New Physics at CEPC

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Institute of High Energy Physics
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CEPC BSM Physics Program

BSM Higgs

Indirect searches from SM precision measurements *(not included here)*

BSM @ flavor
- Flavor violation
- Flavor anomalies
- ……
- More at **Flavor white paper** *(Not included here)*

SUSY
- Light EWKinos
- Light sleptons
- Heavy selectrons
- Axinos
- ……

Z/flavor factory
$\sqrt{s} \sim m_Z, > 2m_W$
$5 \ast 10^{12}$ Z events
Few 10^8 W events
10^{12} bb/cc events
$1.7 \ast 10^{11}$ ττ

Top factory
$\sqrt{s}$=340-365GeV
10^6 HZ events
10^5 WW->H events

CEPC

Global fits
- Global fit of SUSY
- SMEFT global fit

Higgs factory
$\sqrt{s}$=240,365GeV
10^6 HZ events
10^5 WW->H events

Dark Matter & Dark Sector
- Lepton portal DM
- Asymmetric DM
- Dark Sector from exotic Z decay
- Dark Sector-photon interactions
- Millicharged DM, Vector portal DM, DM with EFT interactions
- Mono-gamma
- Dark Fermion in light of Electron Target Absorption
- ……

Long-lived particles
- At both CEPC and it's FAR detector

More exotics
- Heavy neutrinos
- Axion-like particles
- Electroweak phase transition
- Identify CP-odd component in Higgs
- ……

BSM Inputs & 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), Dark Sector-photon interactions (2208.08142)
  - DM (Millicharged DM, Vector portal DM, DM with EFT interactions): 1903.1211
  - Mono-gamma (2205.05560) ,
  - Dark Fermion in light of Electron Target Absorption (Kai Ma's talk)
- **Long-lived particles** (1904.10661, 1911.06576, 2201.08960, Yulei Zhang's Talk, Wei Su's Talk, Cen Mo's Talk;)
- **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 (Changlong Xu's talk)
  - ……
- **Global fits:**
  - Global fit of SUSY (2203.04828, 2203.07883)
  - SMEFT global fit (2206.08326)

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BSM prospects at CEPC are included in CEPC snowmass white paper: arXiv:2205.08553

BSM Higgs

■ **Many BSM models motivate Higgs exotic decay considerations: singlet extensions, two Higgs-doublet-models (2HDM), SUSY models, Higgs portals, gauge extensions of the SM, …**

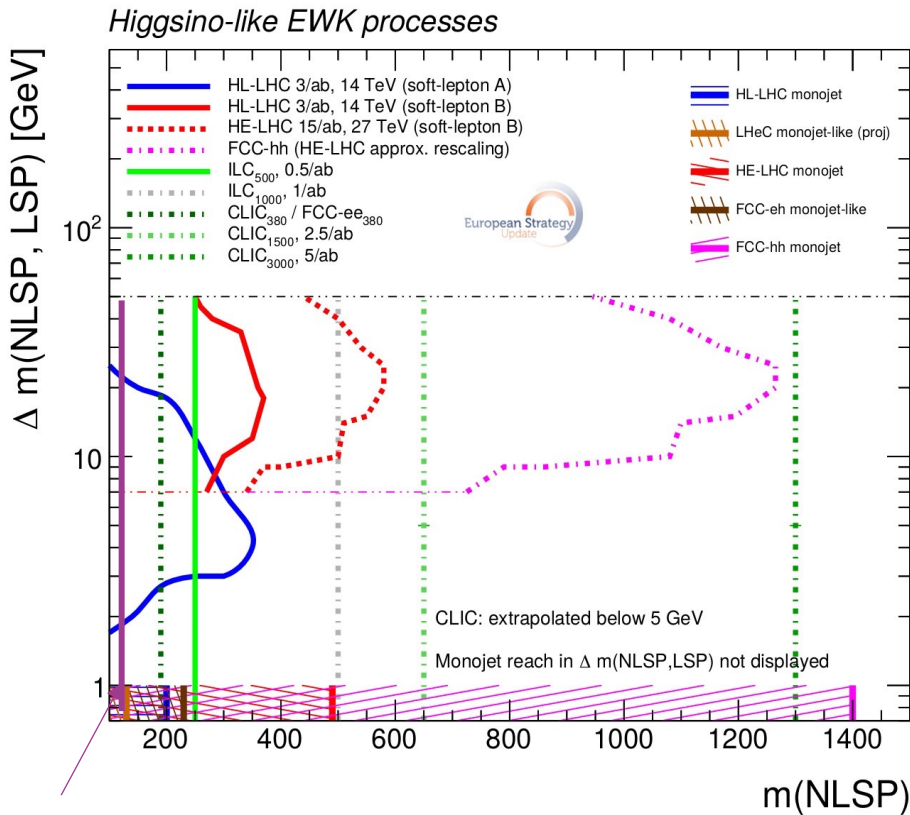Representative topologies of the Higgs exotic decays
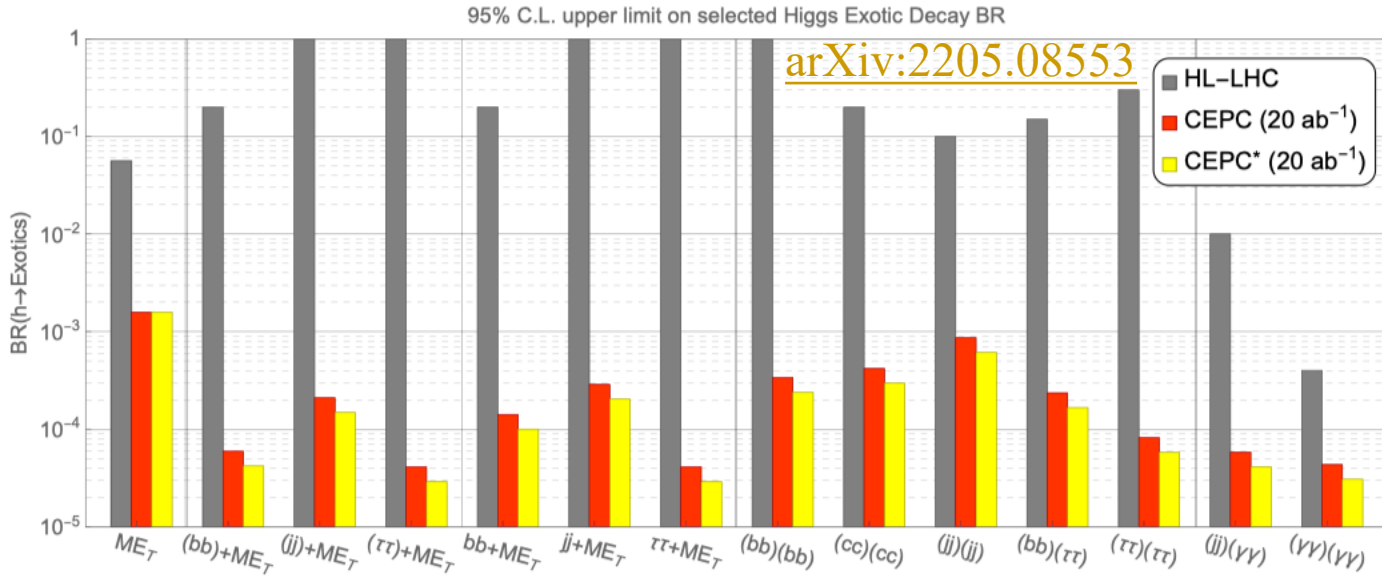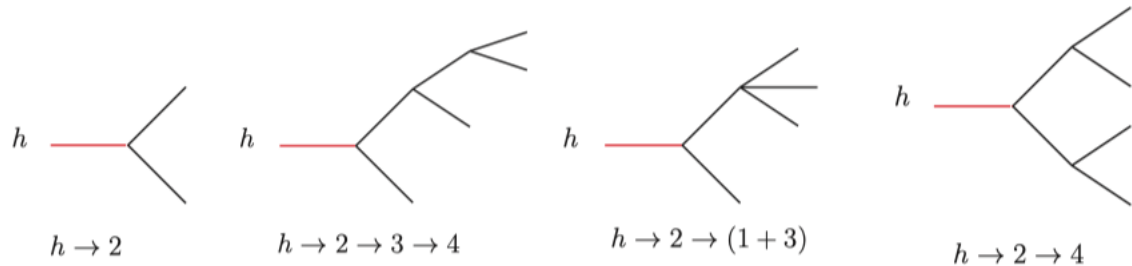
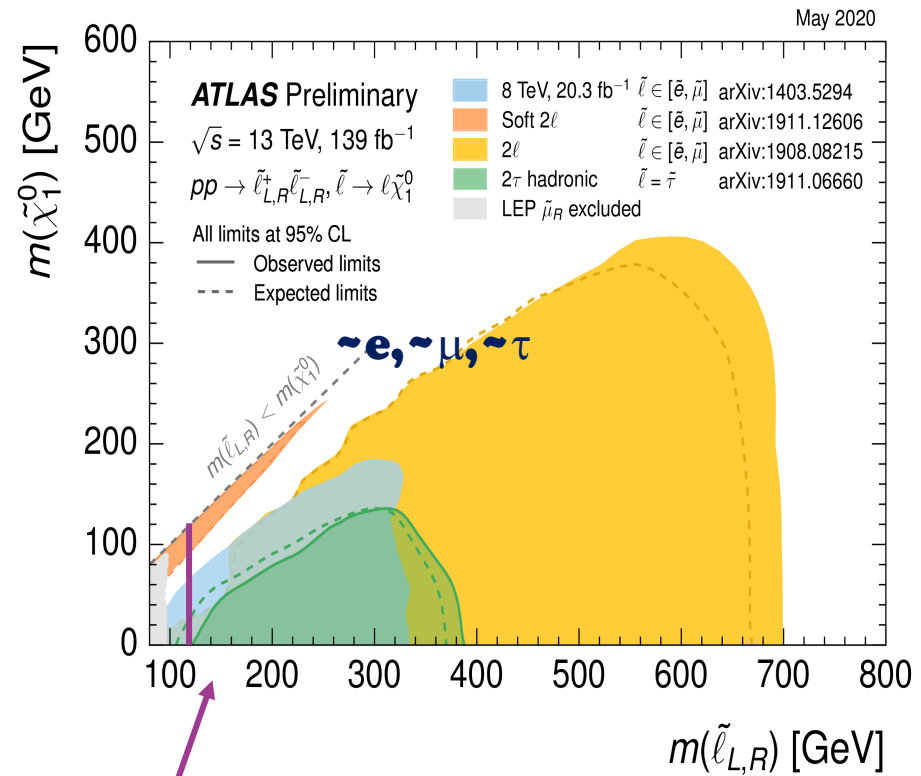The 95% C.L. upper limit on selected Higgs exotic decay BR

arXiv:2205.08553

→ **Good sensitivity of exotic Higgs decay from CEPC**

- **Mainly light EWKino and slepton for CEPC**
- Lepton collider: discovery in all scenarios up to kinematic limit: $\sqrt{s}/2$

CEPC/FCCee(240)

CEPC

$e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0, W^\pm \to \nu\ell^\pm$ (Higgsino LSP)

CEPC Simulation

$\sqrt{s} = 240\ GeV,\ 5.05\ ab^{-1}$

**Higgsino search
CPC46(2022)013106**

**Bino NLSP
arXiv.2101.12131**

$\tilde{B} \to \tilde{G}/\tilde{a} + \gamma$

5σ observation @ 5.6 ab⁻¹
2σ exclusion @ 5.6 ab⁻¹

**Heavy selectron
arXiv: 2202.11011**

$e^+e^- \to \tilde{\chi}_1^0(bino) + \tilde{\chi}_1^0(bino) + \gamma$

Z pole
Higgs pole
5σ
3σ
2σ

**Stau search
arXiv:2203.10580**

$e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-, \tilde{\tau} \to \tau\tilde{\chi}_1^0$

CEPC Simulation

$\sqrt{s} = 240\ GeV,\ 5.05\ ab^{-1}$

$m(\tilde{\chi}_0^1) > m(\tilde{\tau}) - m(\tau)$

5 σ $\tilde{\tau}_{L,R}$
2 σ $\tilde{\tau}_{L,R}$
5 σ $\tilde{\tau}_L$
2 σ $\tilde{\tau}_L$
5 σ $\tilde{\tau}_R$
2 σ $\tilde{\tau}_R$

**Smuon search
arXiv:2211.08132**

$e^+e^- \to \tilde{\mu}_{L,R}^+ \tilde{\mu}_{L,R}^-, \tilde{\mu} \to \mu\tilde{\chi}_1^0$

$\sqrt{s} = 240\ GeV,\ 5.05\ ab^{-1}$

$m_{\tilde{\chi}_1^0} = m_{\tilde{\mu}} - m_\mu$

This work:
2σ
5σ

arXiv:2203.10580
2σ
5σ

+Smuon off-shell decay
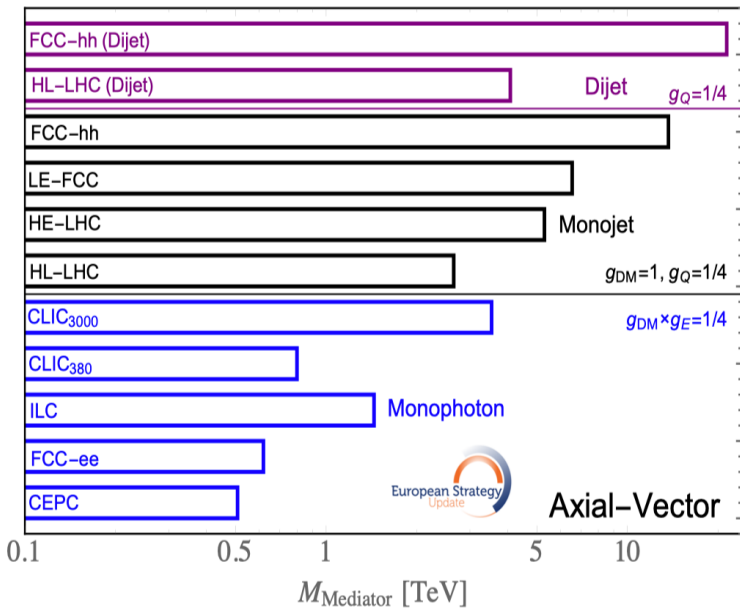
6

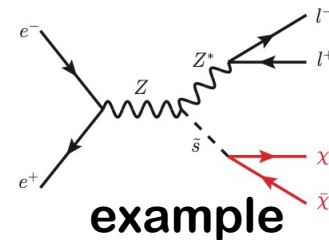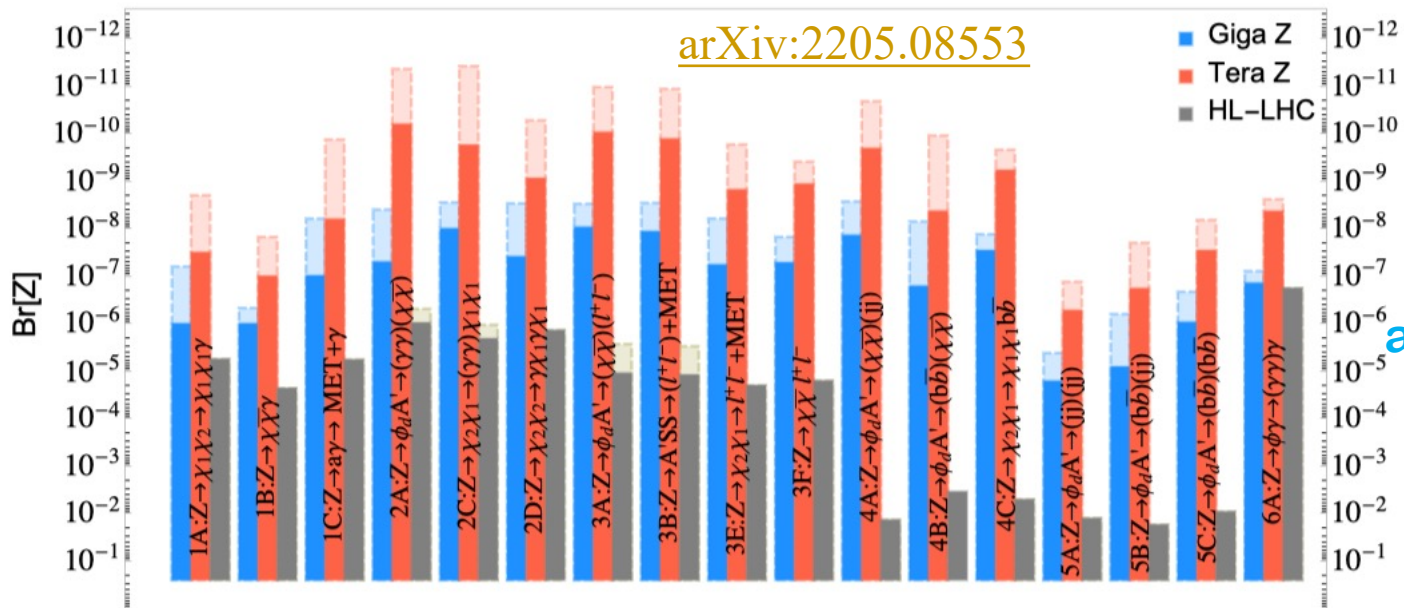# Dark Matter and Dark Sector searches

DM search at CEPC

■ **Exposing Dark Sector via exotic Z-boson decay with** *Future Z-Factories*, **Jia Liu, Lian-Tao Wang, Xiao-Ping Wang, Wei Xue, 1712.07237, PRD 97, 095044 (2018)**

   Four models include: Higgs/Vector portal DM, inelastic dark matter and axion like particles.

→ **Compared with HL-LHC, the reach for the BR of various exotic Z decay modes at Z-factories is sensitive for many decay modes.**

arXiv:2205.08553

example

arXiv: 1712.07237

- **Probing DM particles *at CEPC* (Millicharged DM, Vector portal DM, EFT DM): ZL, Y.-H. Xu, Y. Zhang ,1903.12114**

- **Mono-γ Production of a Vector Dark Matter *at CEPC*, K Ma, 2205.05560**

- **Exposing Dark Sector-photon interactions *at CEPC*, Y. Zhang, M. Song and L. Chen, arXiv: 2208.08142, Yu Zhang's talk**
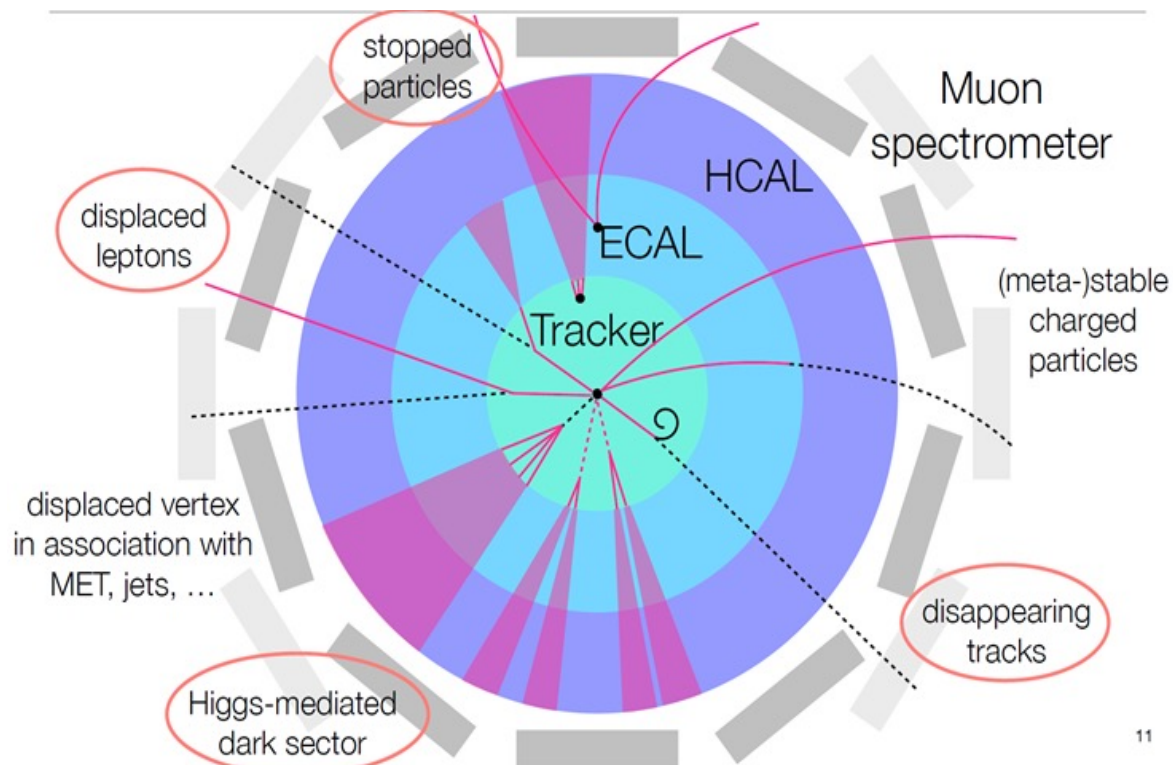
→ **CEPC can probe low-mass light dark states.**
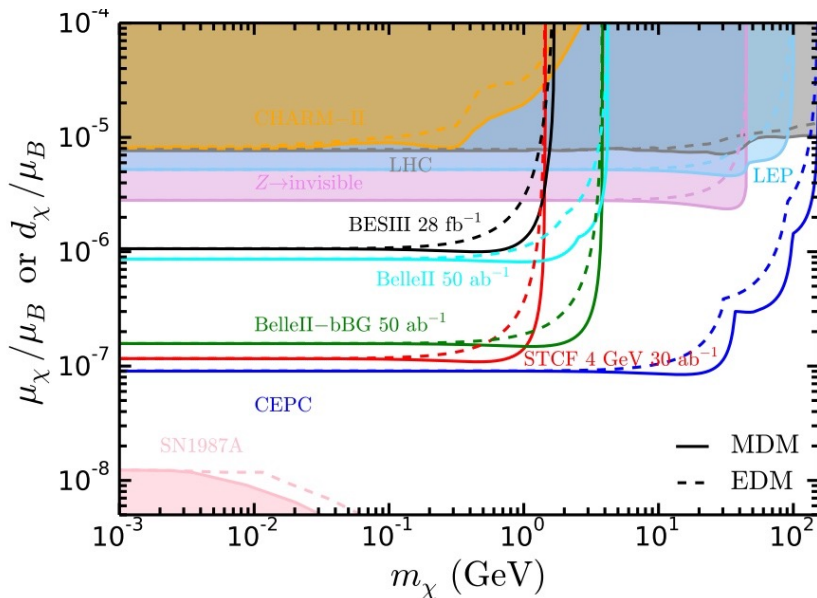
new physics process: $e^+e^- \to \bar{\chi}\chi\gamma$
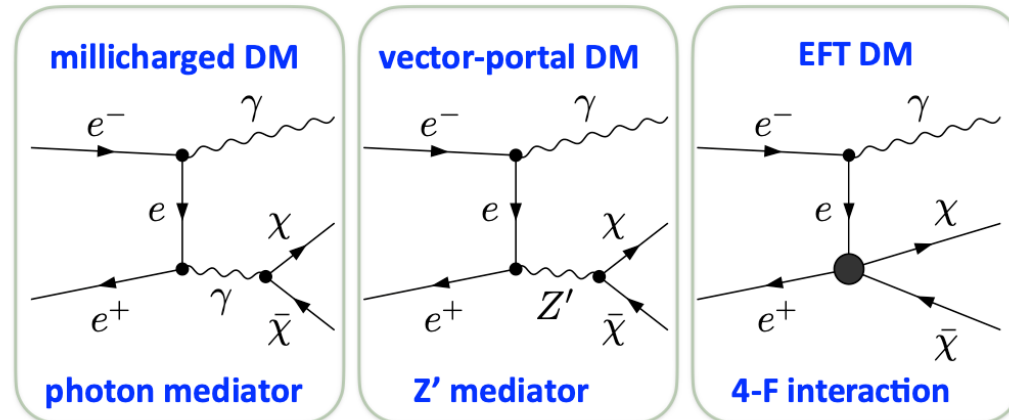
Long-lived particles (LLP)

Long lifetimes result from a few simple physical mechanisms:

- Small couplings (ex. RPV SUSY)

- Limited phase space: small mass splitting (ex. compressed SUSY, …)

- Heavy intermediate states

- ……

■ **Physics with Far Detectors at Future Lepton Colliders, Zeren Simon Wang, Kechen Wang, 1911.06576, PRD 101, 075046 (2020)**

■ **Search for long-lived axions with far detectors at future lepton colliders, Minglun Tian, Kechen Wang, Zeren Simon Wang, 2201.08960**

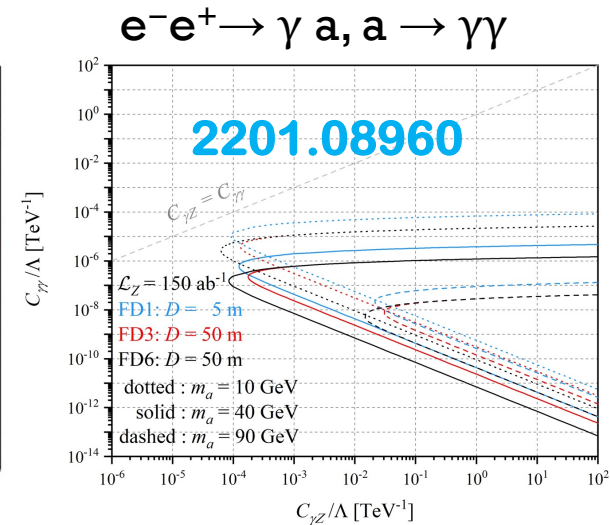→ **FD can extend and complement the sensitivity to the LLPs compared with Near Detector**

$e^-e^+ \rightarrow \gamma\, a,\, a \rightarrow \gamma\gamma$

2201.08960
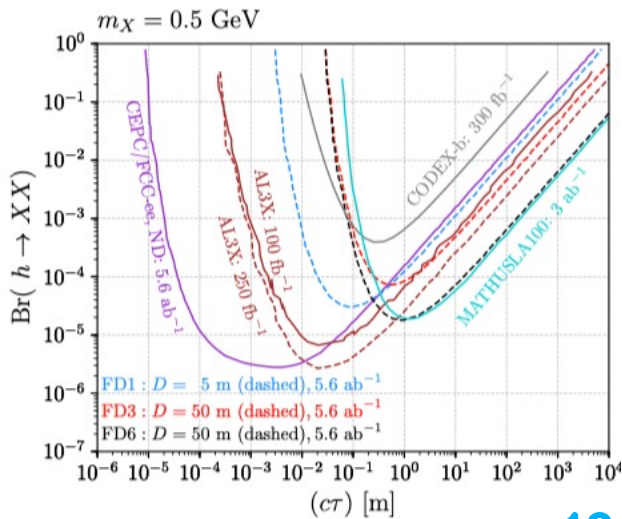
1911.06576

Light Scalars from Exotic Higgs Decays
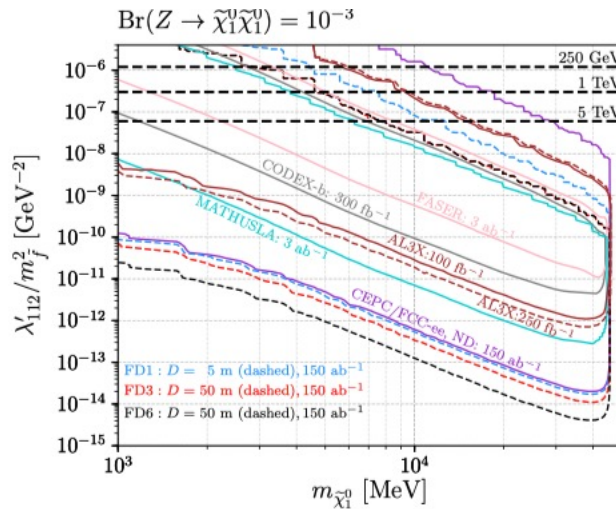
Light Neutralinos from Z-boson Decays
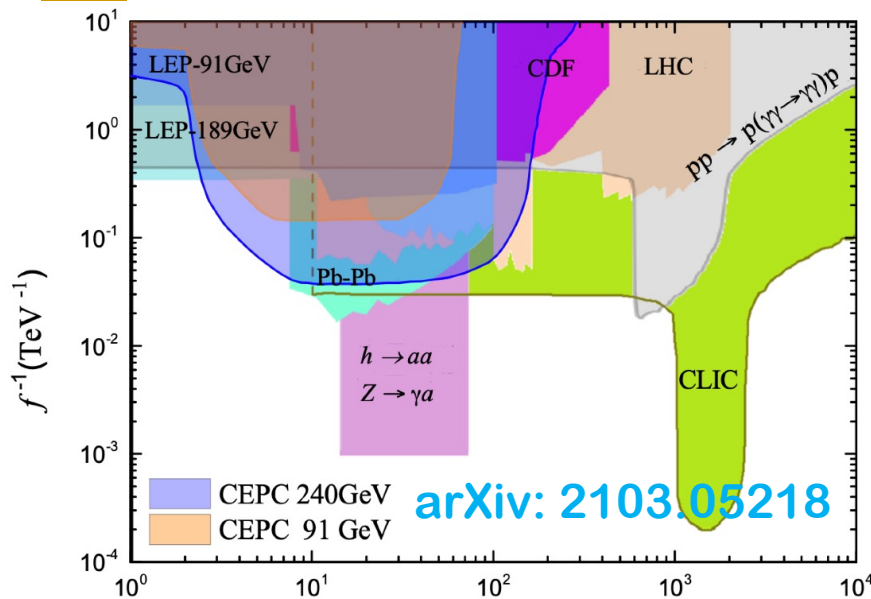
Axion-like Particles

Axion-like particles (ALP)

■ **Searching for ALP** *at future electron-positron colliders*, **H. Y. Zhang, C.X. Yue, Y.C. Guo, and S. Yang,** 2103.05218, PRD104 (2021) 096008

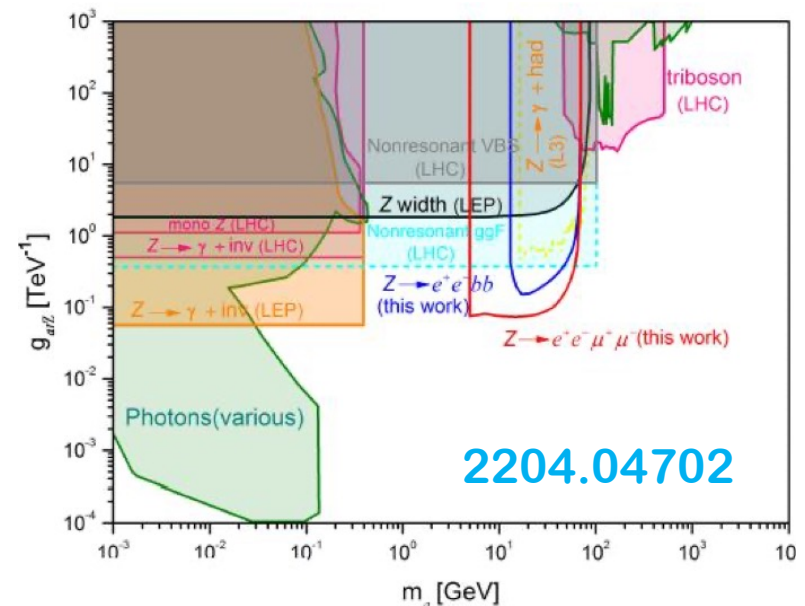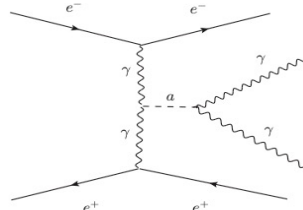→ CEPC is more sensitive to the ALPs couplings $g_{a\gamma\gamma}$ with mass 2-8 GeV than LHC and CLIC.

■ **Searching for ALP via decay Z→aff̄** *at future Z factories*, 2204.04702

■ **Axion-like particle solution to muon g-2 and its test** *at Z-factory*, Jia Liu's **talk**

arXiv: 2103.05218
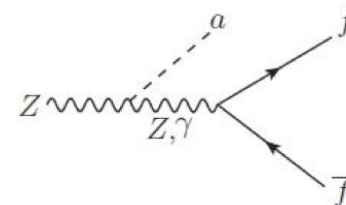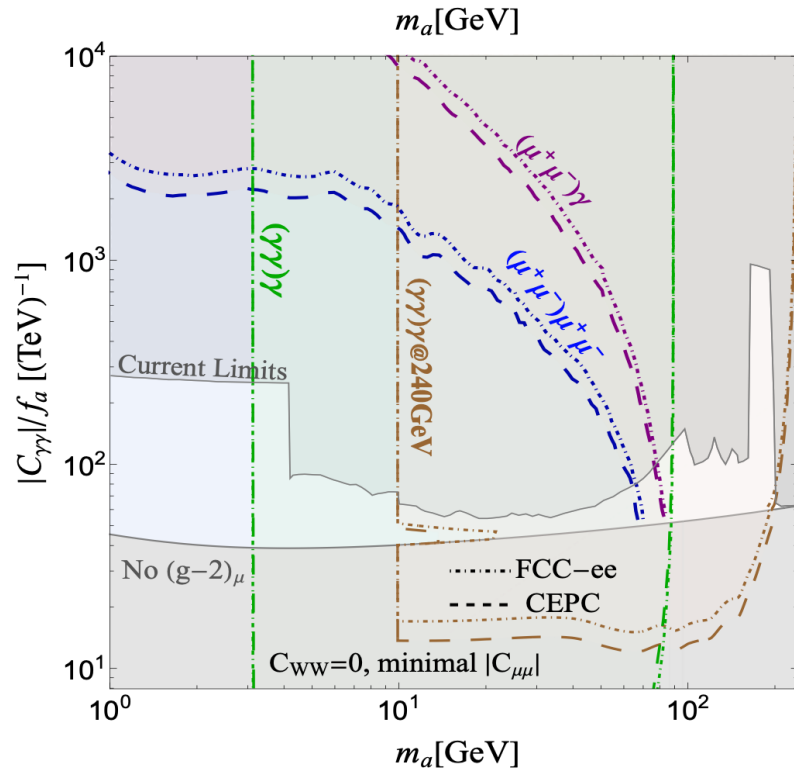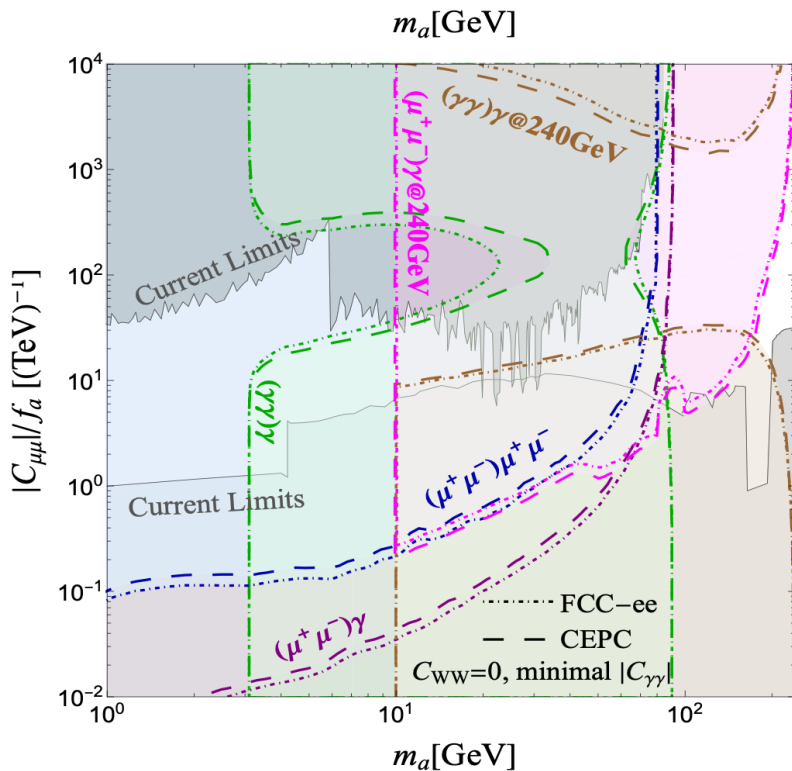
2-8 GeV

M_a (GeV)

2204.04702

5-70 GeV

- **The ALP explanation to muon g-2 and its test at CEPC, J. Liu, X.L. Ma, L.T. Wang, X.P. Wang, arXiv:2210.09335, Xiao-Ping Wang's talk**

→ ALP can provide a g-2 solution with couplings $C\mu\mu$ and $C\gamma\gamma$;

→ Tera-Z and Higgs factories, can completely cover the relevant parameter space through searches with final states $(\gamma\gamma)\gamma$, $(\mu+\mu-)\gamma$ and $(\mu+\mu-)\mu+\mu-$.

■ **Monojet Search for Heavy Neutrinos** *at Future Z-Factories*, **Y.F. Shen, J.N. Ding, Q. Qin, arXiv: 2201.05831, Yin-Fa Shen' talk**

→ The monojet method will be able to fill the gap and has better sensitivity around the mass range between **5-15 GeV**.
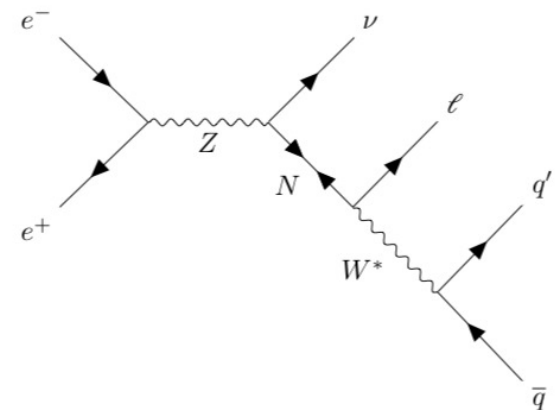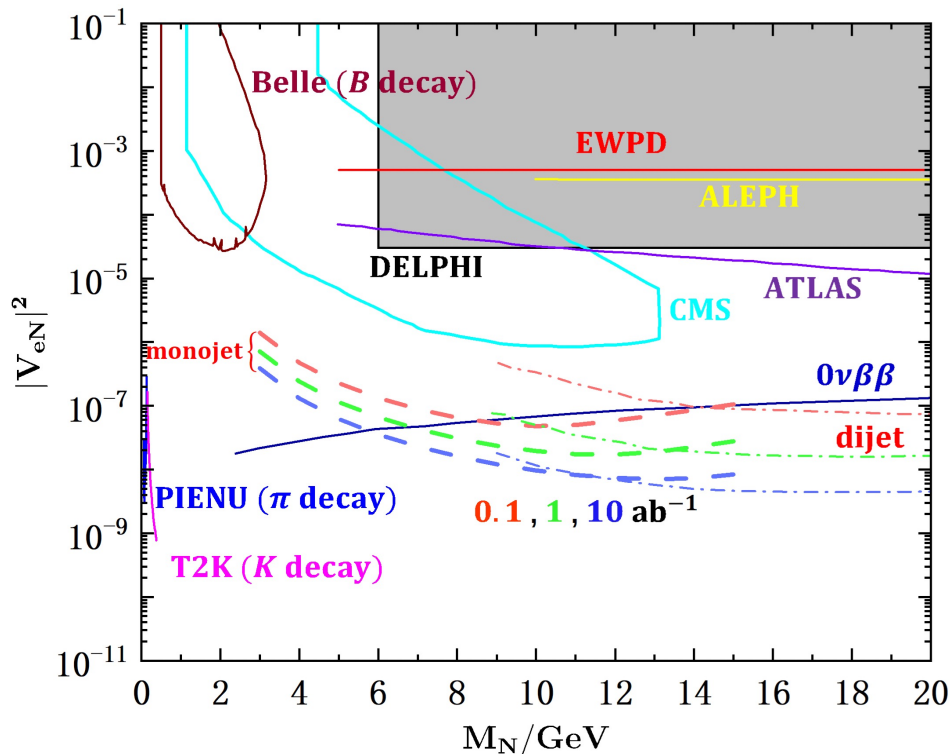
■ **Electroweak Phase Transition in 2HDM under Higgs, Z-pole, and W precision measurements, H. Song, W. Su, and M. Zhang,** *arXiv:2204.05085, JHEP* **10 (2022) 048 , H. Song's** **talk**

→ Under current constraints, both Type-I and Type-II 2HDM can explain the strong first order electroweak phase transition (SFOEWPT), Z-pole, Higgs precision measurements and mW precision measurement of CDF-II at same time.
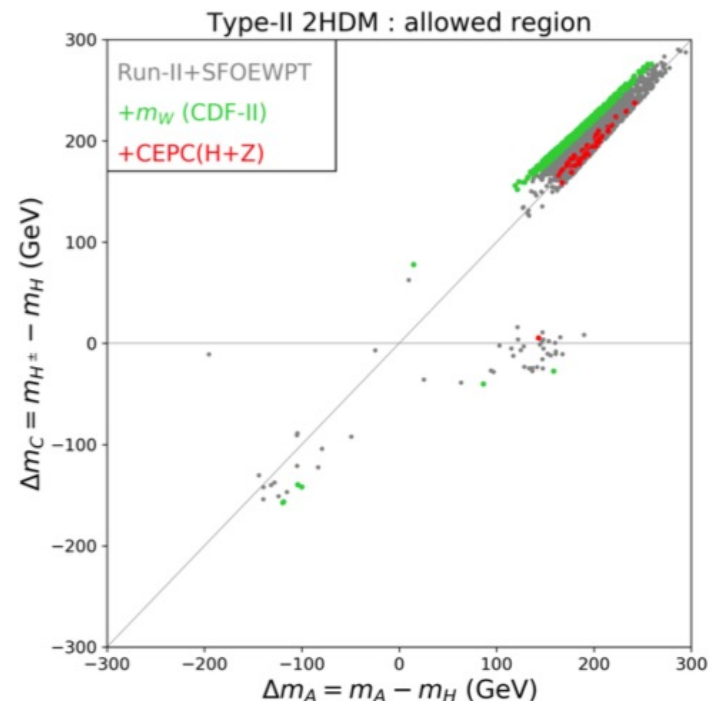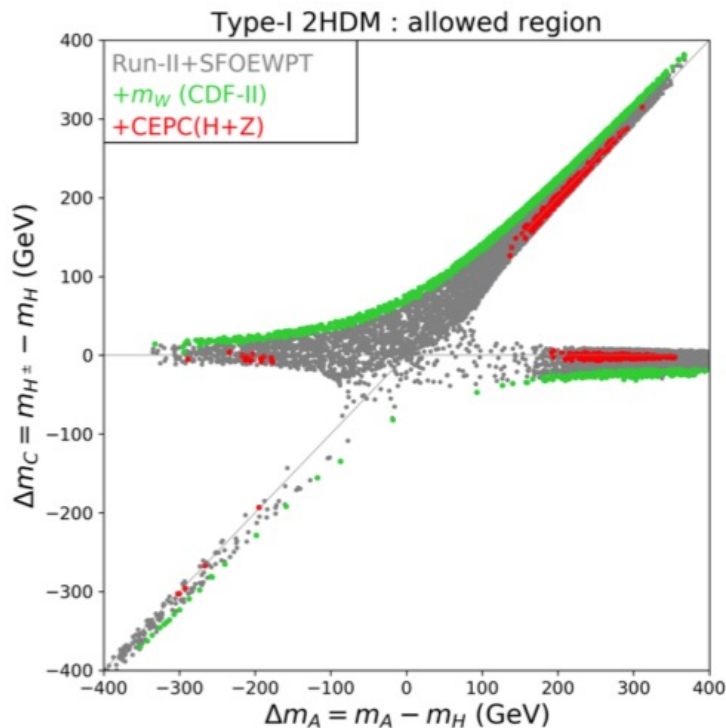
■ **Study of the impact of the Higgs and electroweak precision measurements at the CEPC *with GAMBIT global fits* of the SUSY models, such as CMSSM, NUHM1, NUHM2 and pMSSM-7, Yang Zhang etc, arXiv: 2203.04828**

→ **CEPC can further test the currently allowed parameter space of these models, advance our understanding of the mass spectrum**
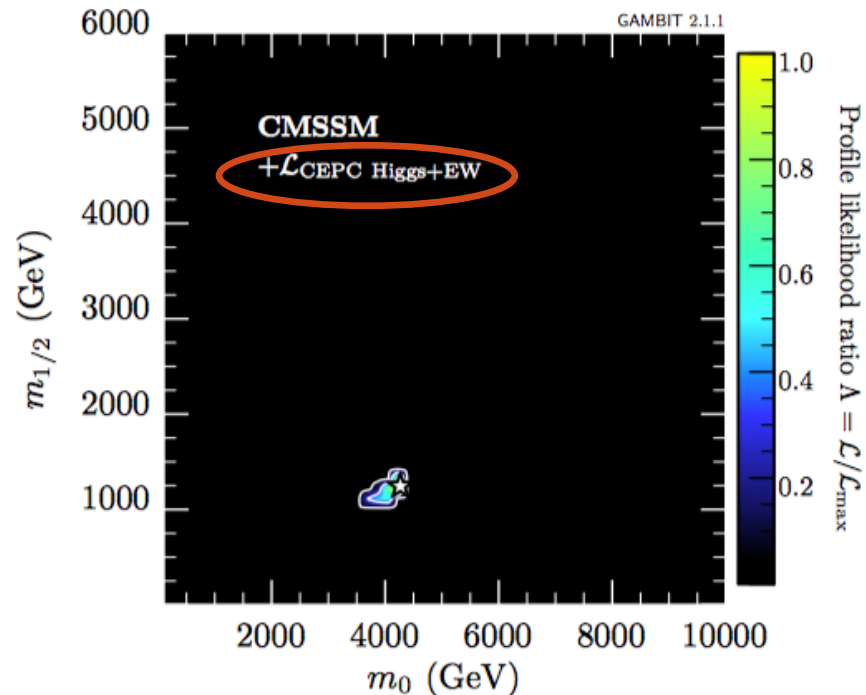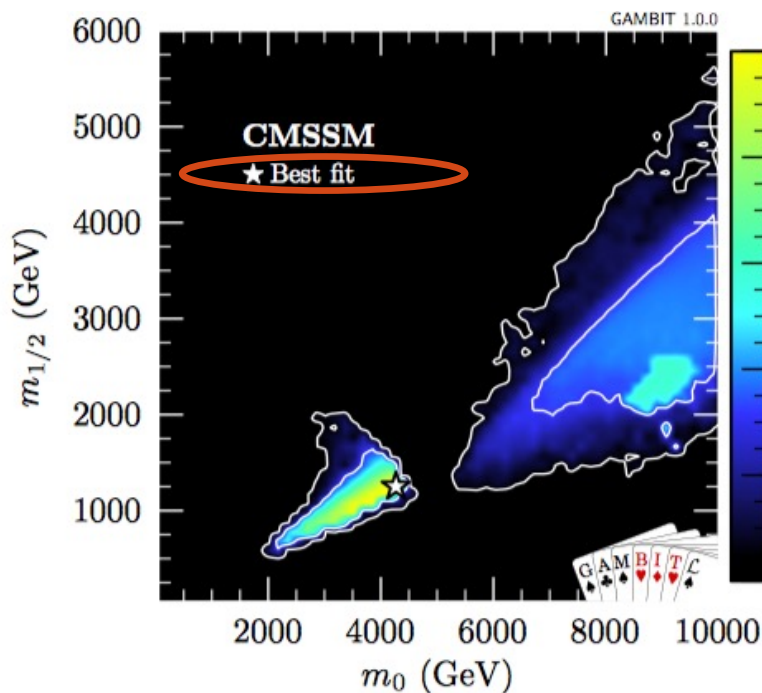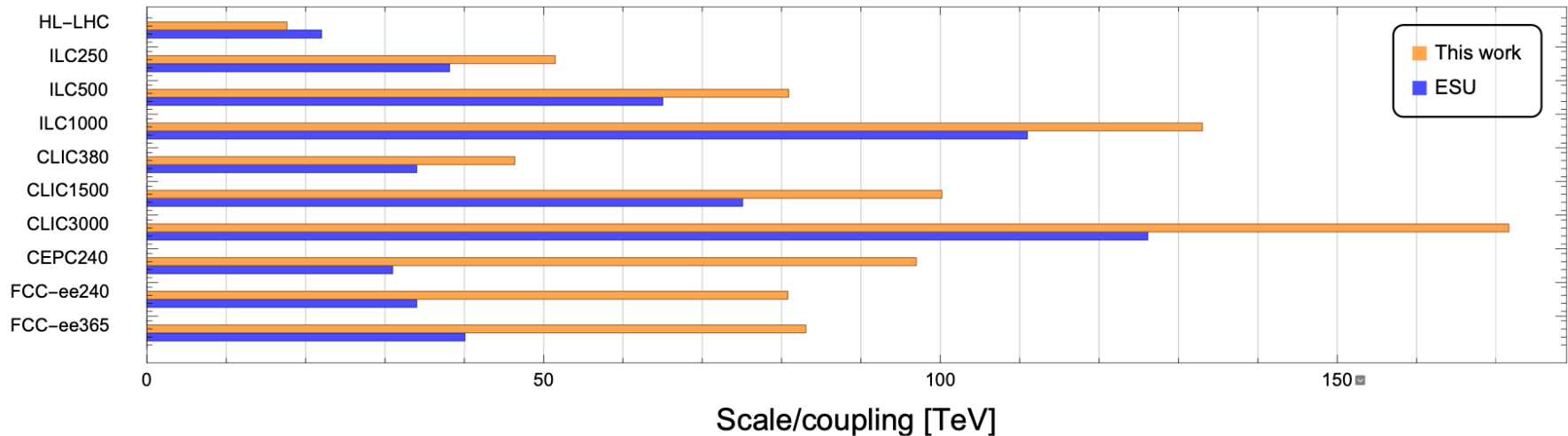
■ **SMEFT global fit for 4-fermion and CPV operators at future colliders, 2206.08326, Yong Du's talk**

→ The sensitivity to new physics from global fit is significantly enhanced thanks to the high energy/ luminosity/beam polarization of future lepton colliders

95% CL scale limits on 4−fermion contact interactions from O_{2B}

Summary and Outlook

- **CEPC has good discovery potential for NP at many scenarios which are challenge for LHC**

- **BSM prospects study at CEPC is going on well, many of the analyses are already public**

- **Plan to organize a workshop this April/May to collect inputs for CEPC BSM white paper**

- **Please let us know if you would like to contribute to the BSM white paper !**

Thanks for your attention!

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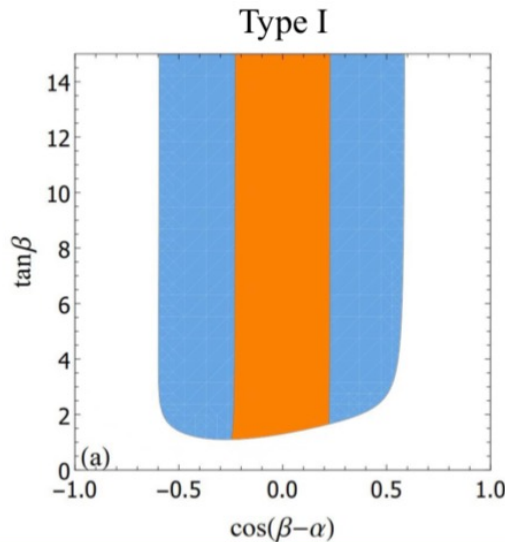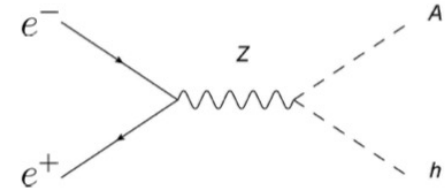# Backup

Identify CP-odd component in Higgs

- **Use di—higgs production to identify CP-odd component in Higgs boson, Changlong Xu's talk**

- Future electron-positron colliders are more powerful for exploring the ZHH Di-Higgs production

Di-Higgs in CEPC/ILC/FCC-ee

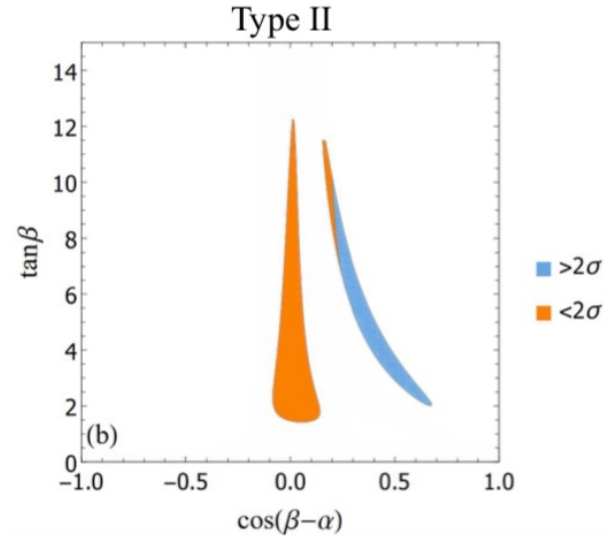**350 GeV e^+e^- collider:** 1 ab^{-1}

$b\bar{b}b\bar{b}$ final state

$$\mathcal{L}_{ZhA} \sim i\left(h\partial_\mu A - A\partial_\mu h\right) Z^\mu \frac{g}{2\cos\theta_w} \cos(\beta - \alpha)$$
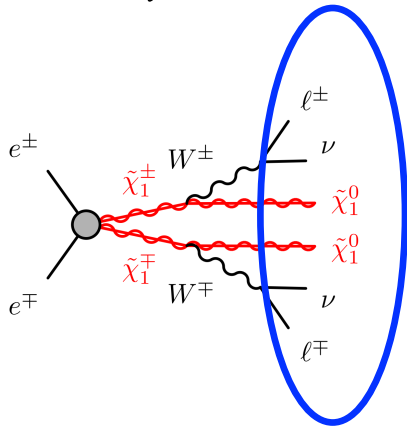

Type I / Type II plots with axes $\tan\beta$ vs $\cos(\beta-\alpha)$

- $>2\sigma$ (blue)
- $<2\sigma$ (orange)

Type-I: $\kappa_h^f = \sin(\beta - \alpha) + \frac{\cos(\beta-\alpha)}{\tan\beta}$

$\kappa_A^u = \frac{1}{\tan\beta}$ $\kappa_A^{d,\ell} = -\frac{1}{\tan\beta}$

Type-II: $\kappa_h^u = \sin(\beta - \alpha) + \frac{\cos(\beta-\alpha)}{\tan\beta}$

$\kappa_h^{d,\ell} = \sin(\beta - \alpha) - \cos(\beta - \alpha)\tan\beta$

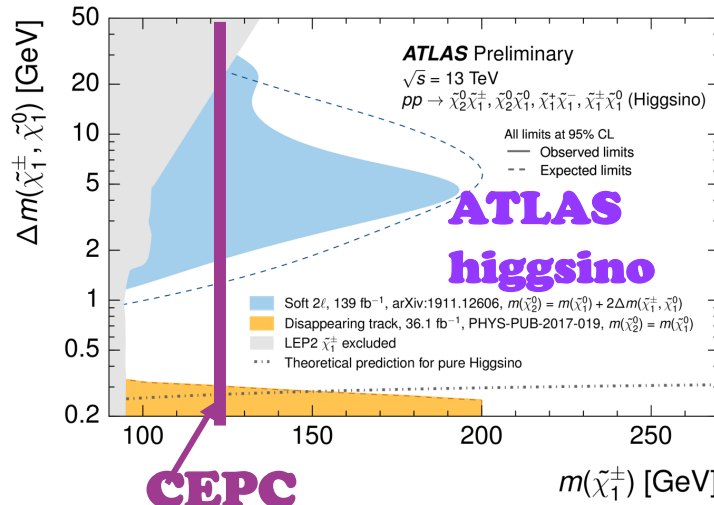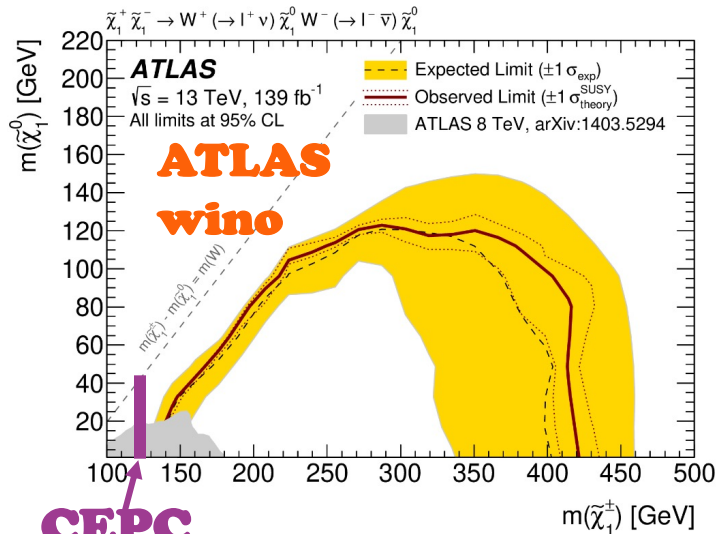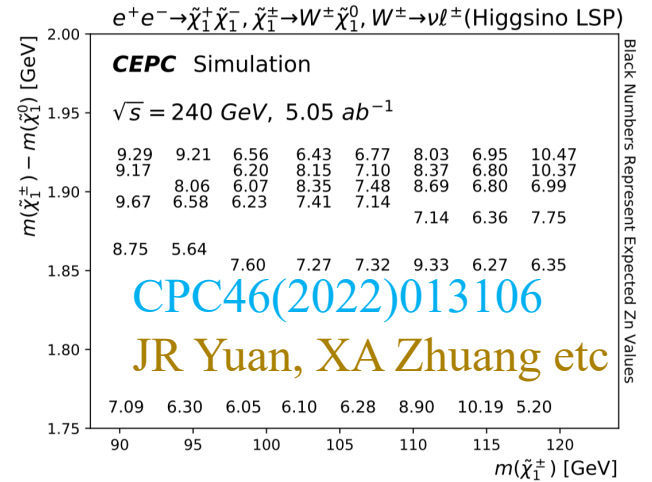$\kappa_A^u = \frac{1}{\tan\beta}$ $\kappa_A^{d,\ell} = \tan\beta$

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- **Prospects for chargino pair production at CEPC, Jia-Rong Yuan, Hua-Jie Cheng, Xu-Ai Zhuang, arXiv:2105.06135.**

Chargino pair via on(off)-shell W decay

Signature:
2 lepton + MET

$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0, W^\pm \rightarrow \nu \ell^\pm$ (Higgsino LSP)

CPC46(2022)013106

JR Yuan, XA Zhuang etc

ATLAS wino

CEPC

ATLAS higgsino
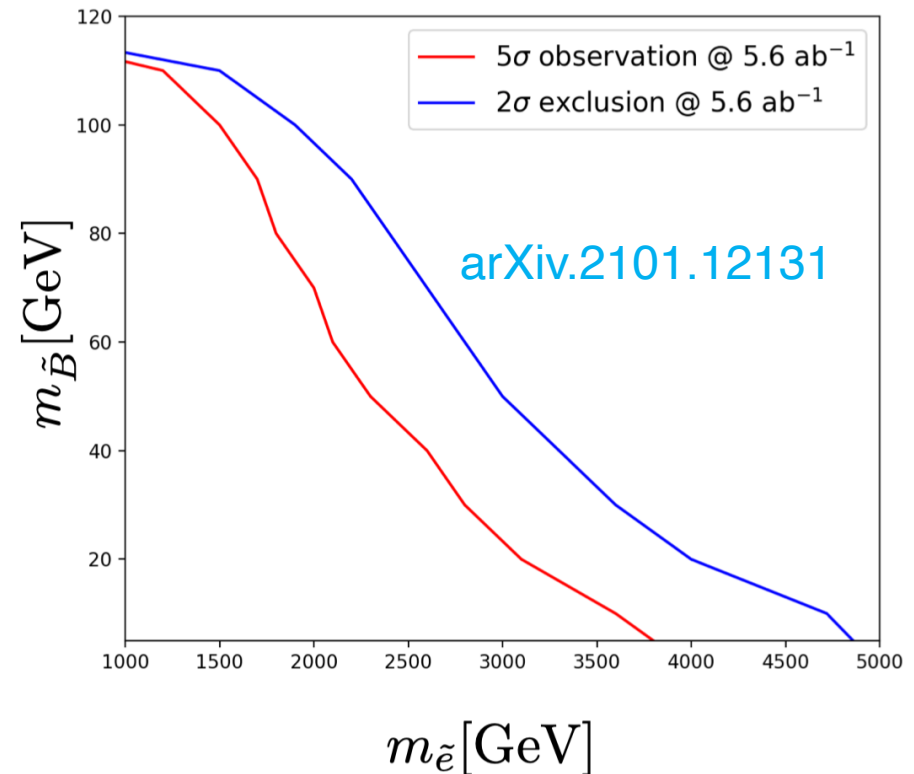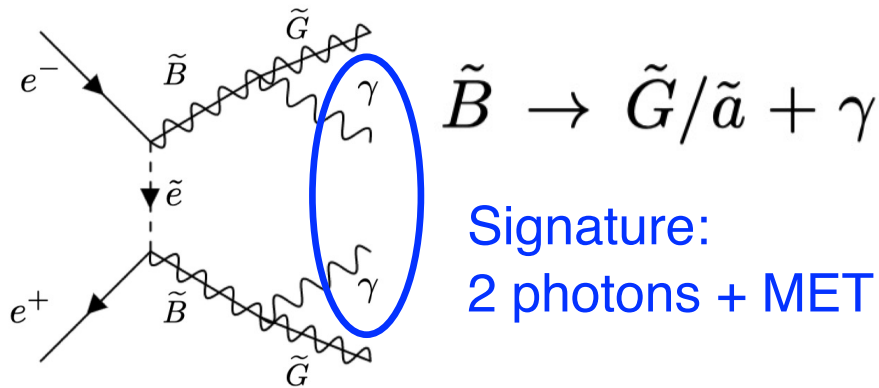
CEPC

Discovery in all scenarios up to kinematic limit: $\sqrt{s}/2$

■ **Probing bino NLSP at lepton colliders with Gravitino DM, Junmou Chen, Chengcheng Han, Jin Min Yang, Mengchao Zhang, arXiv:2101.12131.**

$$\tilde{B} \rightarrow \tilde{G}/\tilde{a} + \gamma$$

Signature:
2 photons + MET

arXiv.2101.12131

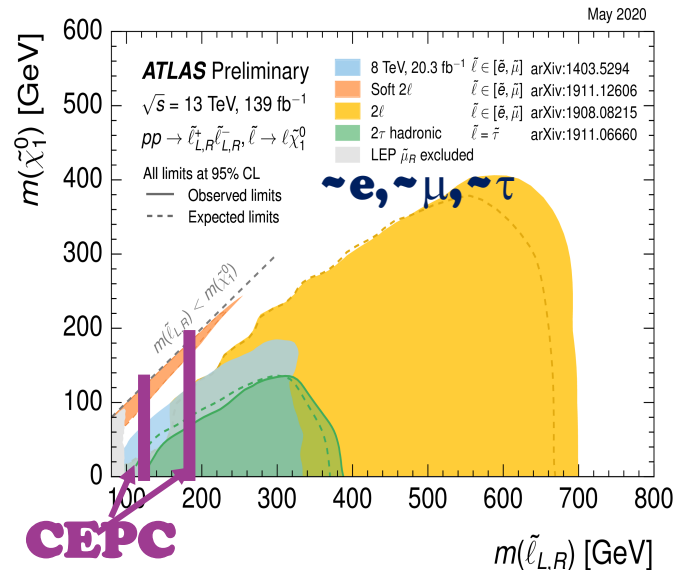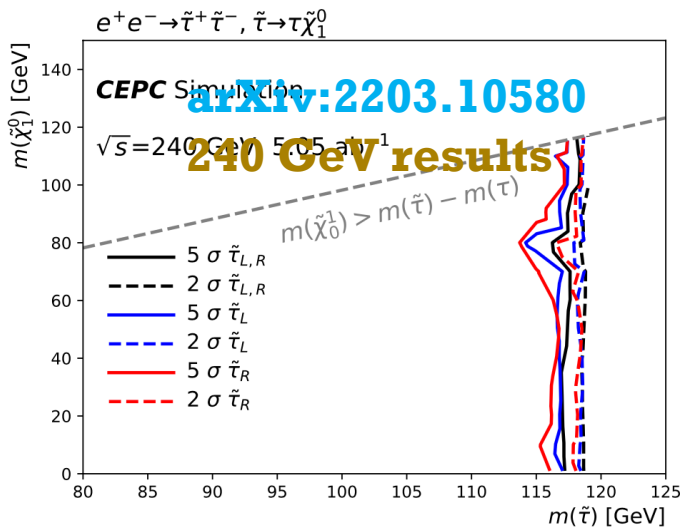■ **Prospects for slepton pair production at CEPC, Jia-Rong Yuan, Hua-Jie Cheng, Xu-Ai Zhuang, arXiv: 2203.10580**

Signature:
2 lepton + MET

arXiv:2203.10580
240 GeV results

~e, ~μ, ~τ

CEPC

First 360 GeV results,
Feng Lv's talk

Including smuon offshell production
Pengxuan Zhu's talk

$$e^+e^- \to \tilde{\mu}\tilde{\mu}^{(*)} \to \mu^+\tilde{\chi}_1^0 \mu^-\tilde{\chi}_1^0$$
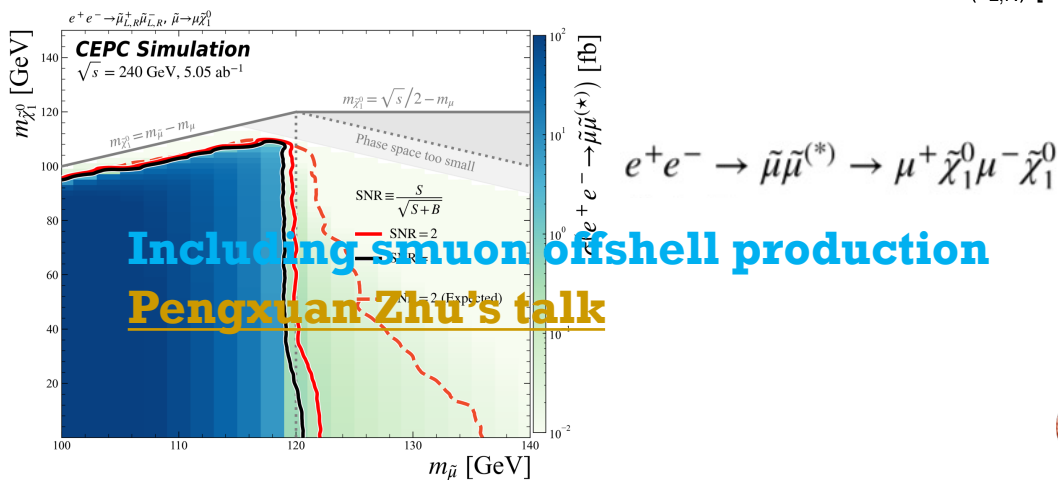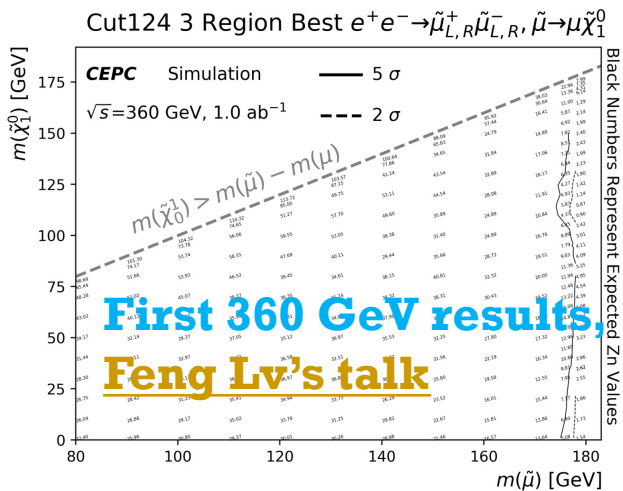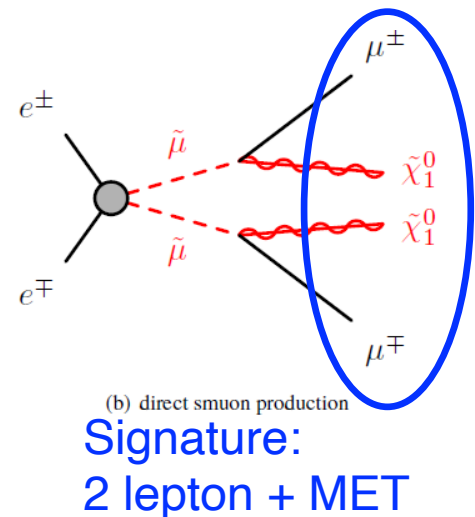
■ **Probing relatively heavier right-handed selectron in the GmSUGRA, by Waqas Ahmed, Imtiaz Khan, Tianjun Li, Shabbar Raza and Wenxing Zhang, arXiv: 2202.11011**

■ **There two types of light neutralinos that achieve the correct relic density by Z-resonance and h-resonance.**

Higgs-pole $\rightarrow m_{\tilde{\chi}_1^0} \approx \frac{1}{2} m_h$ and Z-pole $\rightarrow m_{\tilde{\chi}_1^0} \approx \frac{1}{2} m_Z$.

$$e^+ e^- \rightarrow \tilde{\chi}_1^0 (bino) + \tilde{\chi}_1^0 (bino) + \gamma$$

arXiv: 2202.11011
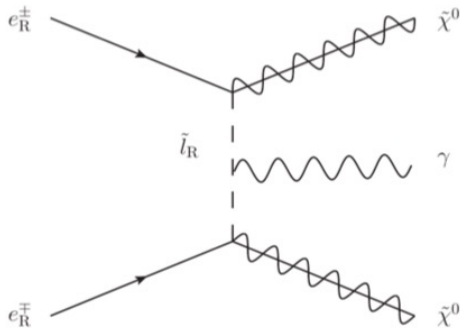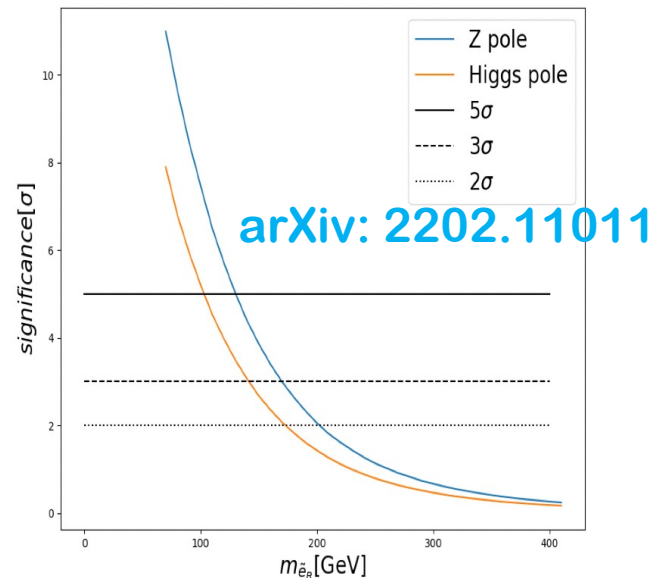
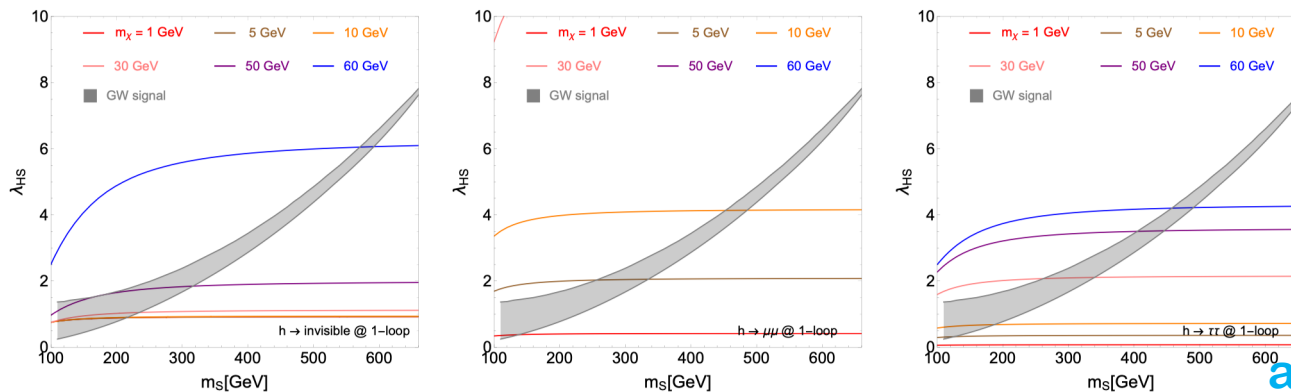- **Searching for lepton portal dark matter with colliders and interplay with the gravitational wave (GW) astronomy, Jia Liu, Xiao-Ping Wang, KePan Xie, 2104.06421, JHEP 06 (2021) 149**

- **The phase transition GWs can also be a probe of the model.**

$$e^+e^- \to S^{\pm(*)}S^{\mp} \to \ell^+\chi\ell'^-\chi \qquad h/Z \to S^{\pm(*)}S^{\mp(*)} \to \ell^+\chi\ell'^-\chi \text{ and } h \to \chi\chi:$$


arXiv: 2104.06421

FIG. 10. Figure from Ref. [168], the interplay between GW detection and future e^+e^- collider searches. The gray shaded region is the LISA detectable parameter space. From left to right, the sensitivities for λ_{HS} are shown from future CEPC precision measurements, in which the region above a given m_χ (corresponding to a colored line) can be probed.

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- **Searching for asymmetric Dark Matter (ADM) at CEPC, Mengchao Zhang, 2104.06988, PRD 104, 055008 (2021)**
- **It is possible to generate dark quark pair through a t-channel process, dark quark q' will be a jet-like object in detector.**


Decay to leptons

Jet-like

Signature:
Lepton + jet + MET

arXiv: 2104.06988
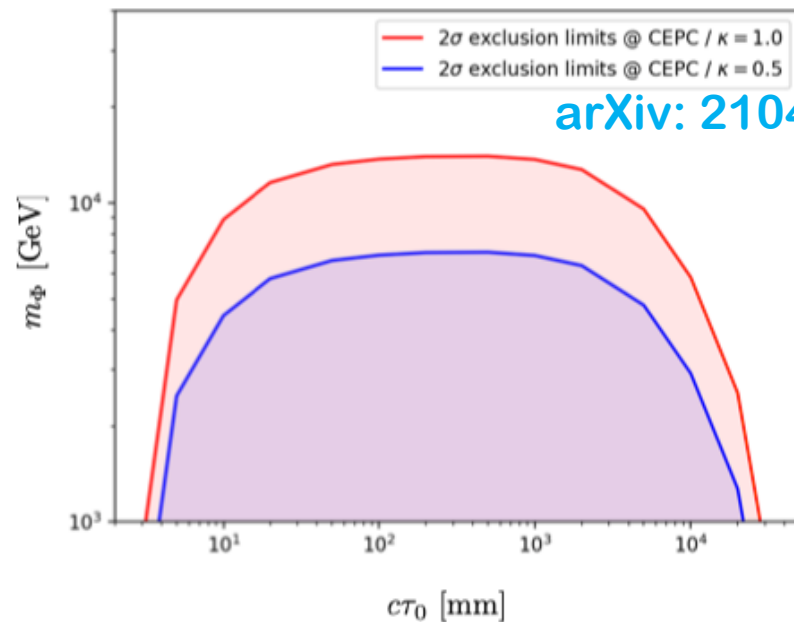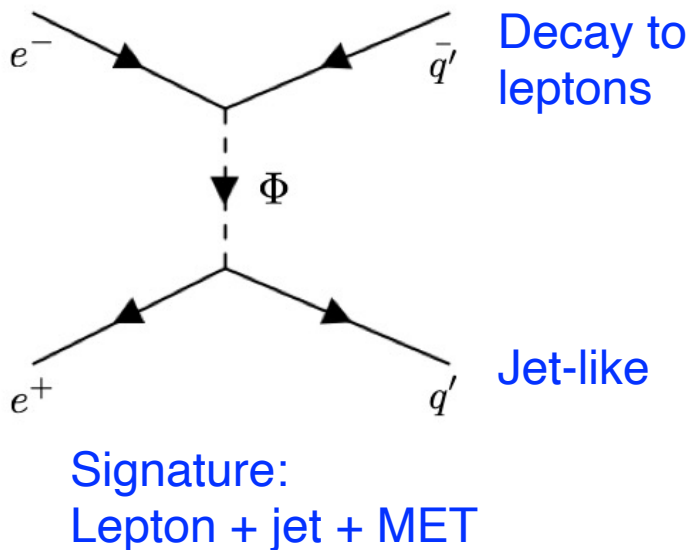
- **The mass of mediator can be excluded up to O(10) TeV, better than LHC**

Dark Matter/Dark Sector searches

- **Exposing Dark Sector-photon interactions at CEPC, Y. Zhang, M. Song and L. Chen, arXiv: 2208.08142, Yu Zhang's talk**

  → **CEPC can probe low-mass light dark states with electromagnetic form factors via mass-dimension 5 operators.**
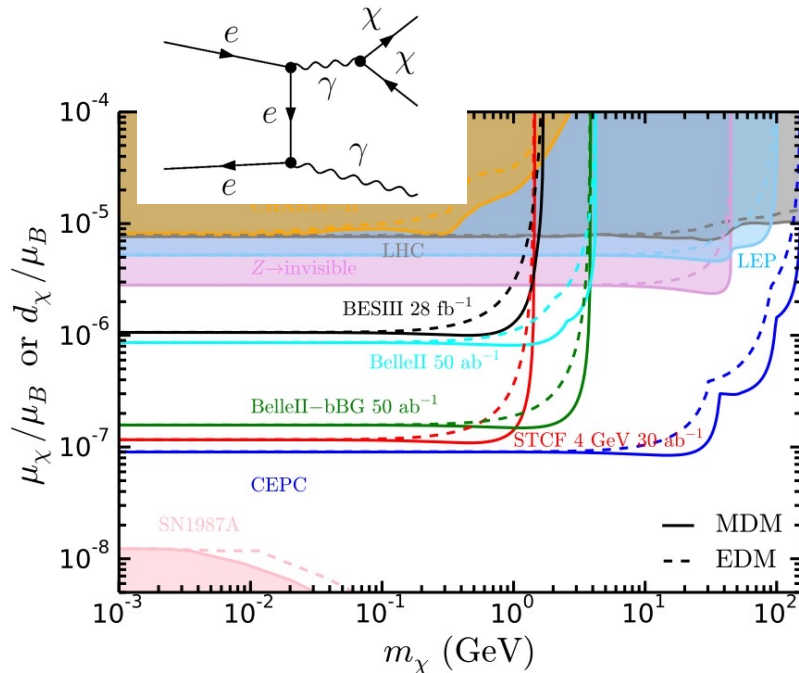
- **Exposing Dark Fermion in light of Electron Target Absorption at CEPC, Shao-Feng Ge and Kai Ma, Kai Ma's talk**

  → **All the effective four-fermion couplings can be constrained to be well above 1TeV scale**
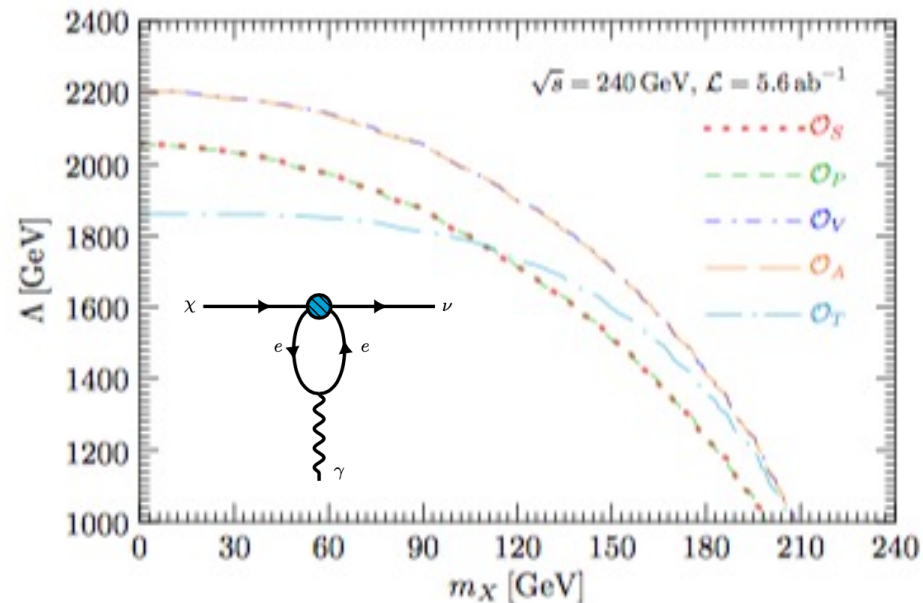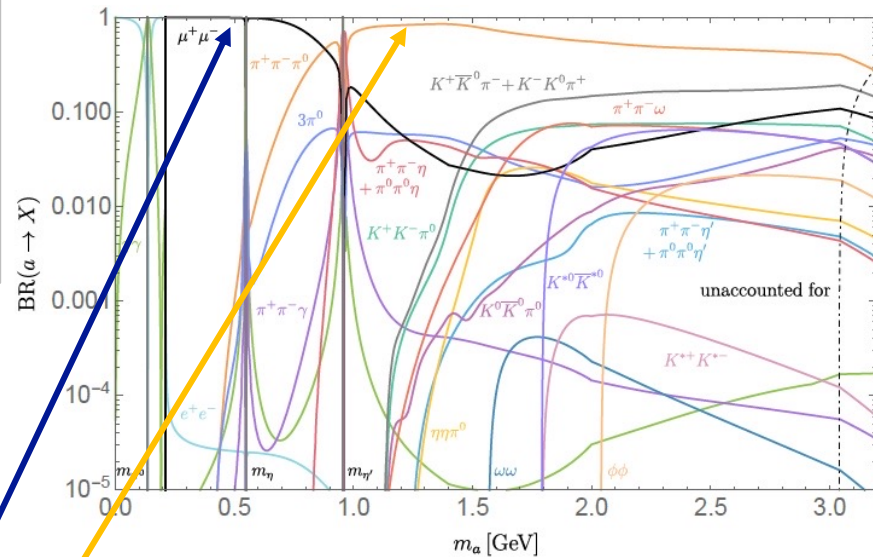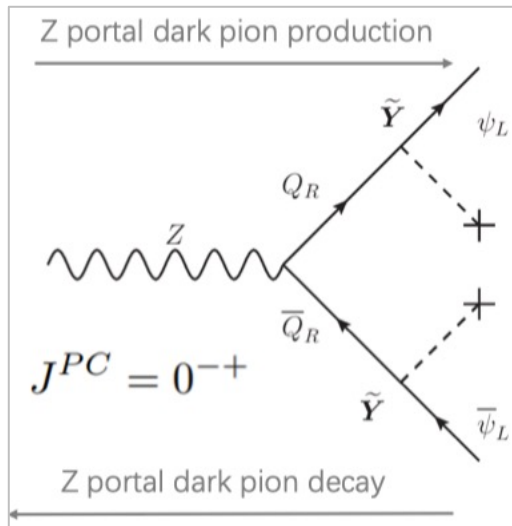
LL Dark Hadrons

■ **A theory of Dark Pions, Hsin-Chia Cheng, Lingfeng Li, Ennio Salvioni, 2110.10691, JHEP 01 (2022) 122, see Lingfeng's talk**

■ **The dark quarks couple to the SM via irrelevant Z- and Higgs-portal operators. The dark pions, behave as either composite axion-like particles (ALPs) mixing with Z or h**

$$\mathcal{L}_{\text{EFT}} = \frac{1}{2}\overline{\psi}_R Y^\dagger M^{-2} Y \left[|H|^2 i\slashed{D} + i\gamma^\mu H^\dagger D_\mu H\right]\psi_R + \text{h.c.}$$
$$+ \frac{1}{2}\overline{\psi}_L \widetilde{Y}^\dagger M^{-2}\widetilde{Y}\left[|H|^2 i\slashed{D} + i\gamma^\mu H^\dagger D_\mu H\right]\psi_L + \text{h.c.}$$
$$- \overline{\psi}_L \boldsymbol{\omega}\psi_R + \overline{\psi}_L \widetilde{Y}^\dagger M^{-1} Y \psi_R |H|^2 + \text{h.c.},$$

Dimension-6 Z portal couplings   Dimension-5 Higgs portal coupling

Z portal dark pion production

Q_R, $\widetilde{Y}$, ψ_L, Z, $\overline{Q}_R$, $\widetilde{Y}$, $\overline{\psi}_L$

$J^{PC} = 0^{-+}$

Z portal dark pion decay

BR($a \to X$) vs m_a [GeV]

● $m\pi < m\eta'$: dimuon mode dominates
● $m\pi > m\eta'$: PPP modes (mostly SM π+ π- π0)

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- **Long-lived light neutralinos at future Z−factories (RPV SUSY), Zeren Simon Wang, Kechen Wang, 1904.10661, PRD 101, 115018 (2020)**

- **The model parameter $\lambda'_{112}/m^2_{\tilde{f}}$ can be discovered down to as low as $\sim 1.5 \times 10^{-14}$ (3.9×10^{-14}) GeV^{-2} at the FCC-ee (CEPC)**

$$\mathrm{BR}(Z \to \tilde{\chi}^0_1 \tilde{\chi}^0_1) = 10^{-3}$$
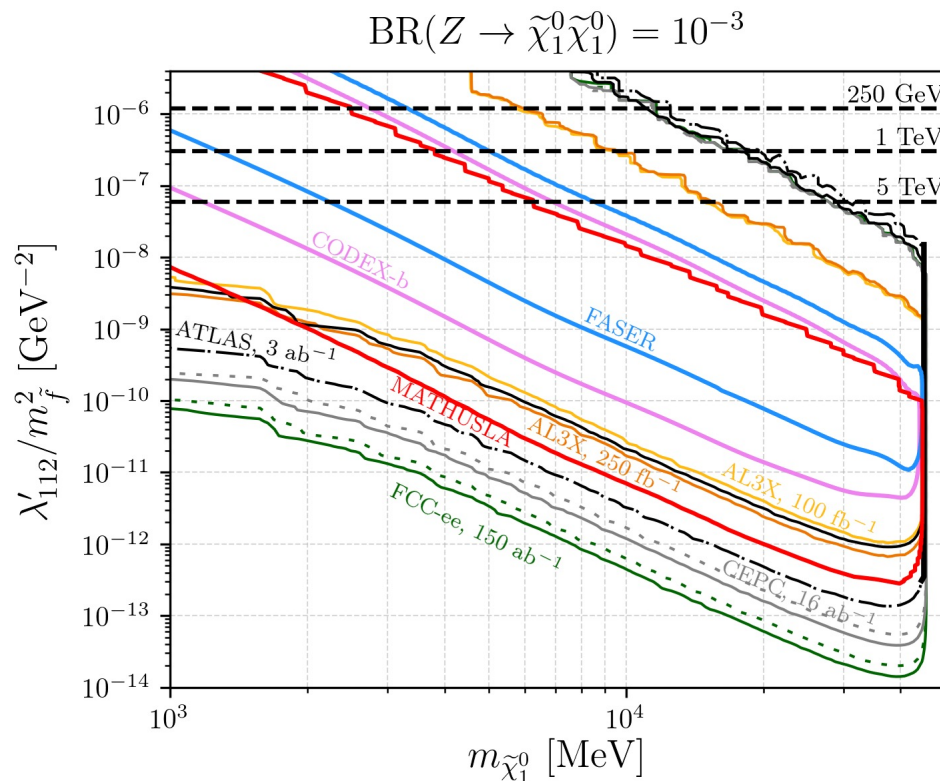
arXiv: 1904.10661

Axion-like particles (ALP)

- **The ALP explanation to muon g-2 and its test at CEPC, J. Liu, X.L. Ma, L.T. Wang, X.P. Wang, arXiv:2210.09335, Xiao-Ping Wang's talk**

- ALP can provide a solution with couplings $C\mu\mu$ and $C\gamma\gamma$;
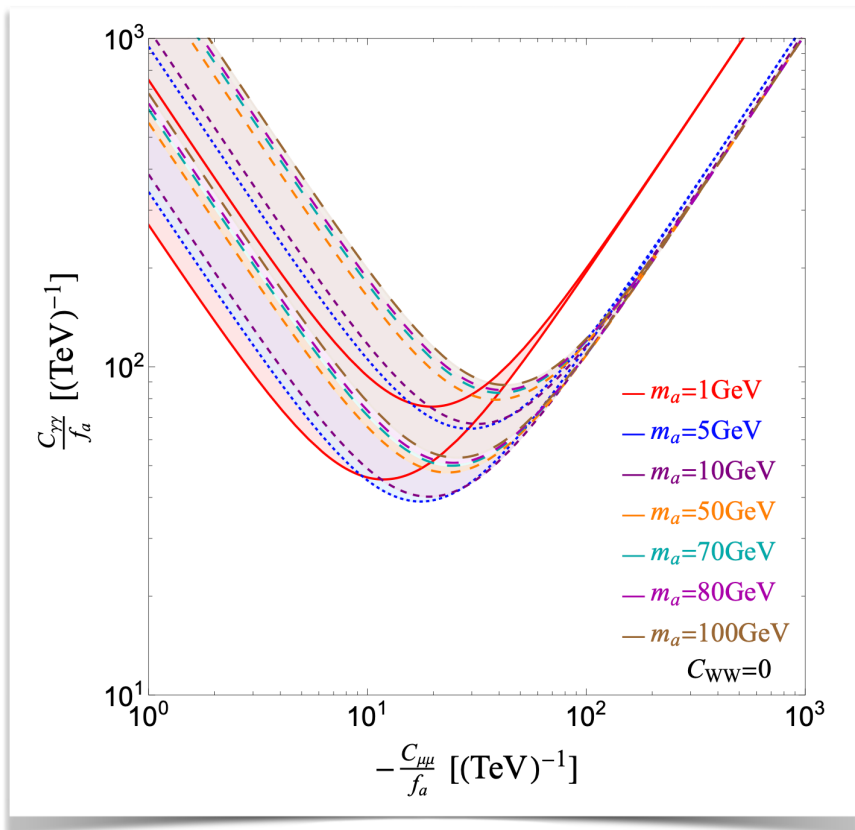
- In g-2 solution region, mostly decay to $a \to \mu^+\mu^-$

- The inclusion of Z diagram makes some difference for large m_a

- Exotic Z decay should happen