New Physics at CEPC

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Introduction

- Besides as a higgs factory, CEPC has a good potential to search for the direct production of new physics states
- With a very clean collision background, CEPC has the discovery advantage in many scenarios which are challenging at hadron colliders (large Bgs, large pile-up, trigger constraints from high energy objects, and difficulties in obj. Rec and ID, …).
  - ✓ Exotic Higgs
  - ✓ SUSY
  - ✓ Dark Matter or Dark sector
  - ✓ Long-lived particles
  - ✓ More exotics: Heavy neutrinos, Axion-like particles, EW phase transition, …

Brief summary of BSM search @CEPC

- BSM working group formed @ 2021.4 Yangzhou WS
- Big updates presented
  - @ 2021.11 CEPC WS (13 talks)
  - @ 2022.5 CEPC WS (17 talks)
  - @ 2022.8 HEP (4-5 Talks)
- BSM white paper is scheduled and going-on smoothly:
  - Preliminary organizers: Liantao Wang, Bruce Mellado, Xuai Zhuang, Jia Liu, Yu Gao, …
    - ✓ **More to be invited, volunteers are very welcome!**
  - Timeline (TBD): collect inputs and a very brief white paper draft ready by end of 2022; First paper draft is ready by next Spring?
- BSM prospects at CEPC are included in CEPC snowmass white paper: arXiv:2205.08553

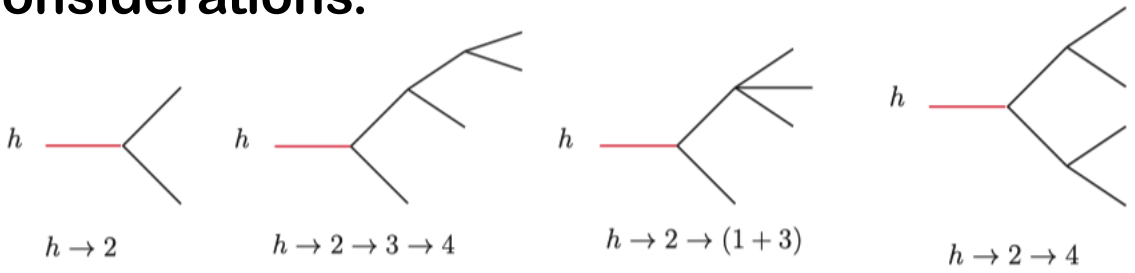
BSM Inputs & Status

- 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)
  - Indirect search of SUSY (2010.09782)
  - Global fit of SUSY (2203.04828)
- 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)
- Long-lived particles (1904.10661, 1911.06576, 2201.08960. **Ongoing:** Yulei Zhang's Talk; Wei Su's Talk; Cen Mo's Talk;)
- More exotics:
  - Heavy neutrinos (2102.12826);
  - Axion-like particles (2103.05218, 2204.04702. **Ongoing:** Jia Liu's talk, J. Phys. G)
  - Electroweak phase transition (1911.10210,1911.10206,2011.04540)
  - ……

Please let me know if any contribution is missing!

BSM Higgs

- A large class of BSM physics, such as singlet extensions, two Higgs-doublet-models (2HDM), SUSY models, Higgs portals, gauge extensions of the SM, motivates these exotic decay considerations.

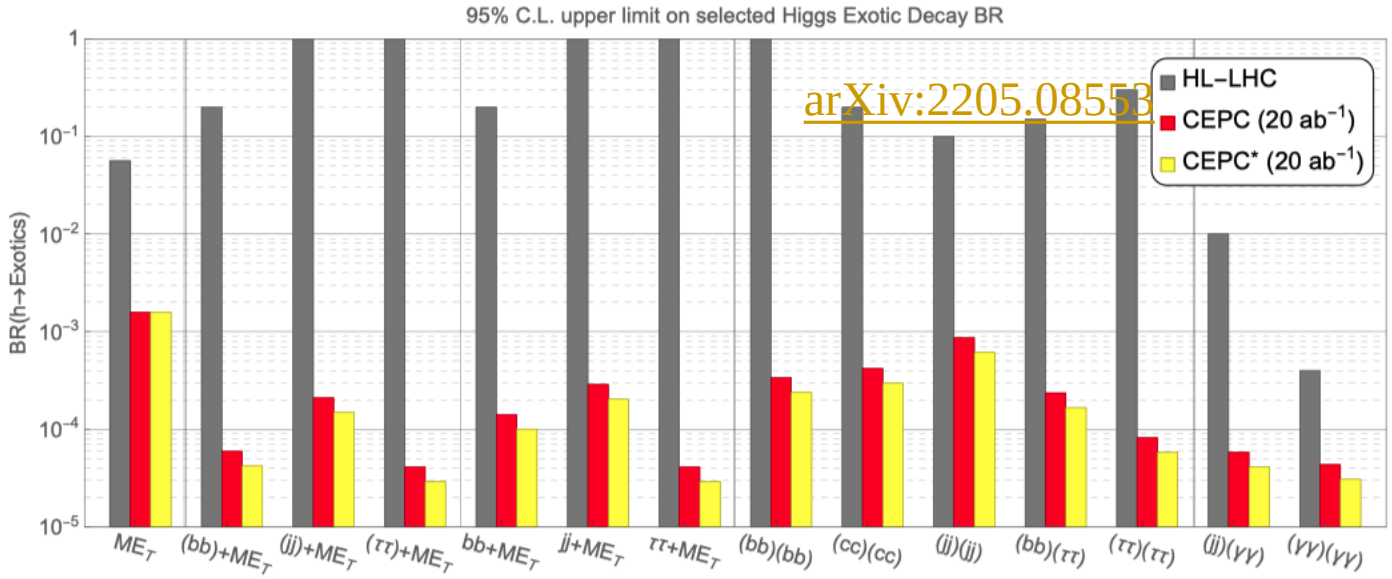


Representative topologies of the Higgs exotic decays

- Reference:
  - 2HDM searches: 1709.06103; 1808.02037; 1912.01431; 2008.05492 ; 2011.04540
  - Exotic higgs decay: 1612.09284 , 2110.13225 , 2203.08206, 2002.05554 , 2003.01662 , 2006.03527 …
  - **Summarized at 2205.08553.**

Exotic Higgs decay

- Exotic decays of the 125 GeV Higgs boson at future e +e − lepton colliders, Z. Liu, L.-T. Wang, and H. Zhang, 1612.09284
- Exotic Higgs Decays to Four Taus at Future Electron-Positron Colliders, J. Shelton and D. Xu, 2110.13225
- CEPC is very sensitive for signals with jets, heavy quarks and taus, which is challenge at LHC

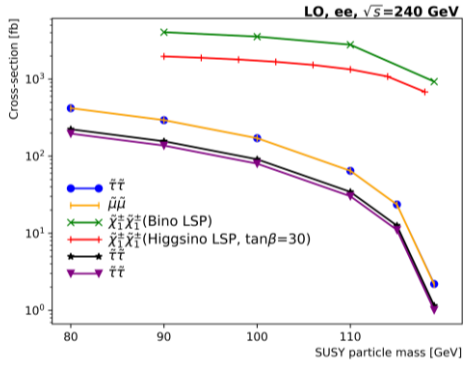


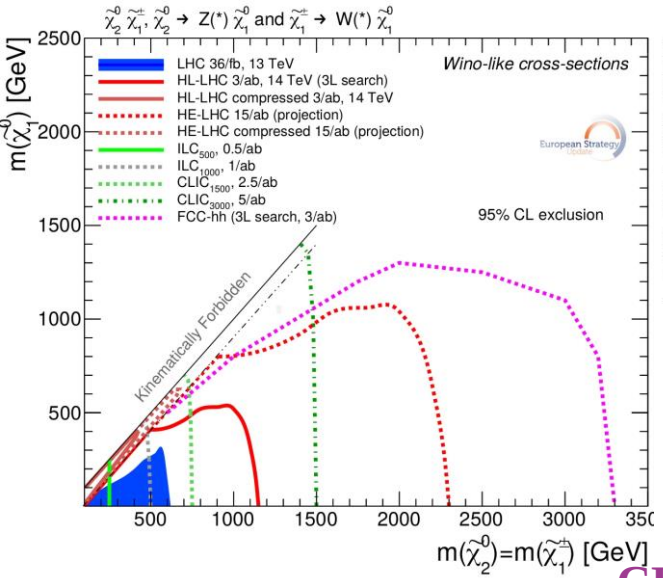
The 95% C.L. upper limit on selected Higgs exotic decay BR

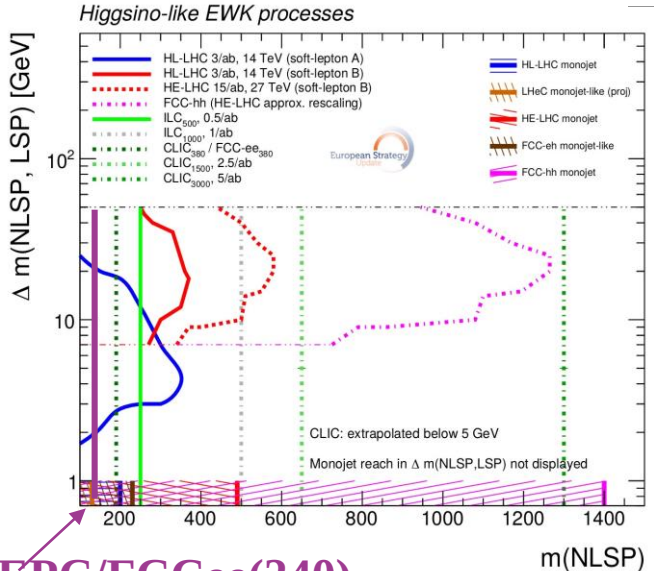
The CEPC* scenario further utilizes the hadronically decaying Z boson and includes an estimated (indicative) improvement of 40%.

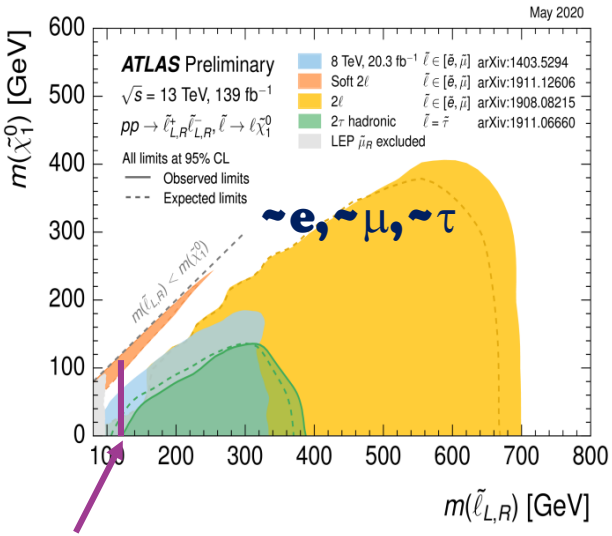
SUSY Searches at CEPC

- Reference: **mainly light EWKino and slepton for CEPC**
  - Electroweakino (wino, higgsino) search: CPC46(2022)013106
  - Bino NLSP at CEP: 2101.12131
  - Slepton search: 2203.10580
  - Heavy selectron search: 2202.11011
  - Indirect search of SUSY: 2010.09782
  - Global fit of SUSY: 2203.04828







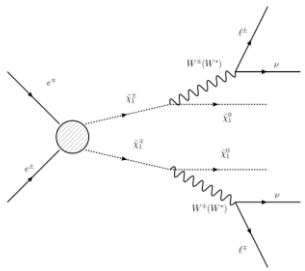


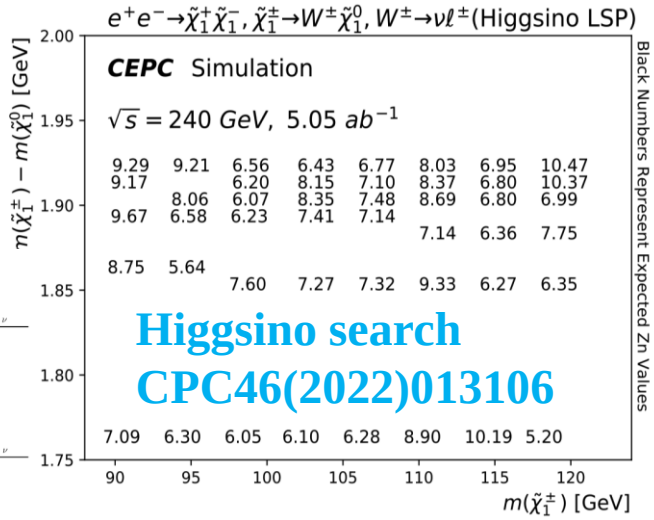
CEPC/FCCee(240)

CEPC

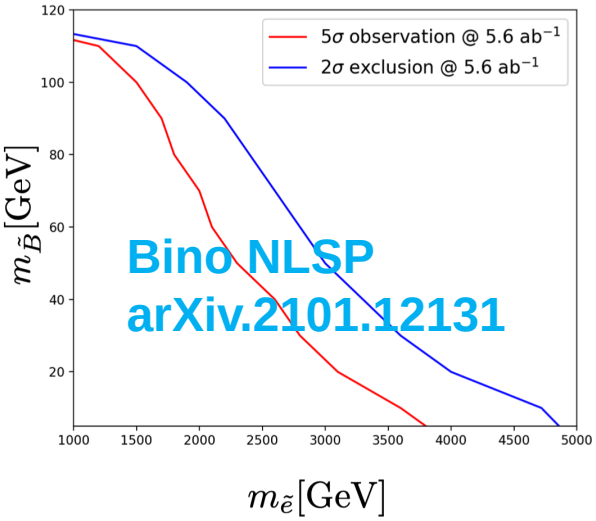
ILC 500/CEPC240: discovery in all scenarios up to kinematic limit: √s/2

SUSY Searches at CEPC

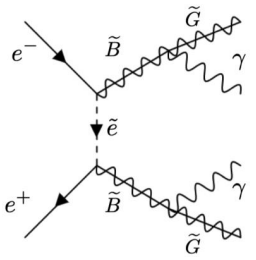




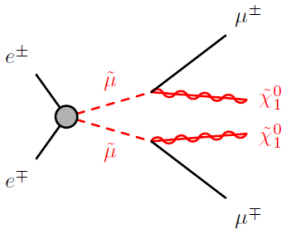
Higgsino search
CPC46(2022)013106

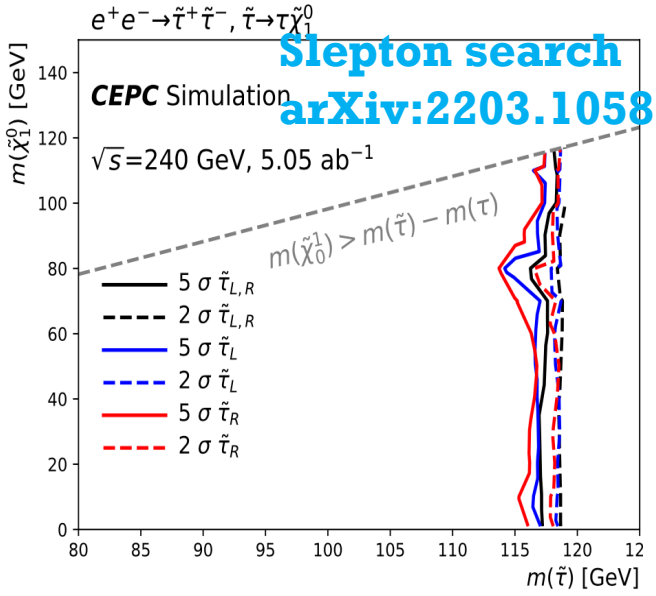


Bino NLSP
arXiv.2101.12131

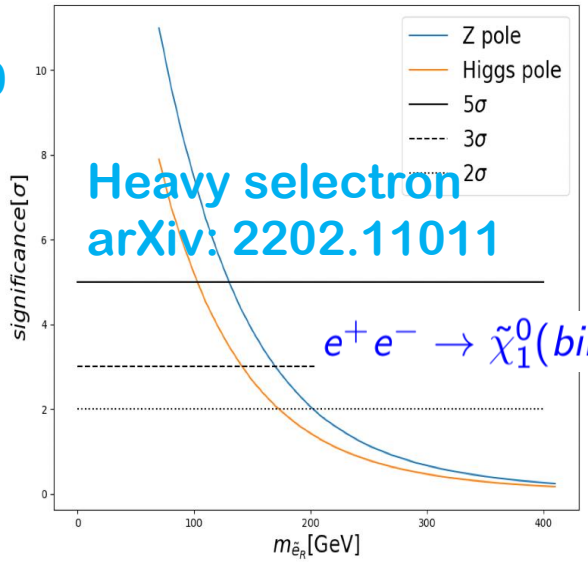


$\tilde{B} \to \tilde{G}/\tilde{a} + \gamma$

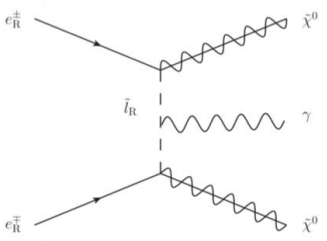




Slepton search
arXiv:2203.10580



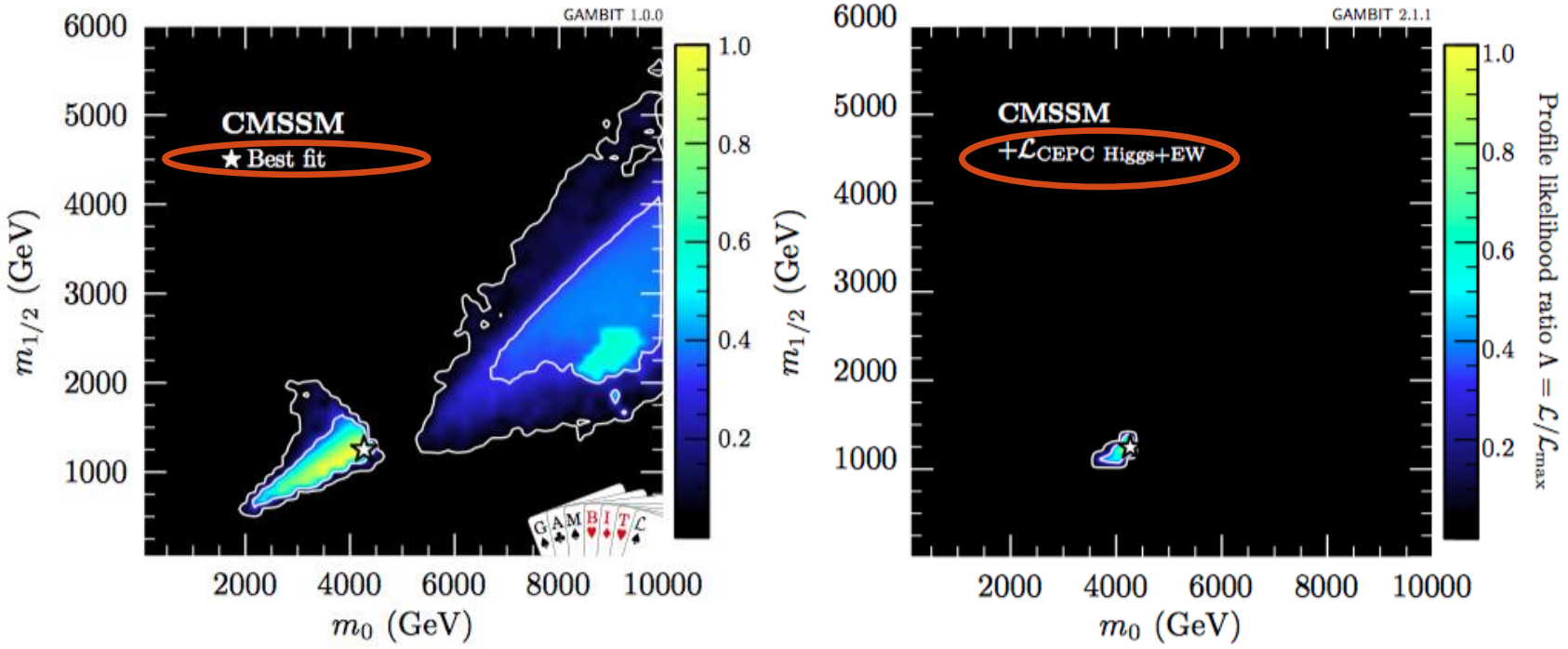
Heavy selectron
arXiv: 2202.11011



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

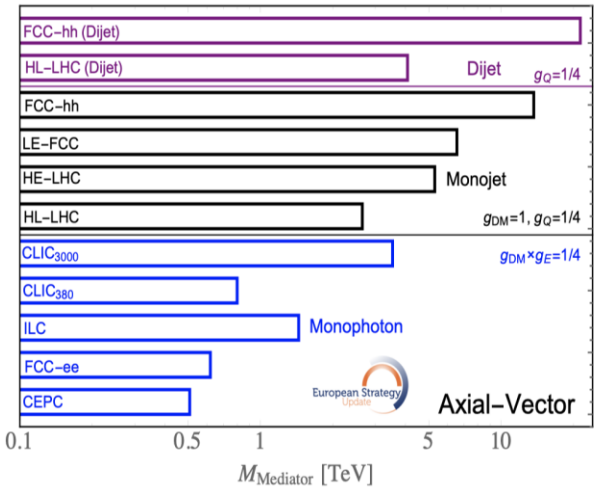
SUSY global fits with CEPC using GAMBIT

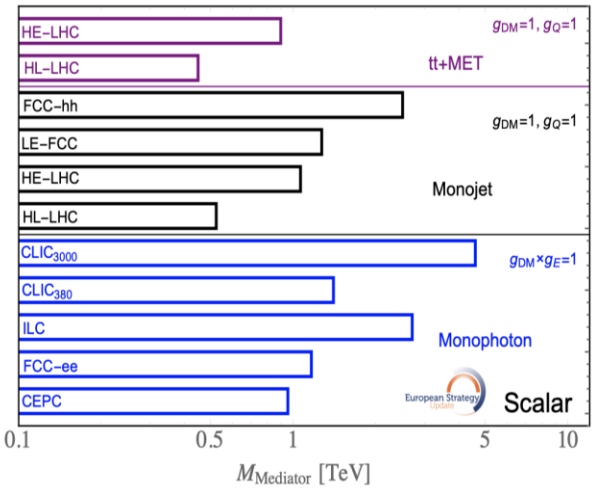
- Study of the impact of the Higgs and electroweak precision measurements at the CEPC with GAMBIT global fits of the SUSY models, such as CMSSM, NUHM1, NUHM2 and pMSSM-7, Yang Zhang etc, arXiv: 2203.04828
- CEPC can further test the currently allowed parameter space of these models, advance our understanding of the mass spectrum

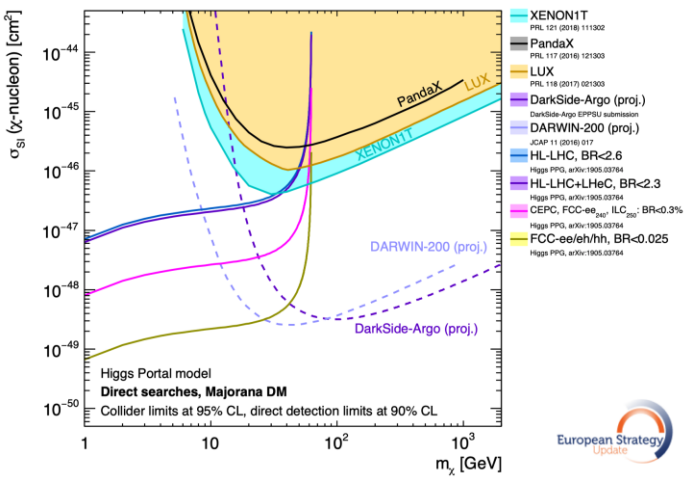


Dark Matter and Dark Sector searches

- Reference:
  - 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)

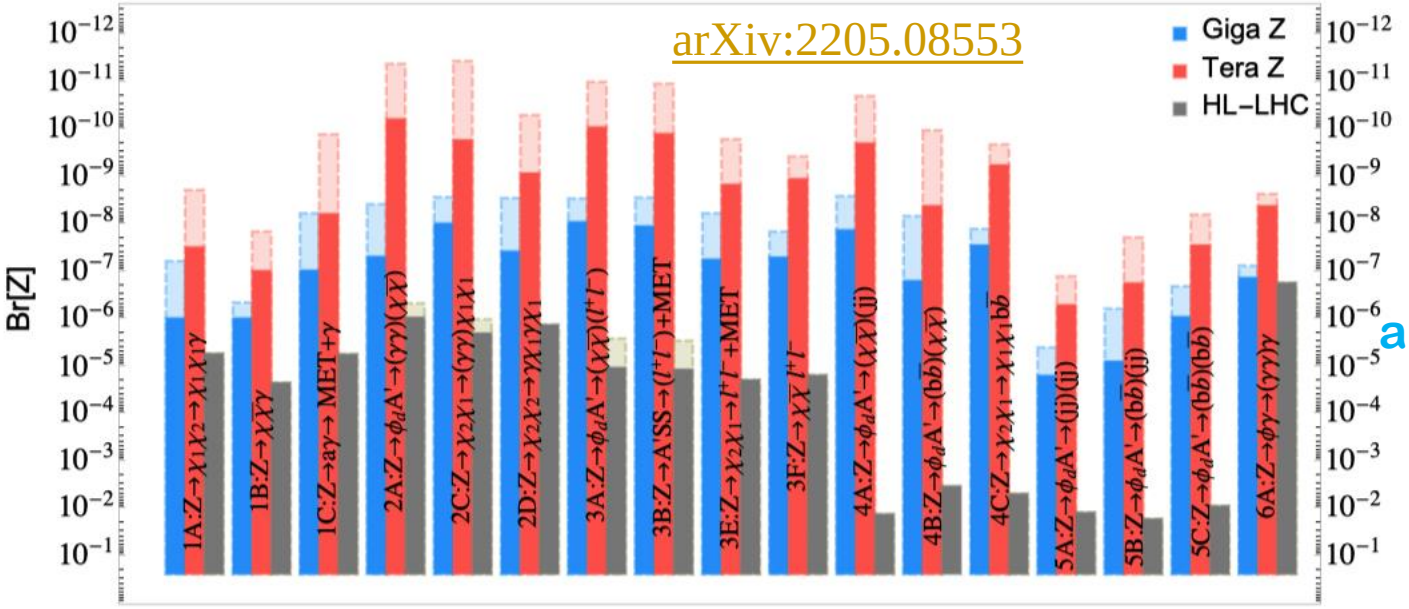


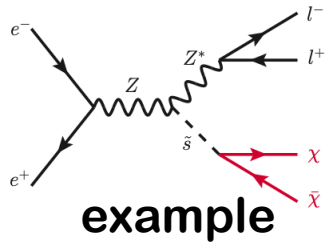




DM search at CEPC

- **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.**





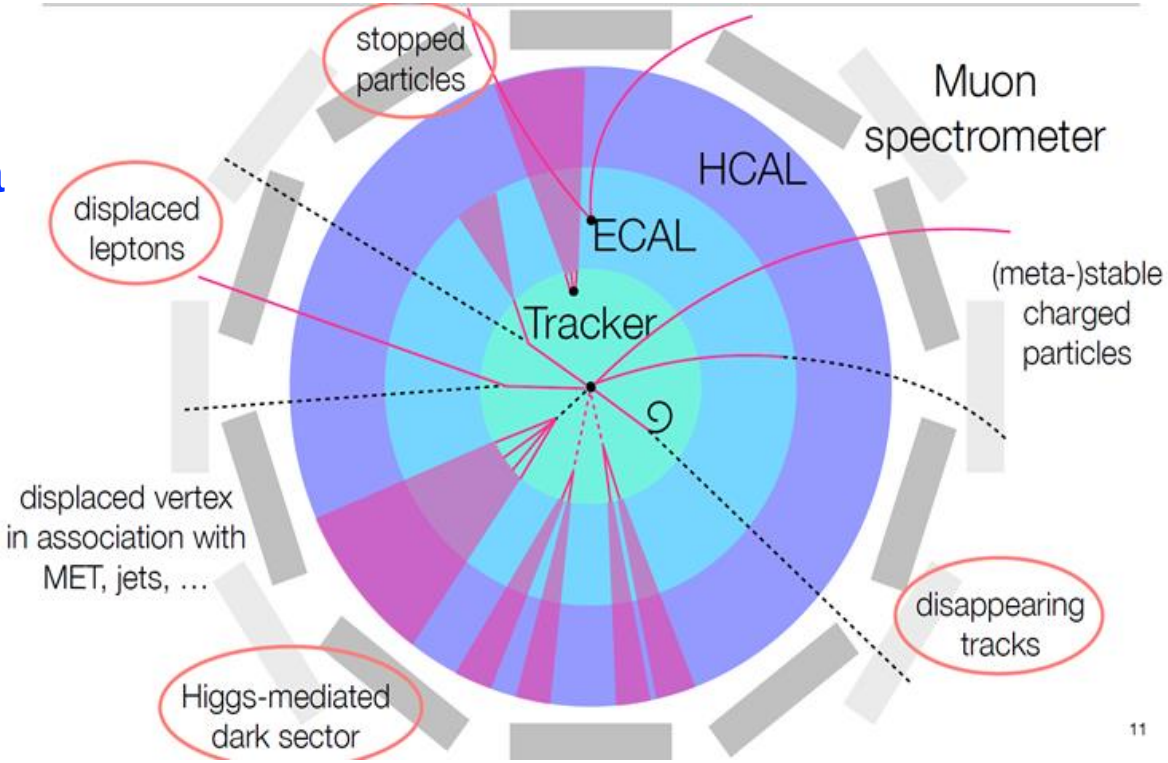
arXiv: 1712.07237

Long-lived particles (LLP)

- Reference:
  - LLP at near Detector:1904.10661
  - LLP at Far Detector: 1911.06576, 2201.0896
  - LL Dark Hadrons: 2110.10691
  - On-going: Yulei Zhang's Talk; Wei Su's Talk; Cen Mo's Talk;

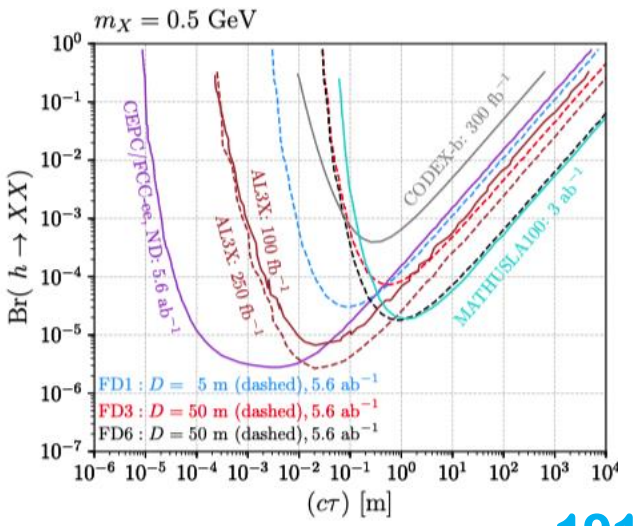
Long lifetimes result from a few simple physical mechanisms:

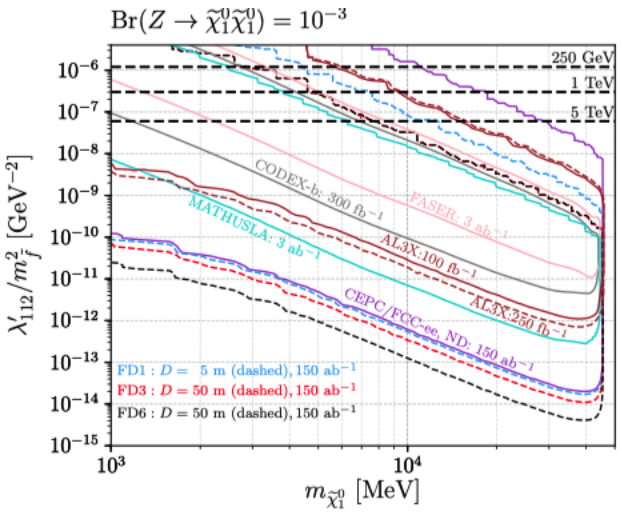
- Small couplings (ex. RPV SUSY)
- Limited phase space: small mass splitting (ex. compressed SUSY, …)
- Heavy intermediate states
- ……

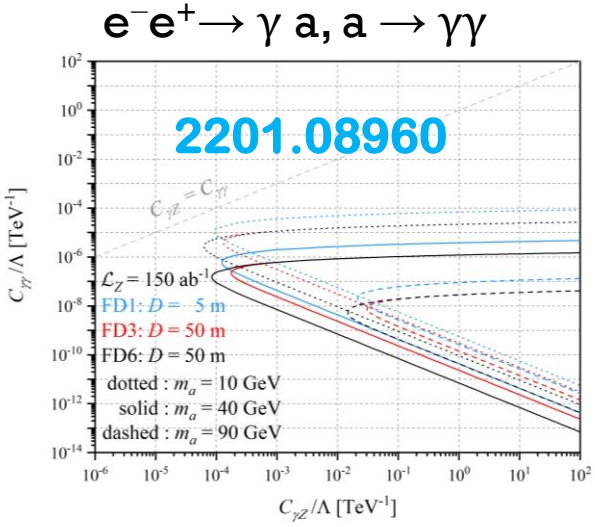


LLP at Far Detector (FD)

- **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**







1911.06576

Light Scalars from Exotic Higgs Decays

Light Neutralinos from Z-boson Decays

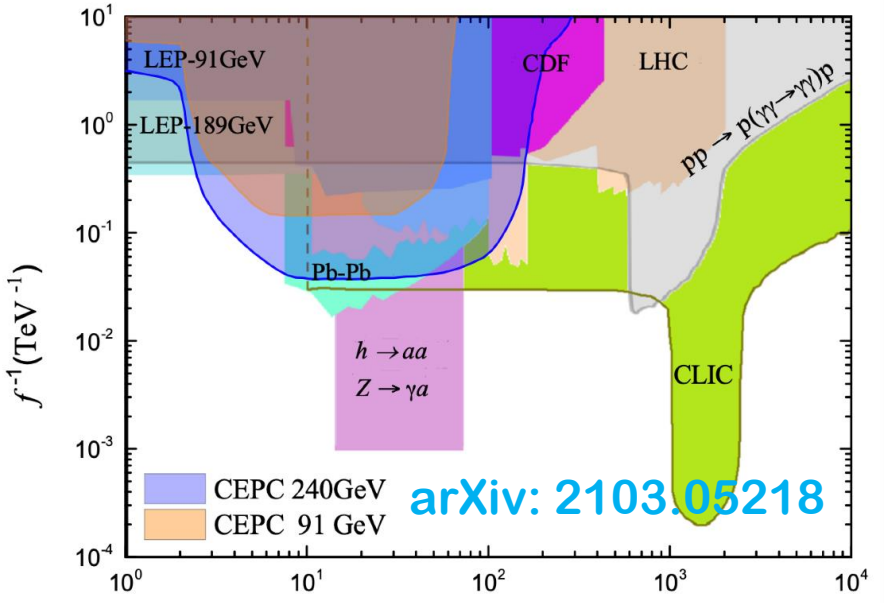
Axion-like Particles

More exotics

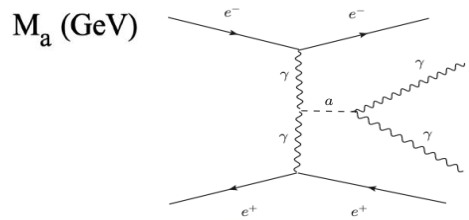
- Reference:
  - Heavy neutrinos (2102.12826);
  - Axion-like particles (2103.05218, 2204.04702, Jia Liu's talk, J. Phys. G)
  - Electroweak phase transition (1911.10210,1911.10206,2011.04540,)
  - ……

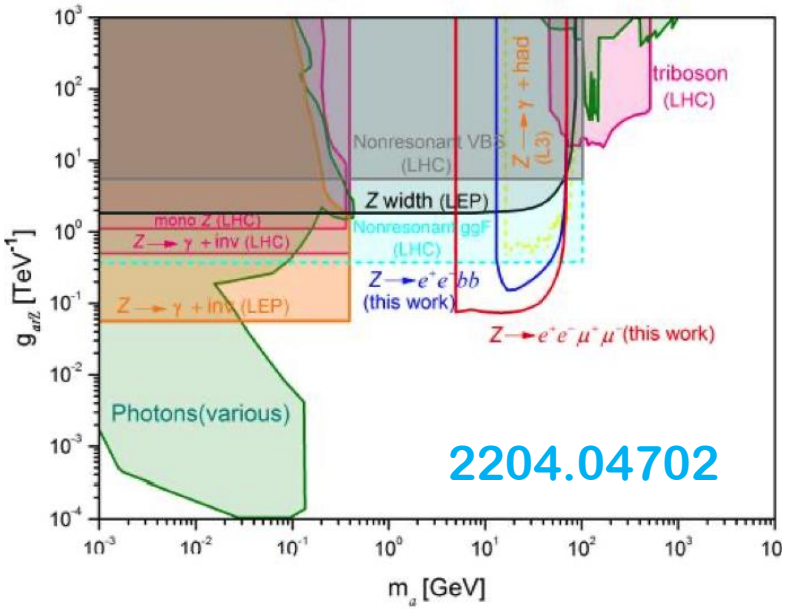
Axion-like particles (ALP)

- **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 $Z \to a f \bar{f}$ at future Z factories, 2204.04702**
- **Axion-like particle solution to muon g-2 and its test at Z-factory, Jia Liu's talk**

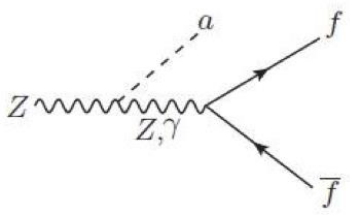


2-8 GeV





5-70 GeV



Summary and Outlook

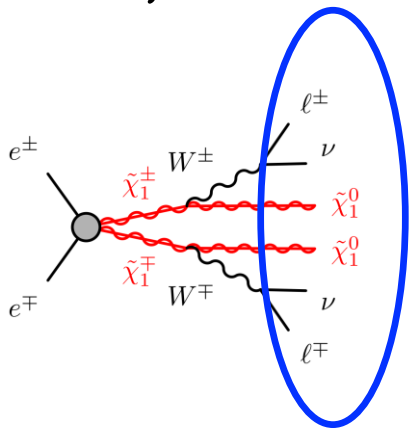
- **CEPC has good discovery potential for NP at many scenarios which are challenge for LHC**
- **BSM prospects study at CEPC is going on well, many of the analyses are already public**
- **Plan to organize a workshop by end of this year to collect inputs for CEPC BSM white paper**
- **Please let us know if you would like to contribute to the BSM white paper !**

Thanks for your attention!

Backup

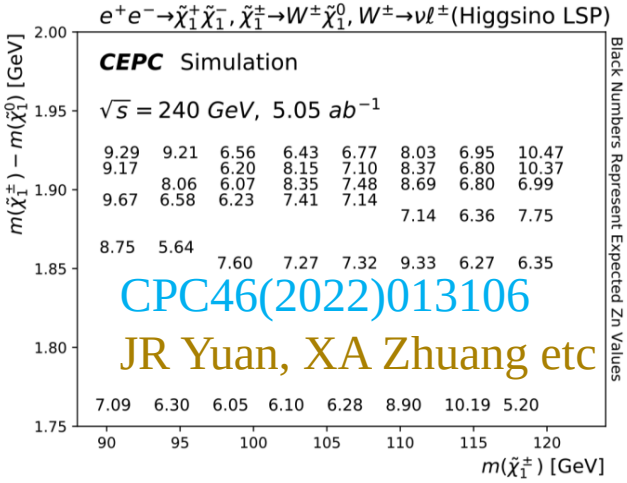
Wino & higgsino

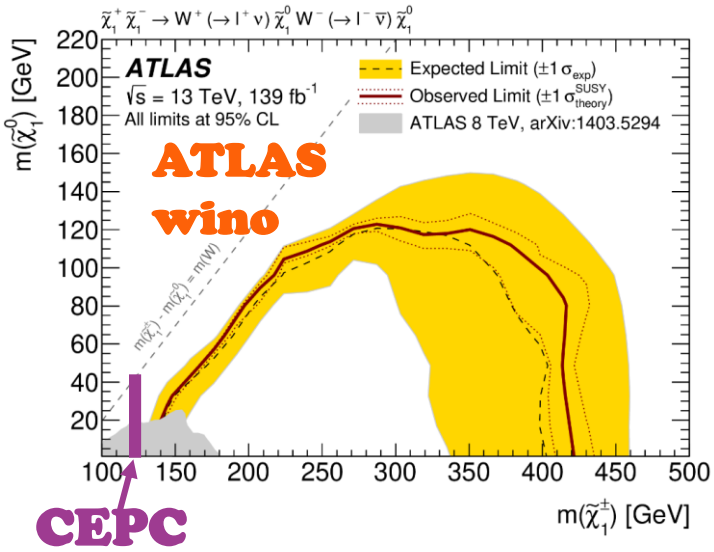
- Prospects for chargino pair production at CEPC, Jia-Rong Yuan, Hua-Jie Cheng, Xu-Ai Zhuang, arXiv:2105.06135.

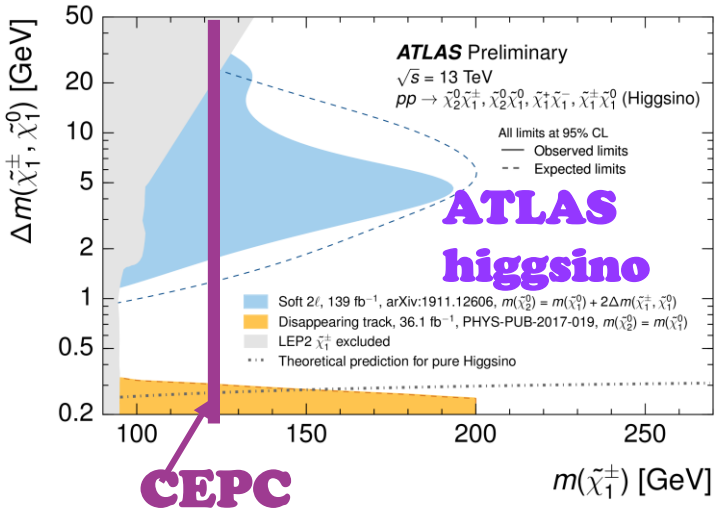


Chargino pair via on(off)-shell W decay

Signature: 2 lepton + MET



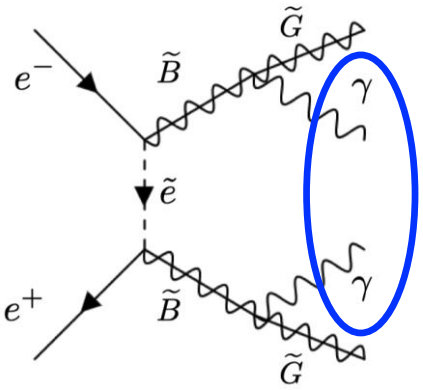




Discovery in all scenarios up to kinematic limit: √s/2

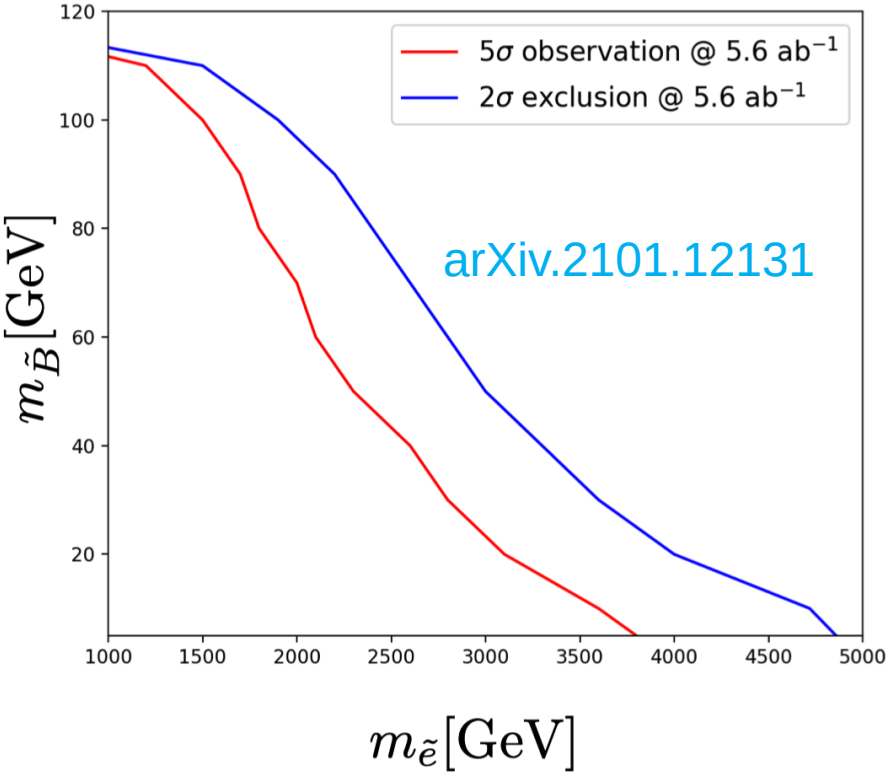
Bino NLSP at CEPC

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



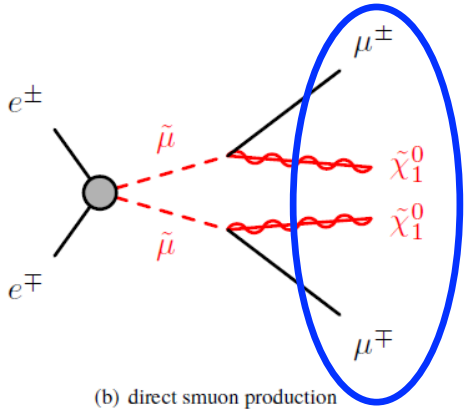
$$\tilde{B} \to \tilde{G}/\tilde{a} + \gamma$$

Signature:
2 photons + MET

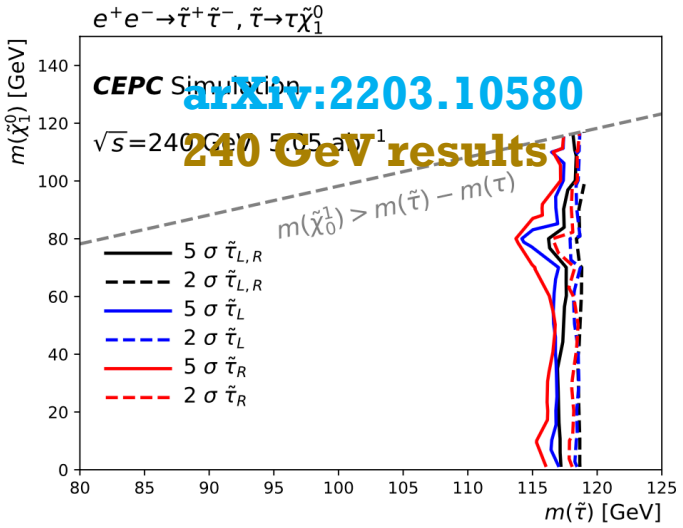


Slepton search

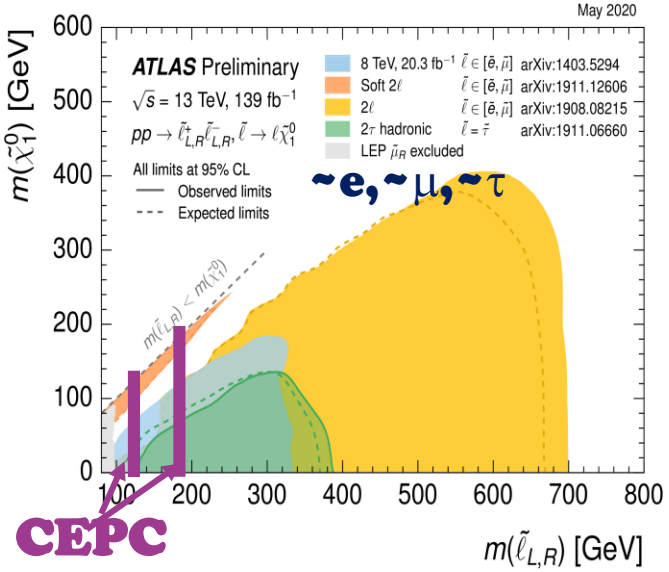
- Prospects for slepton pair production at CEPC, Jia-Rong Yuan, Hua-Jie Cheng, Xu-Ai Zhuang, arXiv: 2203.10580



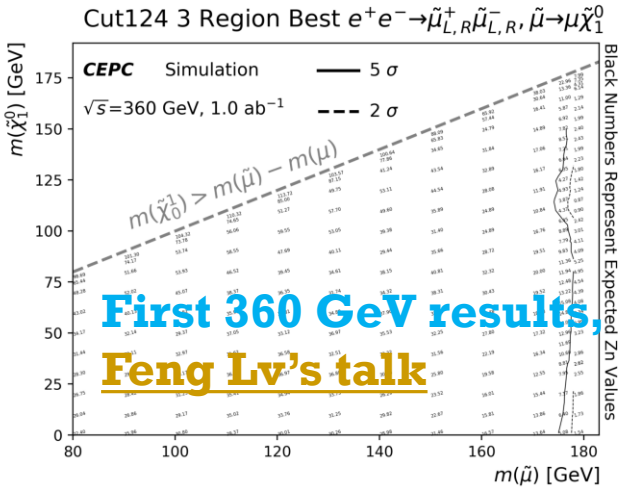
Signature:
2 lepton + MET



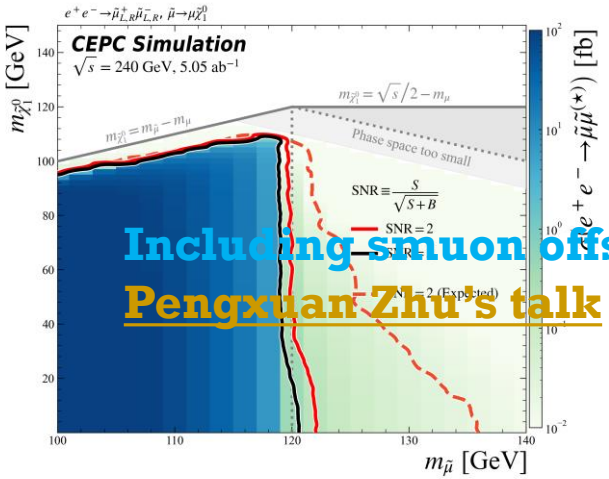
arXiv:2203.10580
240 GeV results



CEPC



First 360 GeV results,
Feng Lv's talk



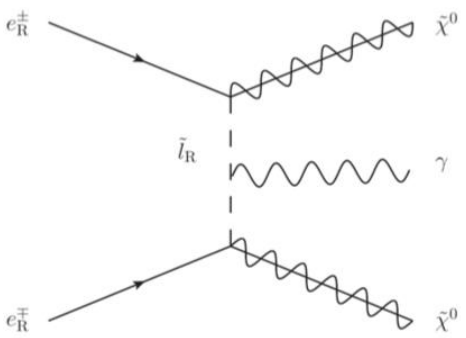
$e^+e^- \to \tilde{\mu}\tilde{\mu}^{(*)} \to \mu^+\tilde{\chi}_1^0\mu^-\tilde{\chi}_1^0$

Including smuon offshell production
Pengxuan Zhu's talk

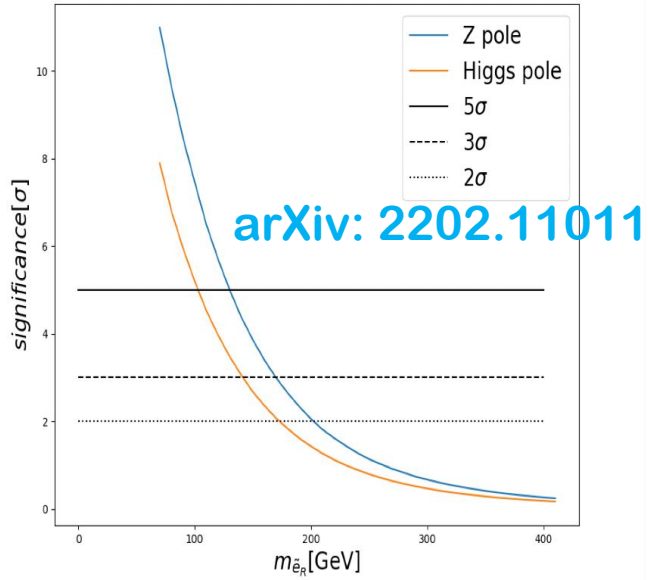
Heavy selectron search

- 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 $\rightarrow m_{\tilde{\chi}_1^0} \approx \frac{1}{2} m_Z$.



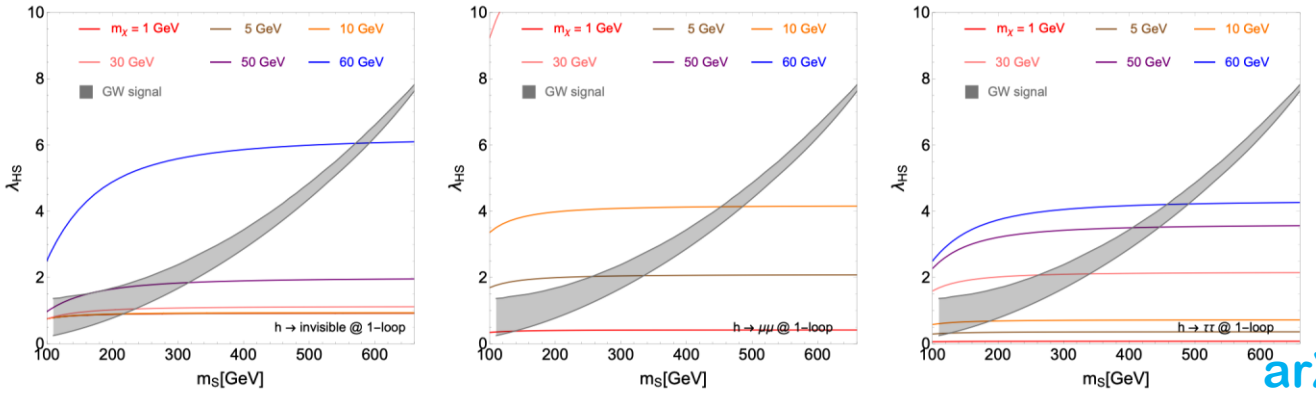
$e^+e^- \rightarrow \tilde{\chi}_1^0(bino) + \tilde{\chi}_1^0(bino) + \gamma$



DM search at CEPC

- 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.

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

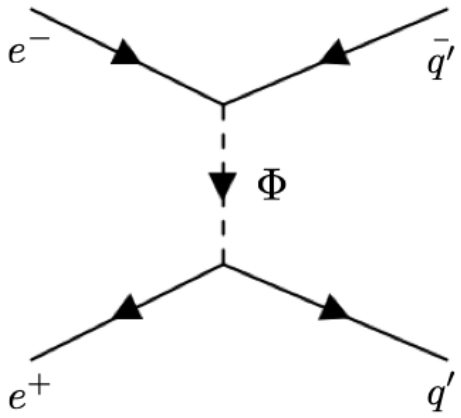


arXiv: 2104.06421

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.

DM search at CEPC

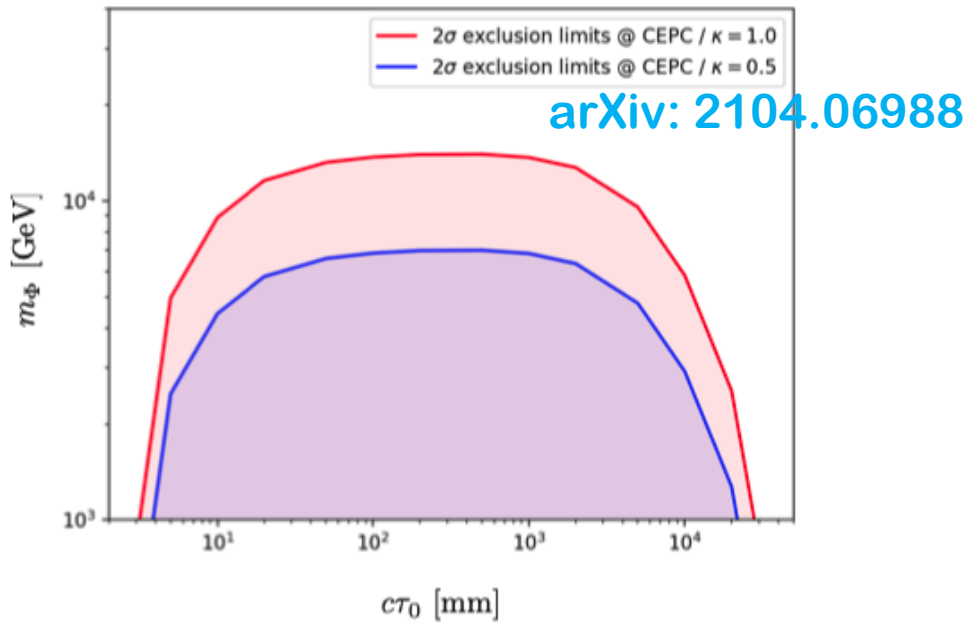
- Searching for asymmetric Dark Matter (ADM) at CEPC, Mengchao Zhang, 2104.06988, PRD 104, 055008 (2021)
- It is possible to generate dark quark pair through a t-channel process, dark quark q' will be a jet-like object in detector.



Decay to leptons

Jet-like

Signature:
Lepton + jet + MET



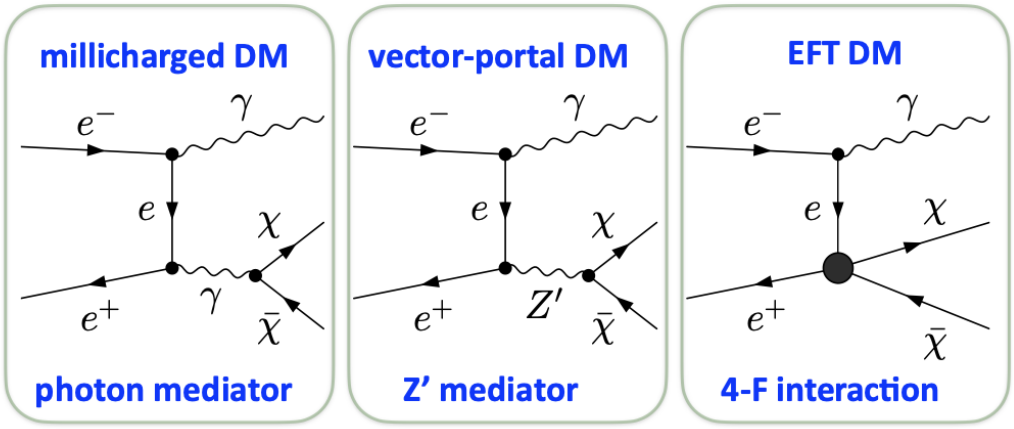
- The mass of mediator can be excluded up to O(10) TeV, better than LHC

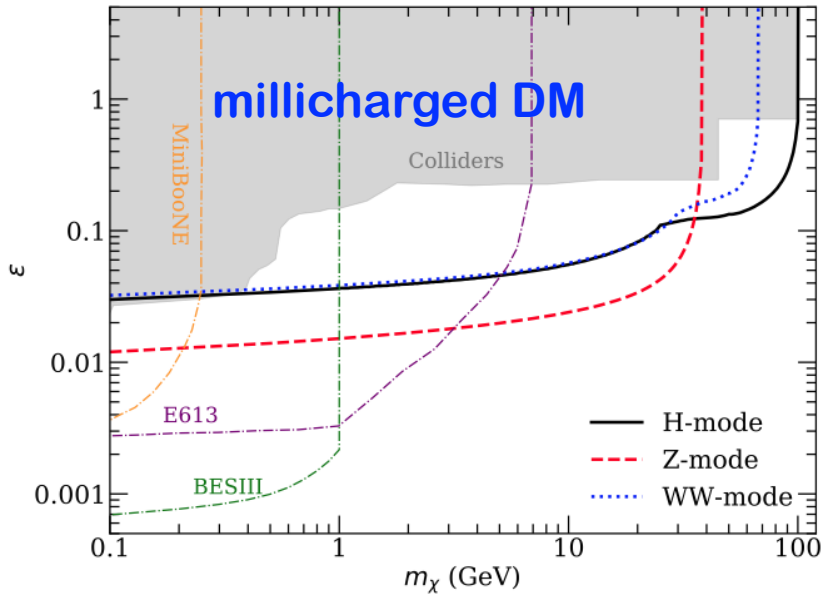
DM search at CEPC

- **Probing DM particles at CEPC (Millicharged DM, Vector portal DM, DM with EFT interactions): ZL, Yong-Heng Xu, Yu Zhang ,1903.1211**
  - ✓ **CEPC can probe millicharged DM that is currently unexplored**
  - ✓ **CEPC can probe the parameter space of vector-portal DM models and EFT DM models that are unconstrained by DMDD**
- **Mono-γ Production of a Vector Dark Matter at CEPC, K Ma, 2205.05560**

[ZL, Y.-H. Xu, and Y. Zhang,1903.12114]

new physics process: $e^+e^- \to \bar{\chi}\chi\gamma$





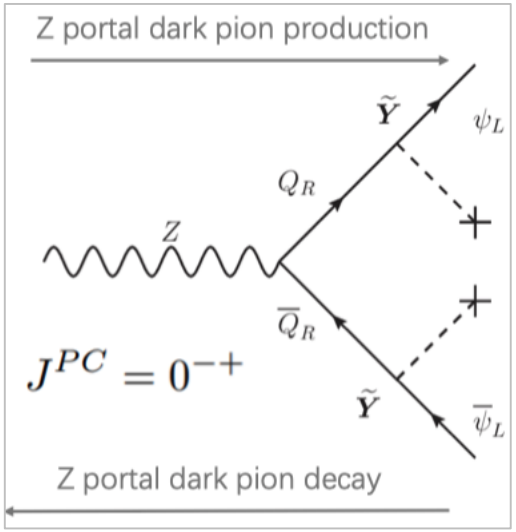
LL Dark Hadrons

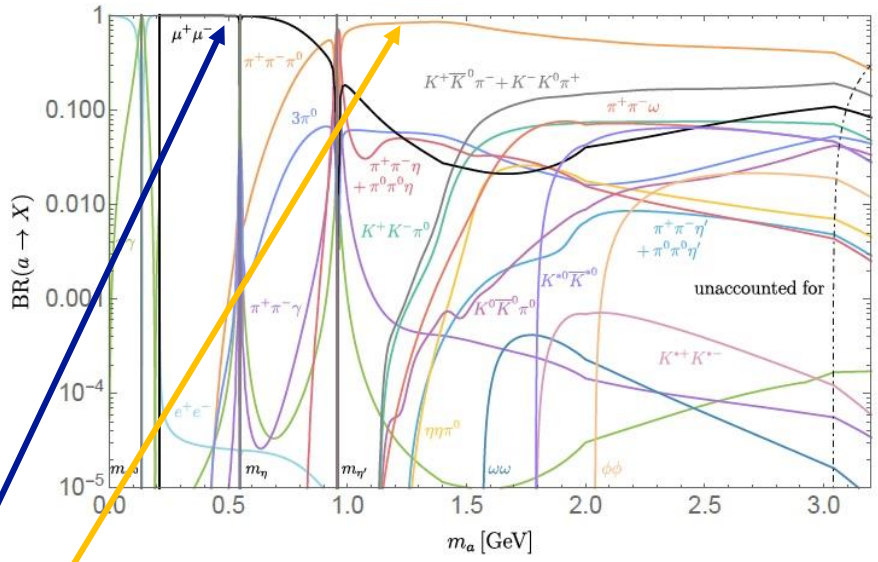
- A theory of Dark Pions, Hsin-Chia Cheng, Lingfeng Li, Ennio Salvioni, 2110.10691, JHEP 01 (2022) 122, see Lingfeng's talk
- The dark quarks couple to the SM via irrelevant Z- and Higgs-portal operators. The dark pions, behave as either composite axion-like particles (ALPs) mixing with Z or h

arXiv: 2110.10691

$$\mathcal{L}_{\rm EFT} = \frac{1}{2}\overline{\psi}_R \boldsymbol{Y}^\dagger \boldsymbol{M}^{-2}\boldsymbol{Y}\left[|H|^2 i\not{D} + i\gamma^\mu H^\dagger D_\mu H\right]\psi_R + \text{h.c.}$$
$$+ \frac{1}{2}\overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-2}\widetilde{\boldsymbol{Y}}\left[|H|^2 i\not{D} + i\gamma^\mu H^\dagger D_\mu H\right]\psi_L + \text{h.c.}$$
$$- \overline{\psi}_L \boldsymbol{\omega}\psi_R + \overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-1}\boldsymbol{Y}\psi_R |H|^2 + \text{h.c.},$$

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

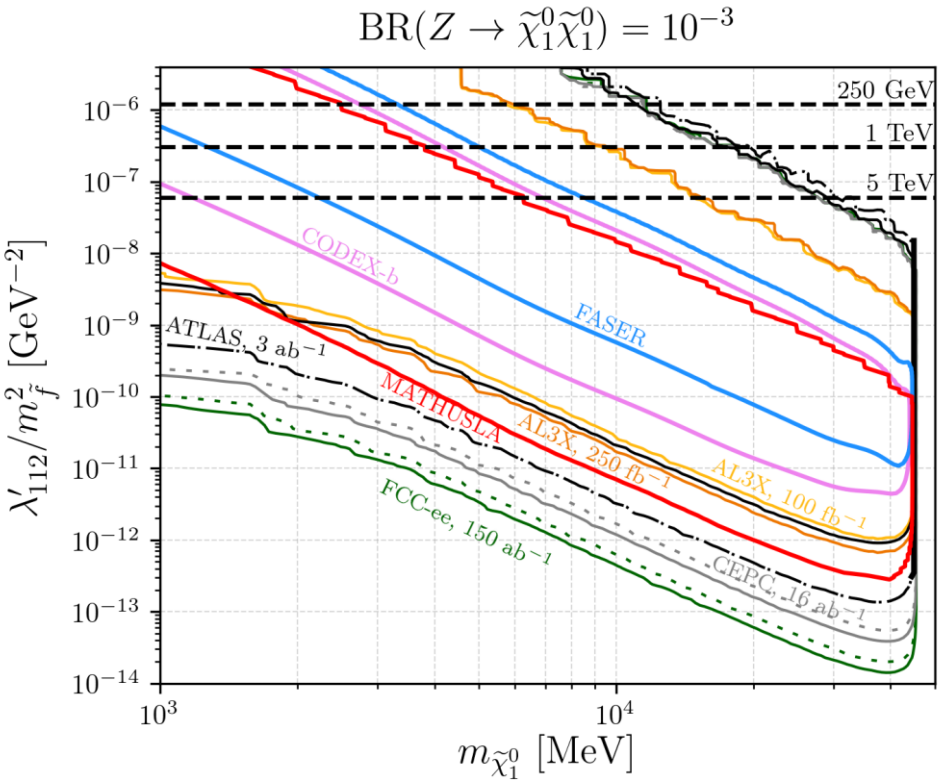




- mπ < m η' : dimuon mode dominates
- m π > m η' : PPP modes (mostly SM π+ π- π0)

LLP at near Detector (ND)

- **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 ~1.5×10^{-14} (3.9×10^{-14}) GeV^{-2} at the FCC-ee (CEPC)**



arXiv: 1904.10661

https://indico.cern.ch/event/687651/contributions/3400865/attachments/1850992/3038683/Wagner-LHCP2019.pdf

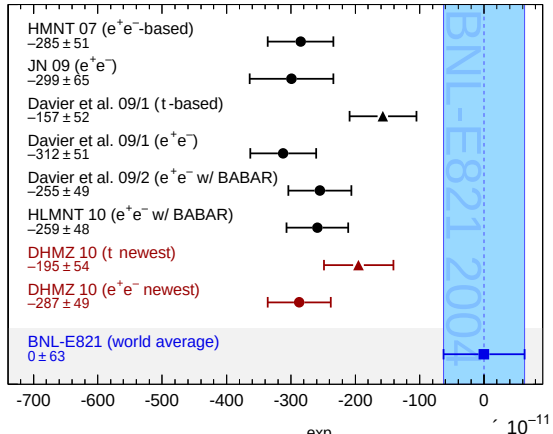
Muon Anomalous Magnetic Moment

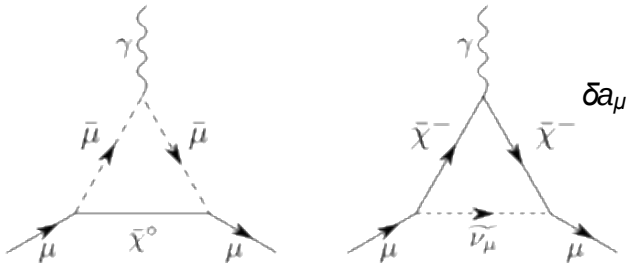
Present status: Discrepancy between Theory and Experiment at more than three Standard Deviation level

$$\delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{theory}} = 268(63)(43) \times 10^{-11}$$

3.6σ Discrepancy

New Physics at the Weak scale can fix this discrepancy. Relevant example : Supersymmetry





$$\delta a_\mu \simeq \frac{m_\mu^2}{8\pi s_W^2}\frac{1}{M_{\text{SUSY}}^2}\,\text{Sgn}(\mu M_2)\tan\beta \simeq 130\times 10^{-11}\left(\frac{100\ \text{GeV}}{M_{\text{SUSY}}}\right)^2 \text{Sgn}(\mu M_2)\tan\beta$$

Grifols, Mendez'85, T. Moroi'95,
Giudice, Carena, C.W.'95, Martin and Wells'00 ....

Here $\tilde{m}$ represents the weakly interacting supersymmetric particle masses.

For $\tan\beta \simeq 10\ (50)$, values of $\tilde{m} \simeq 230\ (510)$ GeV would be preferred.

Masses of the order of the weak scale lead to a natural explanation of the observed anomaly !