The progress of Electroweak and Beyond the Standard Model studies at CEPC

Jia Liu (刘佳)
Peking University

Bias warning: mostly on recent findings of the CEPC study, but work for FCC-ee as well.
Apologize for omitting papers, can not cover all…

The 29th International Workshop on Weak Interactions and Neutrinos
WIN2023 @ Sun Yat-sen University Zhuhai Campus
2023-07-05

Outline

- CEPC and Electroweak Physics
- CEPC and Beyond the Standard Model Physics Searches

The Higgs boson turns ten in 2012

G.P. Salam, L.T. Wang, G. Zanderighi, Nature Perspectives 2022

Higgs boson

Why is the electroweak interaction so much stronger than gravity?
- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs boson with the *W* and *Z* bosons?

Why is there more matter than antimatter in the Universe?
- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-Universe electroweak phase transition?
- Are there multiple Higgs sectors?

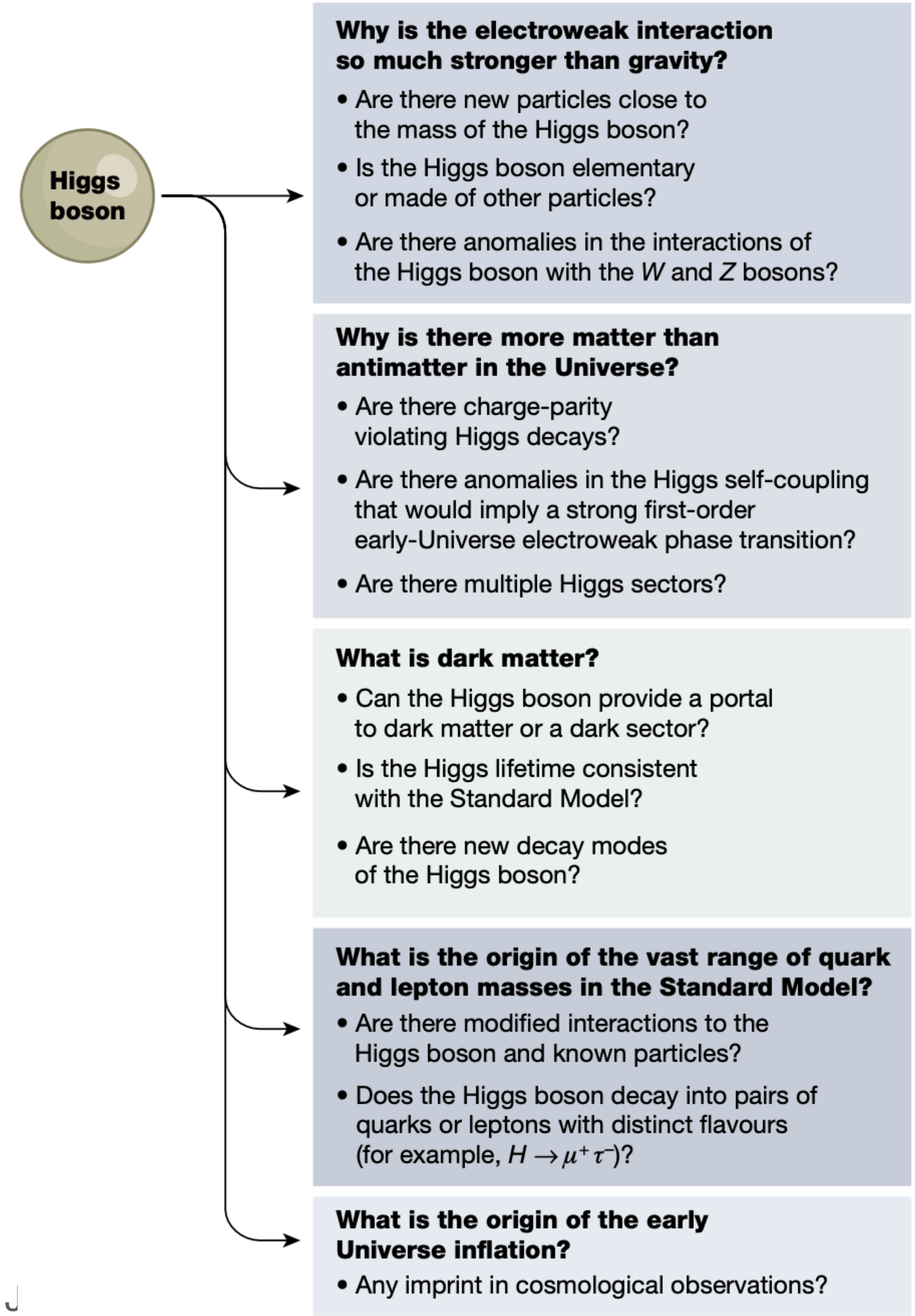
What is dark matter?
- Can the Higgs boson provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs boson?

What is the origin of the vast range of quark and lepton masses in the Standard Model?
- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs boson decay into pairs of quarks or leptons with distinct flavours (for example, $H \to \mu^+ \tau^-$)?

What is the origin of the early Universe inflation?
- Any imprint in cosmological observations?

- Higgs could be the key of the particle physics open questions

The Higgs boson turns ten in 2012

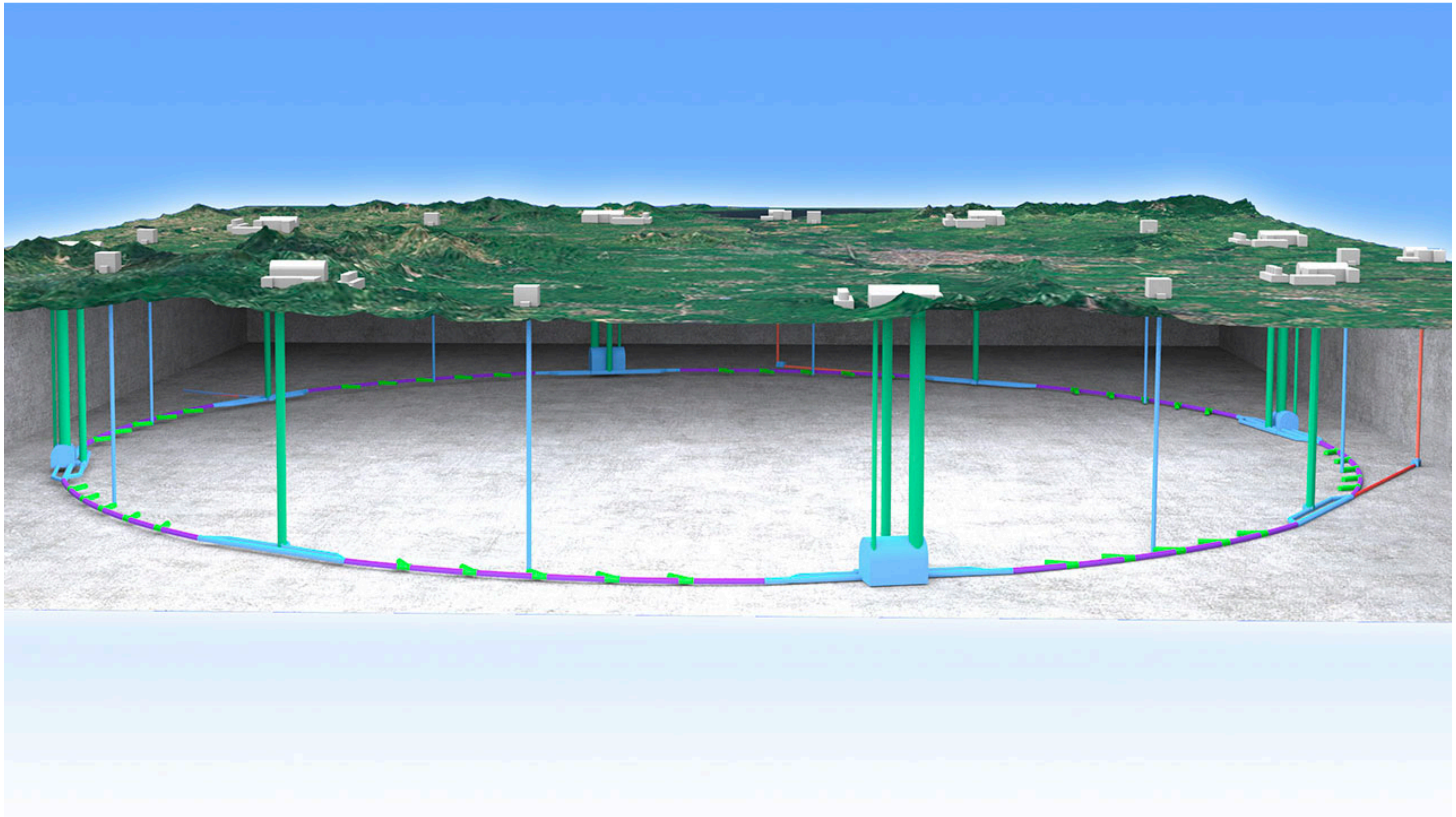


- Higgs could be the key of major particle physics open problems
- Use the Higgs boson as a new tool for discovery
  (Particle Physics Project Prioritization Panel (P5) Strategic Planning 2019)
- Higgs factory is the way to go!

G.P. Salam, L.T. Wang, G. Zanderighi, Nature Perspectives 2022

CEPC and its precision approach to new territories

- A Higgs factory running at 240 GeV with e^+e^- collision
- Later it has added Z, WW, $\bar{t}t$ runs to broadening the physics scope
- It is a multi-purpose precision machine



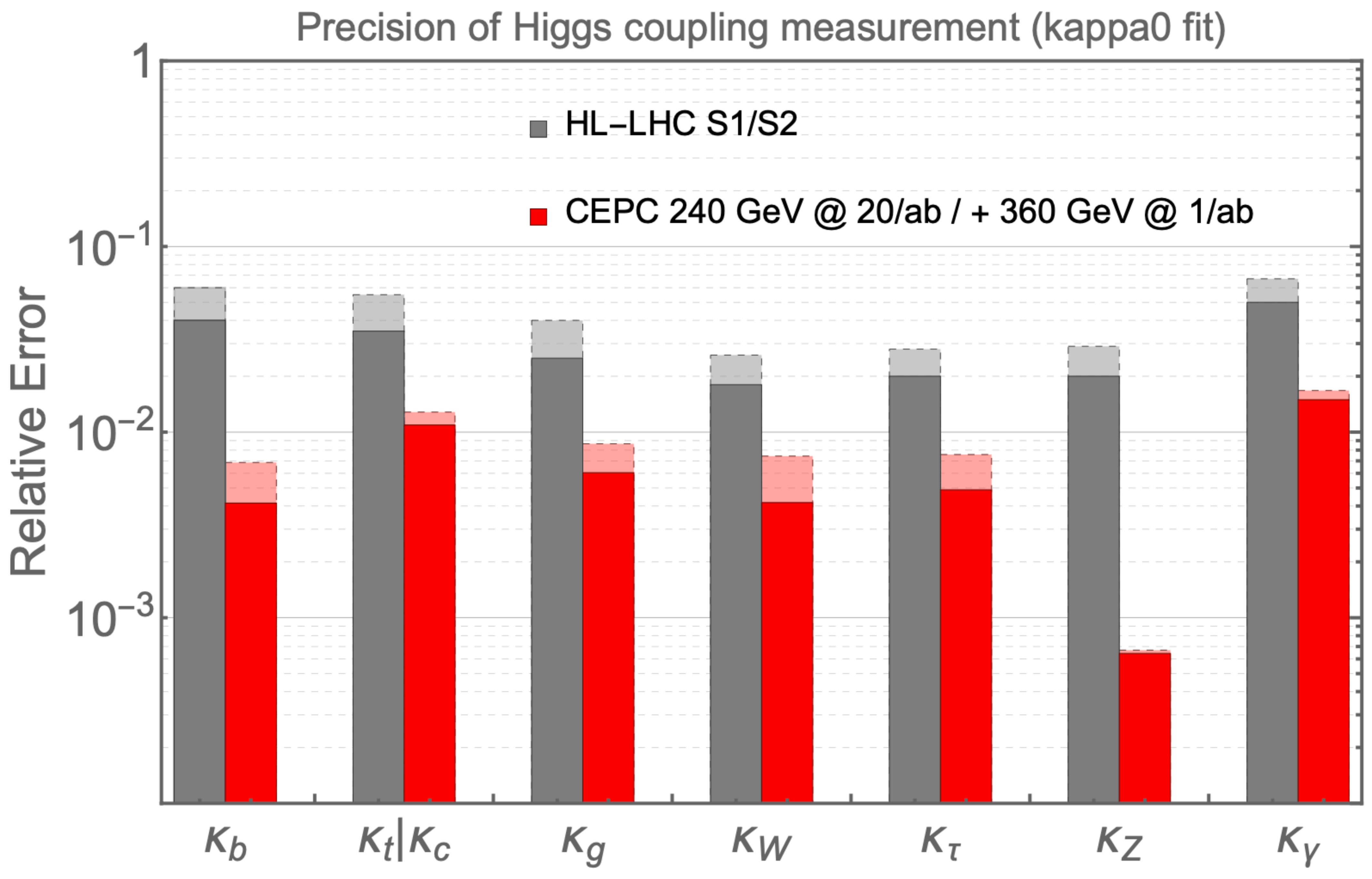
CEPC physics goal

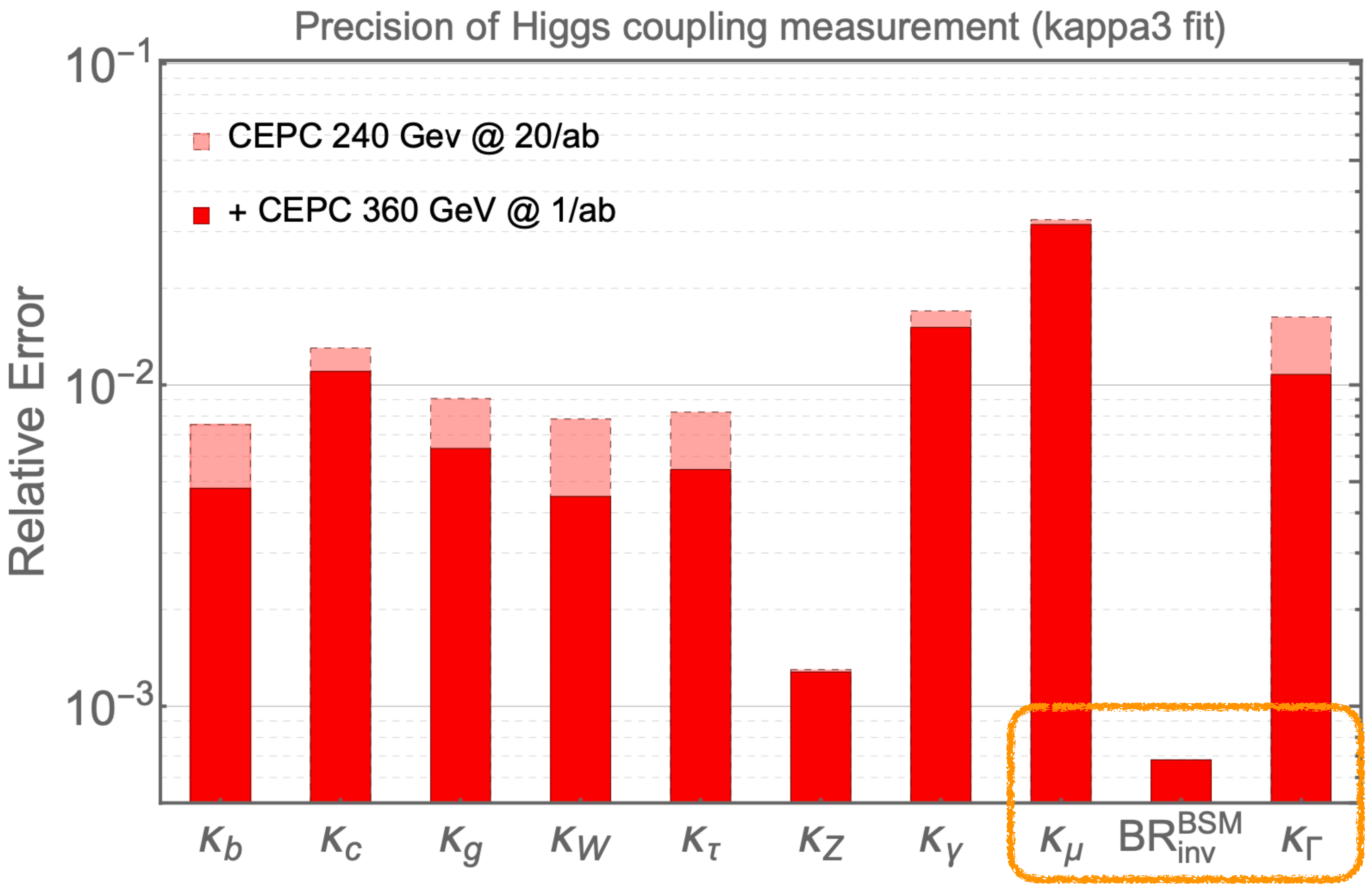
Operation mode			ZH	Z	W^+W^-	$t\bar{t}$
$\sqrt{s}$ [GeV]			240	91	160	360
Run time [years]			7	2	1	-
CDR (30 MW)		L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**3**	**32**	**10**	-
		$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	-
		Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7	-
Run Time [years]			10	2	1	5
TDR (Latest)	30 MW	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	0.5
		$\int L\,dt$ [ab^{-1}, 2 IPs]	13	60	4.2	0.65
		Event yields [2 IPs]	2.6×10^6	2.5×10^{12}	1.3×10^8	4×10^5
	50 MW	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**8.3**	**192**	**26.7**	**0.8**
		$\int L\,dt$ [ab^{-1}, 2 IPs]	21.6	100	6.9	1.0
		Event yields [2 IPs]	4.3×10^6	4.1×10^{12}	2.1×10^8	6×10^5

- Precision measurement of Higgs boson (width, couplings, mass, decay channels…)
- Precision test on SM for electroweak, flavor, and QCD physics
- Exotics from H (4M), Z (4T), W (200M) and top (~1M) measurements
- Searching for BSM physics

The progress of electroweak studies at CEPC

- Precision Higgs coupling measurement
  - Reaching 0.1%-1% of precision
  - Muon coupling, invisible BR and total width measurements

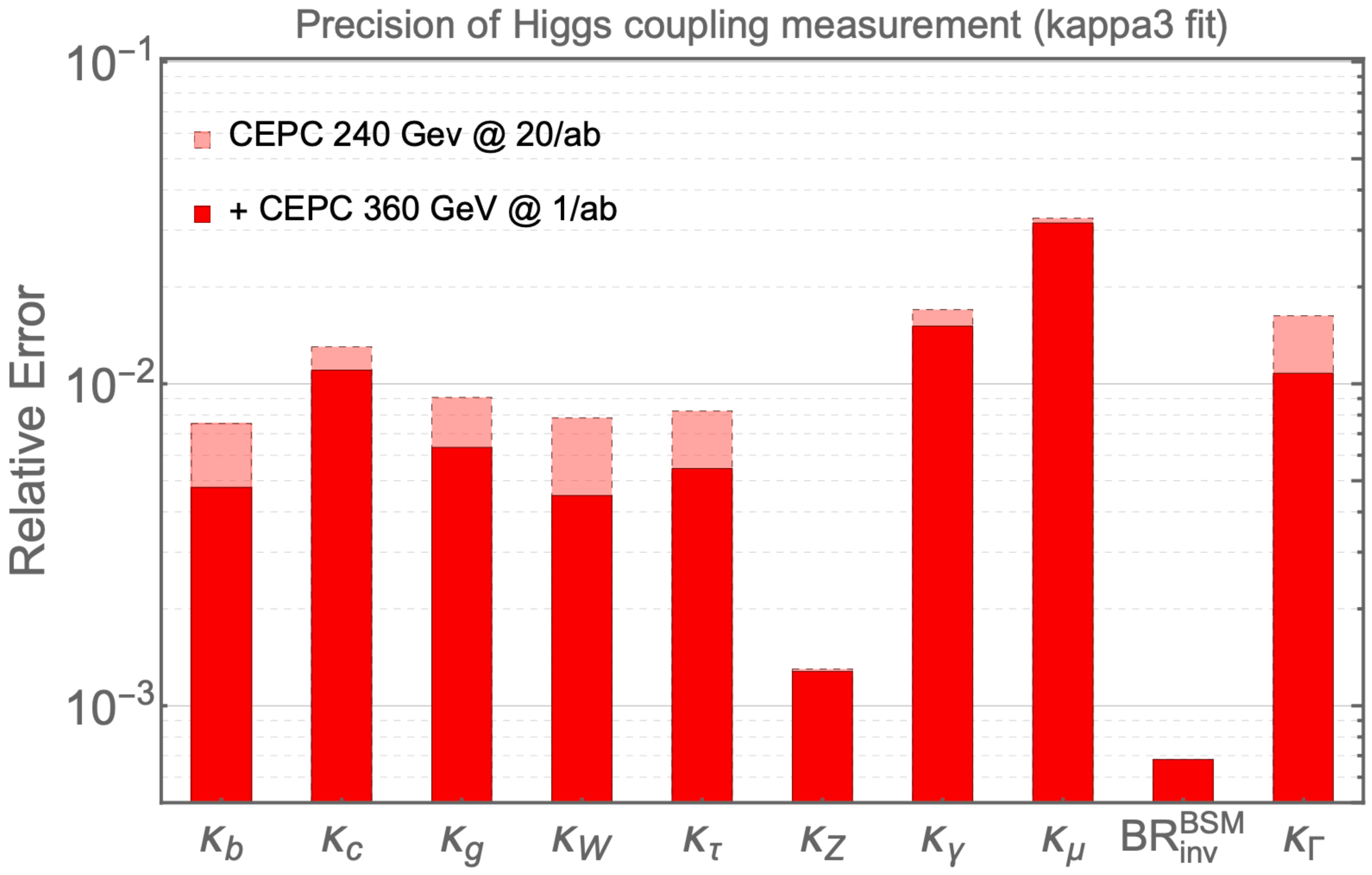




Physics potential of CEPC, 2205.08553 (snowmass 2021)

The progress of electroweak studies at CEPC

- Precision Higgs coupling measurement
  - Reaching 0.1%-1% of precision
  - Muon coupling, BRs and total width measurements



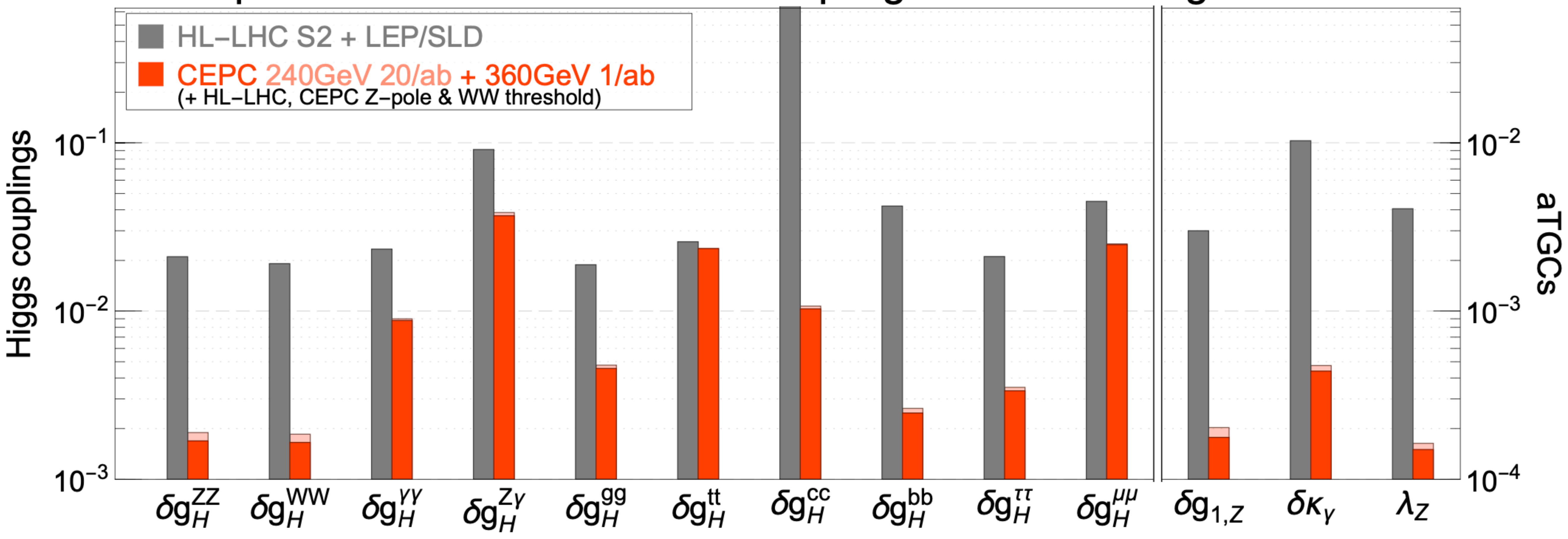
	$240\,\text{GeV},\ 20\ \text{ab}^{-1}$		$360\,\text{GeV},\ 1\ \text{ab}^{-1}$		
BR	ZH	**vvH**	ZH	**vvH**	**eeH**
inclusive	**0.26%**		**1.40%**	\	\
H→bb	**0.14%**	**1.59%**	**0.90%**	**1.10%**	**4.30%**
H→cc	**2.02%**		**8.80%**	**16%**	**20%**
H→gg	**0.81%**		**3.40%**	**4.50%**	**12%**
H→WW	**0.53%**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

Physics potential of CEPC, 2205.08553 (snowmass 2021)

The progress of electroweak studies at CEPC

- Precision electroweak measurement
  - Benefit from Z, WW runs
  - Reaching better precision by factor of 10-100
  - Improving Higgs effective coupling precision reach
  - Indirect constraints on BSM physics

precision reach on effective couplings from SMEFT global fit



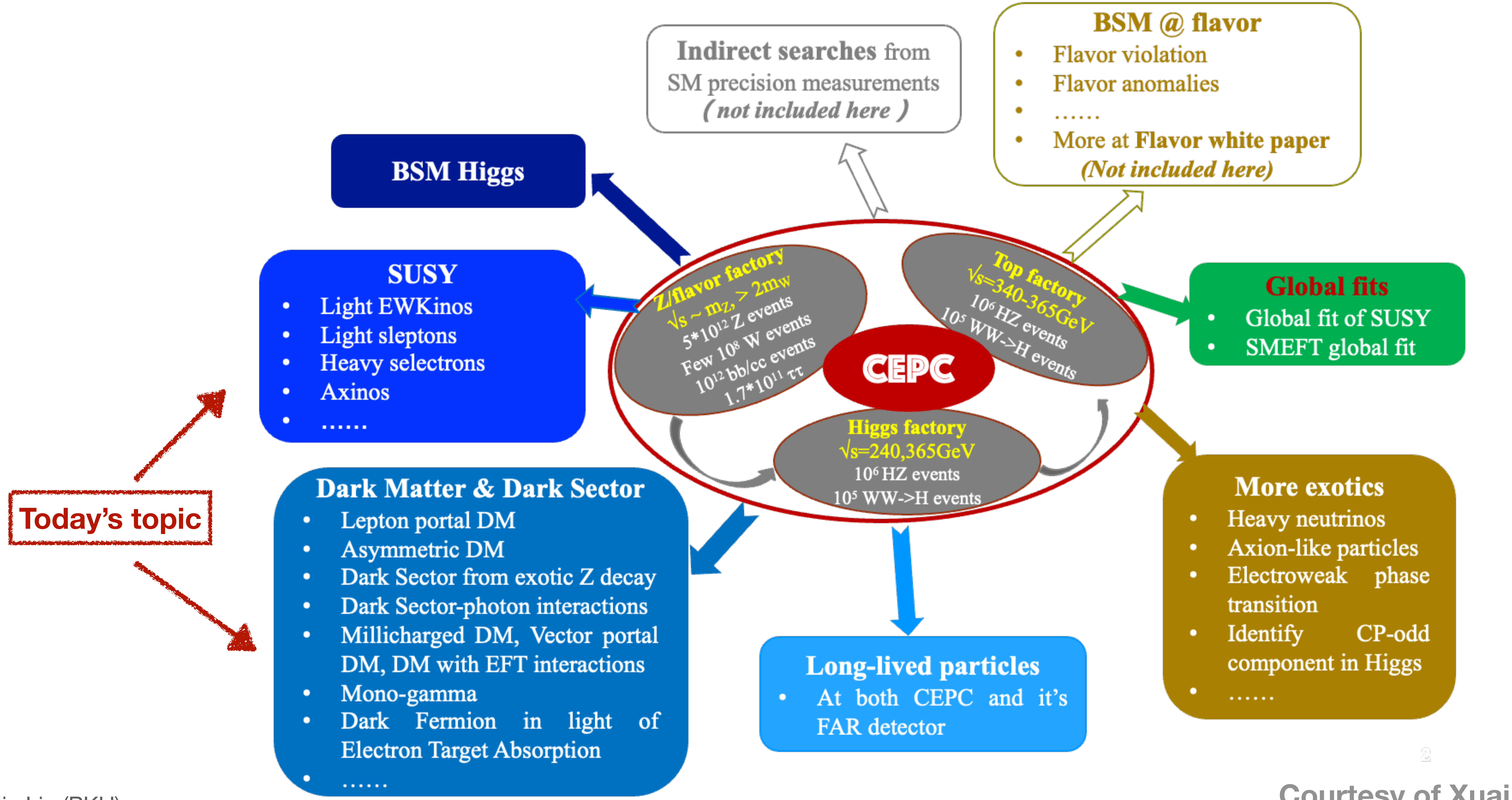
Physics potential of CEPC, 2205.08553 (snowmass 2021)

Observable	current precision	CEPC precision (Stat. Unc.)	CEPC runs	main systematic
Δm_Z	2.1 MeV [37–41]	0.1 MeV (0.005 MeV)	Z threshold	E_{beam}
$\Delta\Gamma_Z$	2.3 MeV [37–41]	0.025 MeV (0.005 MeV)	Z threshold	E_{beam}
Δm_W	9 MeV [42–46]	0.5 MeV (0.35 MeV)	WW threshold	E_{beam}
$\Delta\Gamma_W$	49 MeV [46–49]	2.0 MeV (1.8 MeV)	WW threshold	E_{beam}
Δm_t	0.76 GeV [50]	$\mathcal{O}(10)$ MeV[a]	$t\bar{t}$ threshold	
ΔA_e	4.9×10^{-3} [37, 51–55]	1.5×10^{-5} (1.5×10^{-5})	Z pole ($Z\to\tau\tau$)	Stat. Unc.
ΔA_μ	0.015 [37, 53]	3.5×10^{-5} (3.0×10^{-5})	Z pole ($Z\to\mu\mu$)	point-to-point Unc.
ΔA_τ	4.3×10^{-3} [37, 51–55]	7.0×10^{-5} (1.2×10^{-5})	Z pole ($Z\to\tau\tau$)	tau decay model
ΔA_b	0.02 [37, 56]	20×10^{-5} (3×10^{-5})	Z pole	QCD effects
ΔA_c	0.027 [37, 56]	30×10^{-5} (6×10^{-5})	Z pole	QCD effects
$\Delta\sigma_{had}$	37 pb [37–41]	2 pb (0.05 pb)	Z pole	lumiosity
δR_b^0	0.003 [37, 57–61]	0.0002 (5×10^{-6})	Z pole	gluon splitting
δR_c^0	0.017 [37, 57, 62–65]	0.001 (2×10^{-5})	Z pole	gluon splitting
δR_e^0	0.0012 [37–41]	2×10^{-4} (3×10^{-6})	Z pole	E_{beam} and t channel
δR_μ^0	0.002 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δR_τ^0	0.017 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δN_ν	0.0025 [37, 66]	2×10^{-4} (3×10^{-5})	ZH run ($\nu\nu\gamma$)	Calo energy scale

Outline

- CEPC and Electroweak Physics
- CEPC and Beyond the Standard Model Physics Searches
- Summary

CEPC BSM Physics Program



Courtesy of Xuai Zhuang

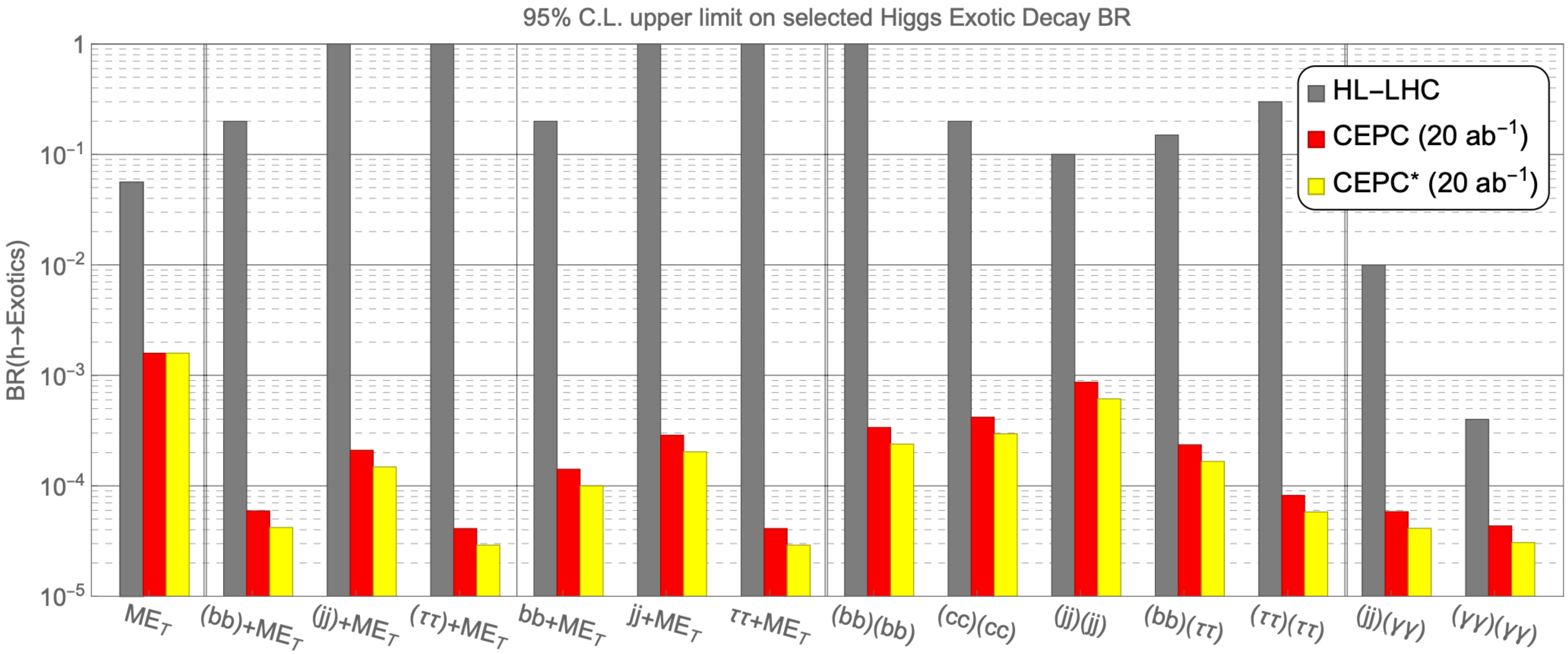
BSM inputs and status

- BSM Higgs (1709.06103; 1808.02037; 1912.01431; 2008.05492 ; 2011.04540)
- SUSY Searches
  - Direct SUSY Searches (CPC46(2022)013106; 2101.12131; 2203.10580;2202.11011, 2211.08132)
  - Indirect search of SUSY (2010.09782)
- Dark Matter and Dark Sector searches
  - Lepton portal DM (JHEP 06 (2021) 149)
  - Asymmetric DM (PRD 104(2021)055008)
  - Dark Sector from exotic Z decay (1712.07237)
  - DM (Millicharged DM, Vector portal DM, DM with EFT interactions): 1903.1211
  - Mono-gamma (2205.05560), Dark Sector-photon interactions (2208.08142)
  - Dark Fermion in light of Electron Target Absorption (2306.00657)
- Long-lived particles (1904.10661, 1911.06576, 2201.08960)
- More exotics:
  - Heavy neutrinos (2102.12826, 2201.05831);
  - Axion-like particles (2103.05218, 2204.04702, 2210.09335, J. Phys. G)
  - Electroweak phase transition (1911.10210,1911.10206,2011.04540, 2204.05085)
  - Identify CP-odd component in Higgs study (2212.05390)
  - ……
- Global fits:
  - Global fit of SUSY (2203.04828, 2203.07883)
  - SMEFT global fit (2206.08326)

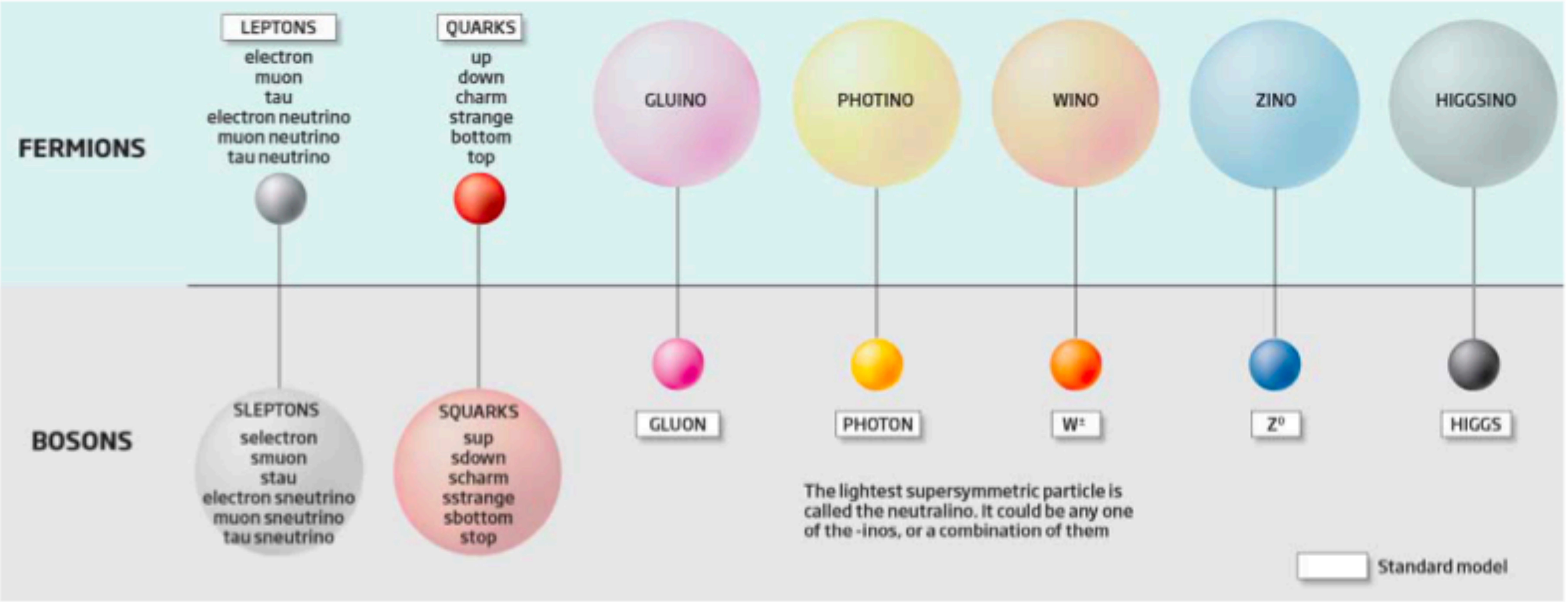
BSM Higgs studies

- CEPC can provide precision test on Higgs exotic decay with production of 4 million Higgs

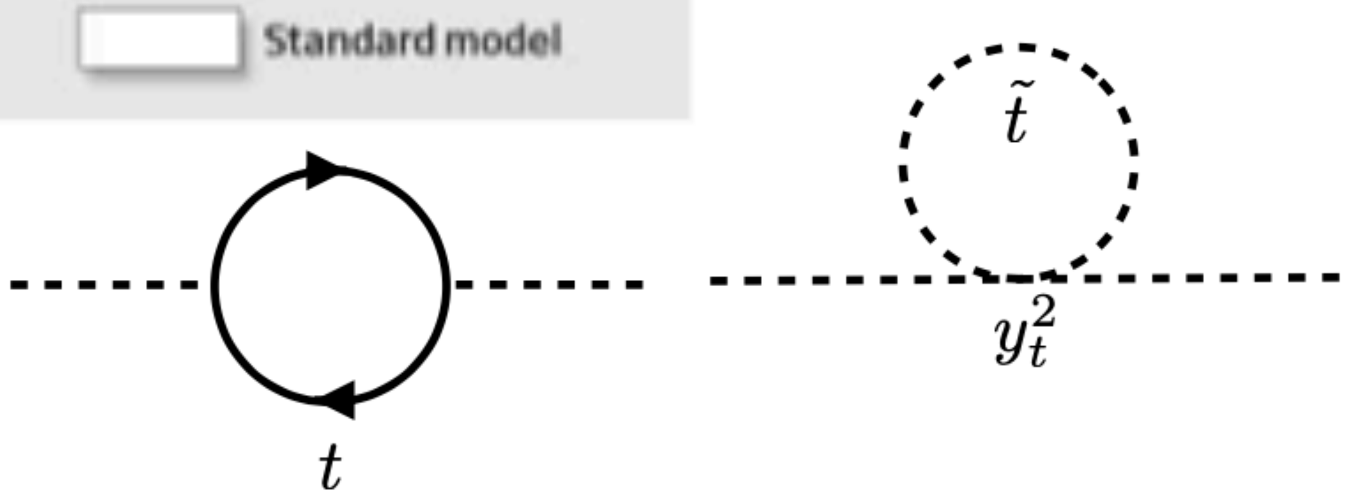
Physics potential of CEPC, 2205.08553 (snowmass 2021)



The motivation for SUSY



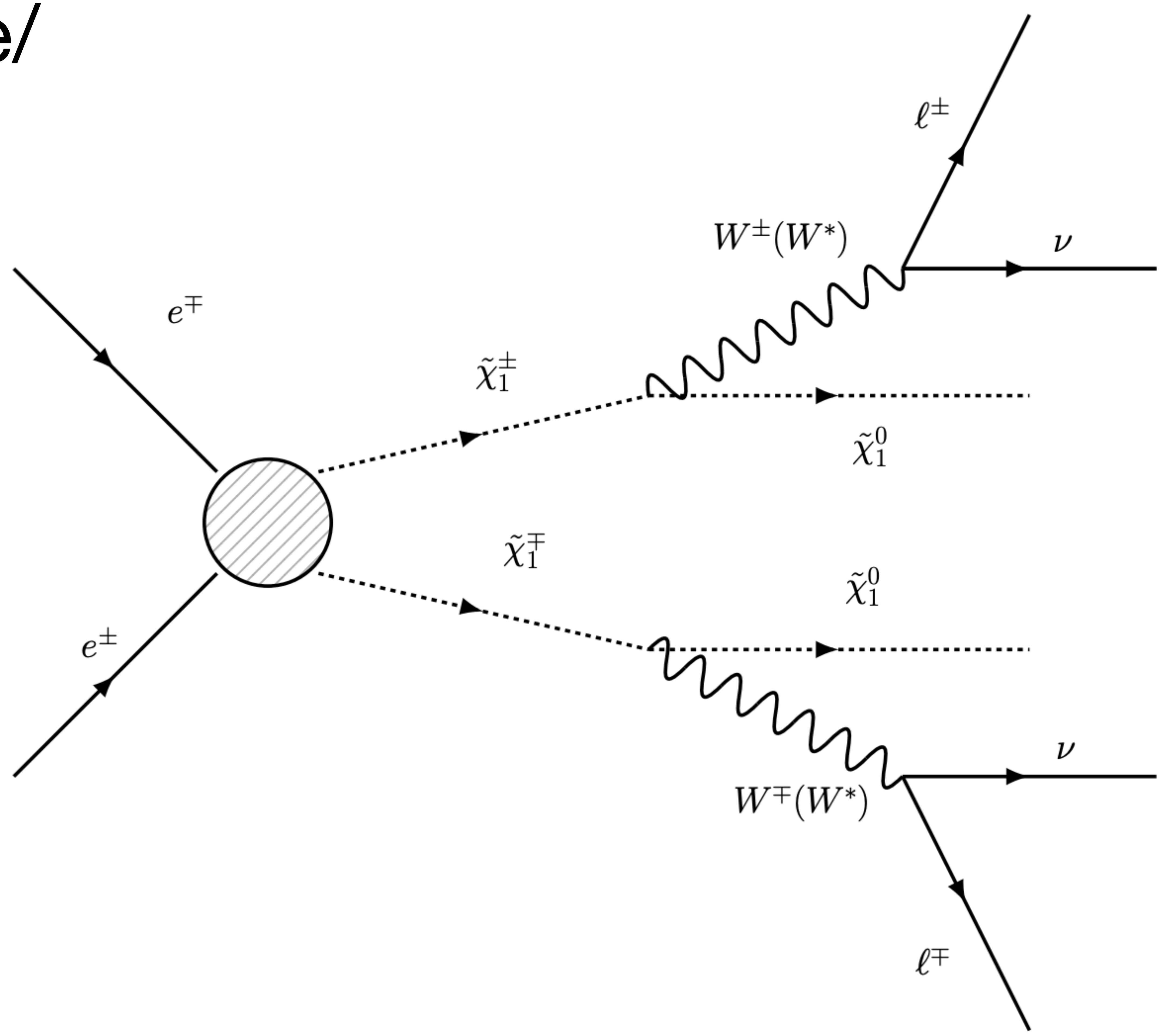
Credit: New Scientist



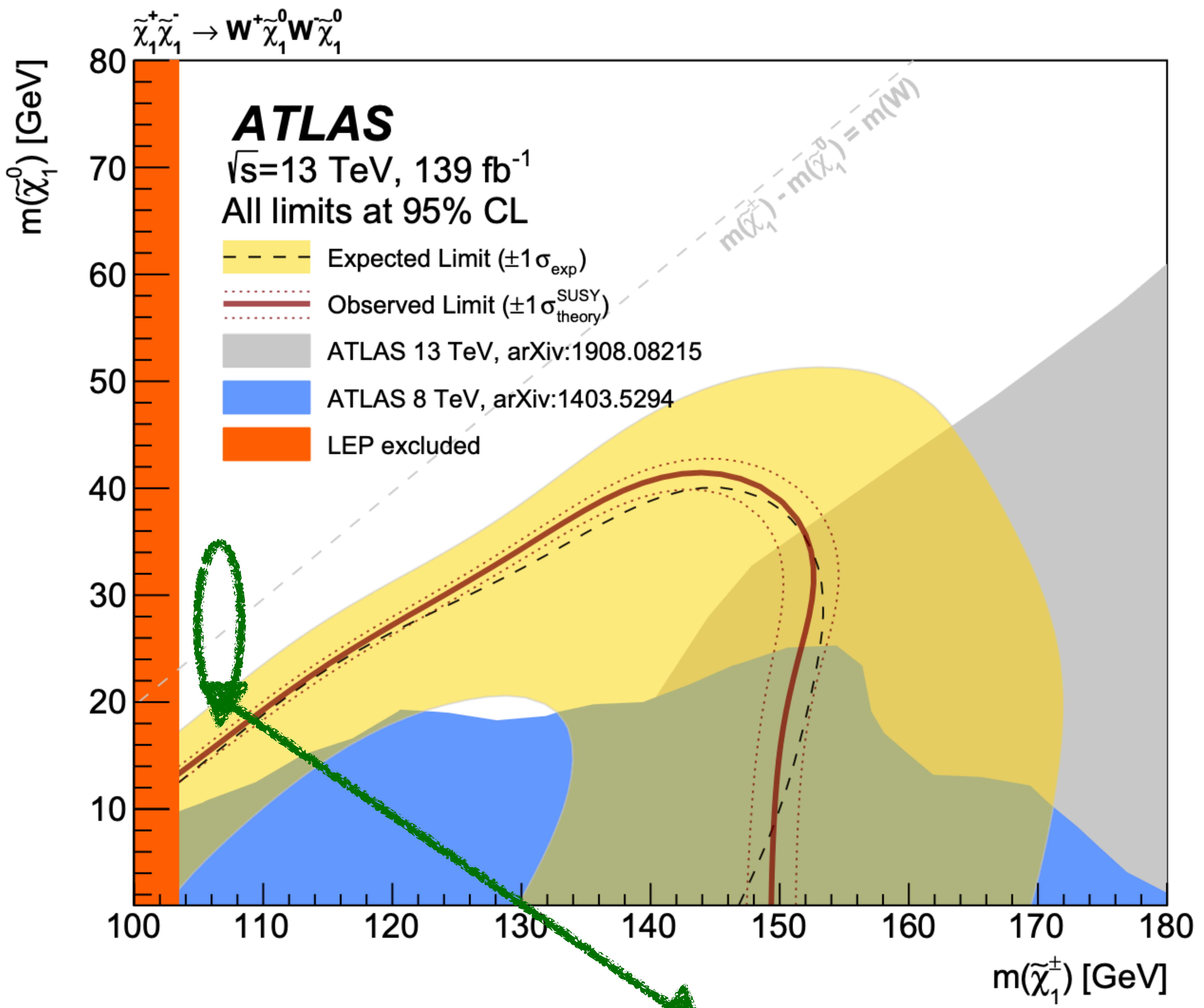
- Stabilize the weak scale from Planck scale via a new space-time symmetry
- MSSM leads to unification of gauge couplings
- EW breaking is induced radiatively
- Neutralino as an excellent candidate for cold dark matter

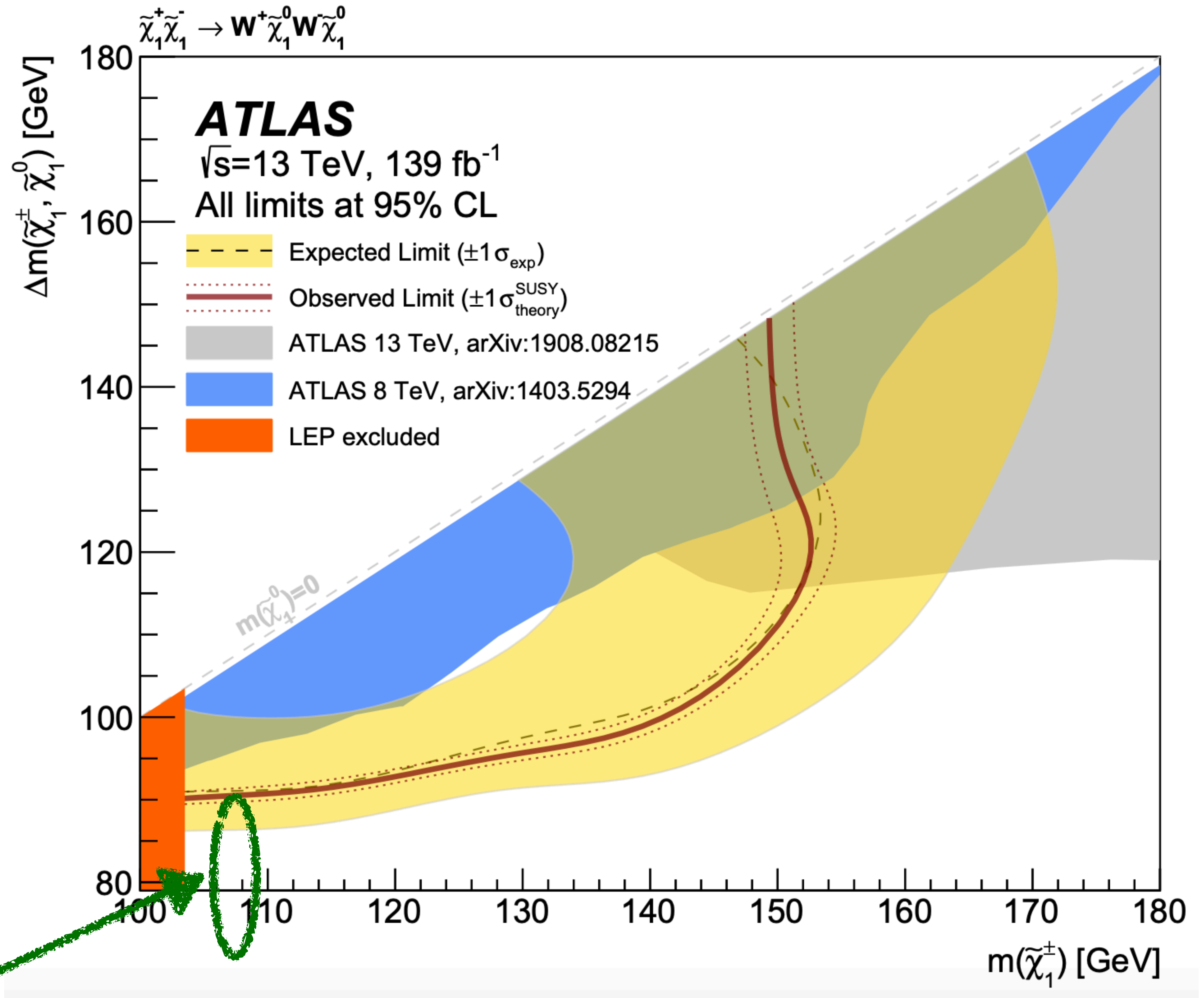
SUSY at future e^+e^- collider

- Why future e^+e^- collider CEPC/FCC-ee/ILC?
- Could be complementary with LHC:
  - Soft energy region
  - Lower mass region
- Study light EWKinos, sleptons
- Indirect searches through precision measurements



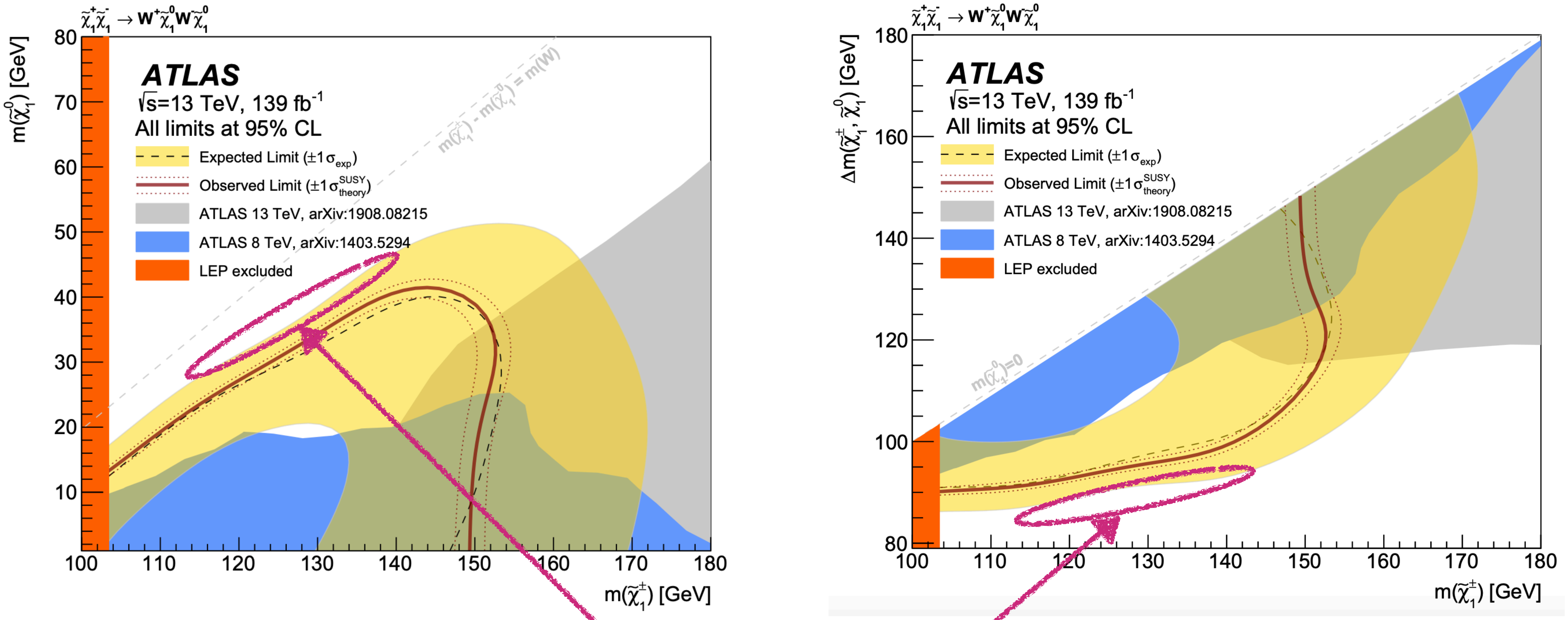
Comparing with recent LHC results: where to go





- Improving low mass boundary: naively up to $\sqrt{s}/2$, but can be better than that
- Improving the soft lepton region

Comparing with recent LHC results: where to go



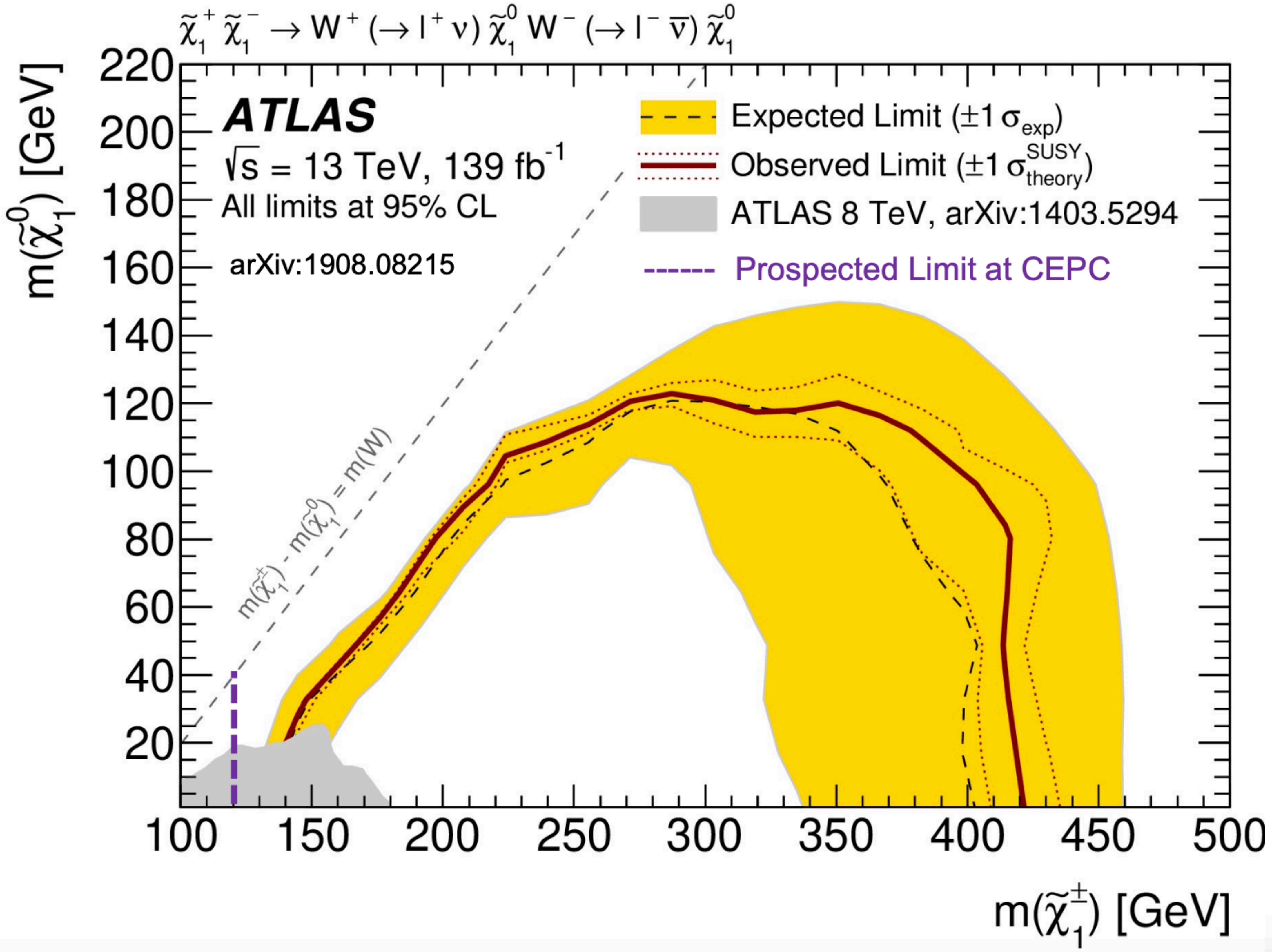
- Improving low mass boundary
- Improving the soft lepton region

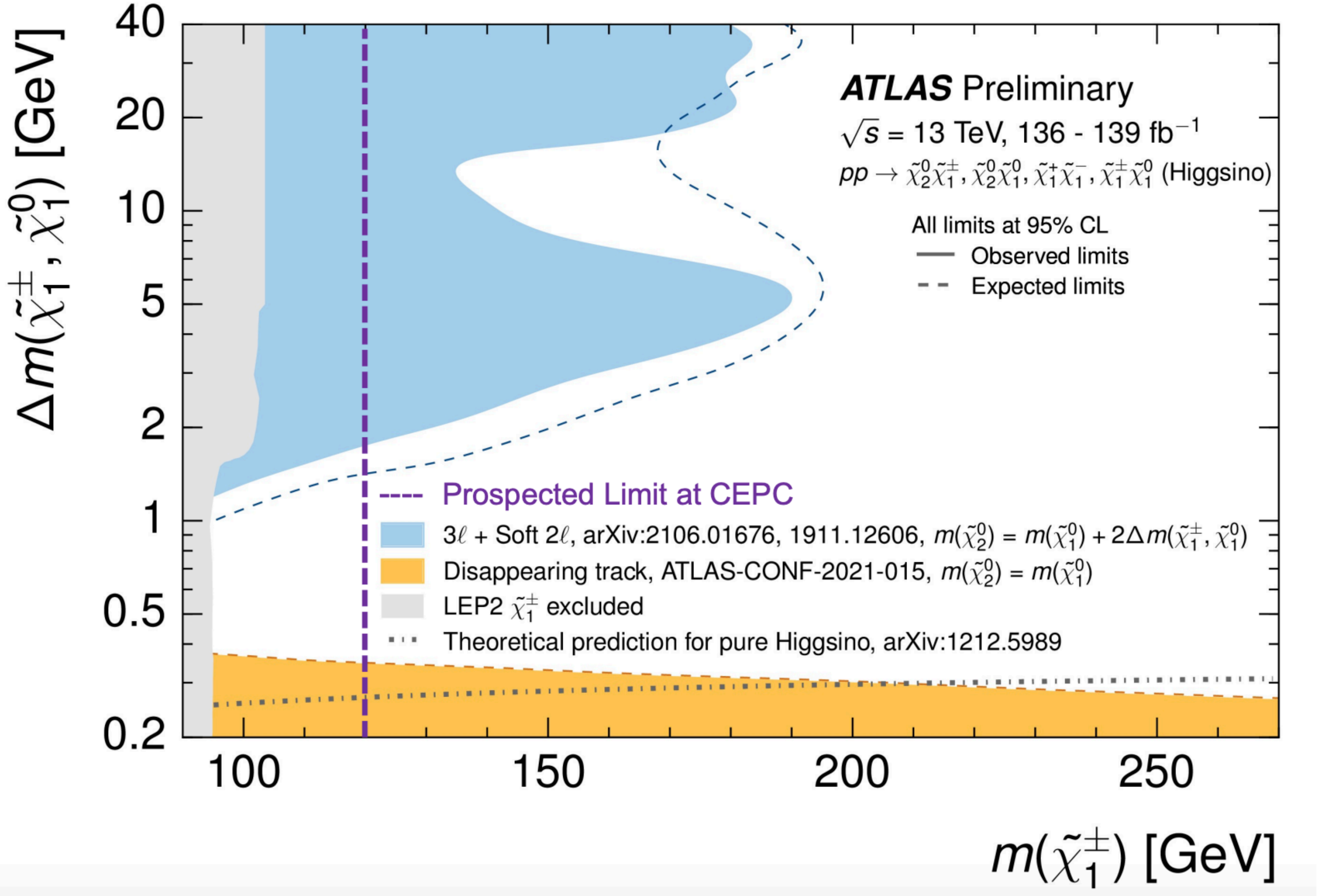
Dilepton + Missing energy signal region

- Focus on opposite-sign dimuon
- Large recoil mass ~ Large missing energy
- Up to mass = $\sqrt{s}/2$

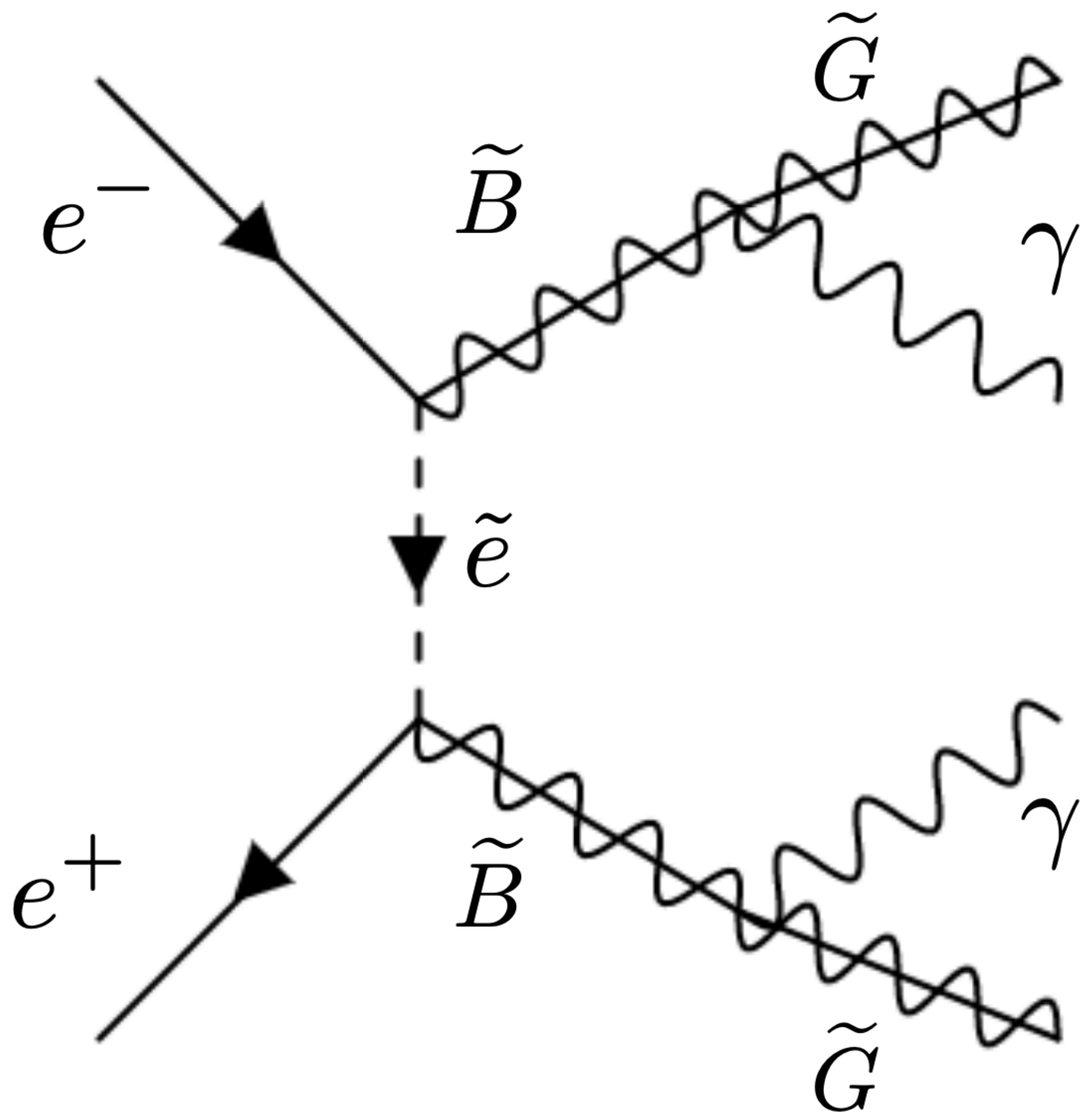
Xuai Zhuang
et al, 2105.06135 (CPC)

Signal Region
== 2 muons (OS)
$E_{\mu^\pm} > 10$ GeV
$0.4 < \Delta R(\mu^+, \mu^-) < 1.6$
$P_T^{\mu^\pm} > 30$ GeV
$M_{recoil} > 130$ GeV



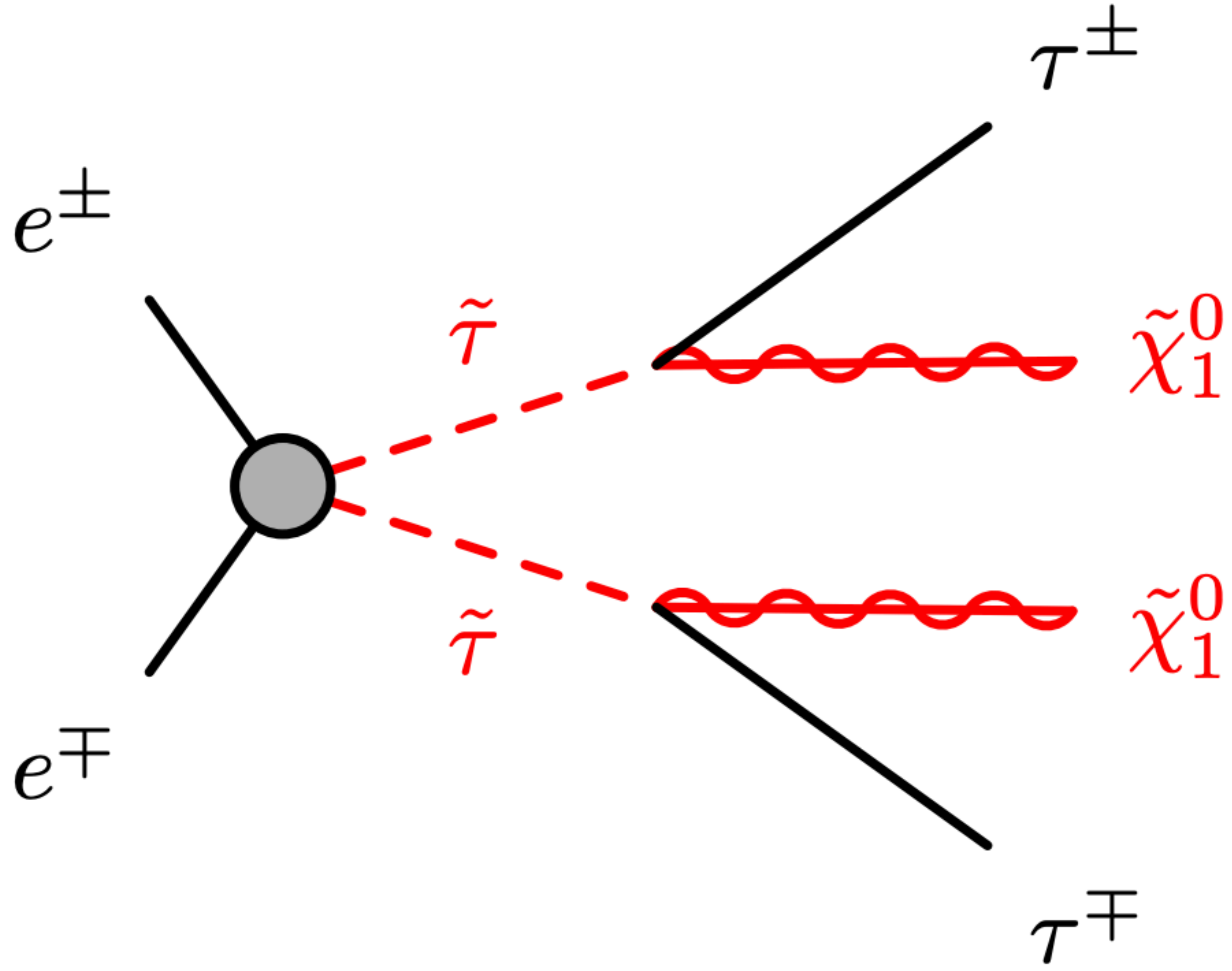


Other possible complementary searches



- Low mass Bino decay ~ O(100) GeV: $\tilde{B} \to \tilde{G} + \gamma$

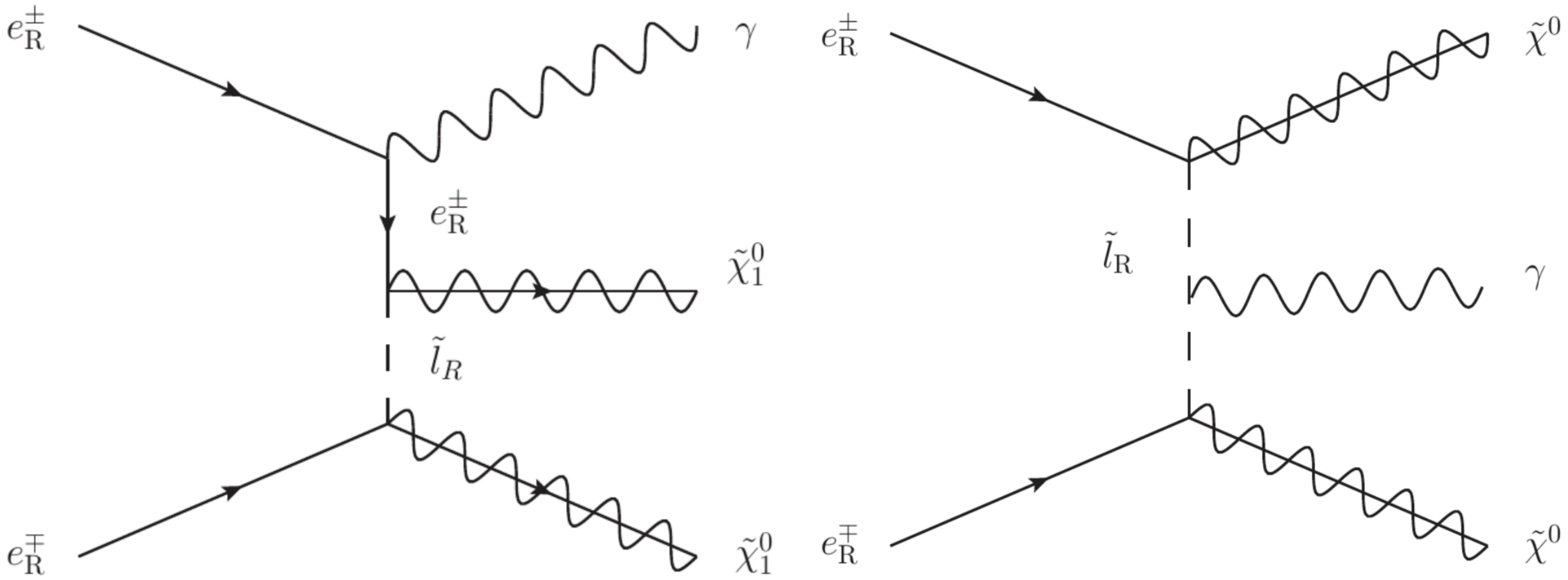
Junmou Chen et al, 2101.12131 (PRD)



- Low mass stau/smuon ~ O(100) GeV: $\tilde{\tau} \to \tilde{\chi}_1^0 + \tau$
- Cleaner background for tau final states comparing with LHC

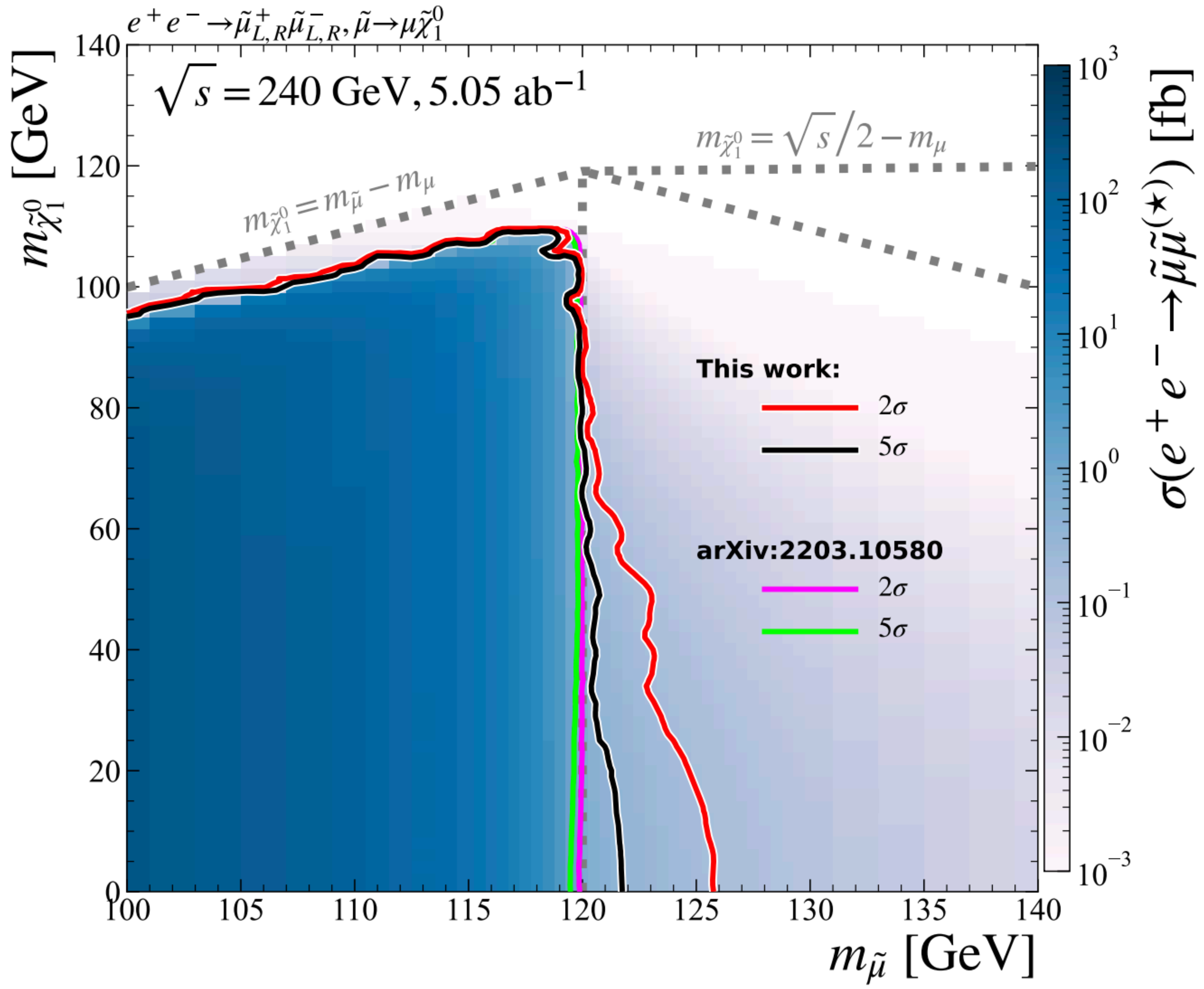
Xuai Zhuang et al, 2203.10580

Other possible complementary searches



- Mono-photon search: $\gamma\tilde{\chi}^1_0\tilde{\chi}^1_0$
- Cleaner background comparing with LHC

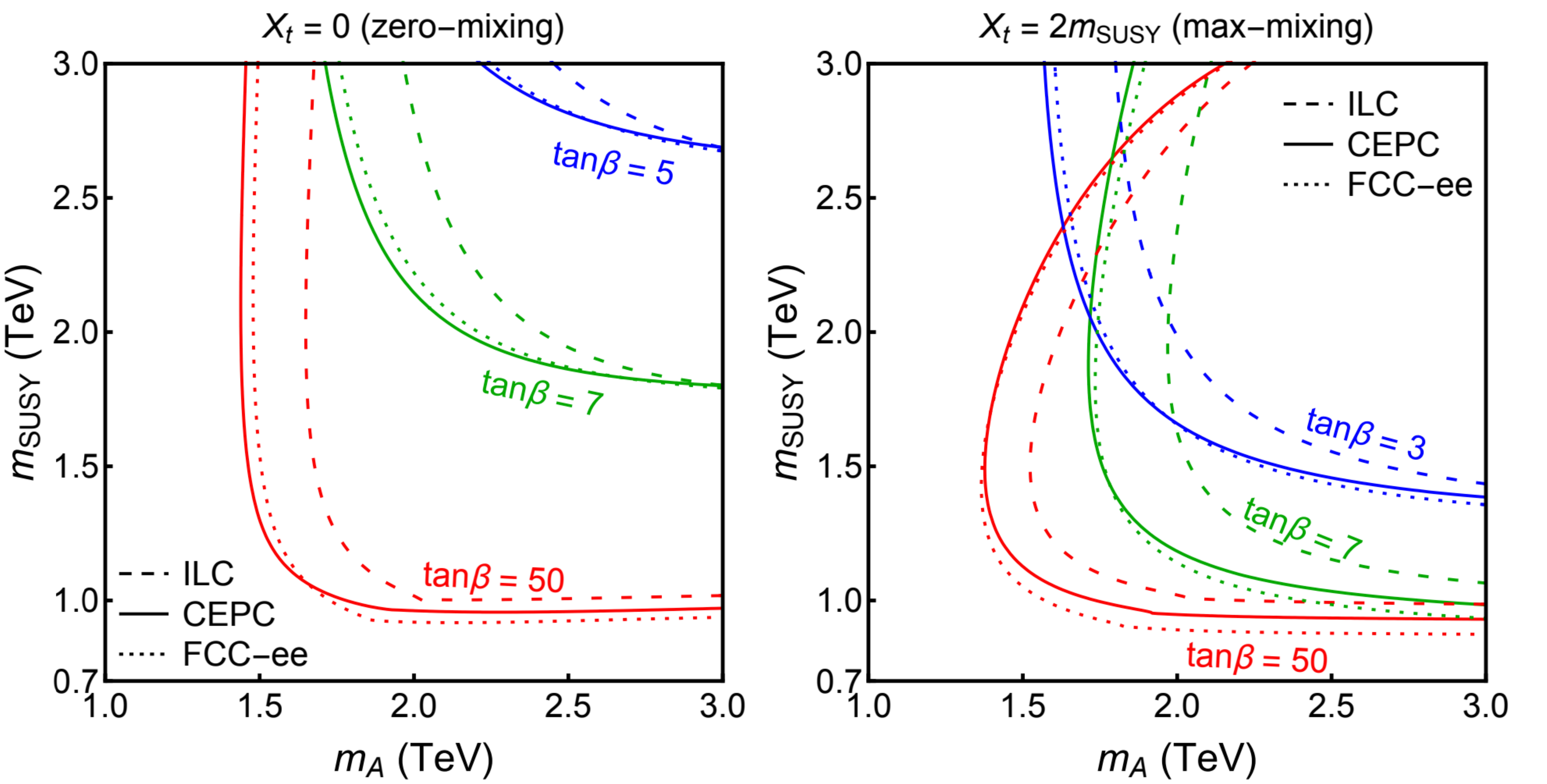
Waqas Ahmed et al, 2202.11011 (PLB)



- Trying to cover higher slepton mass as best as one could

Jinmin Yang et al, 2211.08132

Other possible complementary searches



- Probing SUSY parameters without producing SUSY particles
- Indirect search at Higgs factories through Higgs precision measurements

Honglei Li et al, 2010.09782 (CPC)

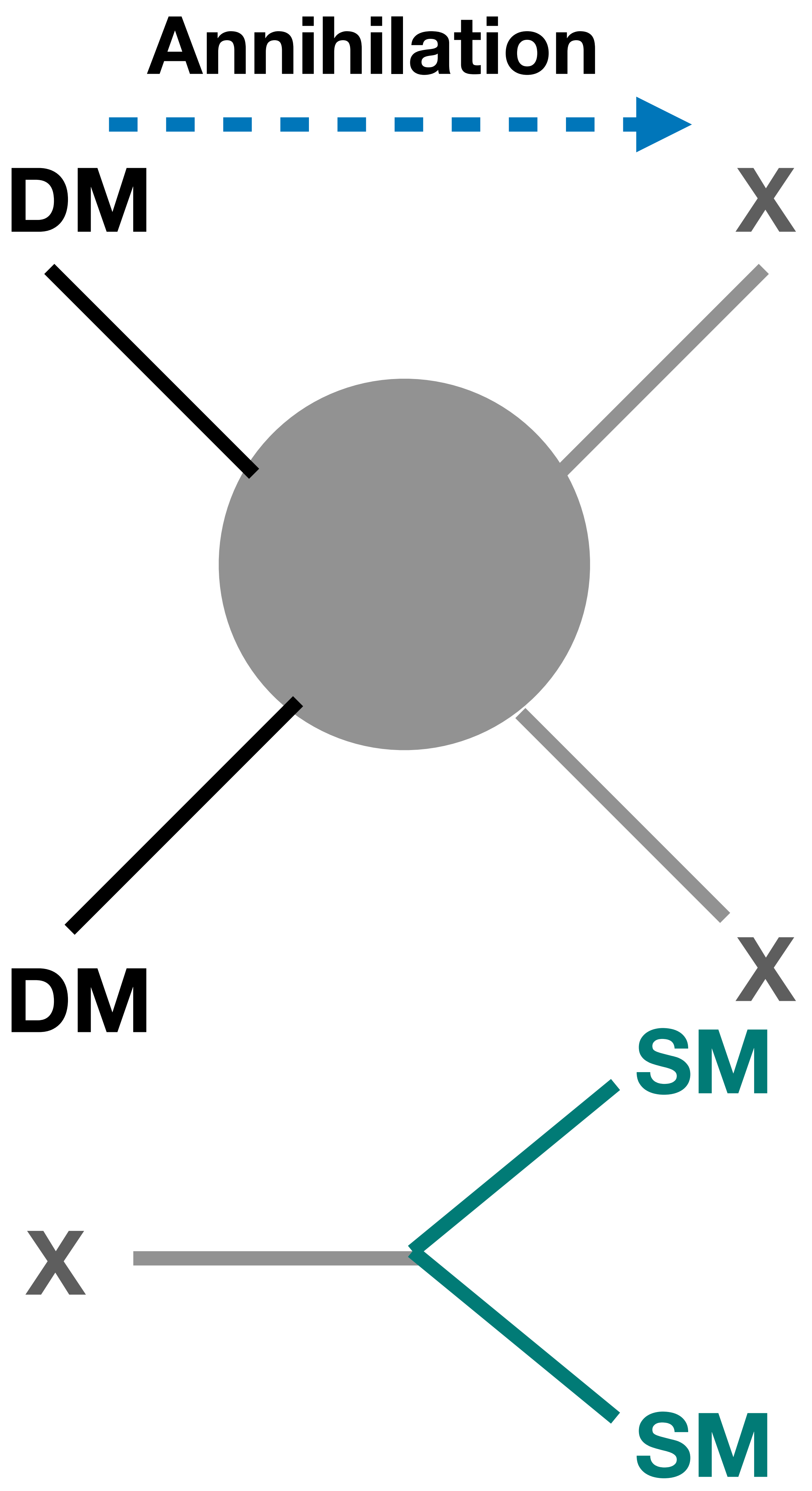
Other possible complementary searches

- Probing SUSY parameters without producing SUSY particles
- Indirect search at Higgs factories through Higgs precision measurements

P. Athron, W. Su, L. Wu, J.M. Yang et al, 2203.04828

Outline

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



Dark mediator X
with small coupling to SM

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

	DM	SM charge	Z_2
ψ	Yes	No	-1
ϕ	No	Yes	-1
$f_{\rm SM}$	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

Searching lepton portal dark sector at CEPC

$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}i\partial\!\!\!/\chi - \frac{1}{2}m_\chi\bar{\chi}\chi + y_\ell\left(\bar{\chi}_L S^\dagger \ell_R + \text{h.c.}\right),$$
$$\mathcal{L}_S = (D^\mu S)^\dagger D_\mu S - V(H,S),$$
$$V(H,S) = \mu_H^2|H|^2 + \mu_S^2|S|^2 + \lambda_H|H|^4 + \lambda_S|S|^4 + 2\lambda_{HS}|H|^2|S|^2$$

- DM (χ) couples to SM via the lepton portal
- Mediated by charged particle (S), similar to slepton
  - DM thermal relic requirements

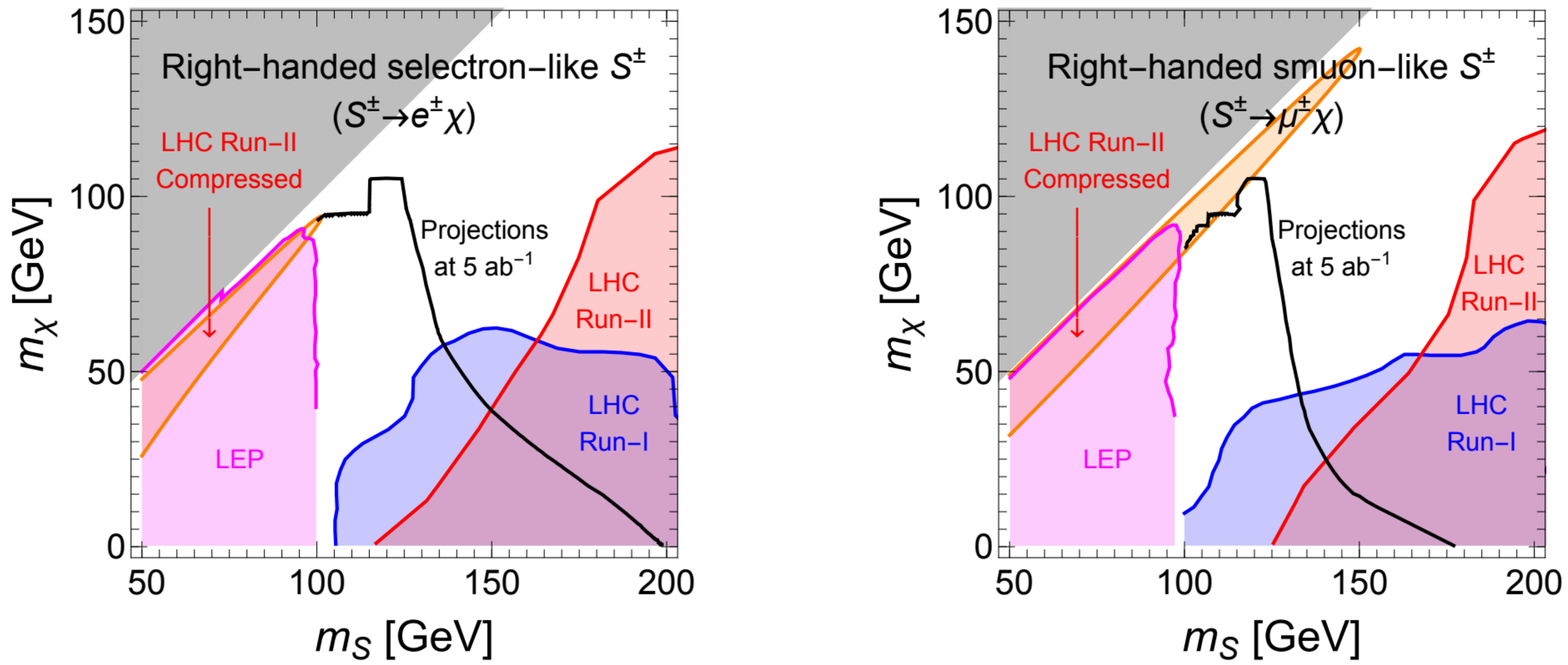
    $\chi\chi \to \ell^+\ell^-$, p-wave annihilation, less constrained by indirect detection
  - Lepton collider production of dark sector particle S
  - Higgs precision test on the model
  - Gravitational Wave signal and its complementary with ee collider

Dark sector particle production in 3-body final state

- 3-body final state: $e^+e^- \to S^+S^{-*} \to S^+\ell^-\chi \to (\ell^+\chi)\ell^-\chi$

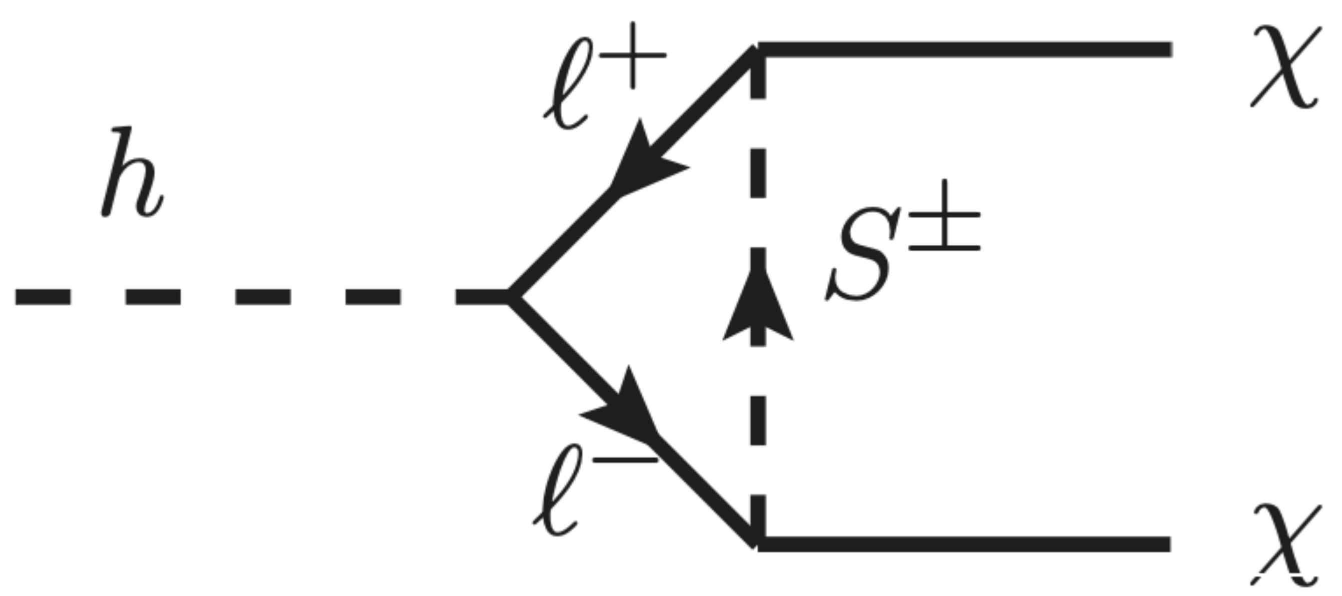
JL, XP Wang, KP Xie, 2104.06421 (JHEP)

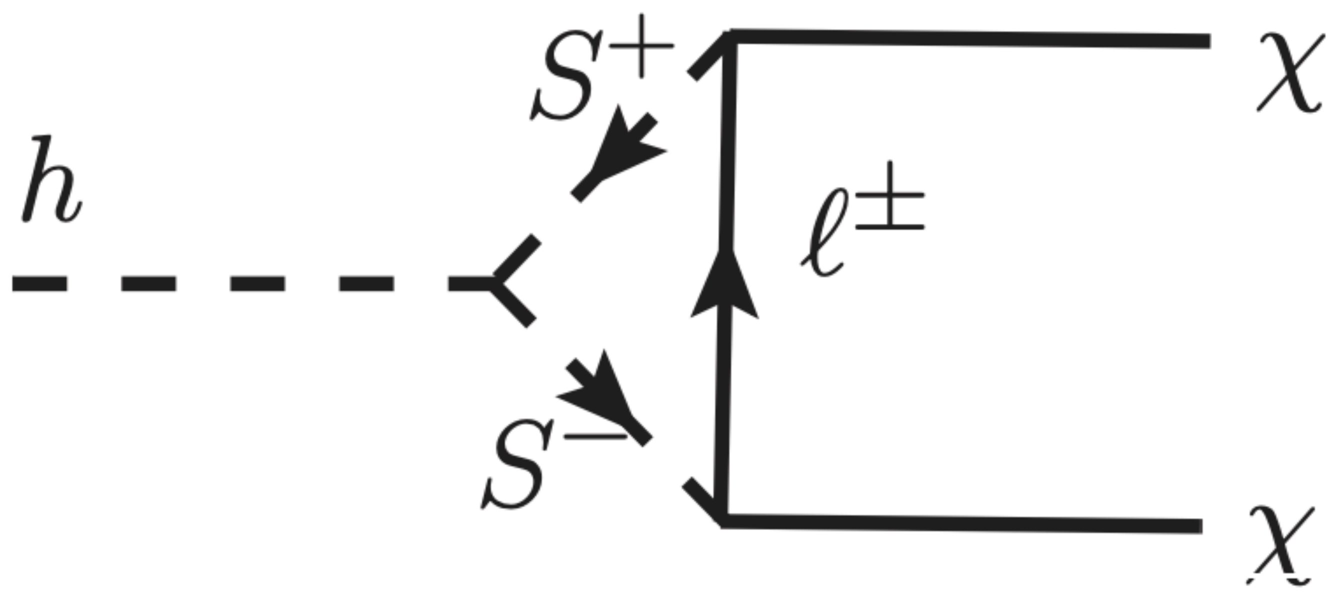
- Reaching higher mass: $m_S \gtrsim \sqrt{s}/2 = 120\ \mathrm{GeV}$



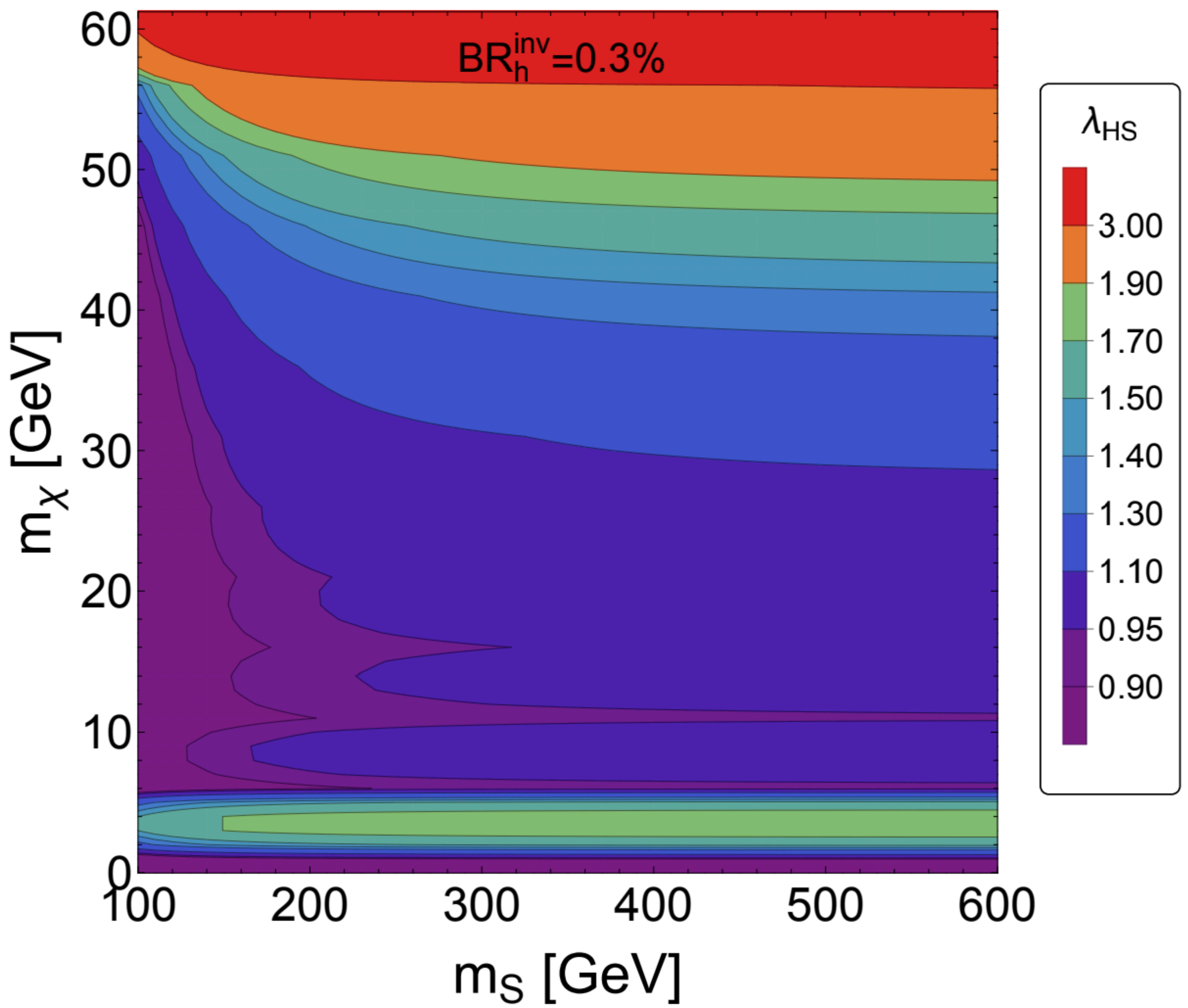
Exotic Higgs decay constraints

- Invisible Higgs decay at 1-loop





- The Higgs-dark sector coupling is constrained

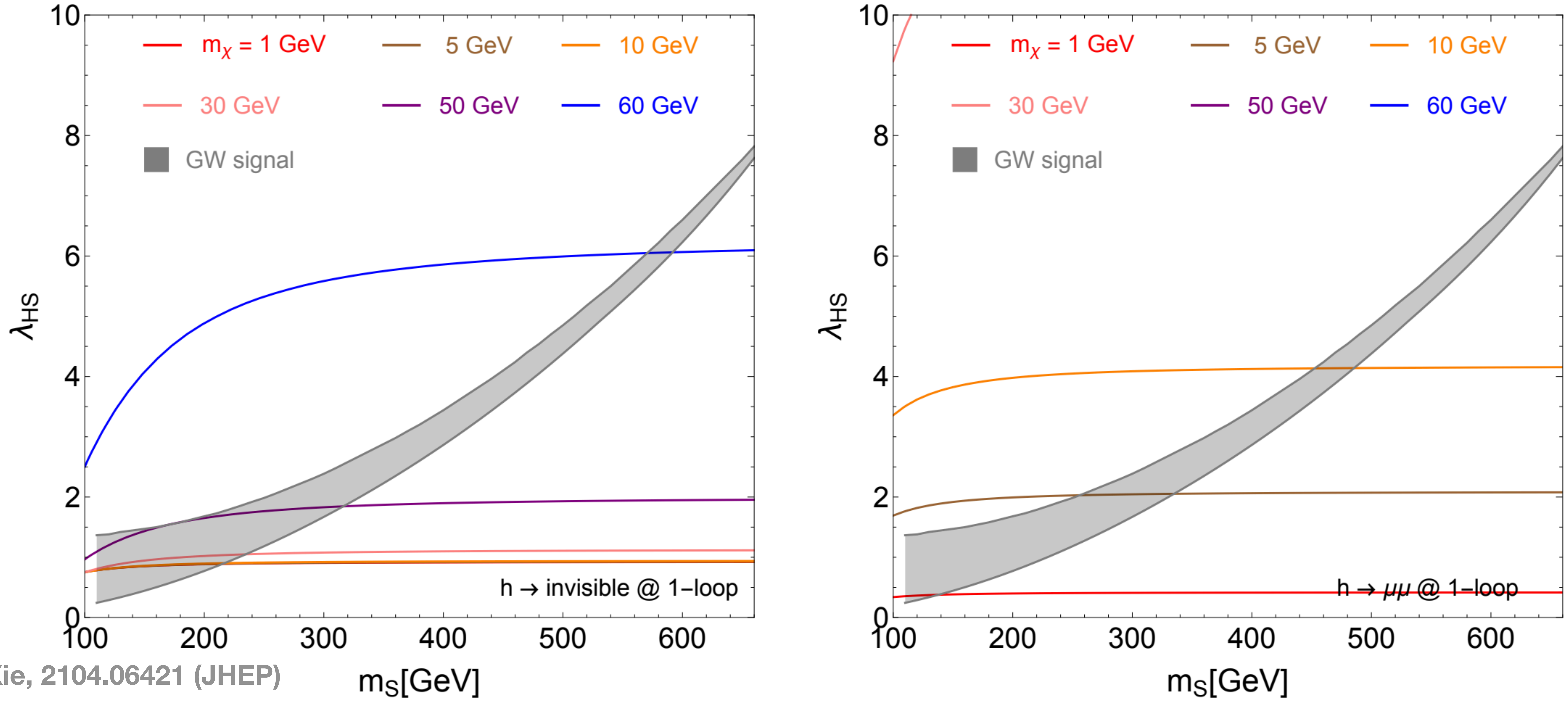


JL, XP Wang, KP Xie, 2104.06421 (JHEP)

Future ee collider search and GW complementarity

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

$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi} i \partial\!\!\!/ \chi - \frac{1}{2} m_\chi \bar{\chi}\chi + y_\ell \left(\bar{\chi}_L S^\dagger \ell_R + \text{h.c.} \right),$$
$$\mathcal{L}_S = \left(D^\mu S\right)^\dagger D_\mu S - V(H,S),$$
$$V(H,S) = \mu_H^2 |H|^2 + \mu_S^2 |S|^2 + \lambda_H |H|^4 + \lambda_S |S|^4 + 2\lambda_{HS} |H|^2 |S|^2$$



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

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 → N_1/N_2

Dark mediators/ Fermion-portal type → Φ, χ

Dark quark/ DM is dark baryon → q'

	$SU(3)'$	$SU(3)$	$U_Y(1)$	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

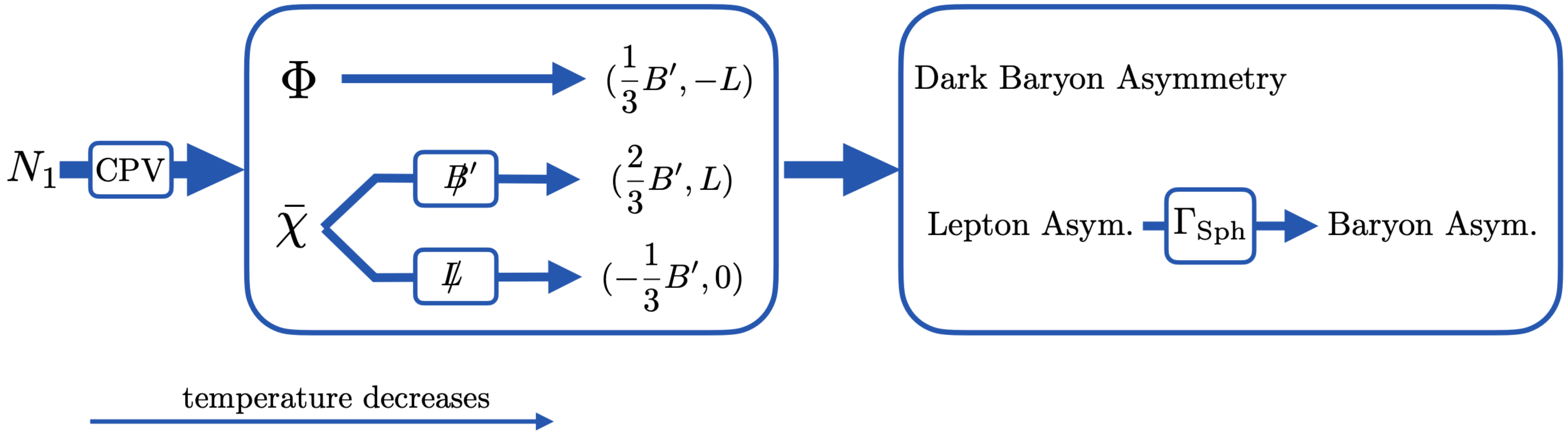
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{2}\sum_{i=1,2} M_{N_i}\overline{N}_i N_i^C - m_\Phi^2 \Phi^\dagger\Phi - m_\chi \bar{\chi}\chi - m_{q'}\bar{q}' q' + \mathcal{L}_{\rm kinetic}$$
$$- \sum_{i=1,2} \lambda_i \overline{N}_i \chi \Phi^\dagger - \kappa \Phi \bar{q}'_L l_R - \frac{1}{\Lambda_1^2}\left(\bar{q}'^C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

Dark matter and Baryon asymmetry

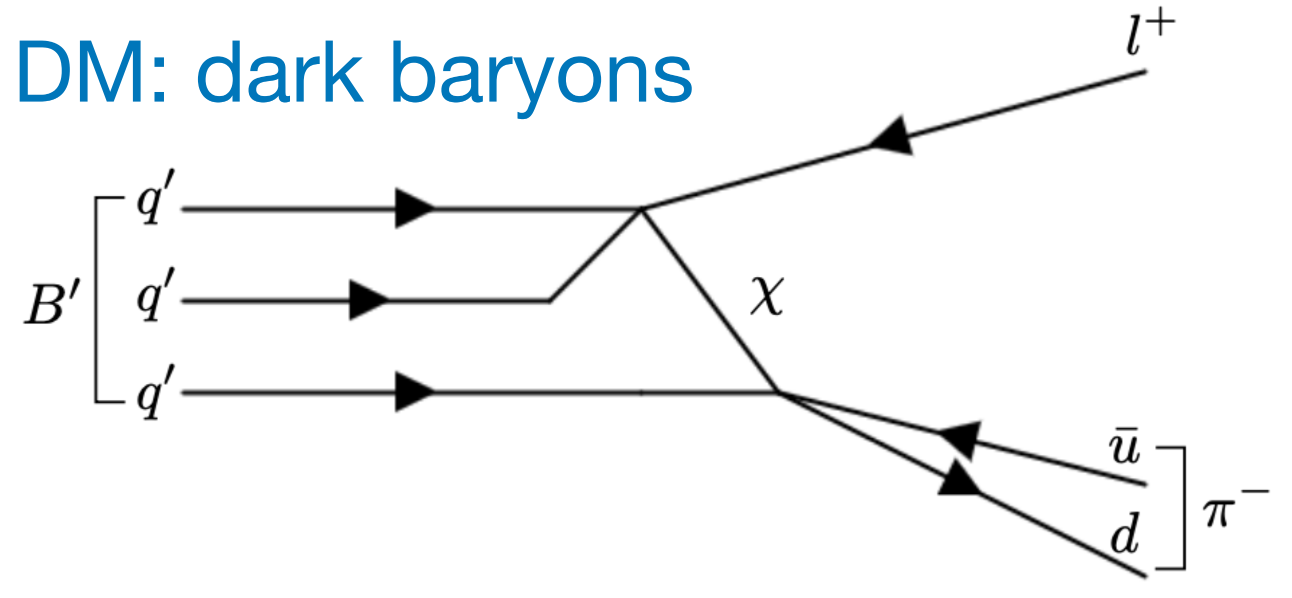
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{2}\sum_{i=1,2} M_{N_i}\overline{N}_i N_i^C - m_\Phi^2 \Phi^\dagger\Phi - m_\chi \bar\chi\chi - m_{q'}\bar{q}' q' + \mathcal{L}_{\rm kinetic}$$
$$- \sum_{i=1,2}\lambda_i \overline{N}_i \chi \Phi^\dagger - \kappa \Phi \bar{q}'_L l_R - \frac{1}{\Lambda_1^2}\left(\bar{q}'^C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

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

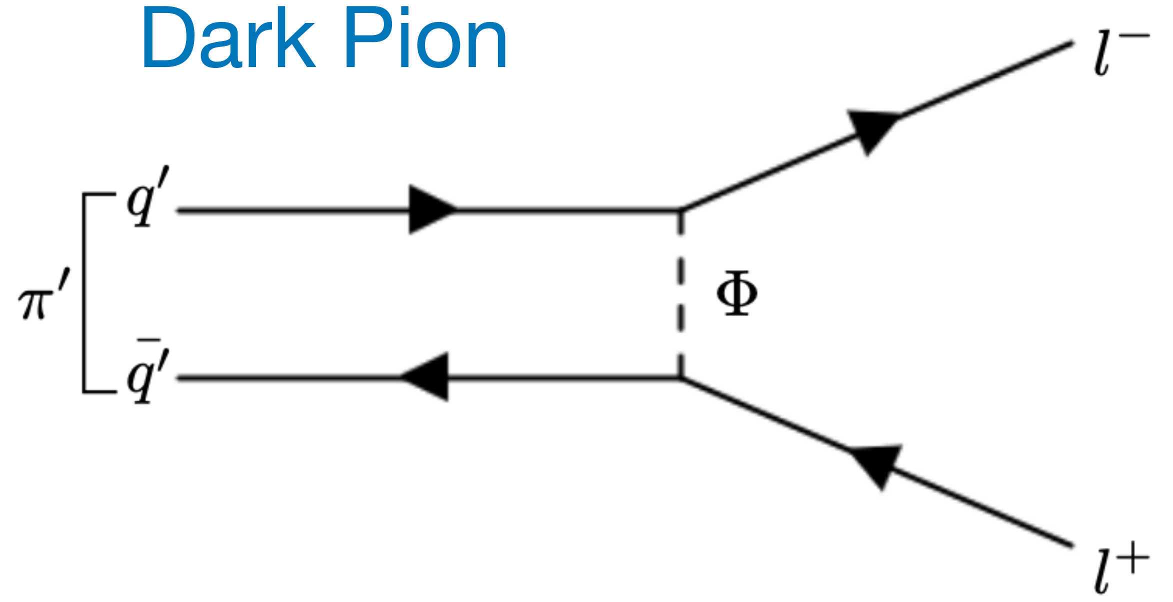
	$SU(3)'$	$SU(3)$	$U_Y(1)$	Spin	L	B	B'
N_1/N_2	1	1	0	1/2	0	0	0
Φ	3	1	1	0	-1	0	1/3
χ	3	1	1	1/2	-1	0	1/3
q'	3	1	0	1/2	0	0	1/3
l_R	1	1	-1	1/2	1	0	0
d_R	1	3	-1/3	1/2	0	1/3	0
u_R	1	3	2/3	1/2	0	1/3	0



DM: dark baryons



Dark Pion



Mengchao Zhang, 2104.06988 (PRD)

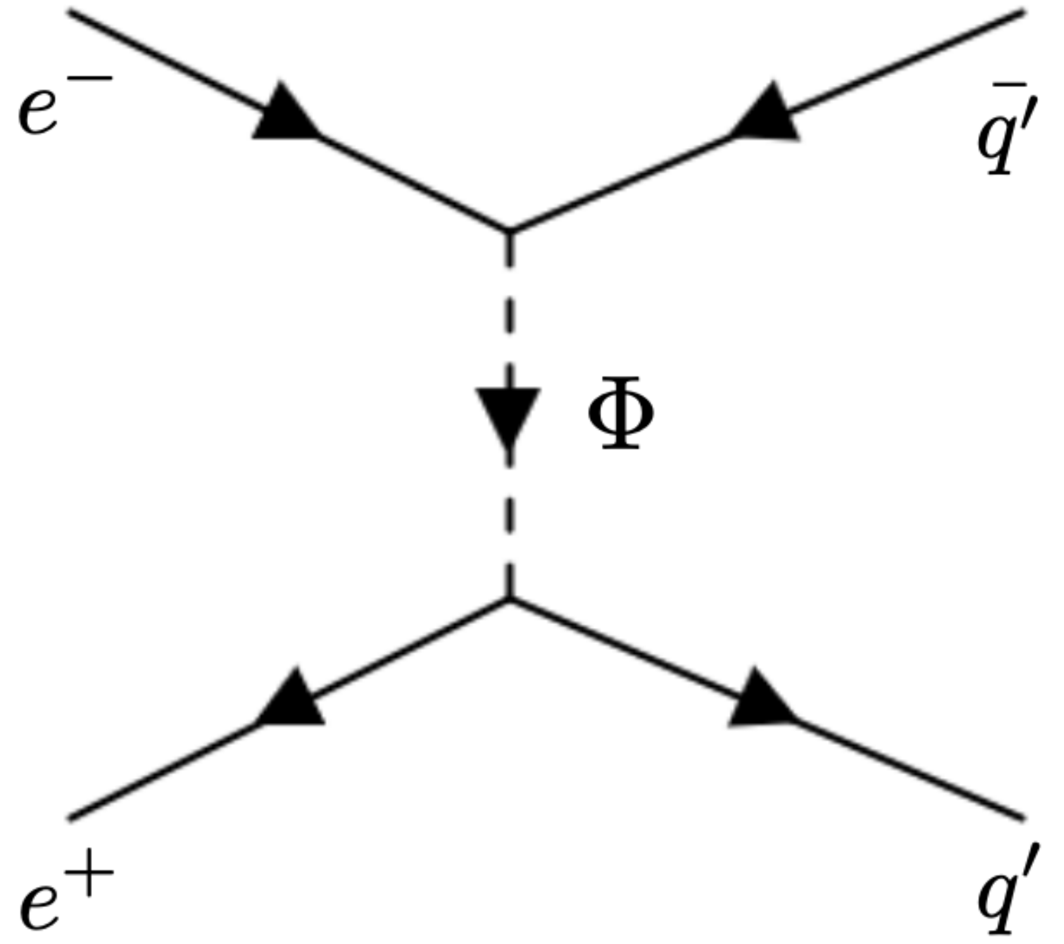
Dark jets at ee collider

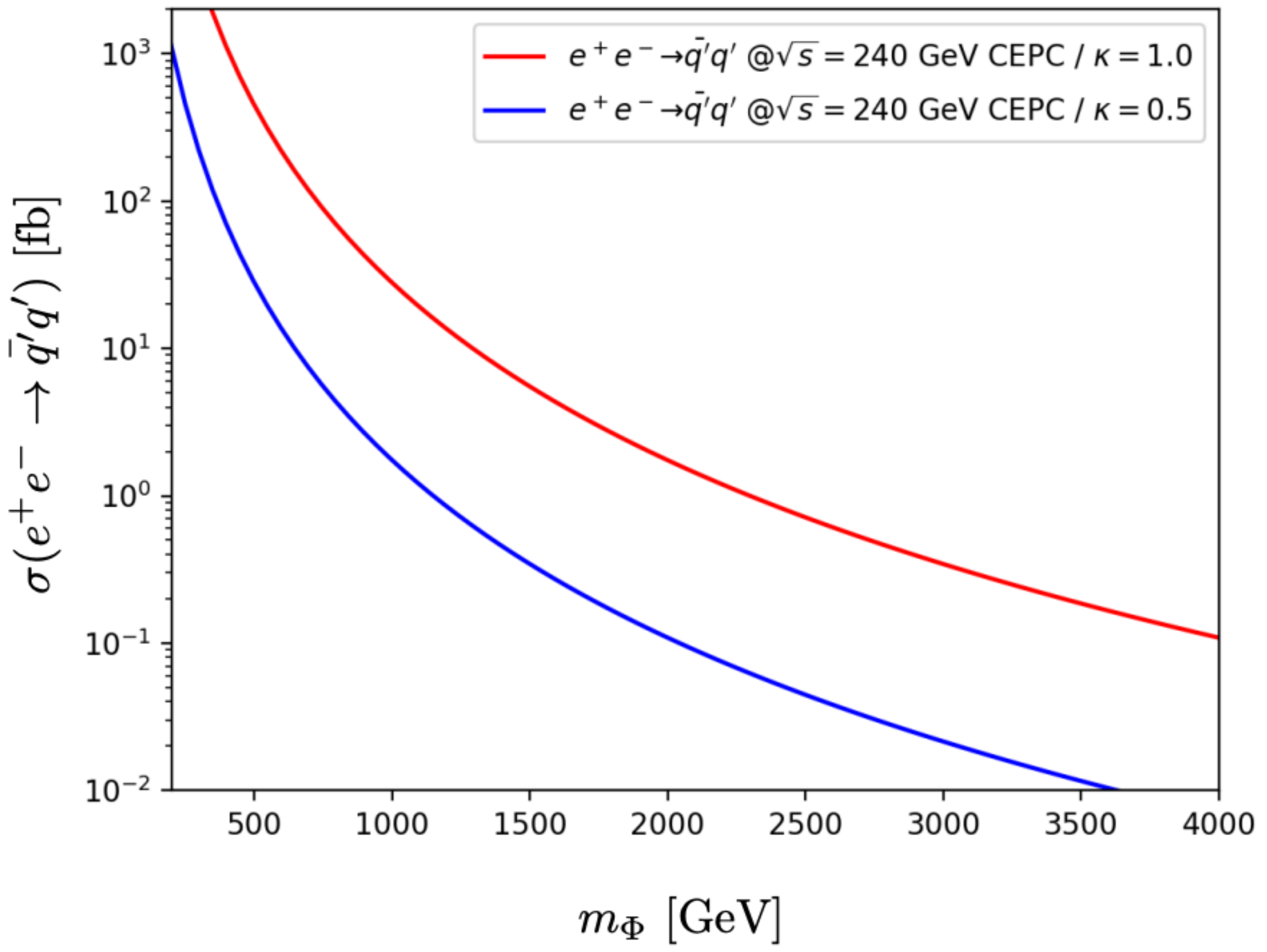
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{2}\sum_{i=1,2} M_{N_i}\overline{N}_i N_i^C - m_\Phi^2 \Phi^\dagger\Phi - m_\chi\bar{\chi}\chi - m_{q'}\bar{q}'q' + \mathcal{L}_{\rm kinetic}$$
$$- \sum_{i=1,2}\lambda_i \overline{N}_i \chi \Phi^\dagger - \kappa\Phi\bar{q}'_L l_R - \frac{1}{\Lambda_1^2}\left(\bar{q}'^C\chi\right)\left(\bar{q}'^C_L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

- Relevant Lagrangian

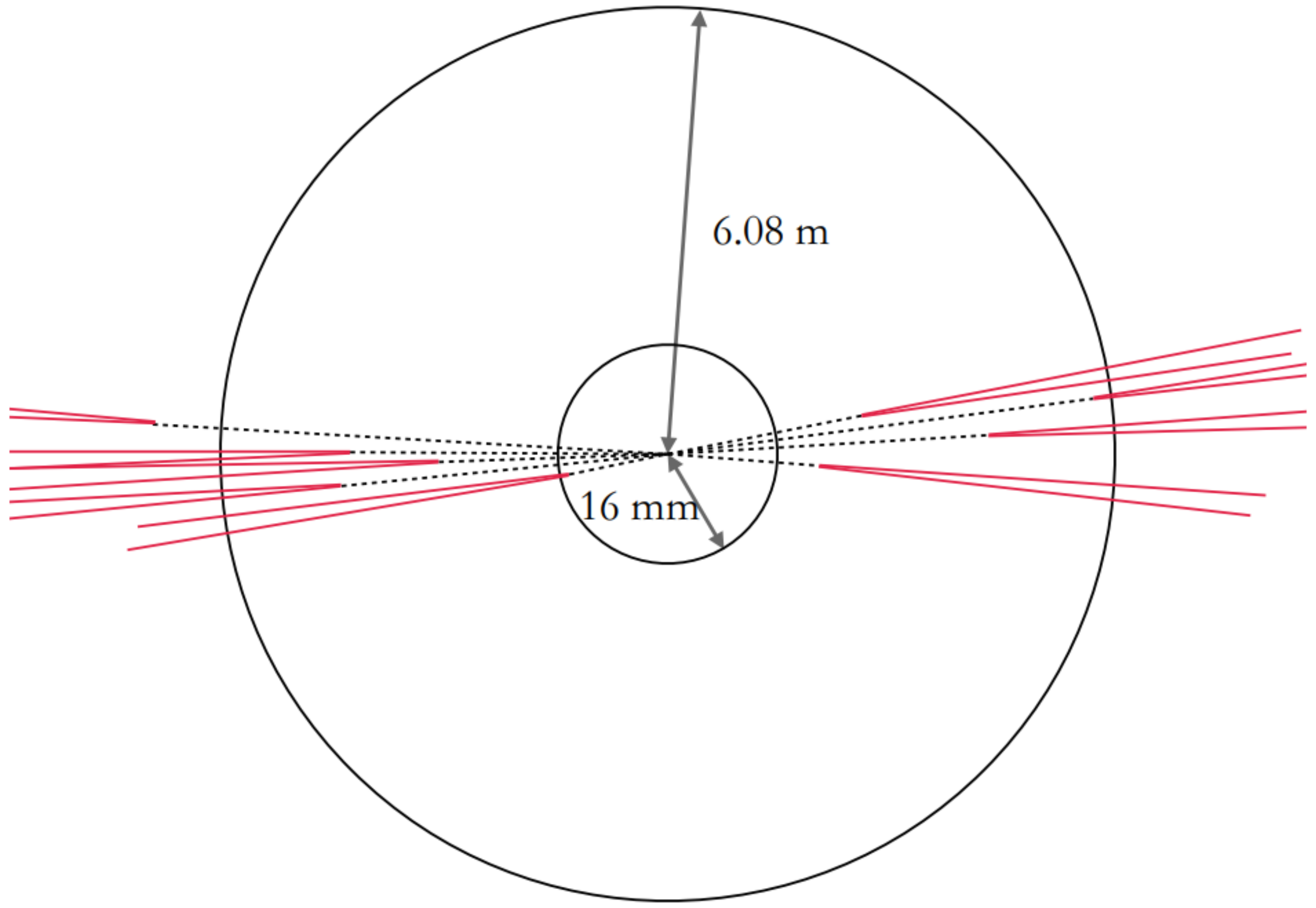
P. Schwaller et al, 1502.05409 (JHEP)

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





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

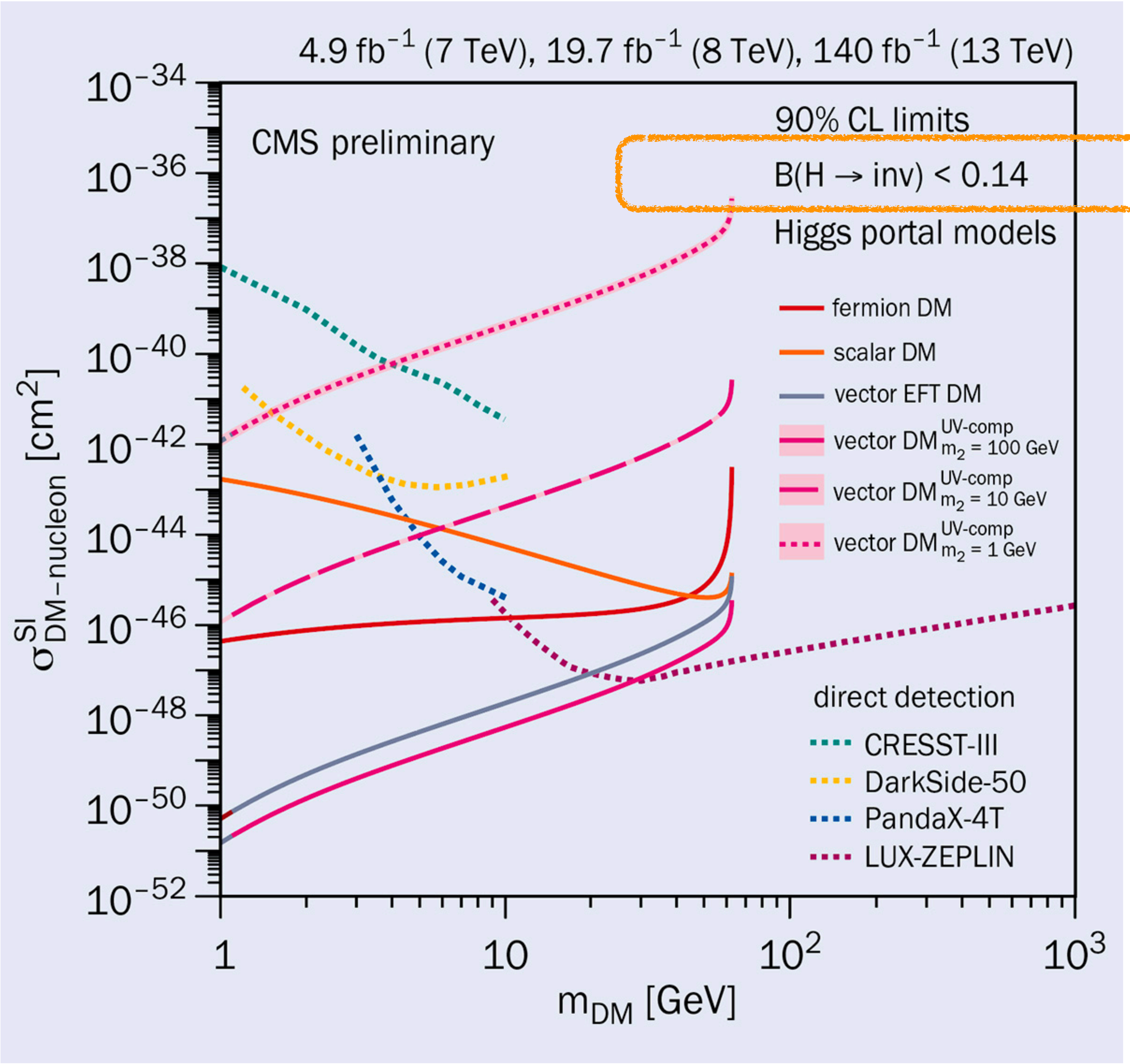


Mengchao Zhang, 2104.06988 (PRD)

Higgs portal DM: invisible Higgs decay

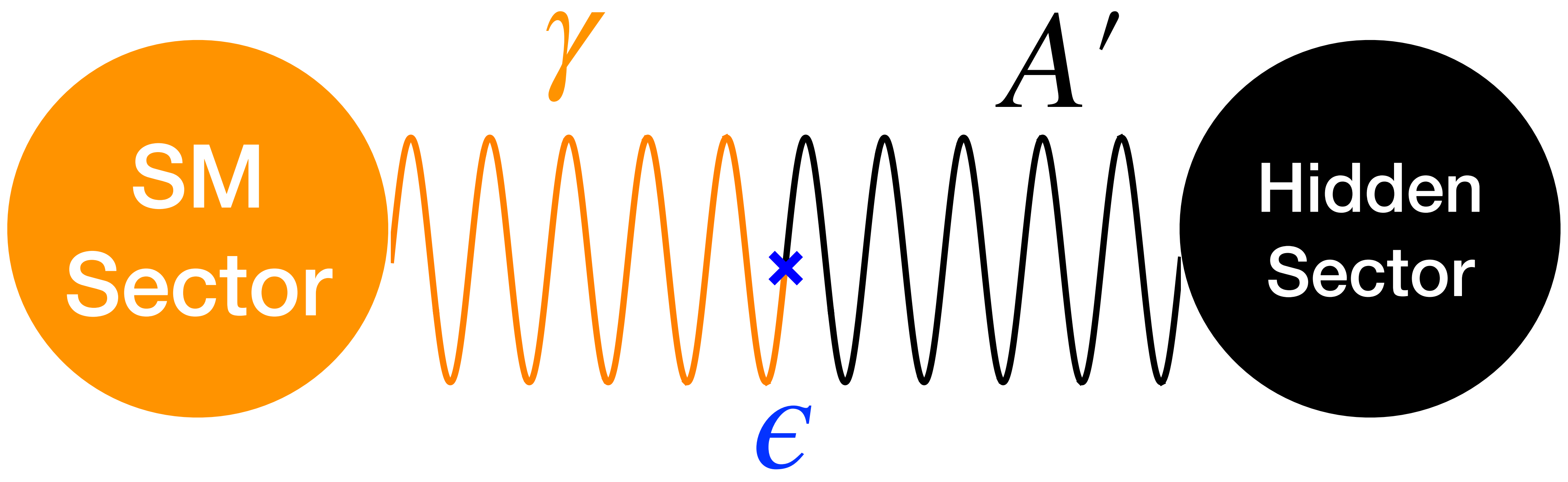
- Precision measurement of Higgs
  - Invisible Higgs test to 0.07%@CEPC

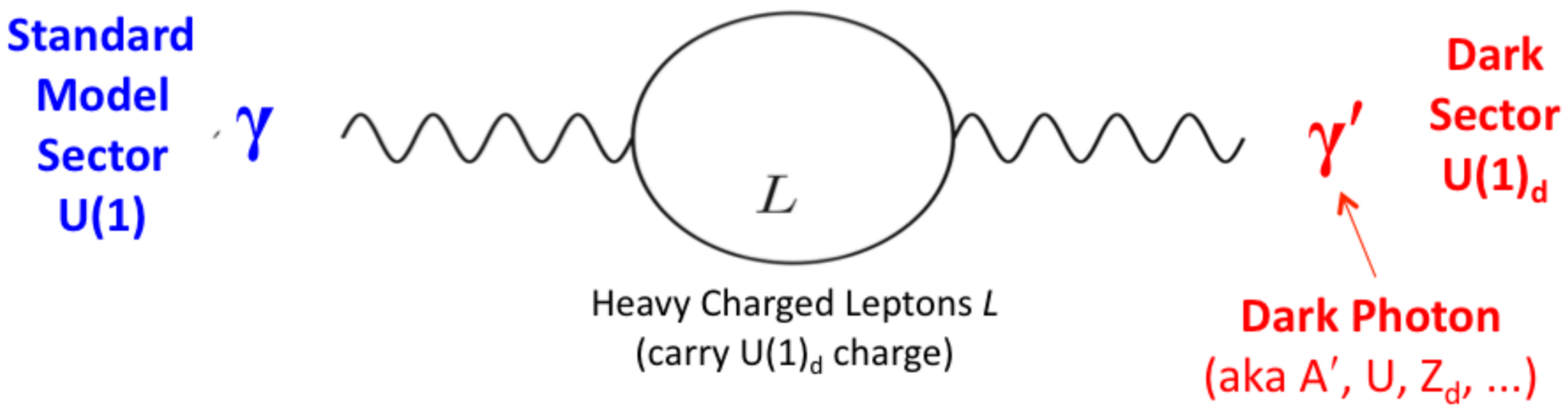
	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	vvH	ZH	vvH	eeH
inclusive	0.26%		1.40%	\	\
H→bb	0.14%	1.59%	0.90%	1.10%	4.30%
H→cc	2.02%		8.80%	16%	20%
H→gg	0.81%		3.40%	4.50%	12%
H→WW	0.53%		2.80%	4.40%	6.50%
H→ZZ	4.17%		20%	21%	
$H \to \tau\tau$	0.42%		2.10%	4.20%	7.50%
$H \to \gamma\gamma$	3.02%		11%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



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

- 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 $(\psi / f_{\rm SM})$ $g' \bar{f}\gamma^\mu f Z'_\mu$

DM χ is charged under U(1)'

	U(1)'	SM charge
ψ	1	Yes
ϕ	1	No
$f_{\rm SM}$	0	Yes

$$\mathscr{L} \supset m_\psi \bar{\psi}\psi + \lambda \bar{\psi}\langle\phi\rangle f_{\rm SM}$$

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

Searching DM via mono-photon at CEPC

- DM searches via mono-photon final states

Millicharged DM

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

Z' portal DM

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

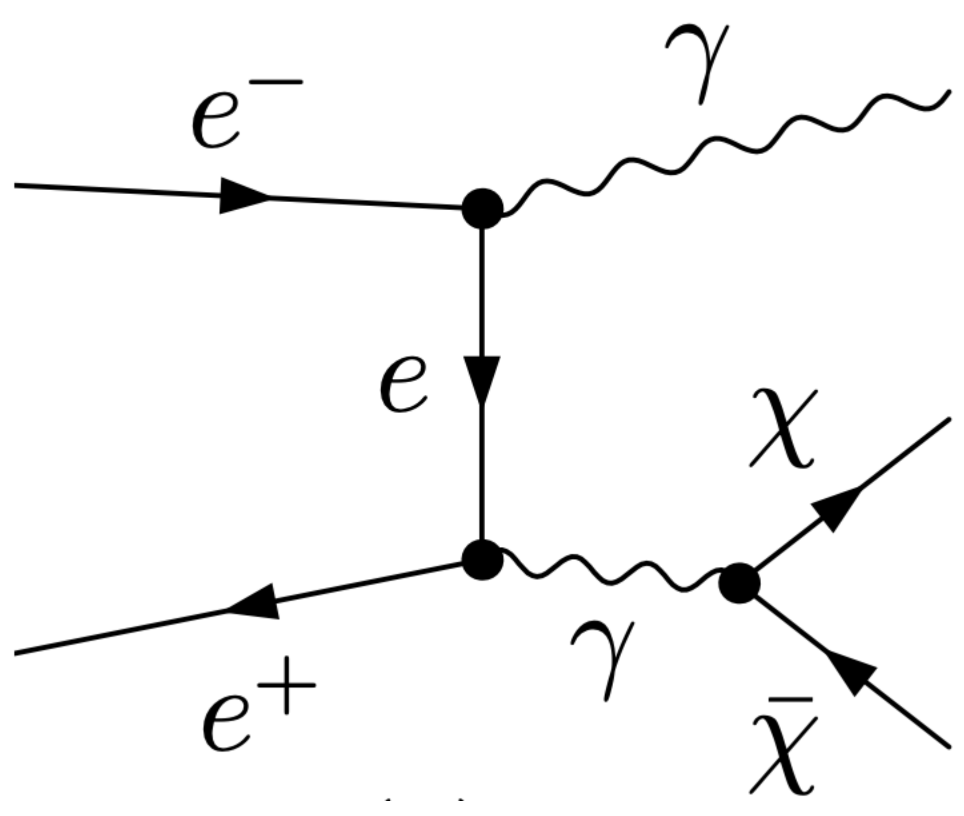
DM EFTs

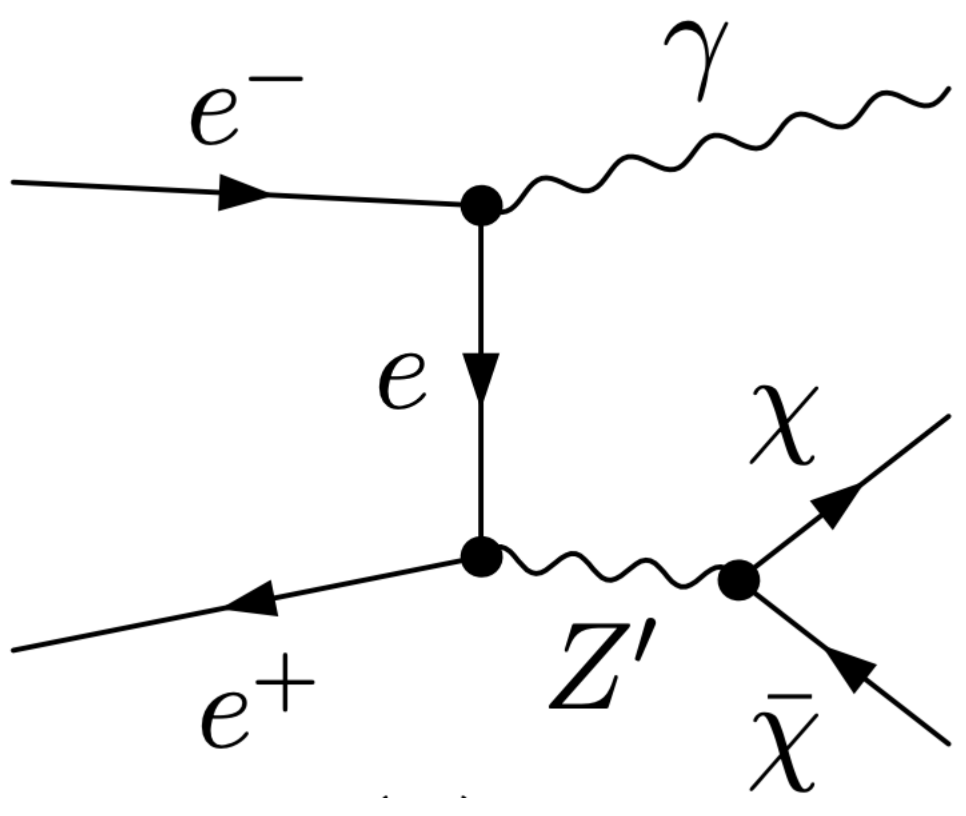
$$\mathcal{L} = \frac{1}{\Lambda_V^2}\bar{\chi}\gamma_\mu\chi\bar{\ell}\gamma^\mu\ell,$$

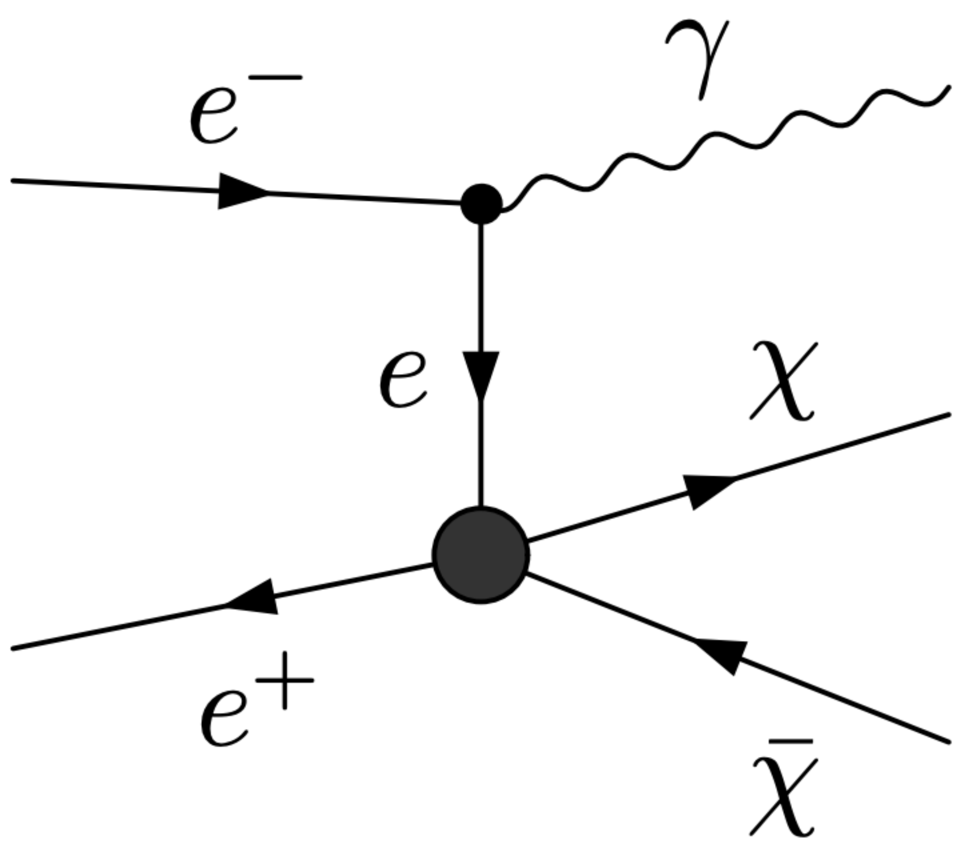
$$\mathcal{L} = \frac{1}{\Lambda_s^2}\bar{\chi}\chi\bar{\ell}\ell,$$

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

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



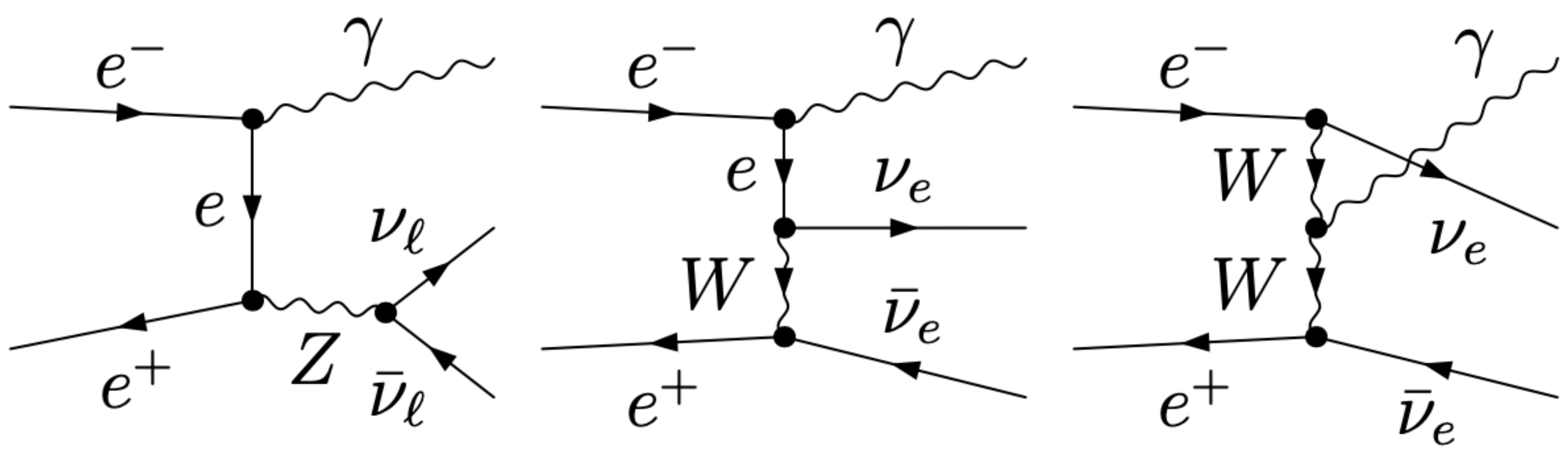




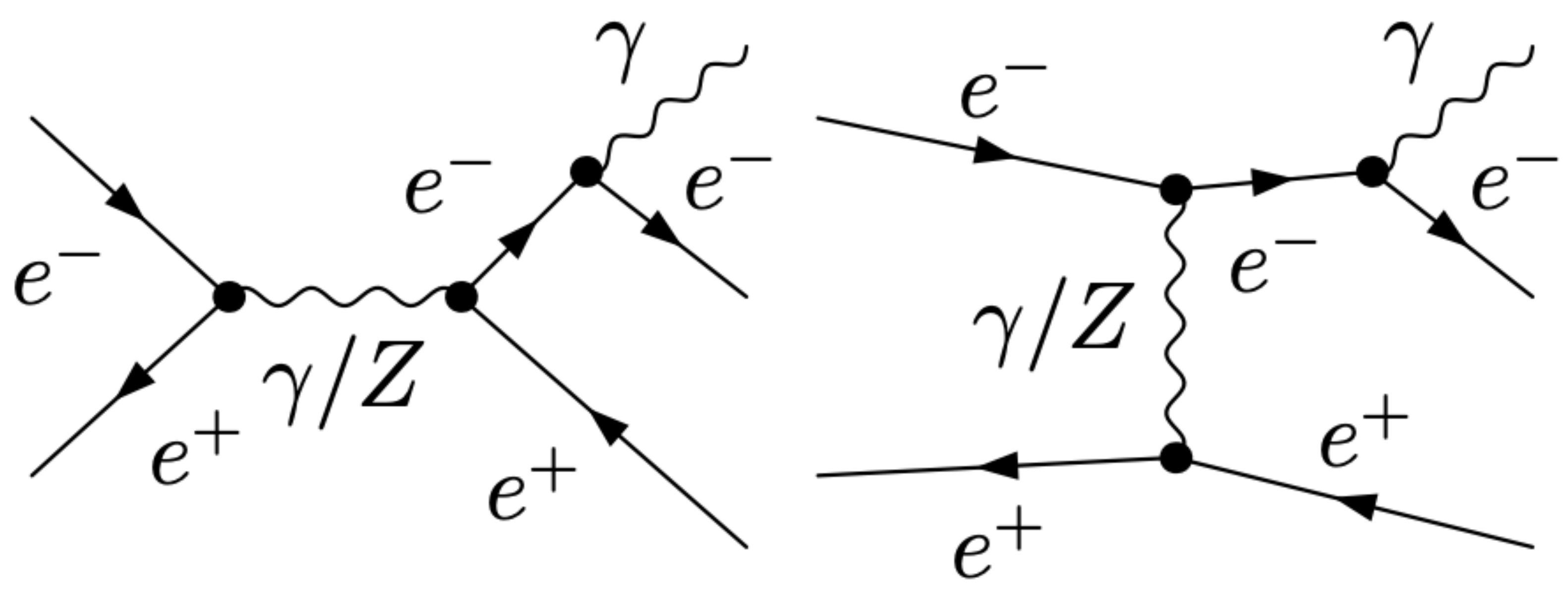
Zuowei Liu et al, 1903.12114 (JHEP)

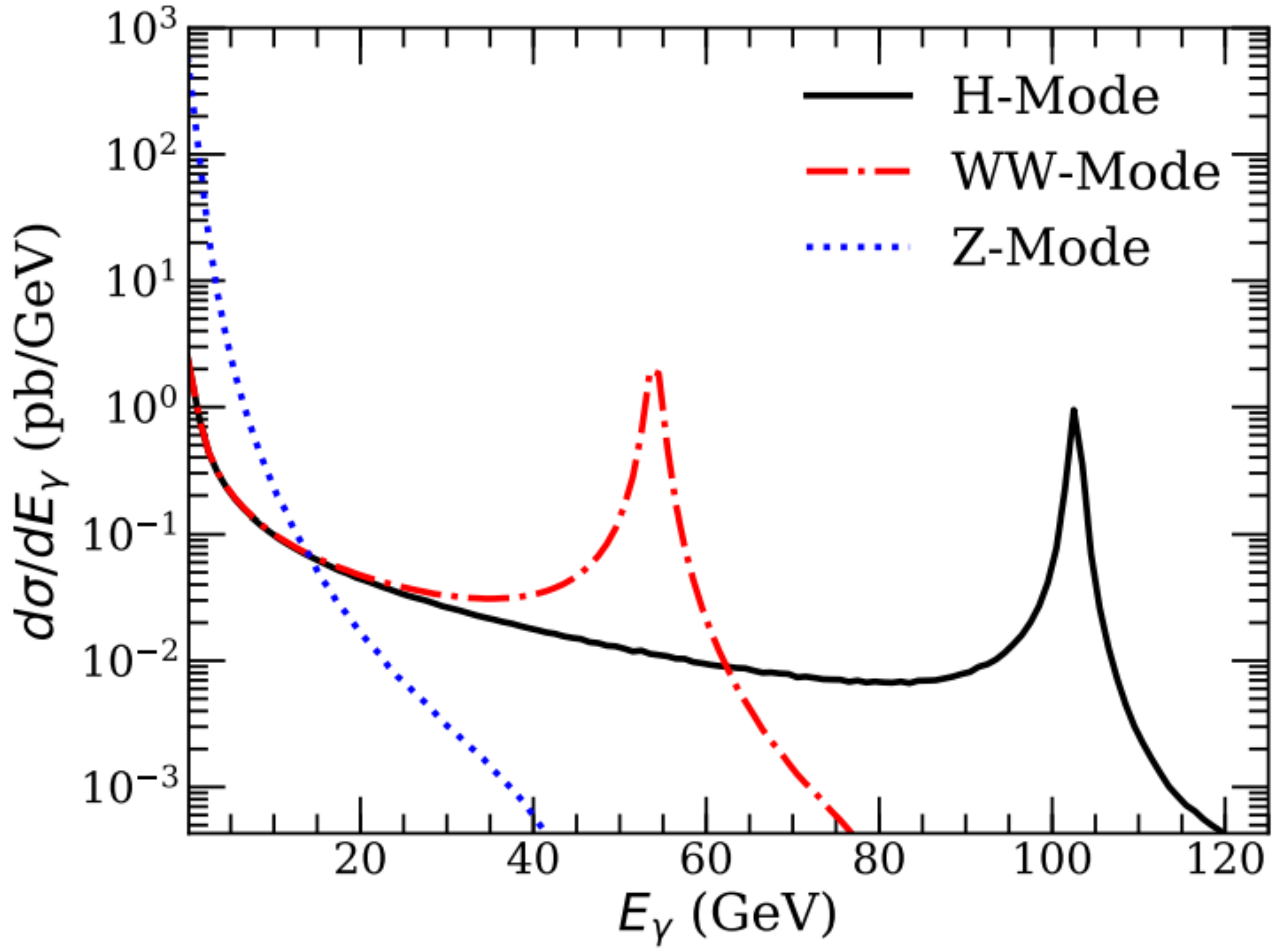
Mono-photon background at CEPC

- Irreducible background
  $e^+e^- \to \gamma\nu\bar{\nu}$



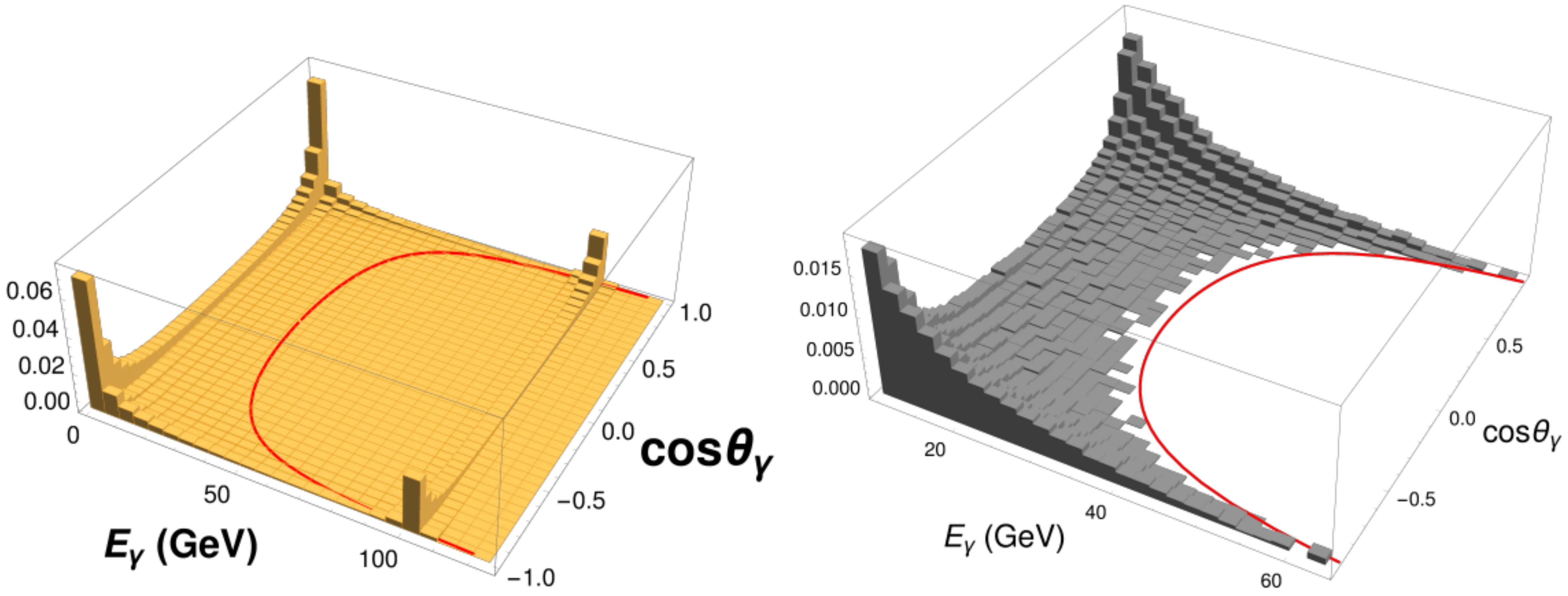
- Reducible background
  $e^+e^- \to \gamma e^+e^-$





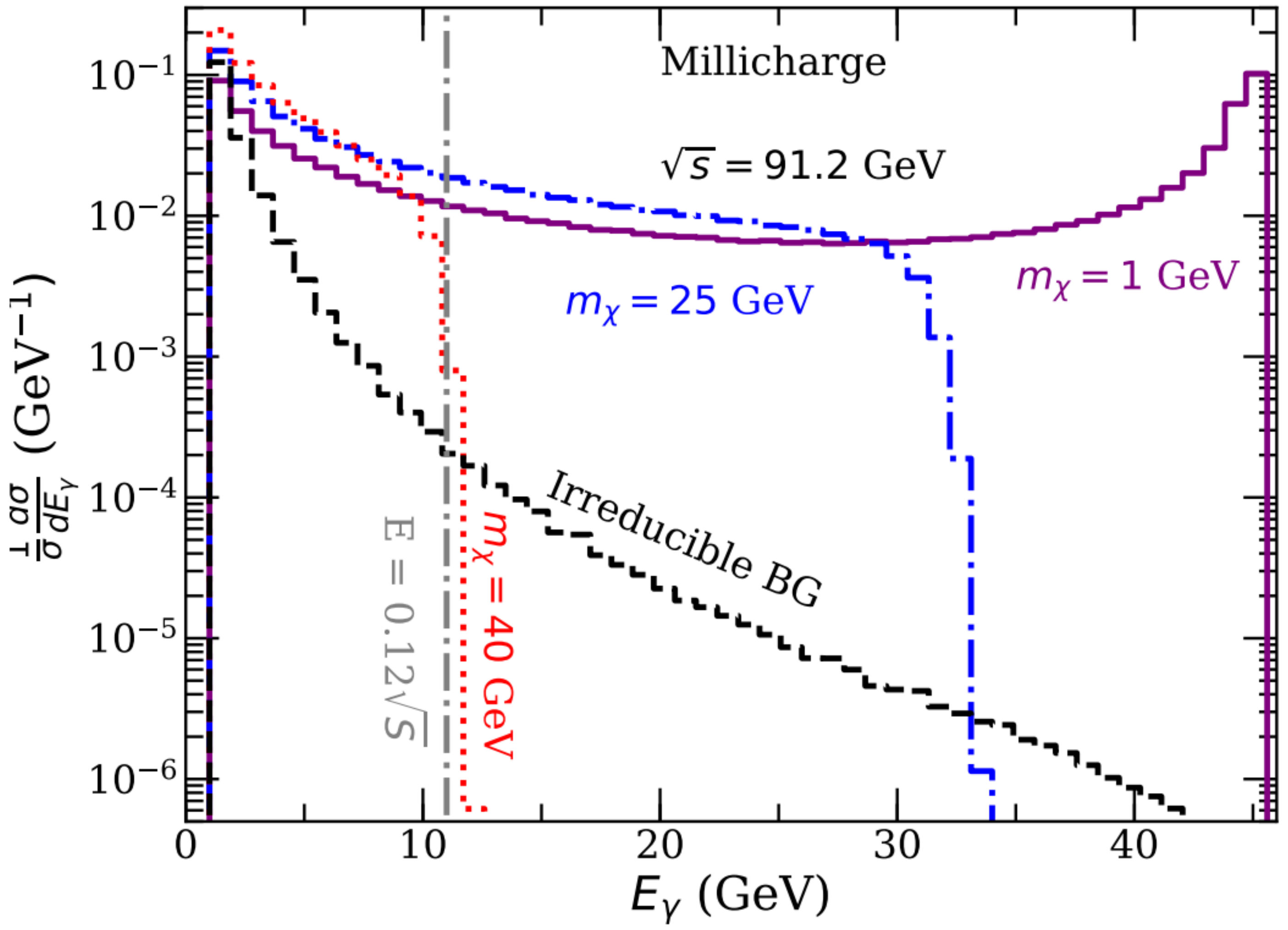
Zuowei Liu et al, 1903.12114 (JHEP)

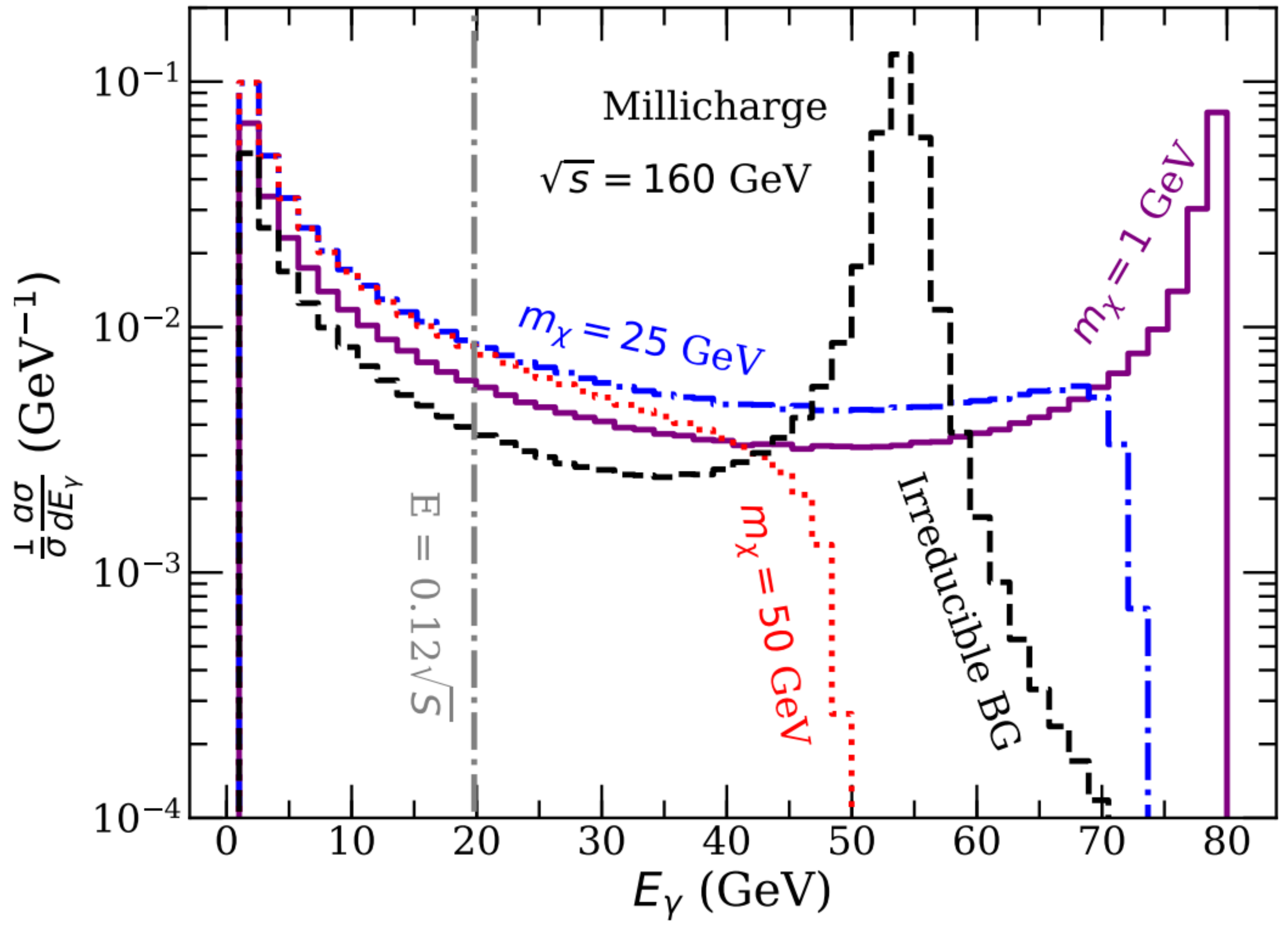
- Red curve shows the signal region



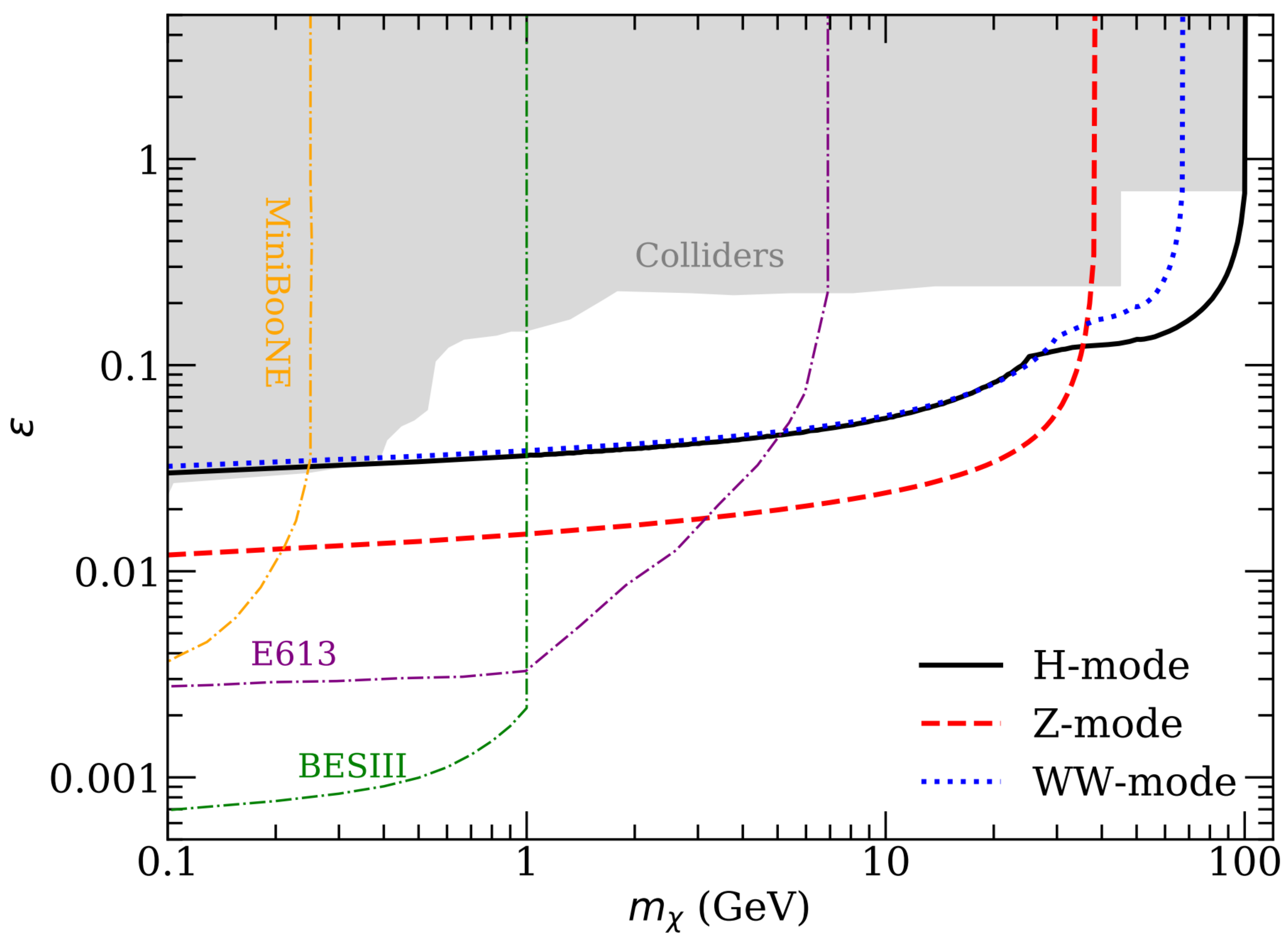
Constraints on millicharged DM

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





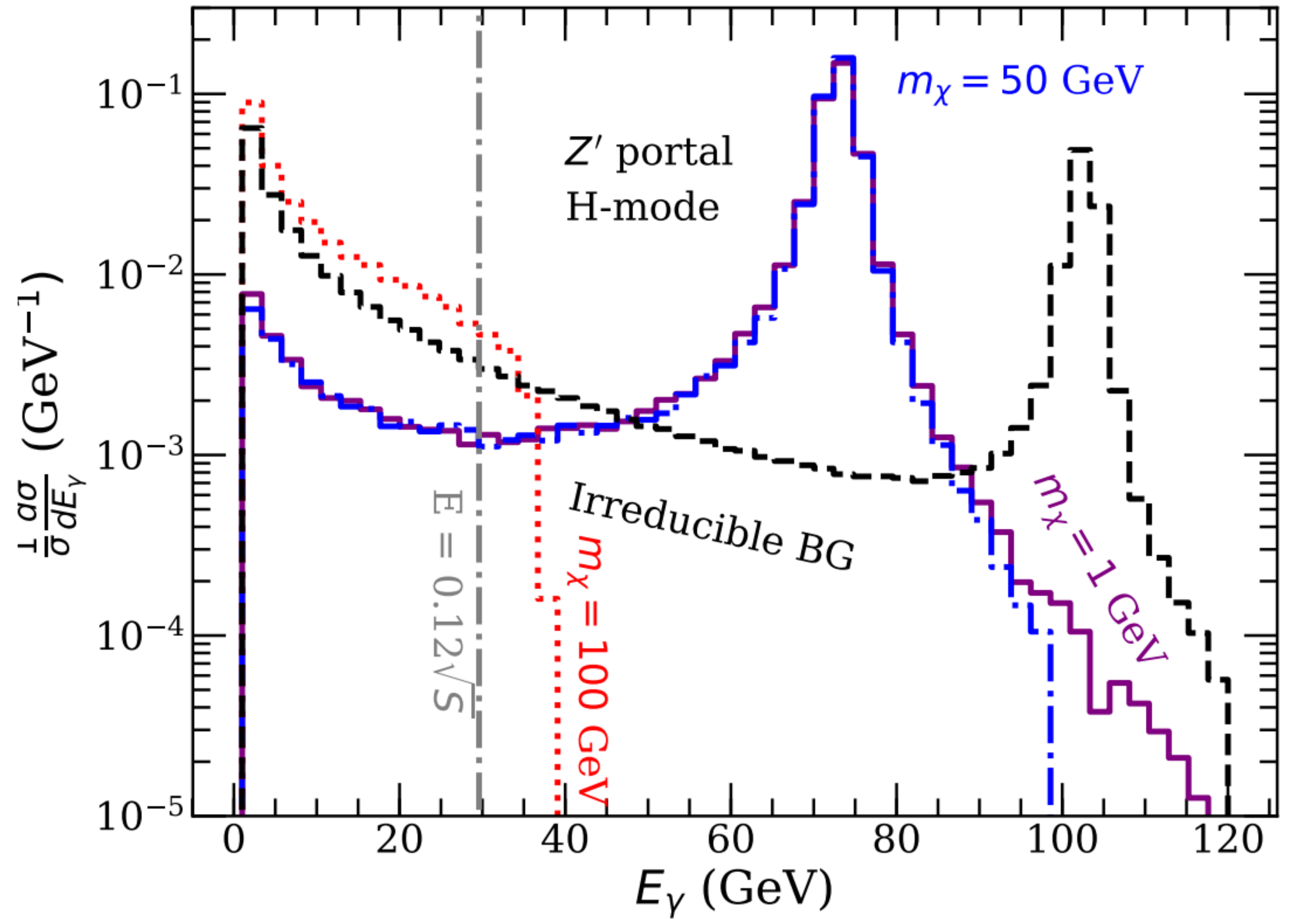
Zuowei Liu et al, 1903.12114 (JHEP)

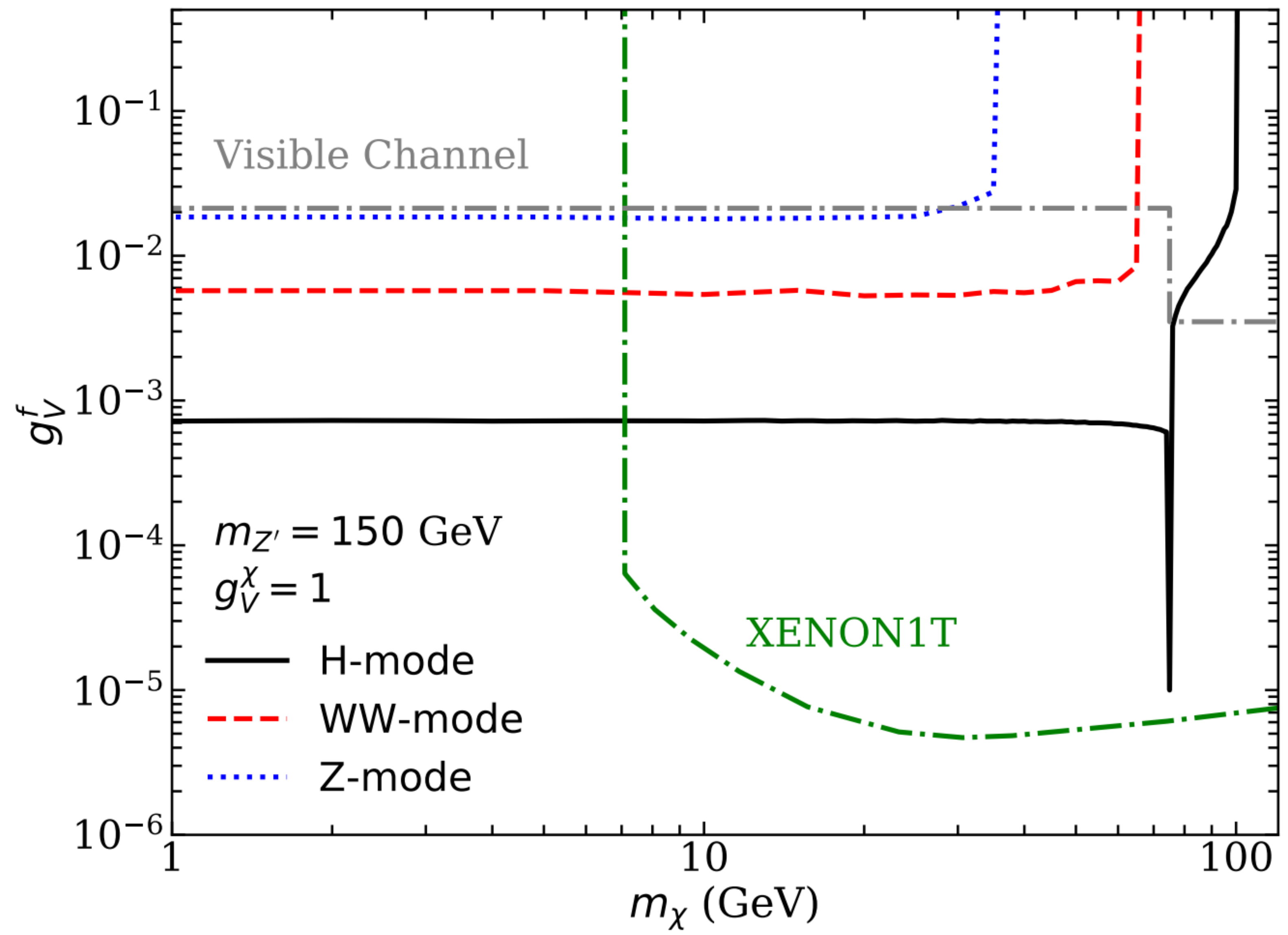


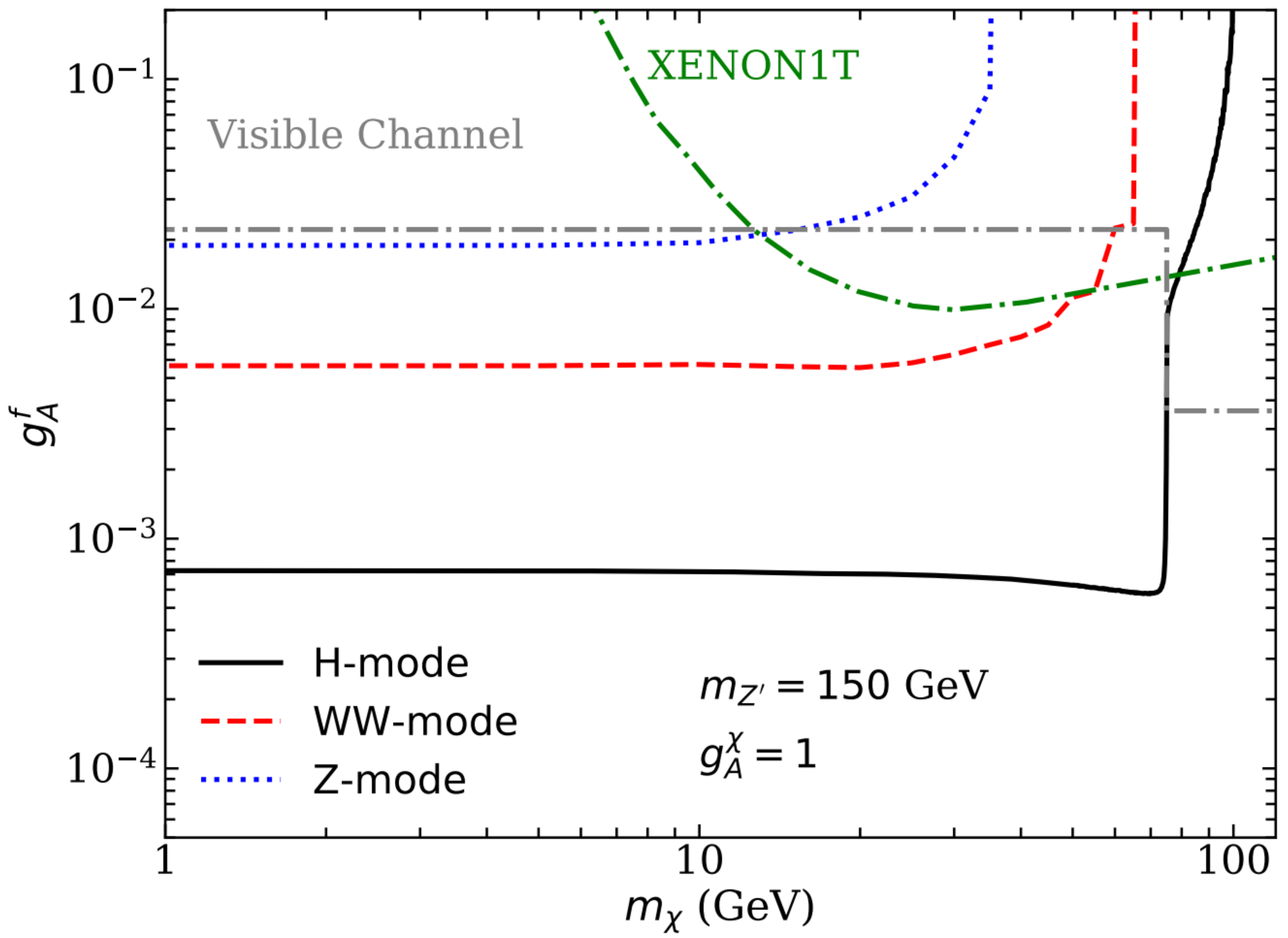
- The Z/Higgs factory modes can provide competitive sensitivity comparing with existing colliders

Constraints on Z' portal DM model

- 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

Zuowei Liu et al, 1903.12114 (JHEP)

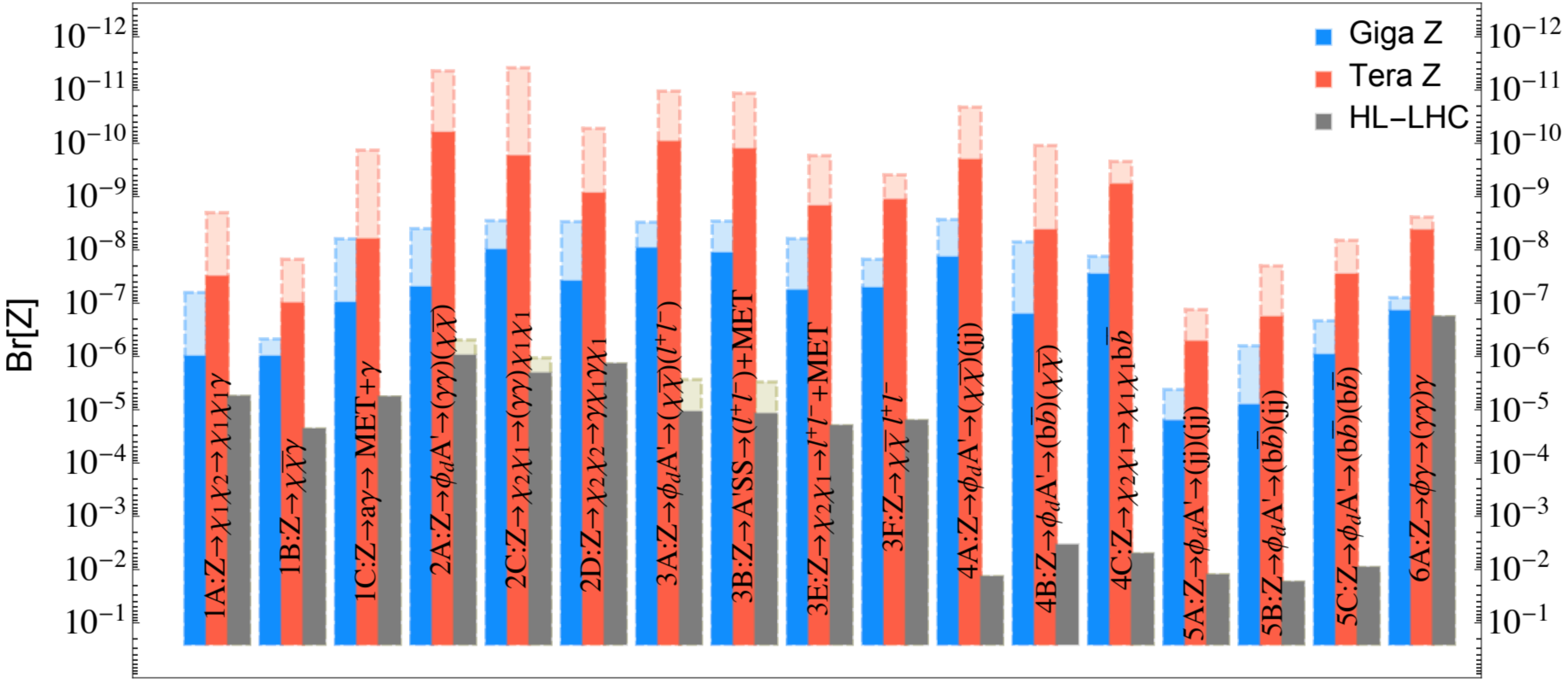
Probing dark sector models at future Z-factory

exotic decays	topologies	n_{res}	models
$Z \to \not{E} + \gamma$	$Z \to \chi_1\chi_2, \chi_2 \to \chi_1\gamma$	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)
	$Z \to A'\gamma \to (\bar{\chi}\chi)\gamma$	1	1D: $\epsilon^{\mu\nu\rho\sigma}A'_{\mu}B_{\nu}\partial_{\rho}B_{\sigma}$ (WZ terms)
$Z \to \not{E} + \gamma\gamma$	$Z \to \phi_d A', \phi_d \to (\gamma\gamma), A' \to (\bar{\chi}\chi)$	2	2A: Vector portal
	$Z \to \phi_H\phi_A,\ \phi_H \to (\gamma\gamma),\ \phi_A \to (\bar{\chi}\chi)$	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

$Z \to \not{E} + \ell^+\ell^-$	$Z \to \phi_d A',\ A' \to (\ell^+\ell^-),\ \phi_d \to (\bar{\chi}\chi)$	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
	$Z \to \chi_2\chi_1 \to \chi_1 A'\chi_1 \to (\ell^+\ell^-)\not{E}$	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
$Z \to \not{E} + JJ$	$Z \to \phi_d A' \to (\bar{\chi}\chi)(jj)$	2	4A: Vector portal
	$Z \to \phi_d A' \to (bb)(\bar{\chi}\chi)$	2	4B: Vector portal + Higgs portal
	$Z \to \chi_2\chi_1 \to bb\chi_1 + \chi_1 \to bb\not{E}$	0	4C: MIDM
$Z \to (JJ)(JJ)$	$Z \to \phi_d A', \phi_d \to jj, A' \to jj$	2	5A: Vector portal + Higgs portal
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to jj$	2	5B: vector portal + Higgs portal
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to b\bar{b}$	2	5C: vector portal + Higgs portal
$Z \to \gamma\gamma\gamma$	$Z \to \phi\gamma \to (\gamma\gamma)\gamma$	1	6A: ALP, Higgs portal

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

Probing dark sector models at future Z-factory



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

Outline

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

Searching DM via mono-photon at CEPC

- DM searches via mono-photon final states

Millicharged DM

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

Z' portal DM

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

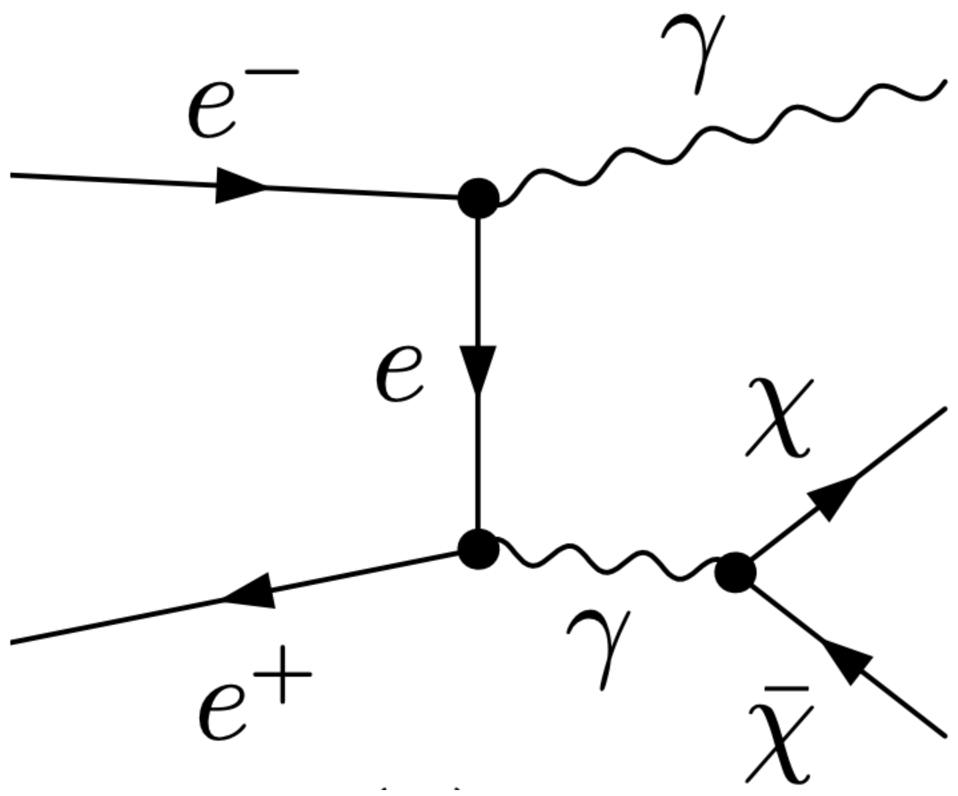
DM EFTs

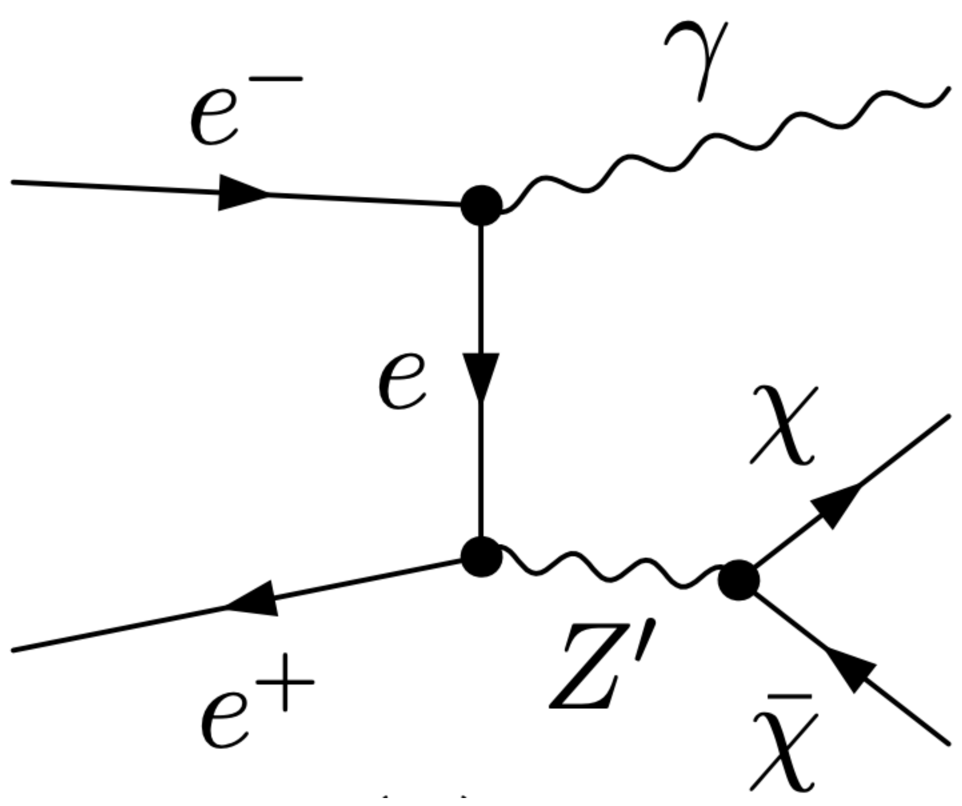
$$\mathcal{L} = \frac{1}{\Lambda_V^2}\bar{\chi}\gamma_\mu \chi \bar{\ell}\gamma^\mu \ell,$$

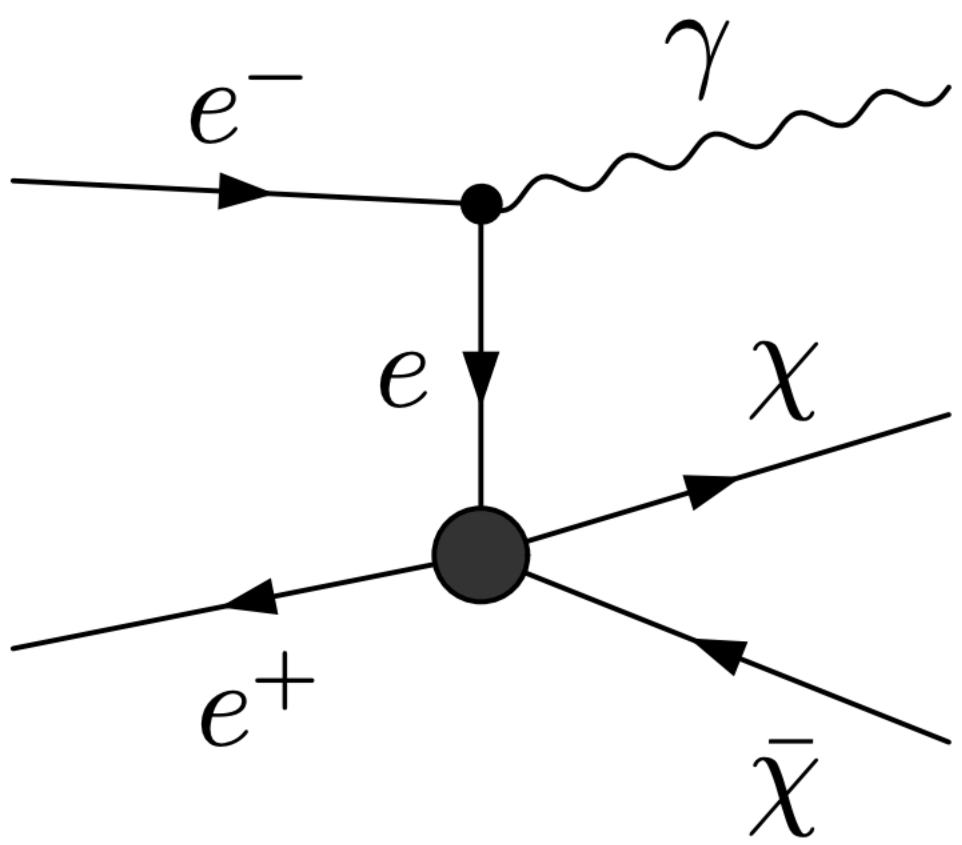
$$\mathcal{L} = \frac{1}{\Lambda_s^2}\bar{\chi}\chi\bar{\ell}\ell,$$

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

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



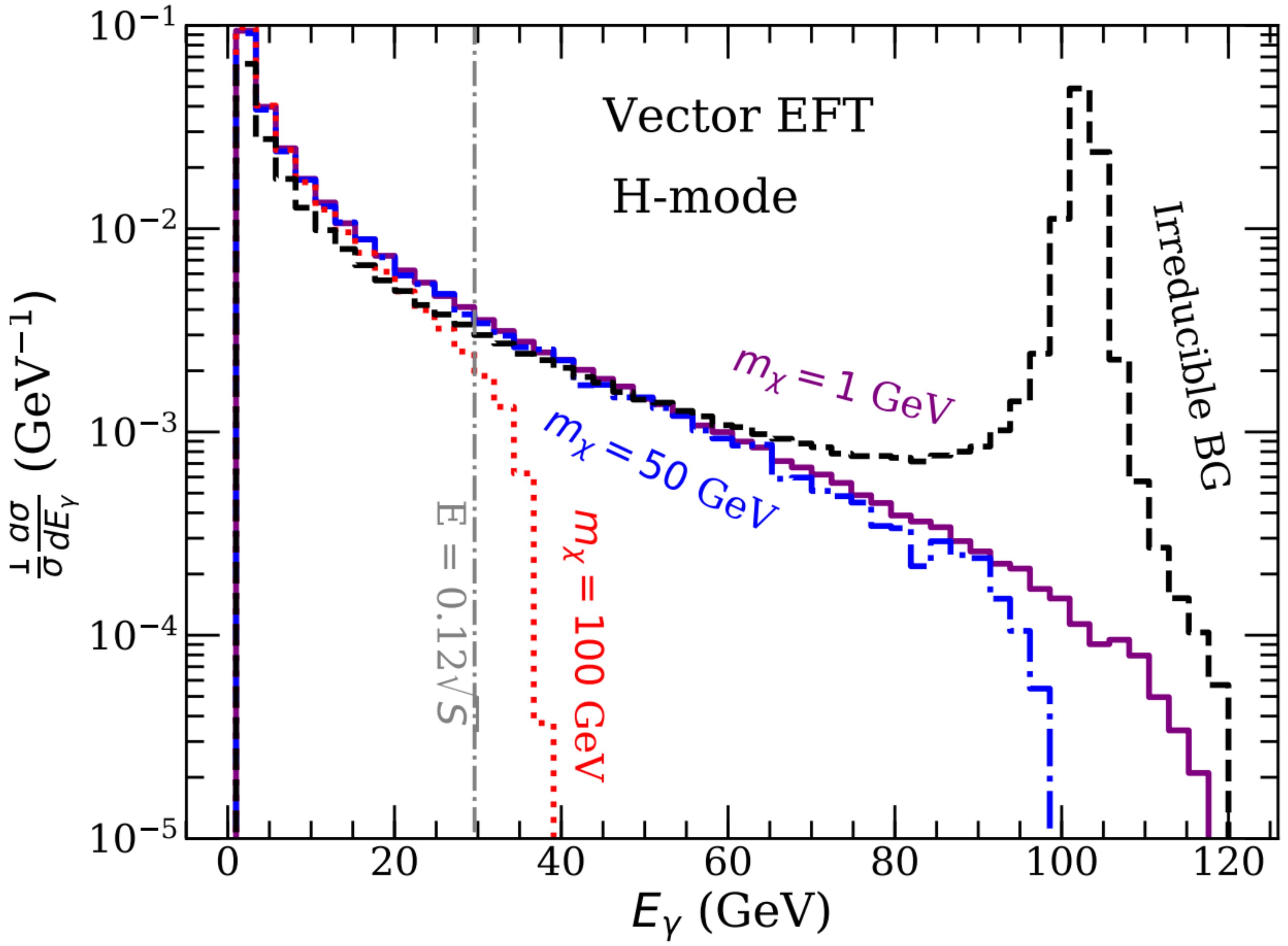


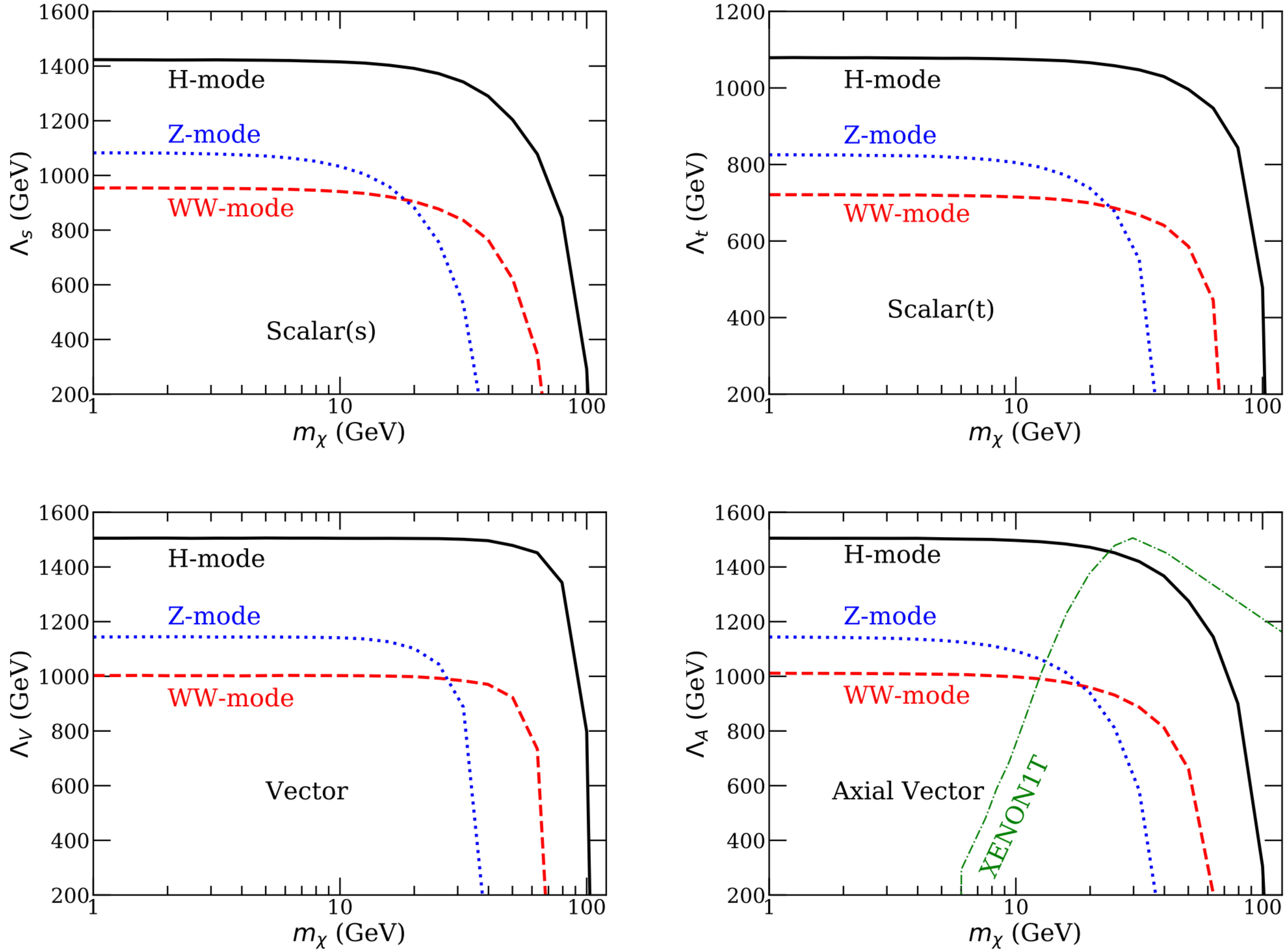


Zuowei Liu et al, 1903.12114 (JHEP)

Constraints on DM EFTs

- 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

Zuowei Liu et al, 1903.12114 (JHEP)

Searching fermionic DM absorption at CEPC

- 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

Shaofeng Ge et al, 2201.11497 (JHEP)

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

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

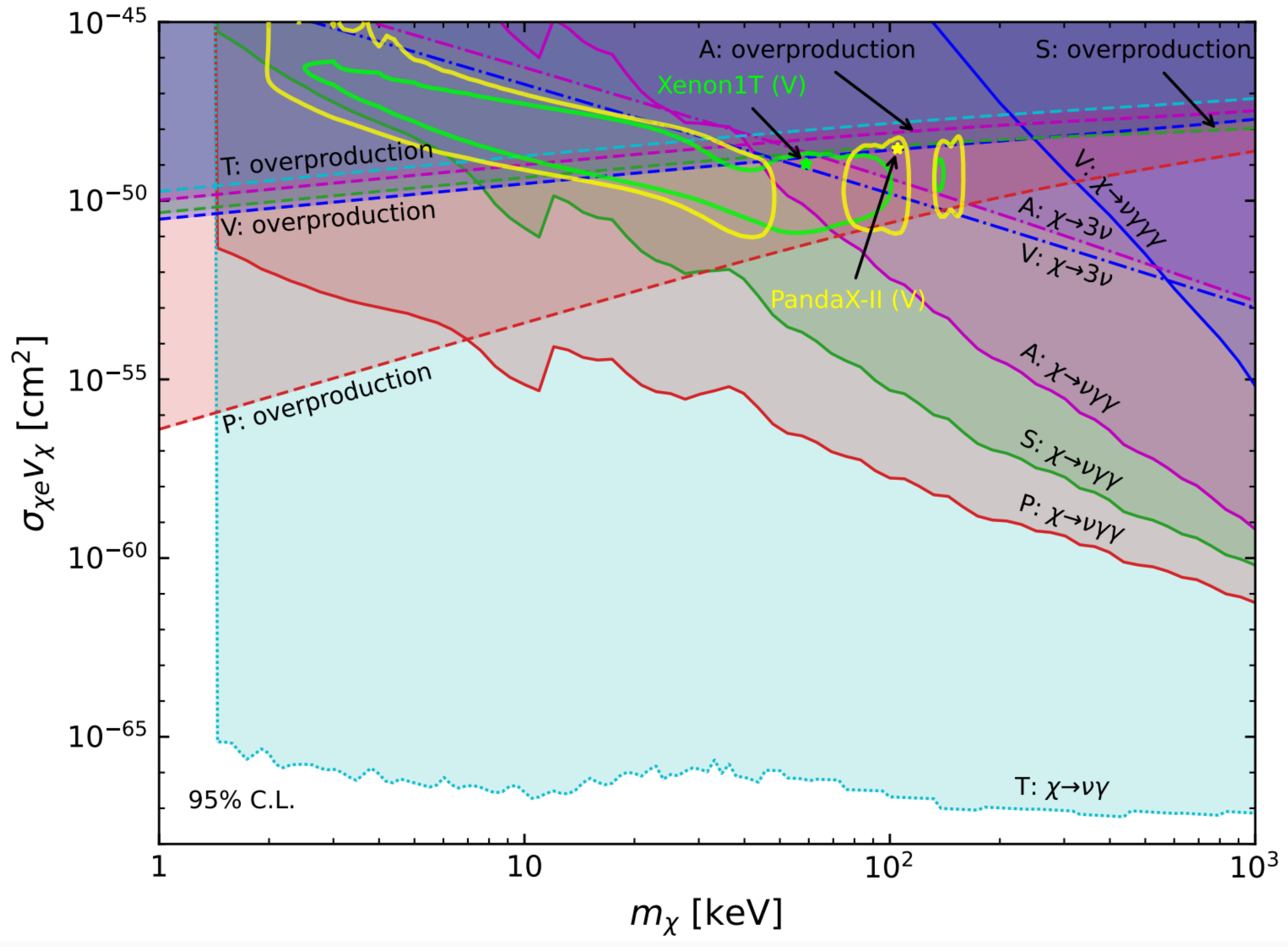
$(\bar{\nu}_L \chi_R) F^2, (\bar{\nu}_L \chi_R) F\tilde{F}$

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: $\mathcal{O}^T_{e\nu\chi}$	✓	×	×!	×!

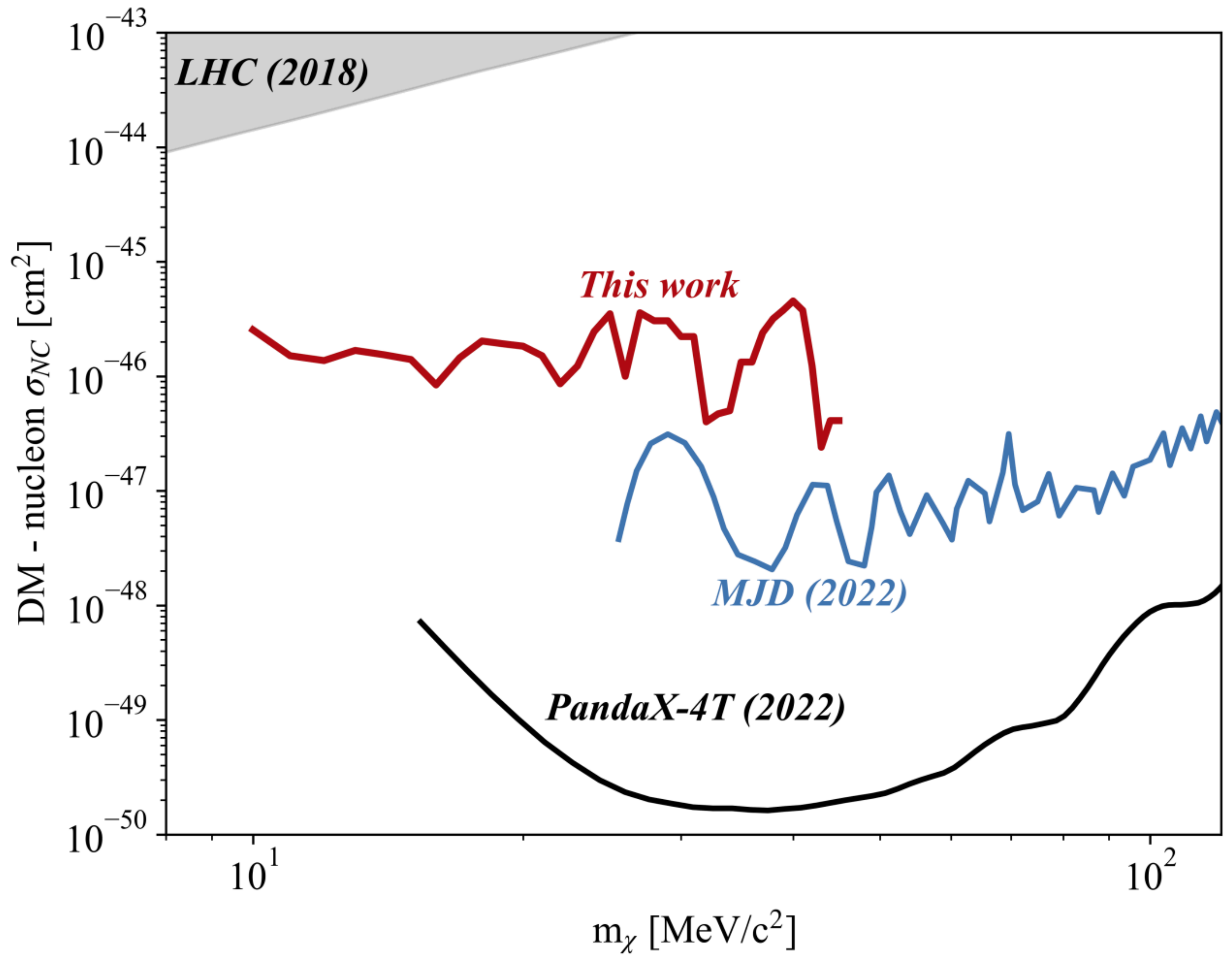
Searching fermionic DM absorption at CEPC

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

Shaofeng Ge et al, 2201.11497 (JHEP)



- Actively searched by DM direct detection experiments

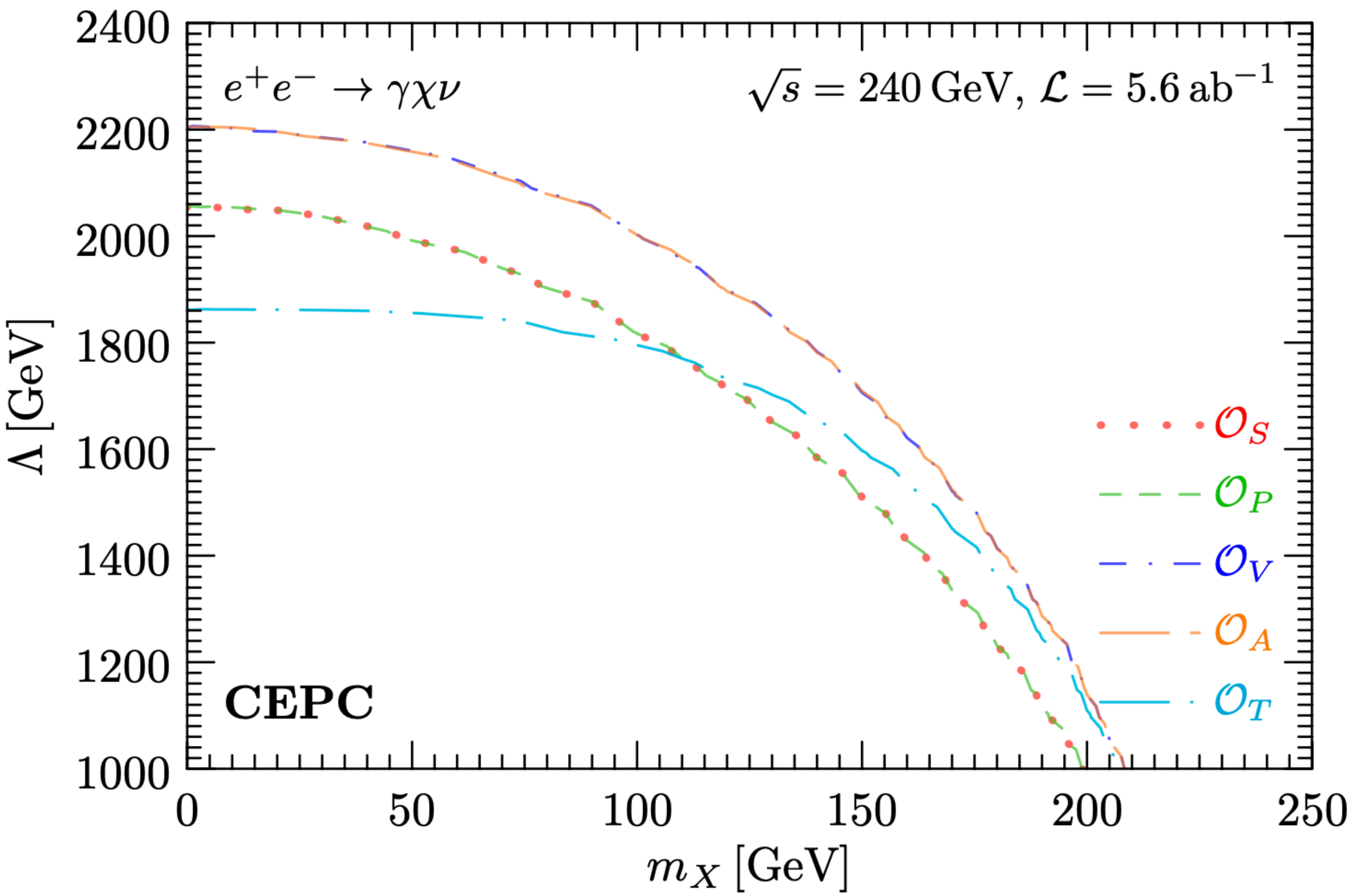


PANDAX 2206.02339 (PRL)
CDEX 2209.00861(PRL)

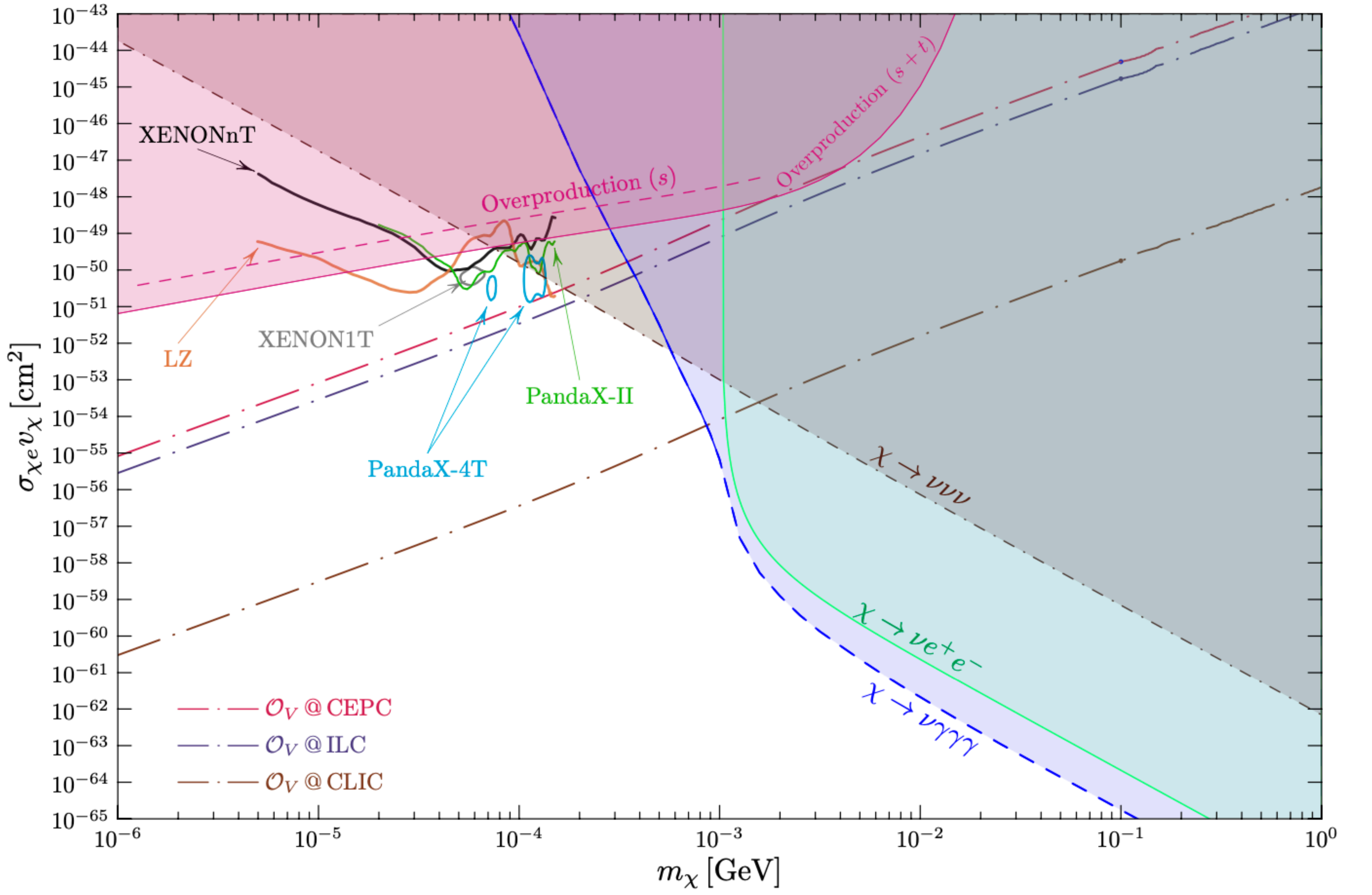
Searching fermionic DM absorption at CEPC

- 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

Shaofeng Ge et al, 2306.00657



- Collider complementary between DM direct and indirect experiments



Summary

- Future ee collider (CEPC/FCC-ee etc) provides valuable opportunities to test Standard Model and Beyond the SM physics
  - Higgs couplings can be precisely tested at 0.1%—1% level
  - Electroweak couplings can be further improved by a factor of O(10)—O(100)
  - Light particles are covered, even larger than $\sqrt{s}/2$ through 3-body final states
  - Heavier particle can be tested indirectly through precision measurements
  - Complementarity with non-collider studies: direct detection, indirect detection of DM, gravitational wave detection
- CEPC offers a diverse and extensive research program covering various areas of fundamental physics

Thank you!

Backup slides