\chi\Phi^\dagger - \boxed{\kappa\Phi\bar{q}'_L l_R} - \frac{1}{\Lambda_1^2}\left(\bar{q}'^C\chi\right)\left(\bar{q}'^C_L l_R\right) - \frac{1}{\Lambda_2^2}\left(\bar{\chi}\gamma^\mu q'\right)\left(\bar{d}_R\gamma_\mu u_R\right) + h.c.$$

- Relevant Lagrangian

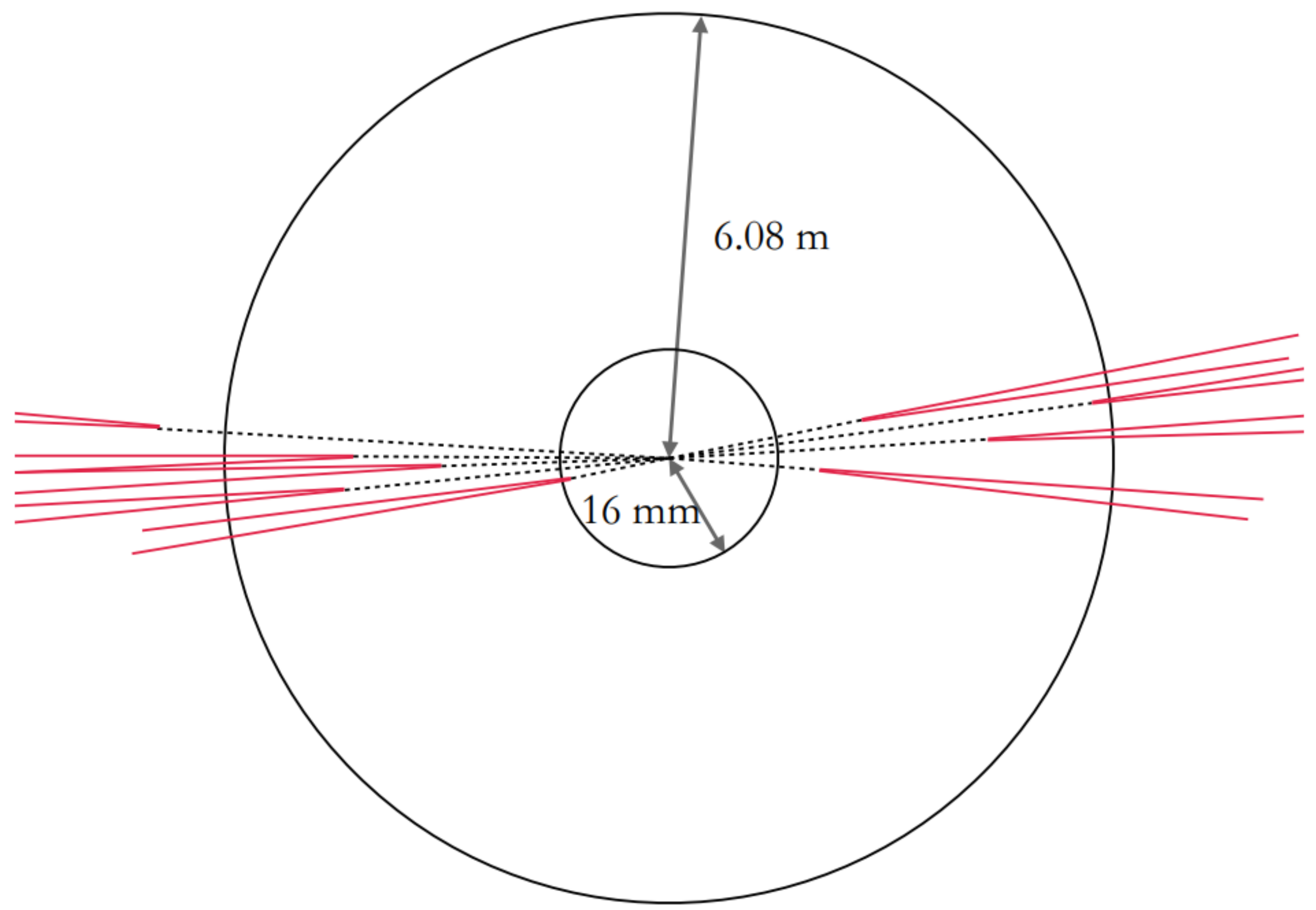
P. Schwaller et al, 1502.05409 (JHEP)

$$\mathcal{L} \supset \bar{q}'(\not{D} - m_{q'})q' + (D_\mu\Phi)^\dagger(D^\mu\Phi) - m_\Phi^2\Phi^\dagger\Phi - \frac{1}{4}G'^{\mu\nu}G'_{\mu\nu} - (\kappa\Phi\bar{q}'_L l_R + h.c.)$$





- $e^+e^- \to \bar{q}'q'$ followed by dark hadronization
- Displaced dark meson decay $\pi_d = (\bar{q}'q')$



Outline

- Dark Matter and Dark Sector
    - Fermion portal — lepton portal
    - Higgs portal
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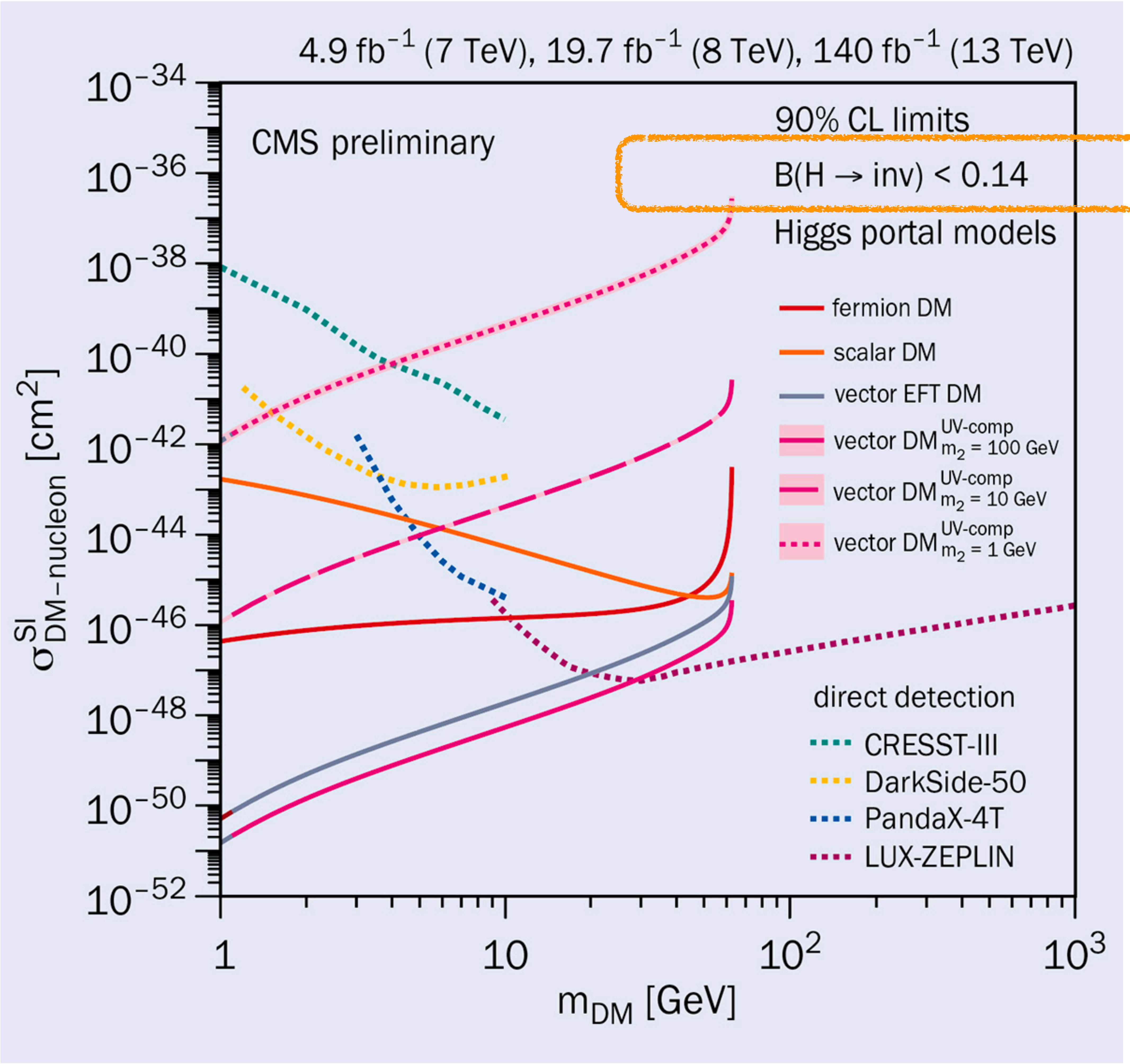
Higgs portal DM: invisible Higgs decay

- Precision measurement of Higgs
  - Invisible Higgs test to 0.07%@CEPC

	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	vvH	ZH	vvH	eeH
inclusive	**0.26%**		**1.40%**	\	\
H→bb	**0.14%**	**1.59%**	**0.90%**	**1.10%**	**4.30%**
H→cc	**2.02%**		**8.80%**	**16%**	**20%**
H→gg	**0.81%**		**3.40%**	**4.50%**	**12%**
H→WW	**0.53%**		**2.80%**	**4.40%**	**6.50%**
H→ZZ	**4.17%**		**20%**	**21%**	
$H\rightarrow\tau\tau$	**0.42%**		**2.10%**	**4.20%**	**7.50%**
$H\rightarrow\gamma\gamma$	**3.02%**		**11%**	**16%**	
$H\rightarrow\mu\mu$	**6.36%**		**41%**	**57%**	
$H\rightarrow Z\gamma$	**8.50%**		**35%**		
$\mathrm{Br}_{upper}(H\rightarrow inv.)$	**0.07%**				
Γ_H	**1.65%**		**1.10%**		

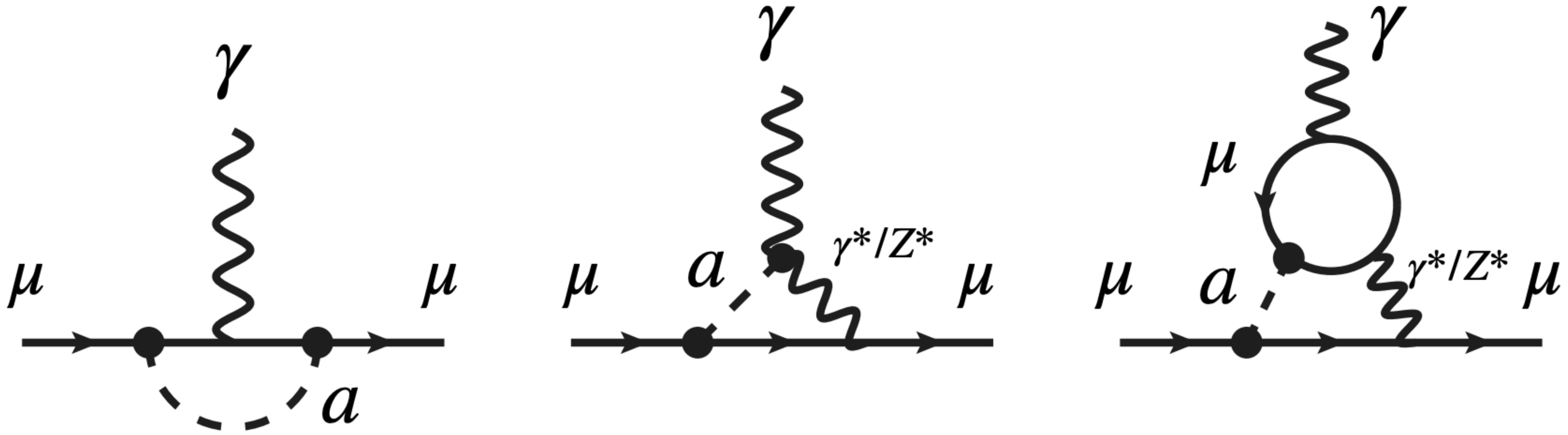


Pseudo-Scalars at the Z-factory

- A pseudo-scalar connection to muon g-2

$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar\psi_F \boldsymbol{C}_F \gamma_\mu \psi_F$$
$$+ g_s^2 C_{GG}\frac{a}{\Lambda}G_{\mu\nu}^A \tilde G^{\mu\nu,A} + g^2 C_{WW}\frac{a}{\Lambda}W_{\mu\nu}^A \tilde W^{\mu\nu,A} + g'^2 C_{BB}\frac{a}{\Lambda}B_{\mu\nu}\tilde B^{\mu\nu}$$

- Couplings to muon, Hypercharge field B, and SU(2) W



W.Y. Keung et al, hep-ph/0009292
W.J. Marciano et al. 1607.01022
M. Bauer, M. Neubert, A. Thamm, 1708.00443
M. A. Buen-Abad, J. Fan, M. Reece, C. Sun 2104.03267
JL, X. Ma, L.T. Wang, W.P. Wang 2210.09335 (PRD)

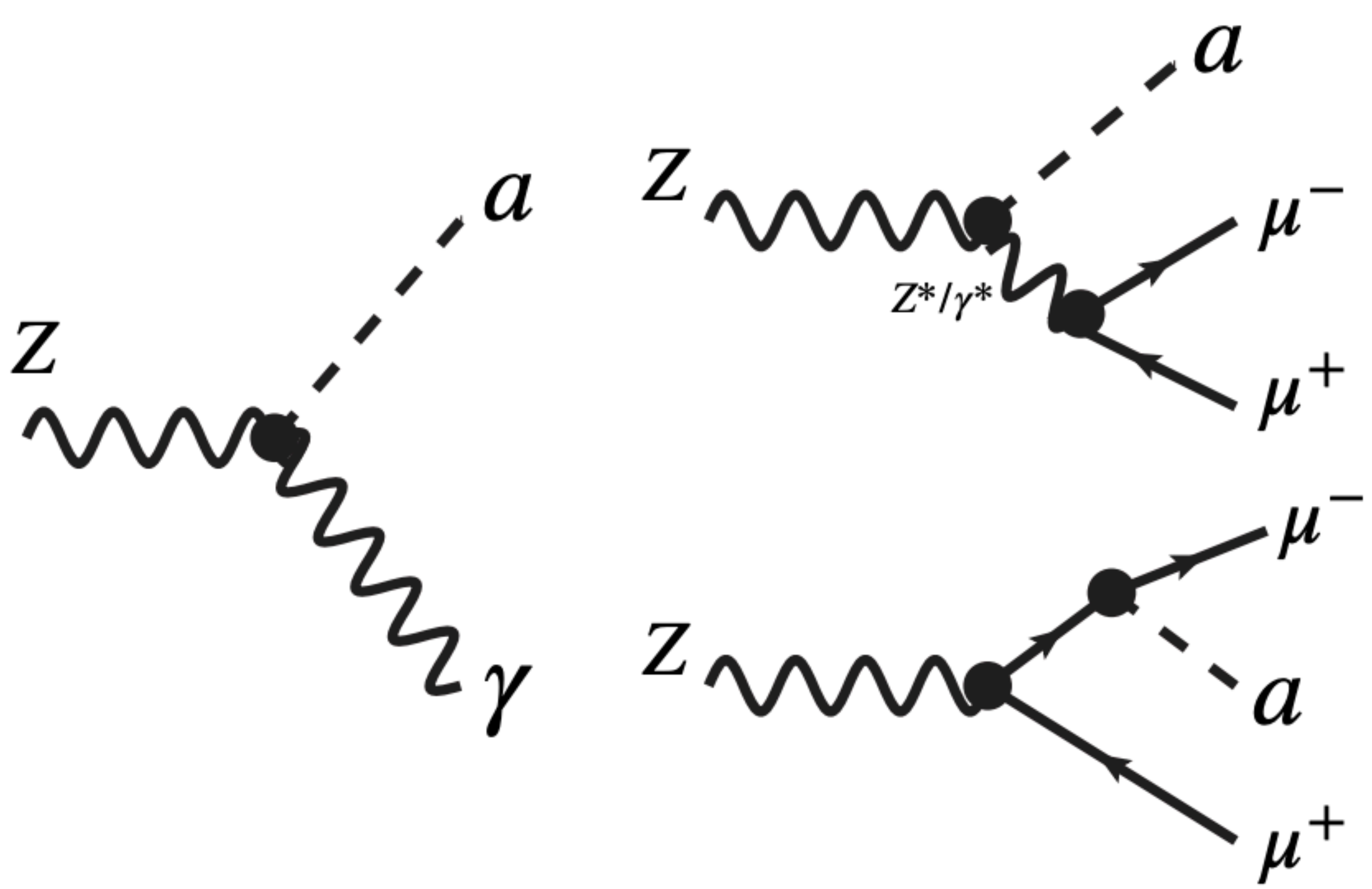
Pseudo-Scalars at the Z-factory

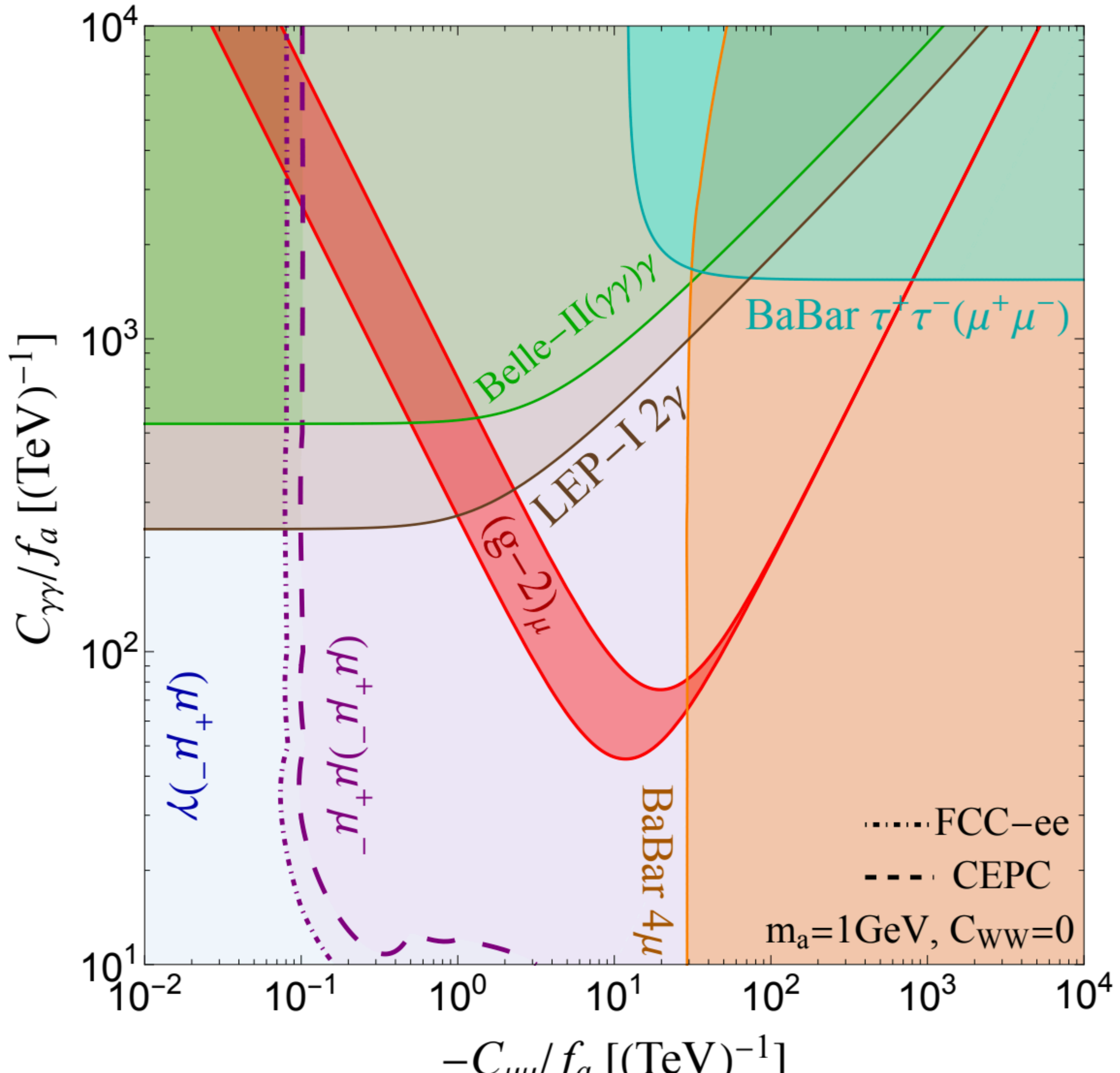
JL, X. Ma, L.T. Wang, W.P. Wang 2210.09335 (PRD)

- A pseudo-scalar connection to muon g-2 and future Z-factory

$$\mathcal{L}_{\rm eff}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar\psi_F \boldsymbol{C}_F \gamma_\mu \psi_F$$
$$+ g_s^2 C_{GG}\frac{a}{\Lambda}G^A_{\mu\nu}\tilde G^{\mu\nu,A} + g^2 C_{WW}\frac{a}{\Lambda}W^A_{\mu\nu}\tilde W^{\mu\nu,A} + g'^2 C_{BB}\frac{a}{\Lambda}B_{\mu\nu}\tilde B^{\mu\nu}$$

- Z exotic decays





Outline

- Dark Matter and Dark Sector
  - Fermion portal — lepton portal
  - Higgs portal
  - Vector portal
  - EFT models
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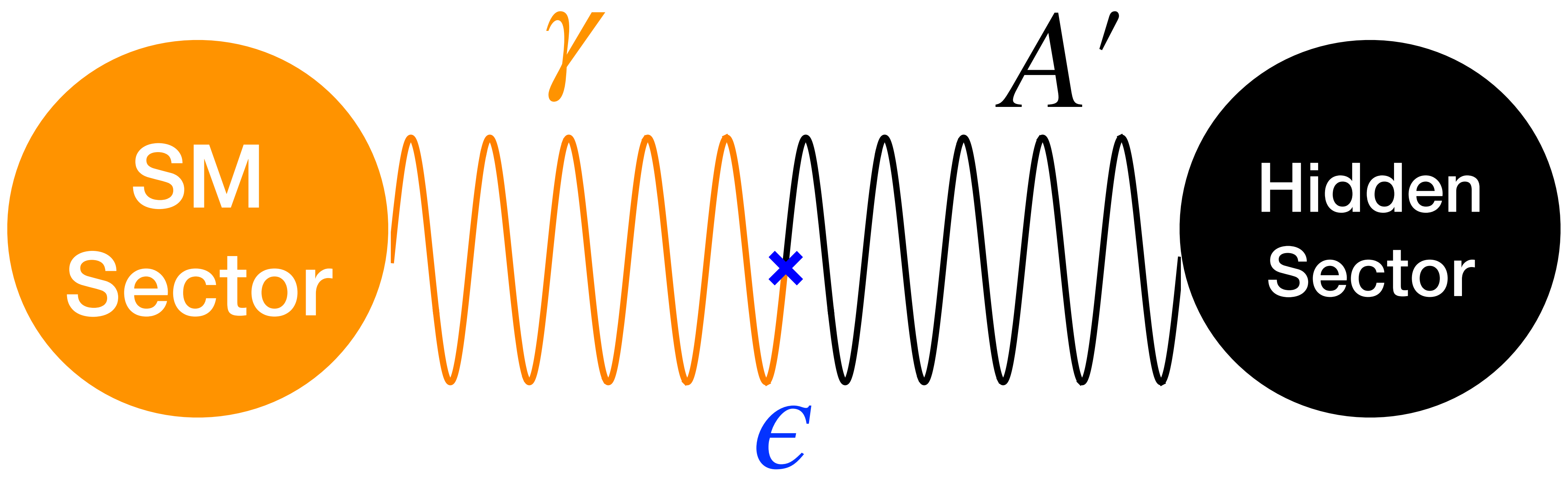
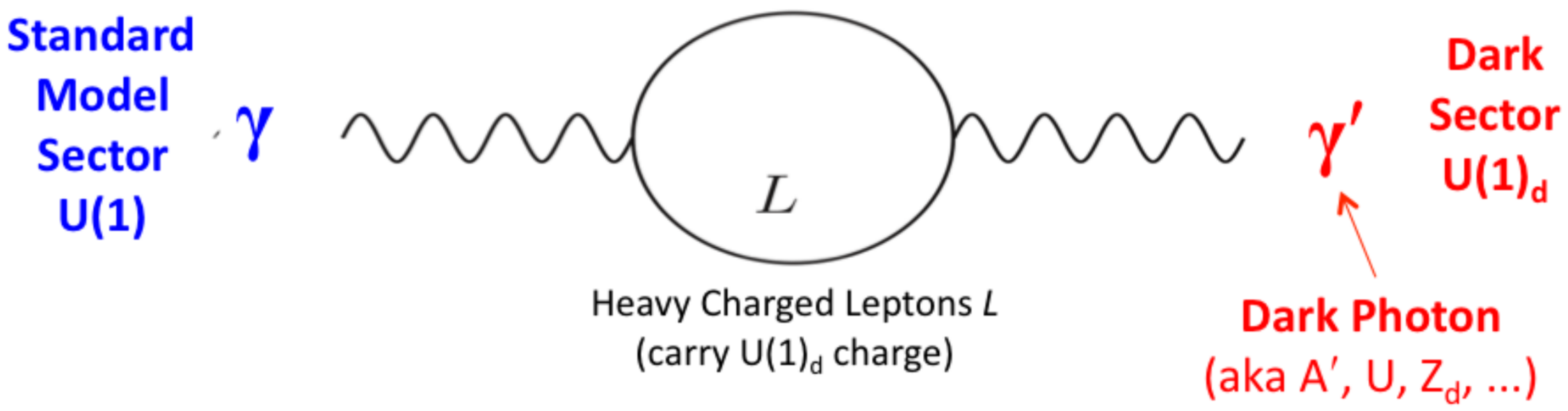
Vector portal

- The vector portal to DM
  - The Interaction: $g'\bar{\chi}\gamma^{\mu}\chi Z'_{\mu}$
    - Millicharged DM: EM with ϵe
    - Kinetic mixing portal
    - Effective Z' through fermion mass mixing





$$\epsilon \sim -\frac{gg'}{16\pi^2}\log\left(\frac{m_L^2}{\mu^2}\right)$$

$$\mathscr{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}{}^2 A'^{\mu}A'_{\mu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu}$$

Vector portal

P. Fox, JL, D.T. Smith, N. Weiner, 1104.4127 (JHEP)

- The vector portal to DM
  - The Interaction: $g'\bar{\chi}\gamma^\mu\chi Z'_\mu$
    - Millicharged DM: EM with ϵe
    - Kinetic mixing portal
    - Effective Z' through fermion mass mixing $(\psi/f_{\rm SM})$

	U(1)'	SM charge
Millicharged DM	1	Yes
Kinetic mixing portal	1	No
Effective Z'	0	Yes

Searching DM via mono-photon at CEPC

Zuowei Liu et al, 1903.12114 (JHEP)

- DM searches via mono-photon final states

Millicharged DM

$$\mathcal{L} = e\varepsilon A_\mu \bar{\chi}\gamma^\mu \chi,$$

Z' portal DM

$$\mathcal{L} = Z'_\mu \bar{\chi}\gamma^\mu (g_V^\chi - g_A^\chi \gamma_5)\chi + Z'_\mu \bar{f}\gamma^\mu (g_V^f - g_A^f \gamma_5) f,$$

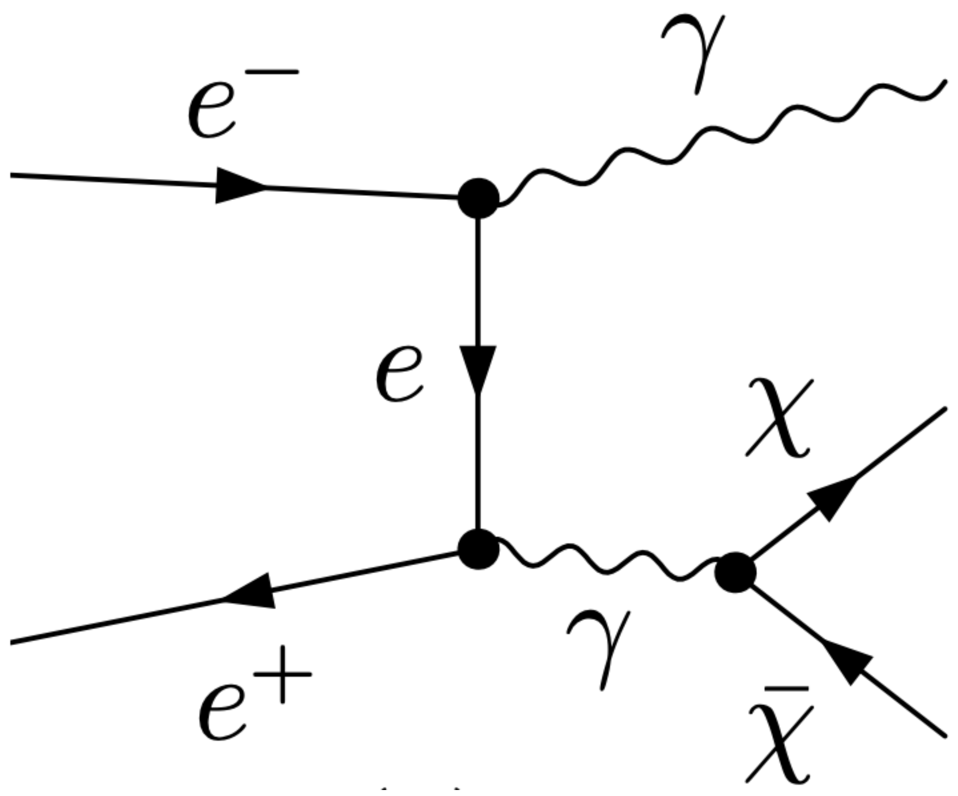
DM EFTs

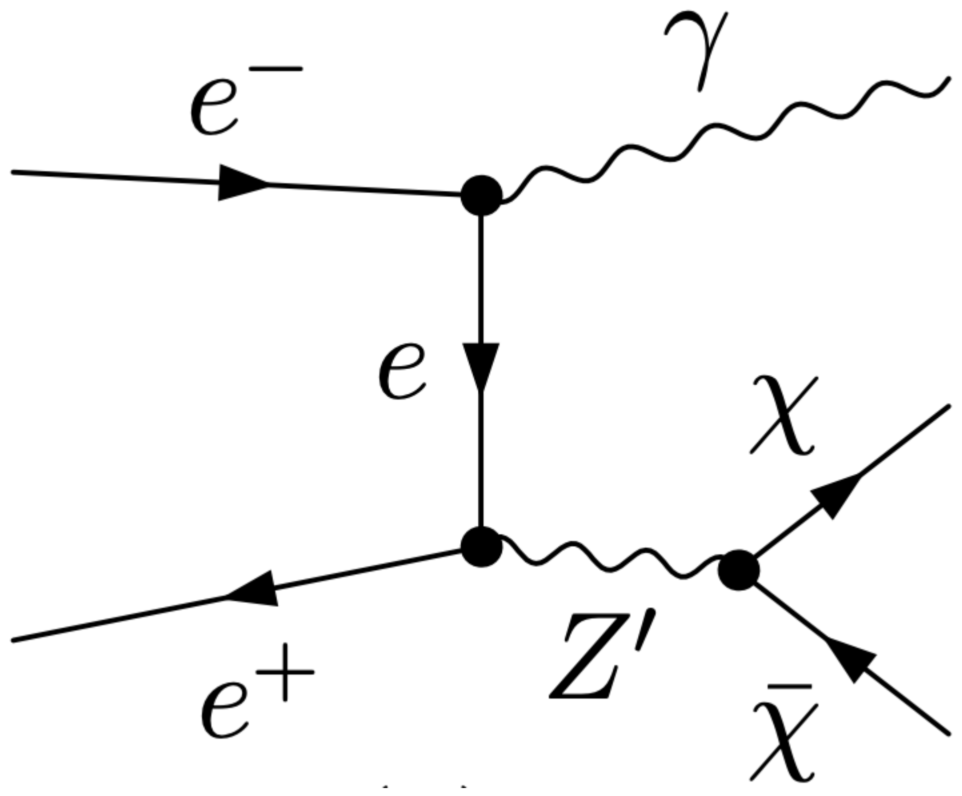
$$\mathcal{L} = \frac{1}{\Lambda_V^2}\bar{\chi}\gamma_\mu\chi\bar{\ell}\gamma^\mu\ell,$$

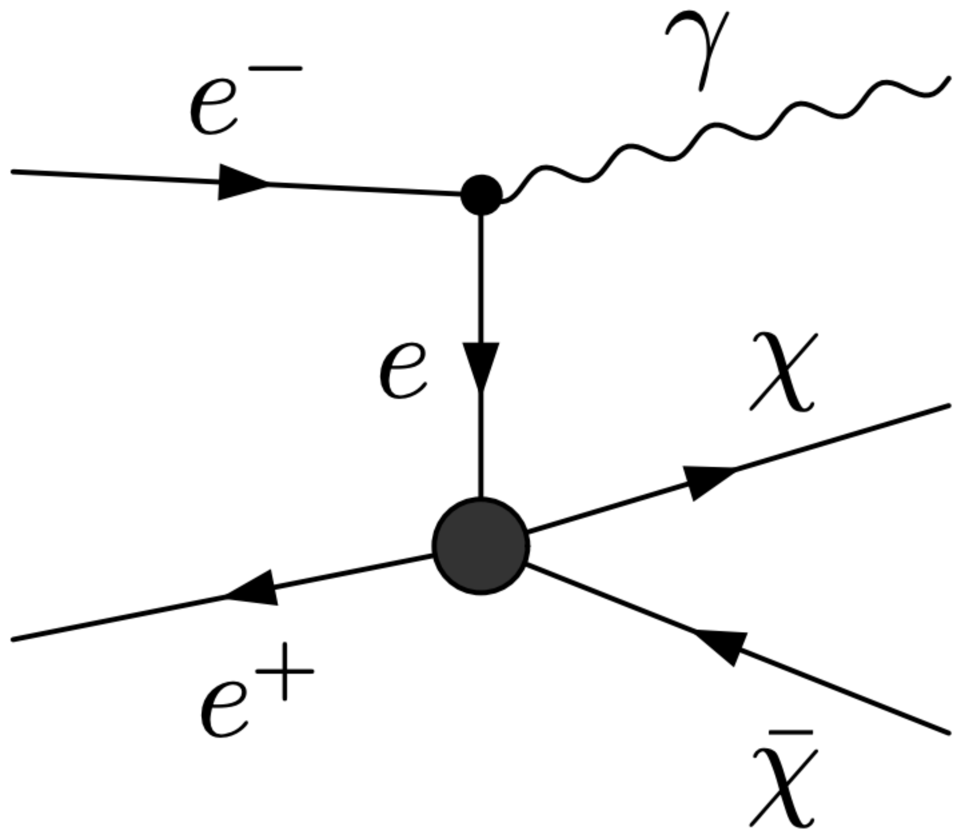
$$\mathcal{L} = \frac{1}{\Lambda_s^2}\bar{\chi}\chi\bar{\ell}\ell,$$

$$\mathcal{L} = \frac{1}{\Lambda_A^2}\bar{\chi}\gamma_\mu\gamma_5\chi\bar{\ell}\gamma^\mu\gamma_5\ell,$$

$$\mathcal{L} = \frac{1}{\Lambda_t^2}\bar{\chi}\ell\bar{\ell}\chi$$



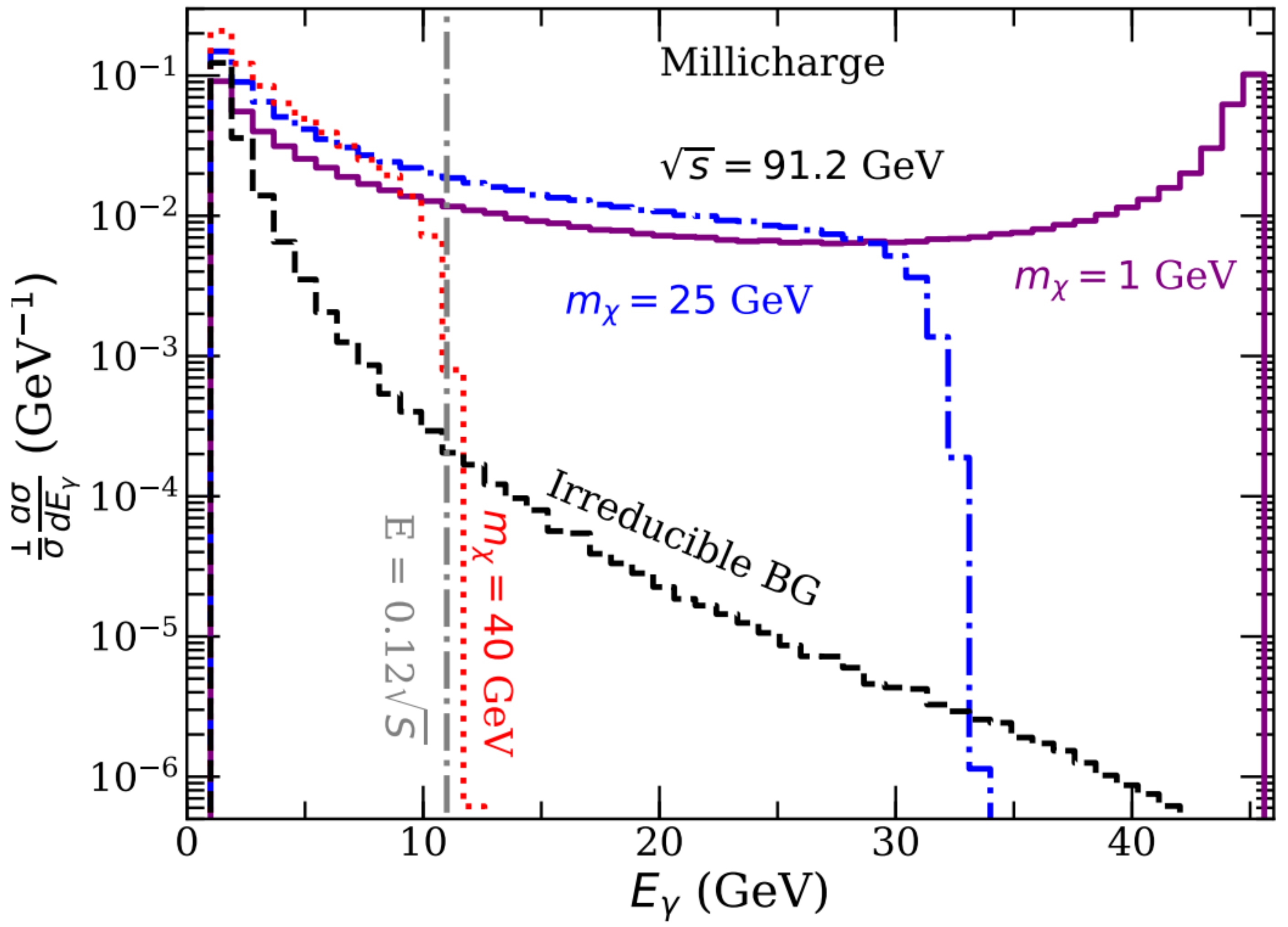


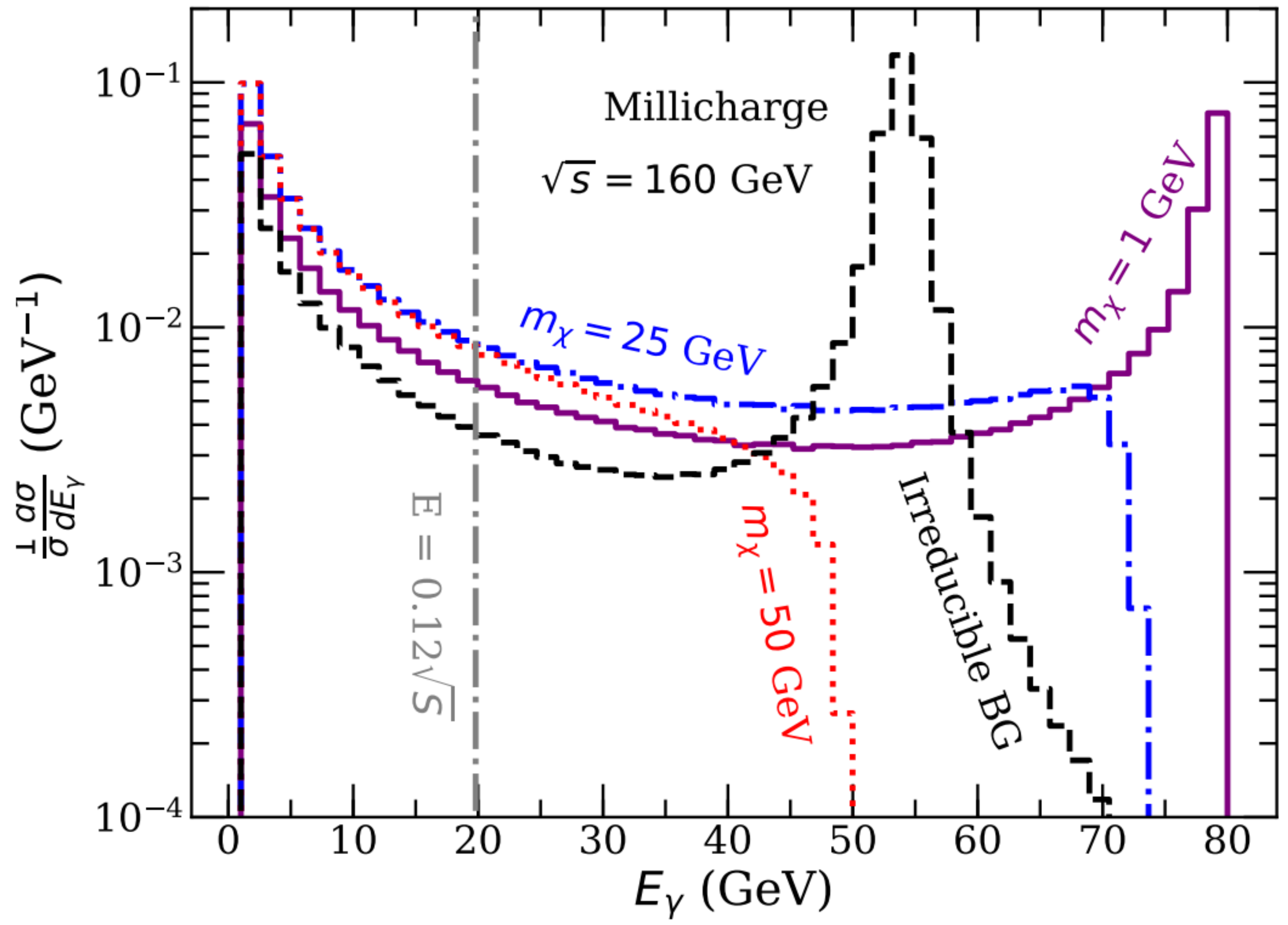


Constraints on millicharged DM

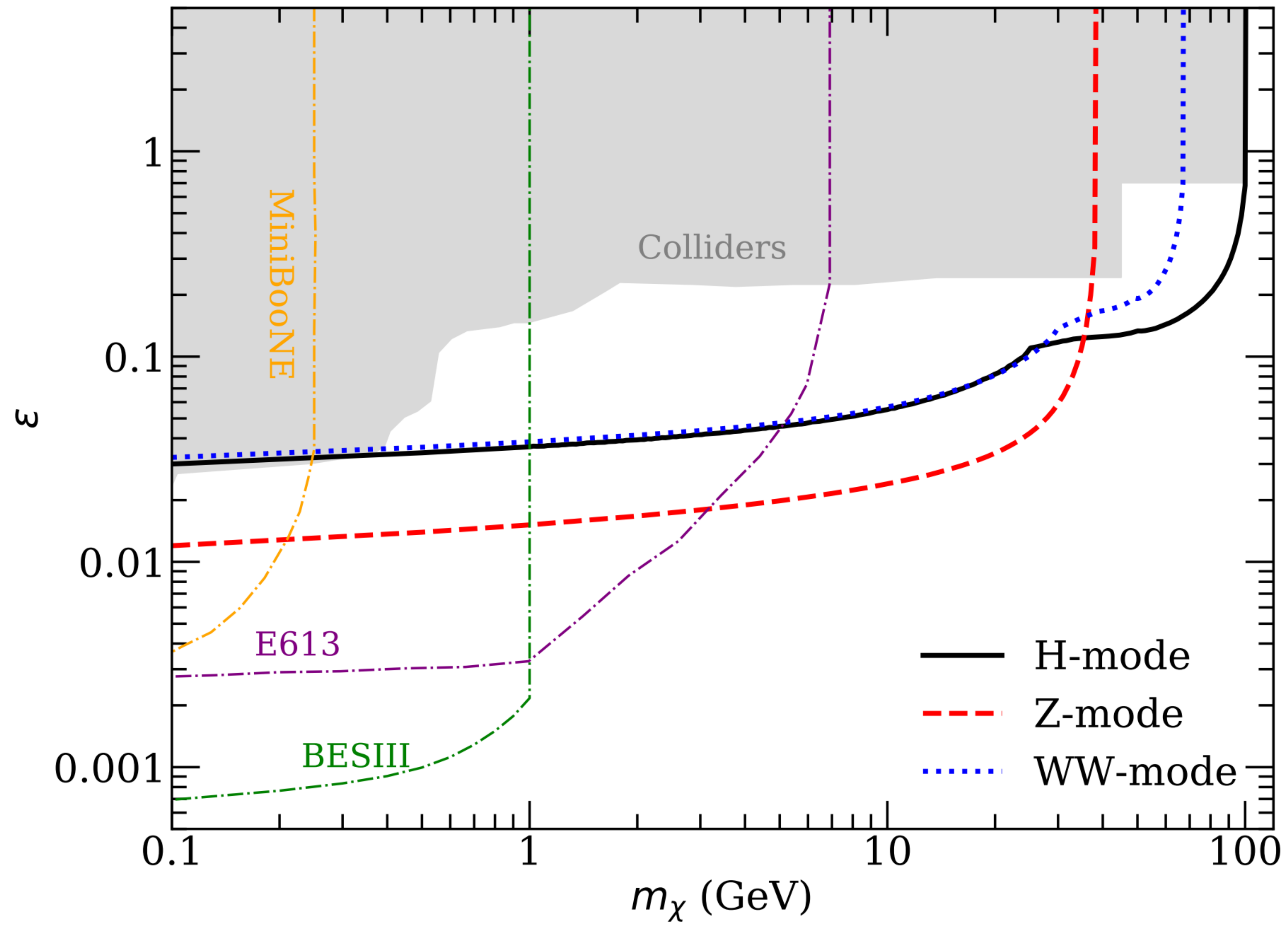
Zuowei Liu et al, 1903.12114 (JHEP)

- The signal distribution at Z ($2.6\ \mathrm{ab}^{-1}$), H ($5.6\ \mathrm{ab}^{-1}$), WW modes ($16\ \mathrm{ab}^{-1}$)





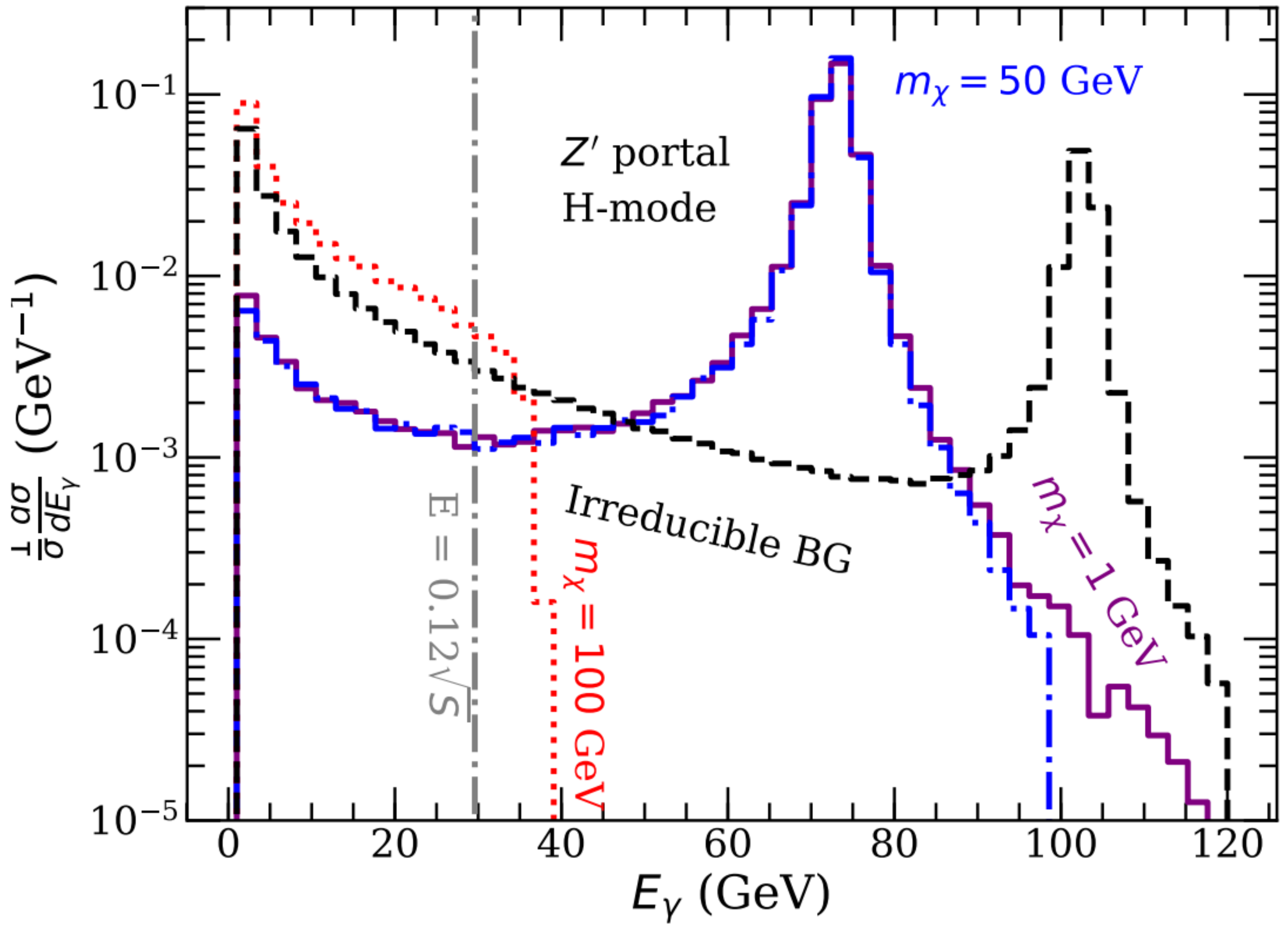
- The Z/Higgs factory modes can provide competitive sensitivity comparing with existing colliders

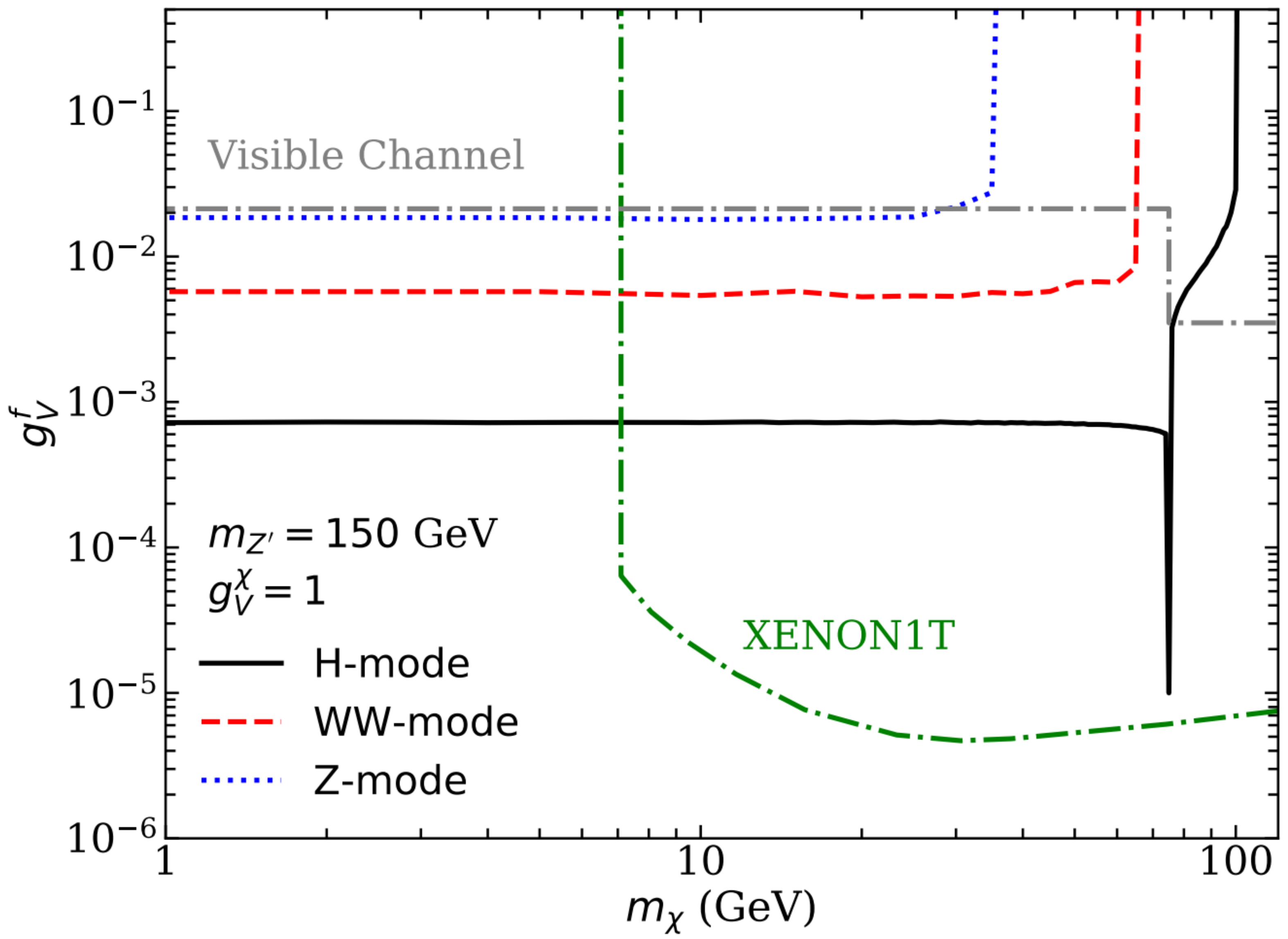


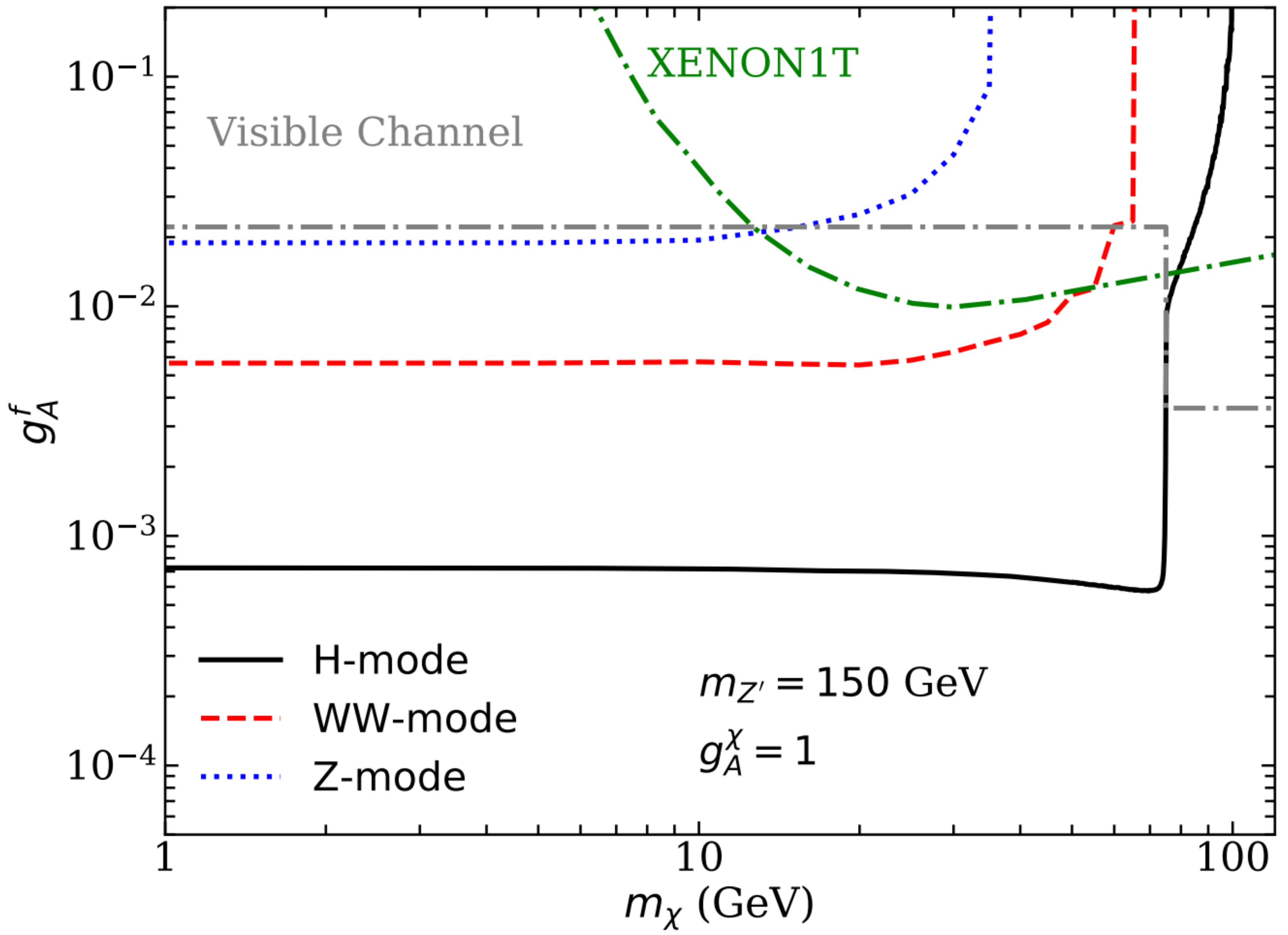
Constraints on Z' portal DM model

Zuowei Liu et al, 1903.12114 (JHEP)

- The signal distribution at Z $(2.6\ \mathrm{ab}^{-1})$, H $(5.6\ \mathrm{ab}^{-1})$, WW modes $(16\ \mathrm{ab}^{-1})$







- The Z/Higgs factory modes can provide competitive sensitivity comparing with existing colliders and direct detection searches

UV Complete model for dark Z'

JL, Xiao-Ping Wang, Felix Yu, 1704.00730 (JHEP)

- Kinetic Mixing Portal: A' should kinetic mixing with Hypercharge field

$$\mathscr{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}{}^2 A'^{\mu}A'_{\mu} - \frac{1}{2}\epsilon F'_{\mu\nu}B^{\mu\nu} + g' A'_{\mu} j^{\mu}_{D}$$

- Z gauge boson is involved (K denotes A')

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

$$+\frac{1}{2}\begin{pmatrix} Z^{\mu}_{\rm SM} & A^{\mu}_{\rm SM} & K^{\mu} \end{pmatrix} \begin{pmatrix} m^2_{Z,\,\rm SM} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m^2_K \end{pmatrix} \begin{pmatrix} Z_{\mu,\,\rm SM} \\ A_{\mu,\,\rm SM} \\ K_{\mu} \end{pmatrix},$$

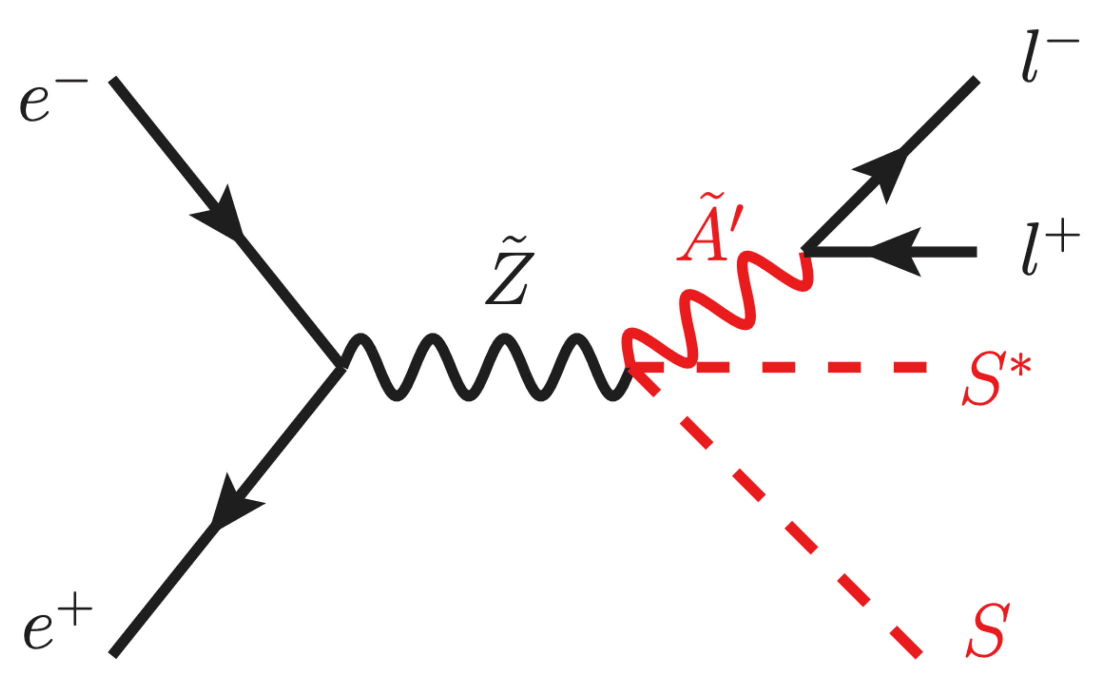
UV Complete model for dark Z’

$$
\begin{aligned}
\mathcal{L} \supset\ & g Z_{\mu,\,\mathrm{SM}} J_Z^\mu + e A_{\mu,\,\mathrm{SM}} J_{\mathrm{em}}^\mu + g_D K_\mu J_D^\mu \\
=\ & \tilde{Z}_\mu \left(g J_Z^\mu - \boxed{g_D \frac{m^2_{Z,\,\mathrm{SM}} t_W}{m^2_{Z,\,\mathrm{SM}} - m_K^2} \epsilon J_D^\mu} + g \frac{m^2_{Z,\,\mathrm{SM}} (m^2_{Z,\,\mathrm{SM}} - 2 m_K^2) t_W^2}{2 (m_K^2 - m^2_{Z,\,\mathrm{SM}})^2} \epsilon^2 J_Z^\mu - e \frac{m^2_{Z,\,\mathrm{SM}} t_W}{m^2_{Z,\,\mathrm{SM}} - m_K^2} \epsilon^2 J_{\mathrm{em}}^\mu \right) \\
& + \tilde{K}_\mu \left(\boxed{g_D J_D^\mu} + \boxed{g \frac{m_K^2 t_W}{m^2_{Z,\,\mathrm{SM}} - m_K^2} \epsilon J_Z^\mu} + \boxed{e \epsilon J_{\mathrm{em}}^\mu} + g_D \frac{(m^4_{Z,\,\mathrm{SM}} c_W^2 - 2 m_K^2 m^2_{Z,\,\mathrm{SM}} + m_K^4) c_W^{-2}}{2 (m^2_{Z,\,\mathrm{SM}} - m_K^2)^2} \epsilon^2 J_D^\mu \right) \\
& + \tilde{A}_\mu e J_{\mathrm{em}}^\mu \,.
\end{aligned}
$$

Exist but usually overlooked

Could be tested at future Z-factory (e.g. CEPC)

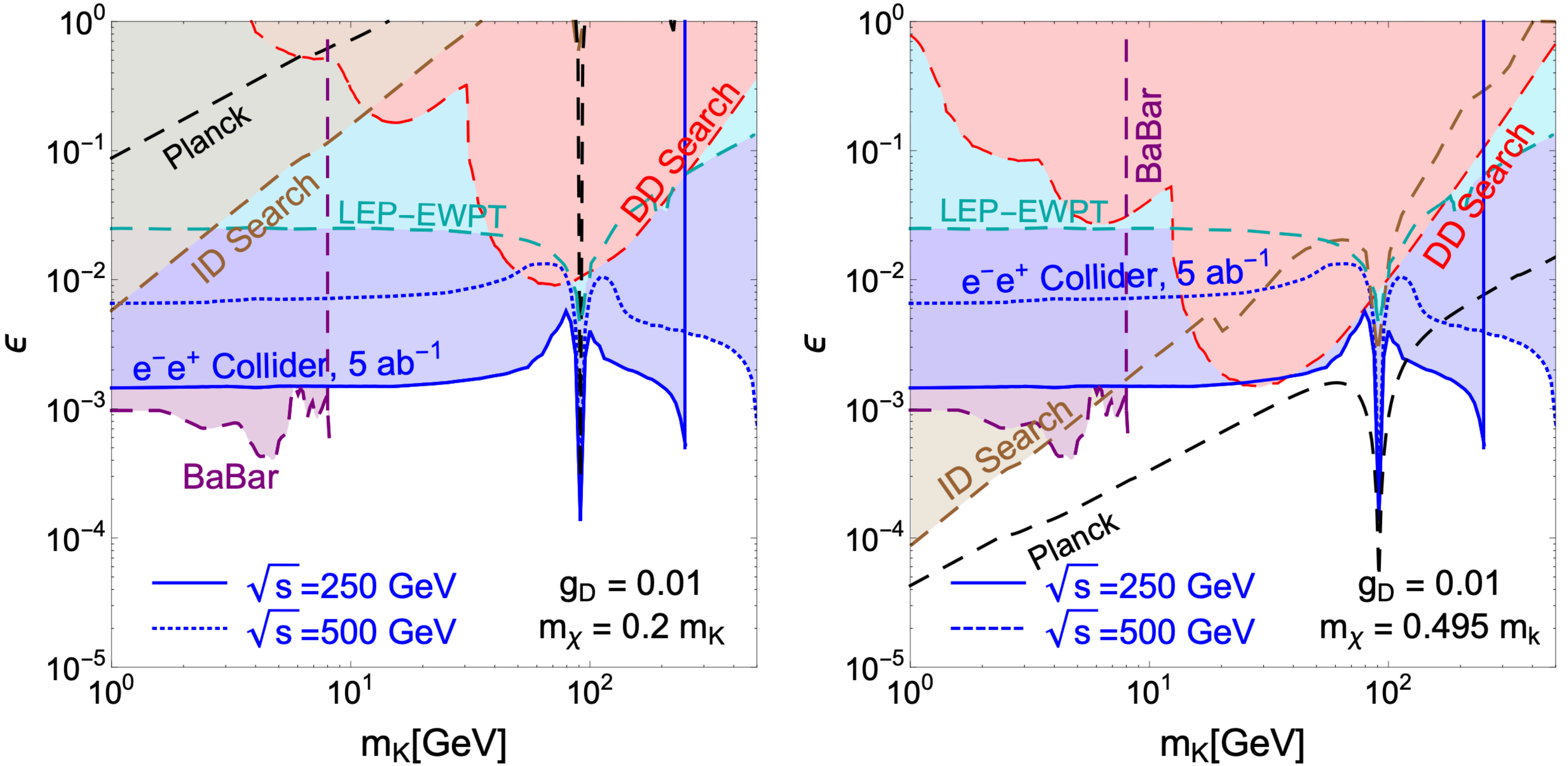
Vanish in the $m_{A'} \ll m_Z$ limit



E.g. if dark scalar is contained in the current j_D

UV Complete model for dark Z'

JL, Xiao-Ping Wang, Felix Yu, 1704.00730 (JHEP)



Outline

- Dark Matter and Dark Sector
  - Fermion portal — lepton portal
  - Higgs portal
  - Vector portal
  - EFT models
- Summary

Searching fermionic DM absorption at CEPC

Shaofeng Ge et al, 2201.11497 (JHEP)

- Light DM can provide enough energy to direct detection via down-scattering (fermionic)/absorption (bosonic)

- Inelastic DM $\chi_2 q \to \chi_1 q$, Luminous DM long-lived $\chi_2 \to \chi_1 \gamma$

- Fermionic DM down-scattering: $\chi e \to \nu e$, no Z_2 protection

$$
\begin{aligned}
\mathcal{O}^S_{e\nu\chi} &\equiv (\bar{e}e)(\bar{\nu}_L \chi_R), \\
\mathcal{O}^P_{e\nu\chi} &\equiv (\bar{e}i\gamma_5 e)(\bar{\nu}_L \chi_R), \\
\mathcal{O}^V_{e\nu\chi} &\equiv (\bar{e}\gamma_\mu e)(\bar{\nu}_L \gamma^\mu \chi_L), \\
\mathcal{O}^A_{e\nu\chi} &\equiv (\bar{e}\gamma_\mu \gamma_5 e)(\bar{\nu}_L \gamma^\mu \chi_L), \\
\mathcal{O}^T_{e\nu\chi} &\equiv (\bar{e}\sigma_{\mu\nu} e)(\bar{\nu}_L \sigma^{\mu\nu} \chi_R),
\end{aligned}
$$

- DM is stable, because
  - $m_\chi < 2m_e$
  - Radiative decay to $\nu + \gamma^n$ is small enough

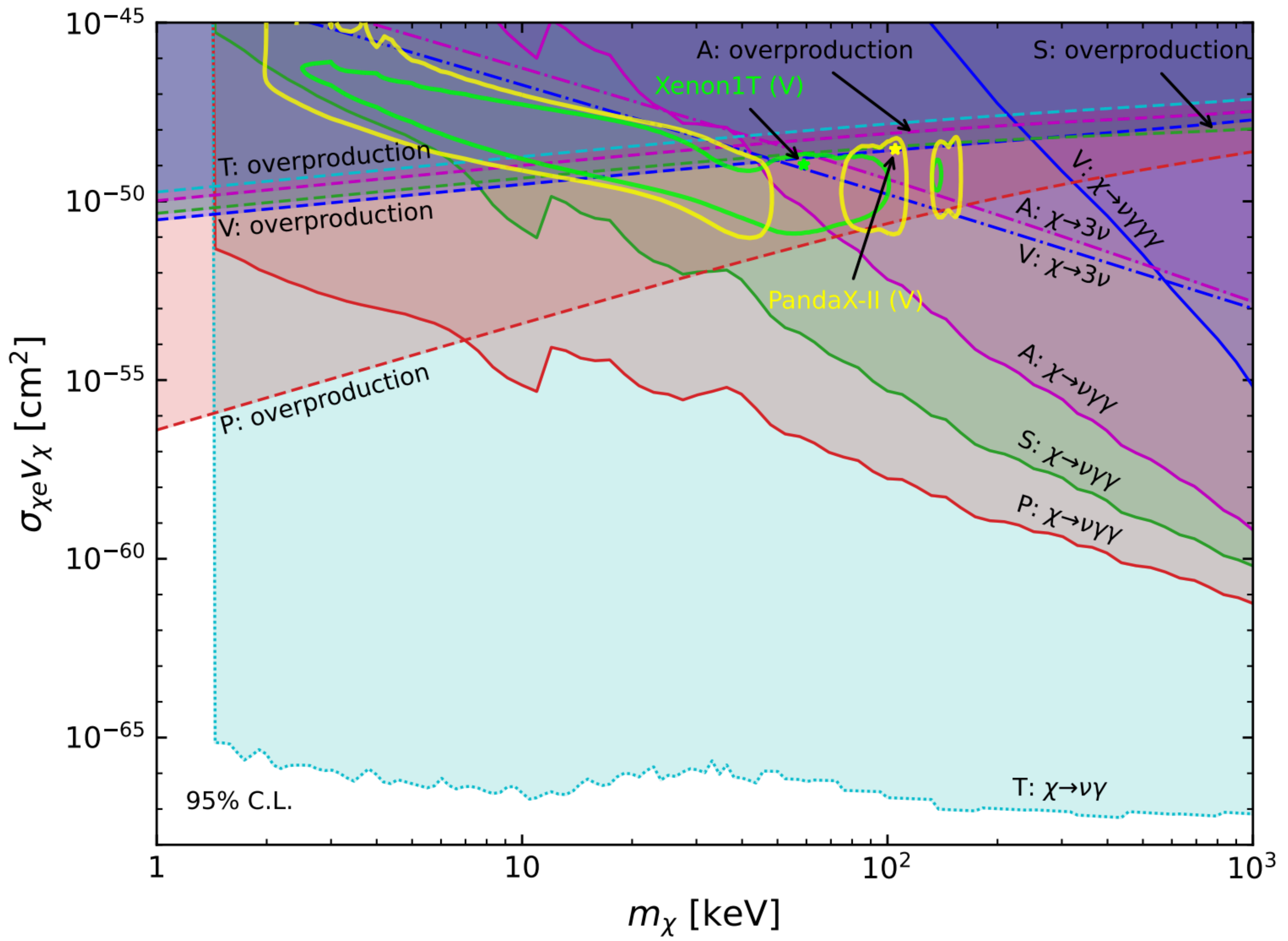
$(\bar{\nu}_L \chi_R) F^2, (\bar{\nu}_L \chi_R) F\tilde{F}$

Operator \ Process	$\chi \to \nu\gamma$	$\chi \to \nu\gamma\gamma$	$\chi \to \nu\gamma\gamma\gamma$	$\chi \to 3\nu$
S: $\mathcal{O}^S_{e\nu\chi}$	×	✓	×	×
P: $\mathcal{O}^P_{e\nu\chi}$	×	✓	×	×
V: $\mathcal{O}^V_{e\nu\chi}$	×	×	✓	✓
A: $\mathcal{O}^A_{e\nu\chi}$	×	✓	×	✓
T: $\mathcal{O}^T_{e\nu\chi}$	✓	×	×!	×!

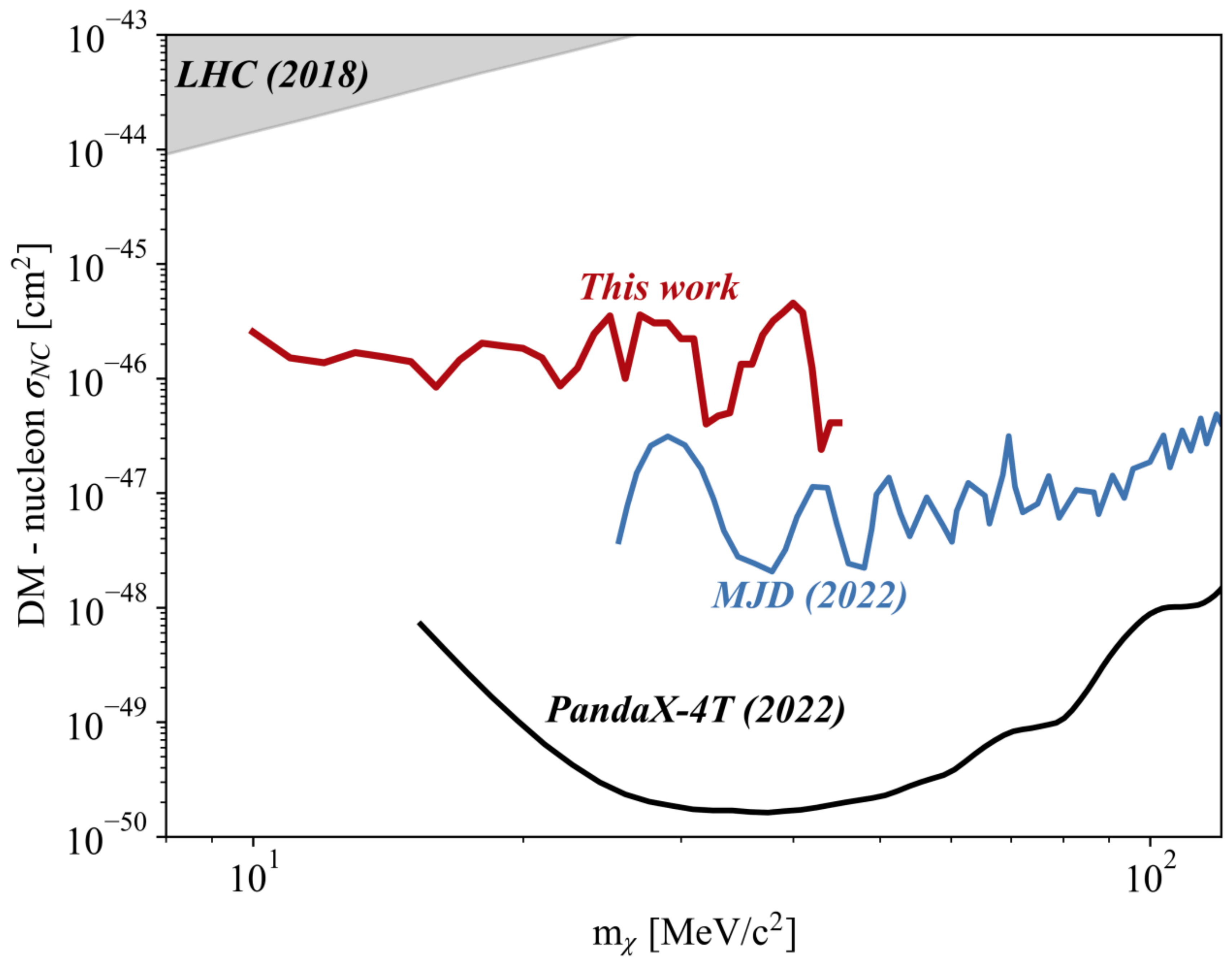
Searching fermionic DM absorption at CEPC

Shaofeng Ge et al, 2201.11497 (JHEP)

- Light DM can provide enough energy to direct detection via fermionic DM down-scattering: $\chi e \to \nu e$



- Actively searched by DM direct detection experiments

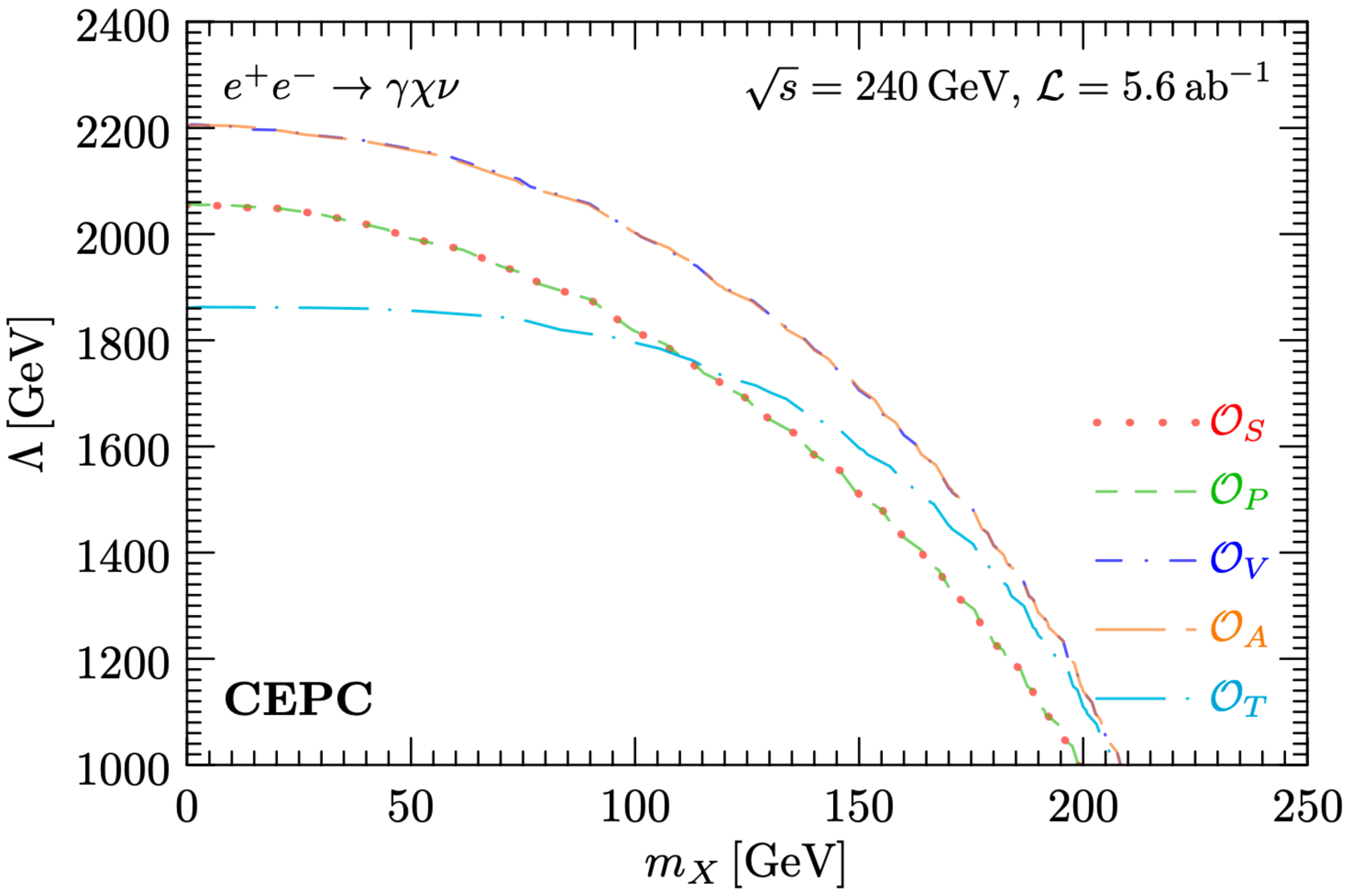


PANDAX 2206.02339 (PRL)
CDEX 2209.00861(PRL)

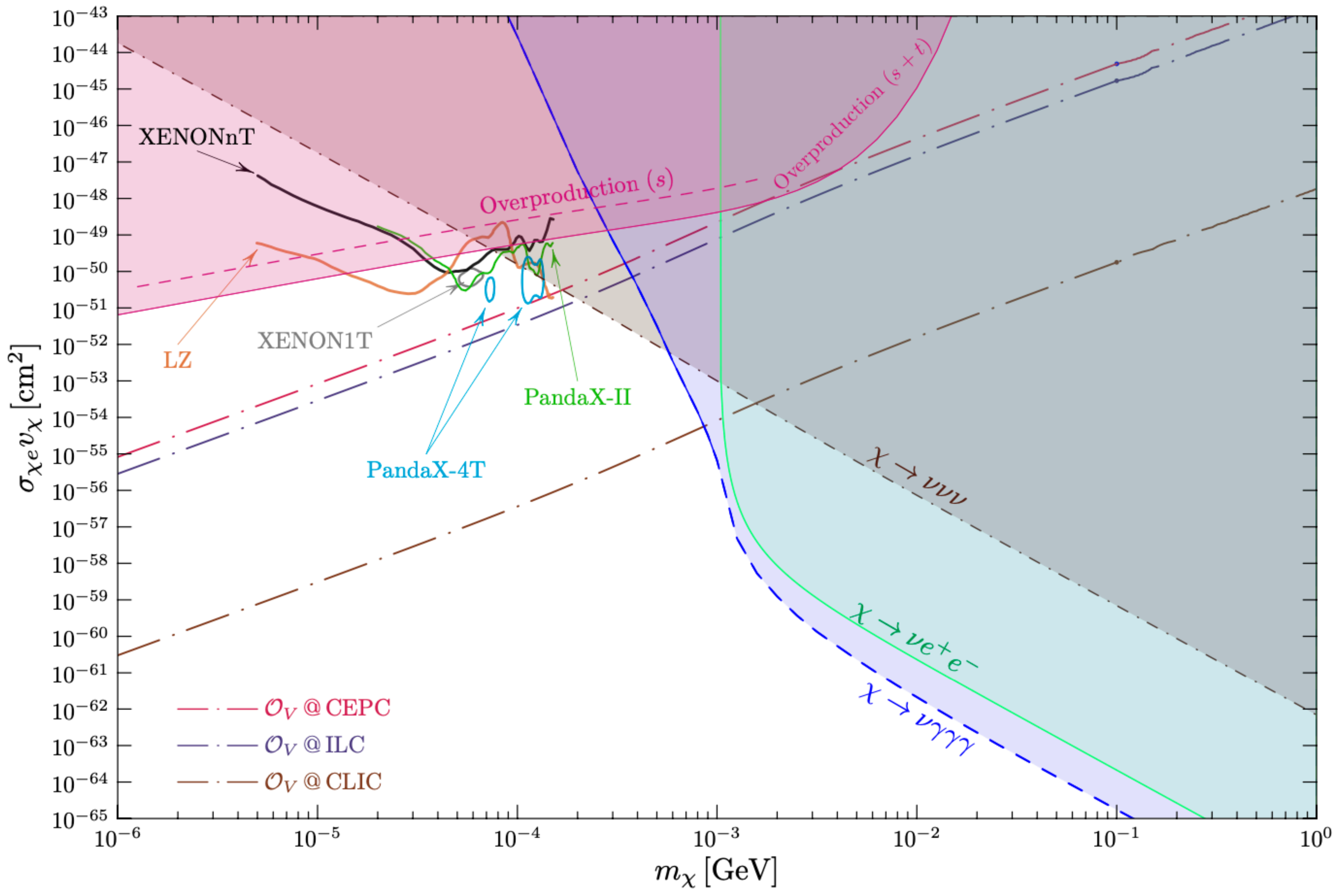
Searching fermionic DM absorption at CEPC

Shaofeng Ge et al, 2201.11497 (JHEP)

- The future ee collider can also test this scenariom via
  - $e^+e^- \to \gamma\nu\bar{\chi}, e^+e^-\nu\bar{\chi}, e^+e^-\nu\bar{\nu}$, in multi-particle final states



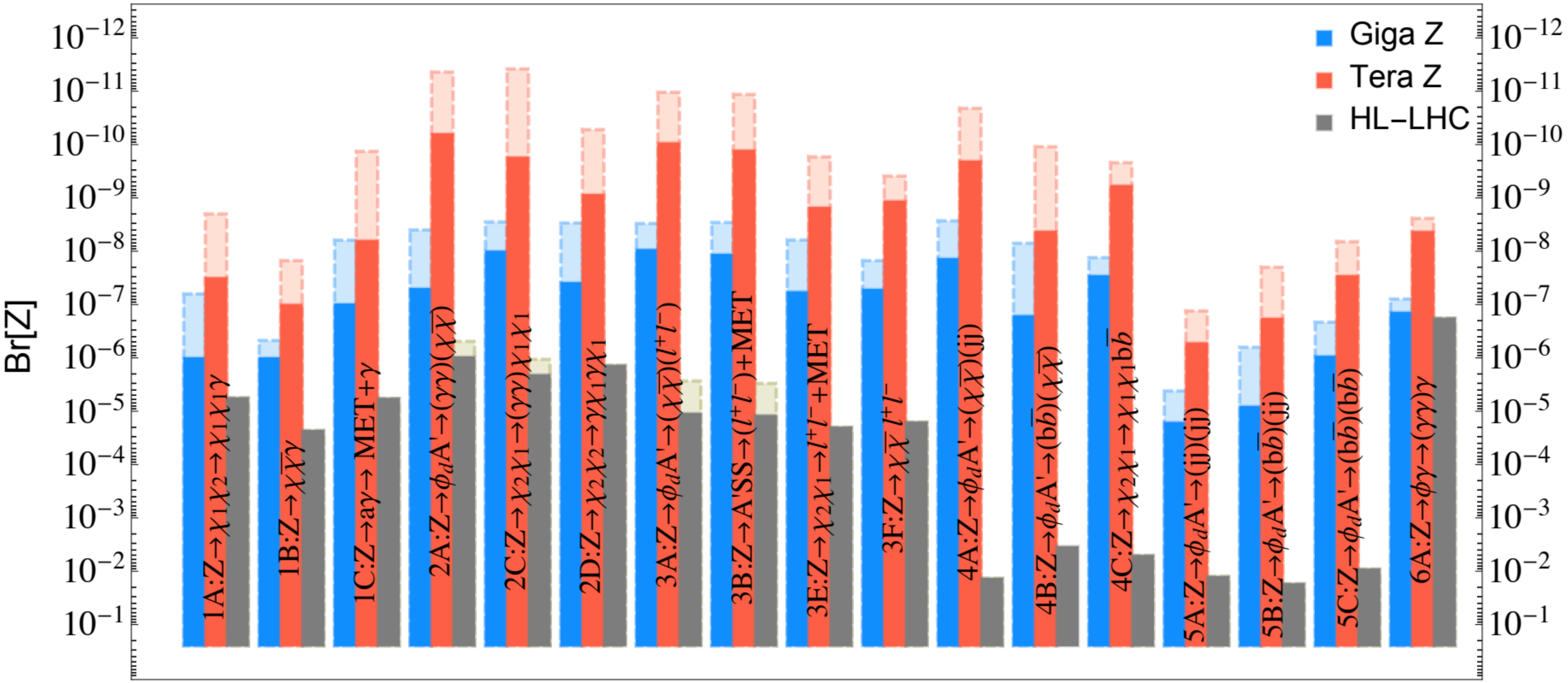
- Collider complementary between DM direct and indirect experiments



Summary

- Future ee collider (CEPC/FCC-ee etc) provides valuable opportunities to dark matter and dark sector

JL, LT Wang, XP Wang, W. Xue, 1712.07237 (PRD)



Thank you!