Slepton and Electroweakino Searches at the CEPC

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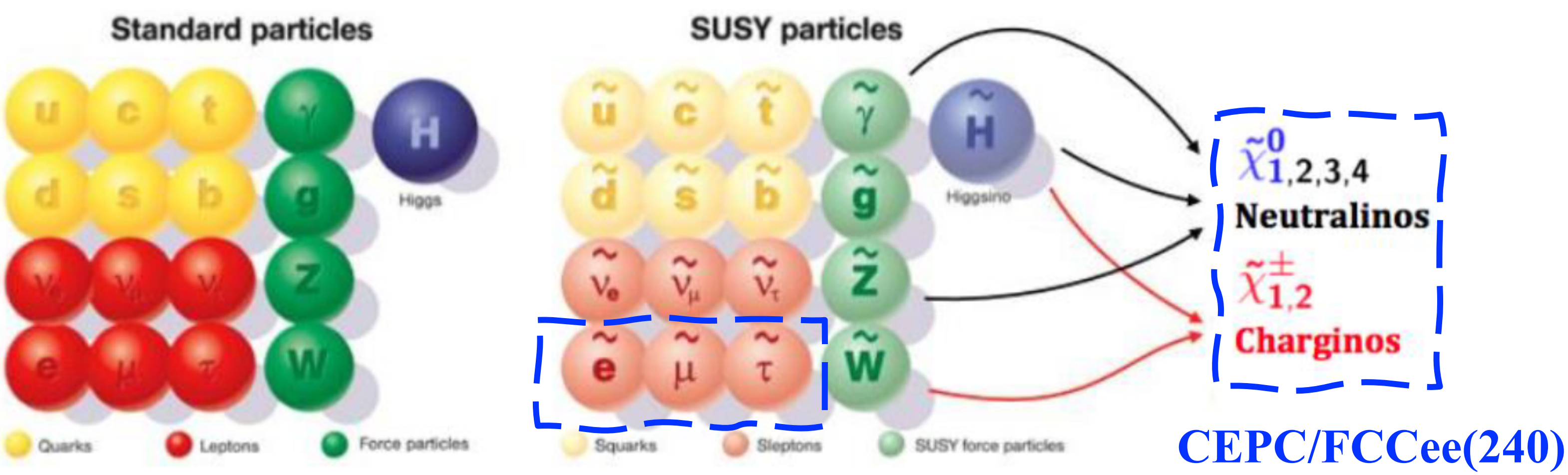
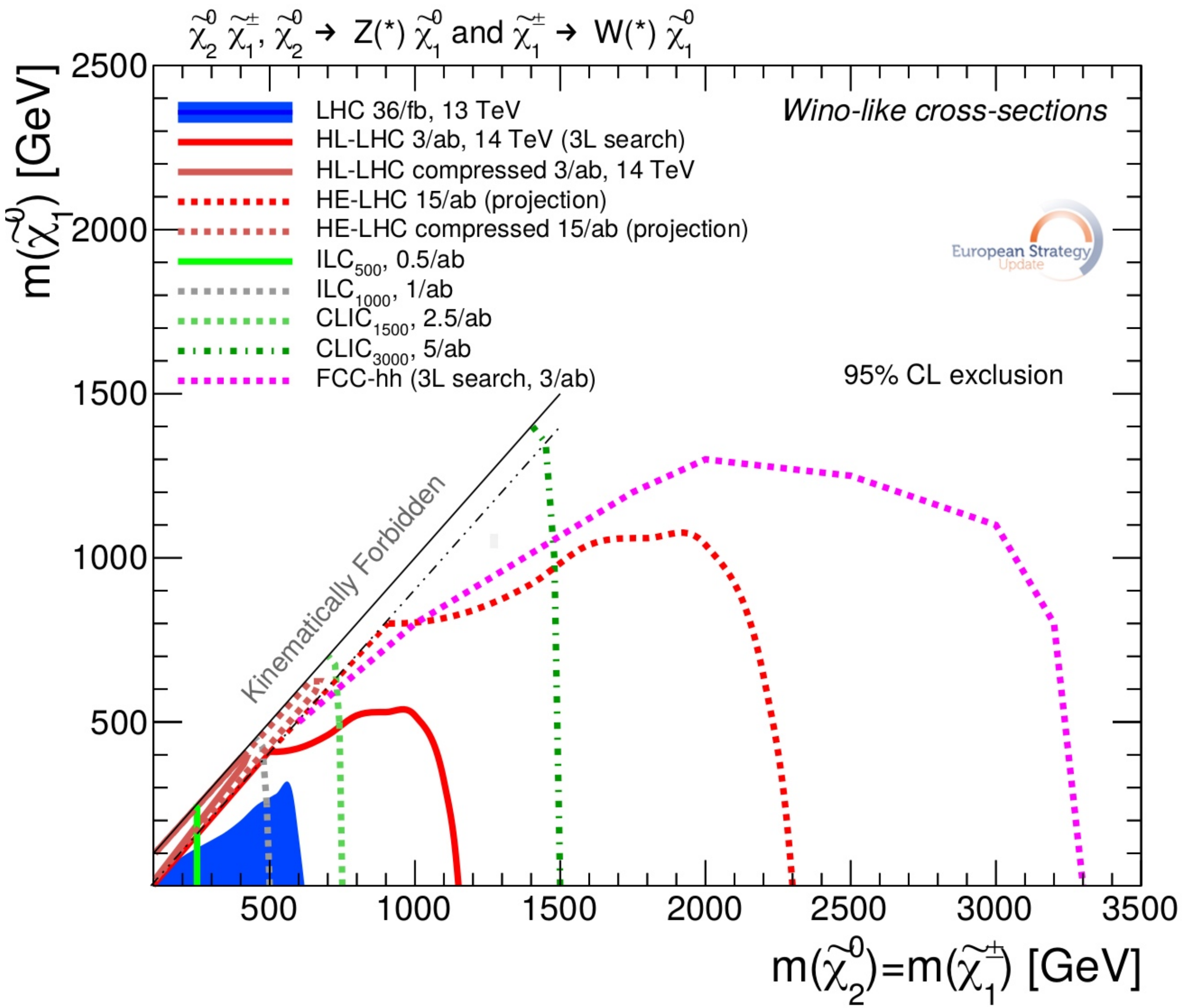
中國科學院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

SUSY Introduction



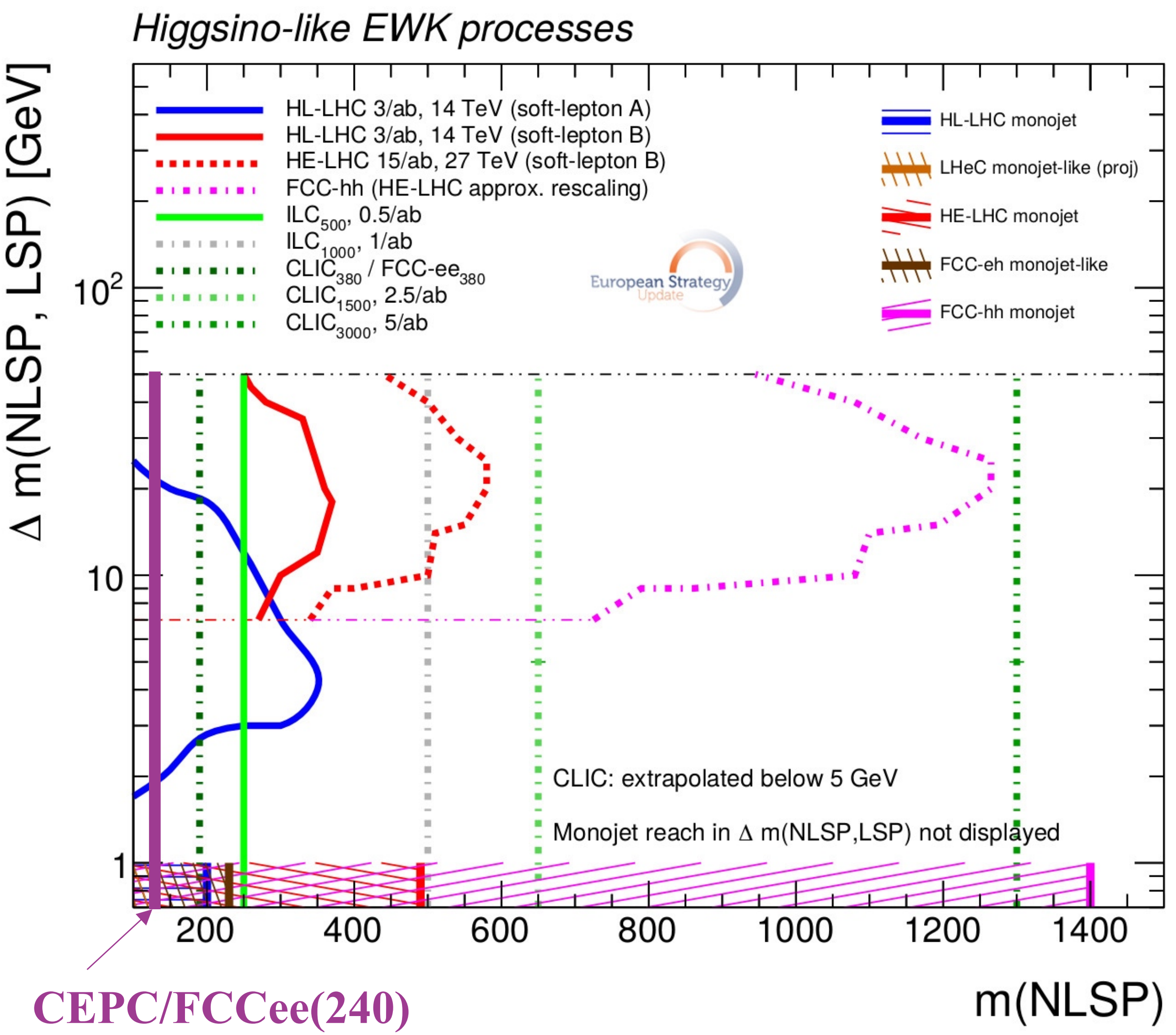
- **SUSY is one of the most favorite candidate for physics BSM, which can**
  - **provide a natural solution to the gauge hierarchy problem,**
  - **provide DM candidate with PRC ,**
  - **achieve gauge coupling unification,**
  - **……**
- **CEPC would mainly concentrate on the generic searches for the charginos, neutralinos, and sleptons. And some relevant dark matter searches as well.**

Current status: EU Strategy- Wino

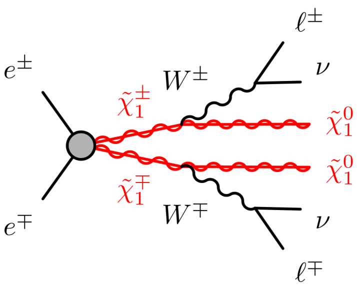


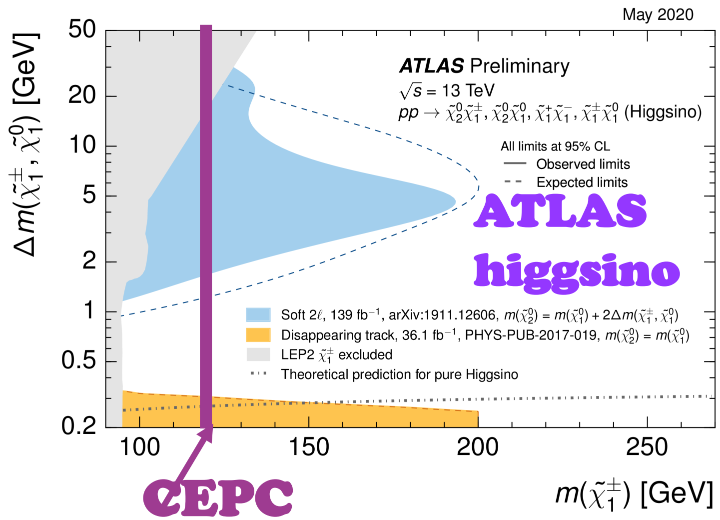
ILC 500/CEPC240: discovery in all scenarios up to kinematic limit: √s/2

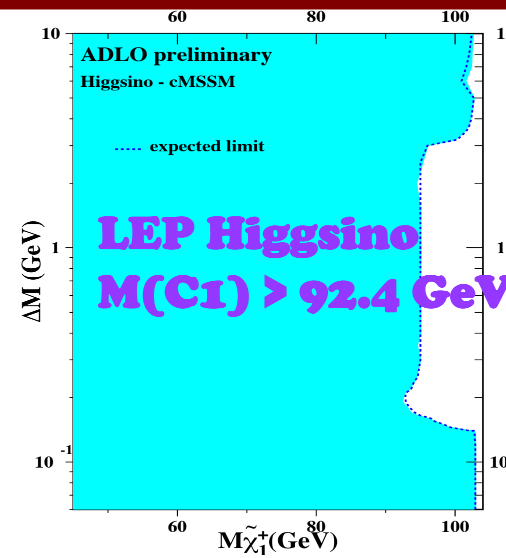
Current status: EU Strategy- Higgsino



Wino & Higgsino

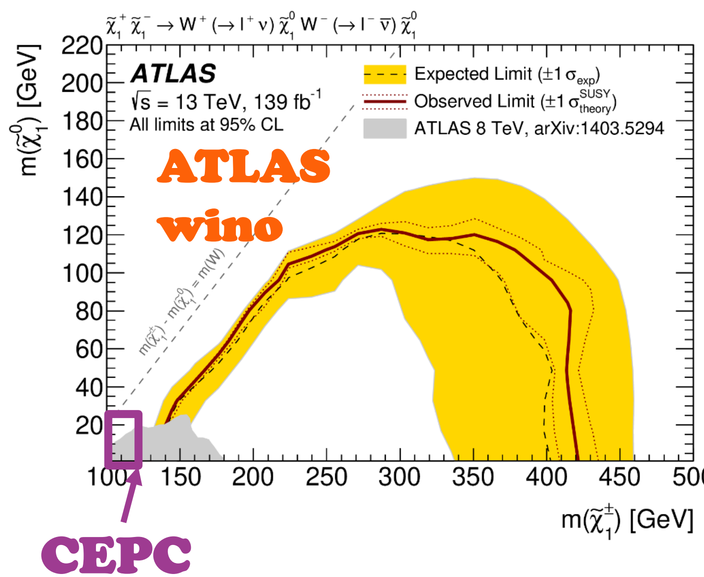


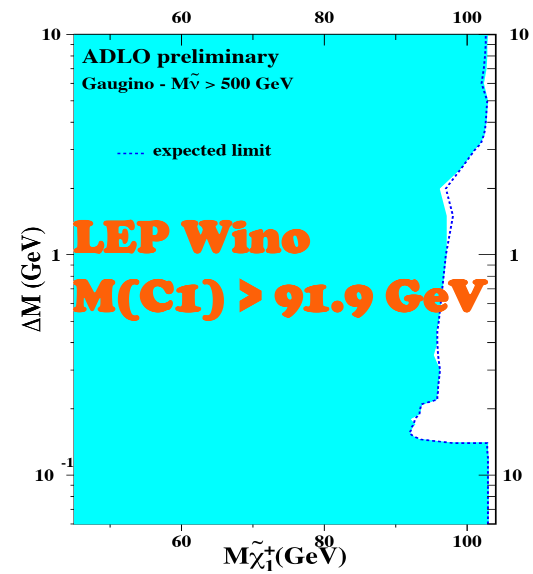




The naturalness conditions from the low-energy fine-tuning measures 【1-3】 generically predict the light Higgsinos

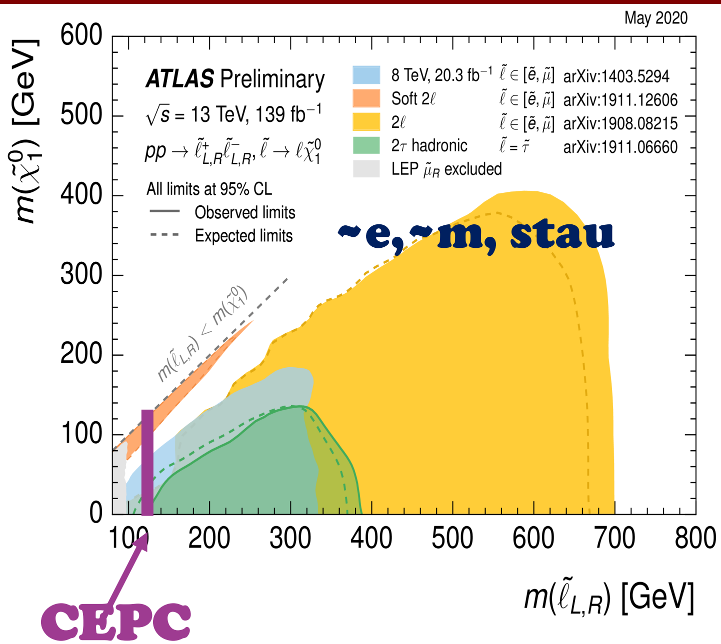
CEPC240(FCCee/ILC): discovery for gauginos up to kinematic limit: √s/2

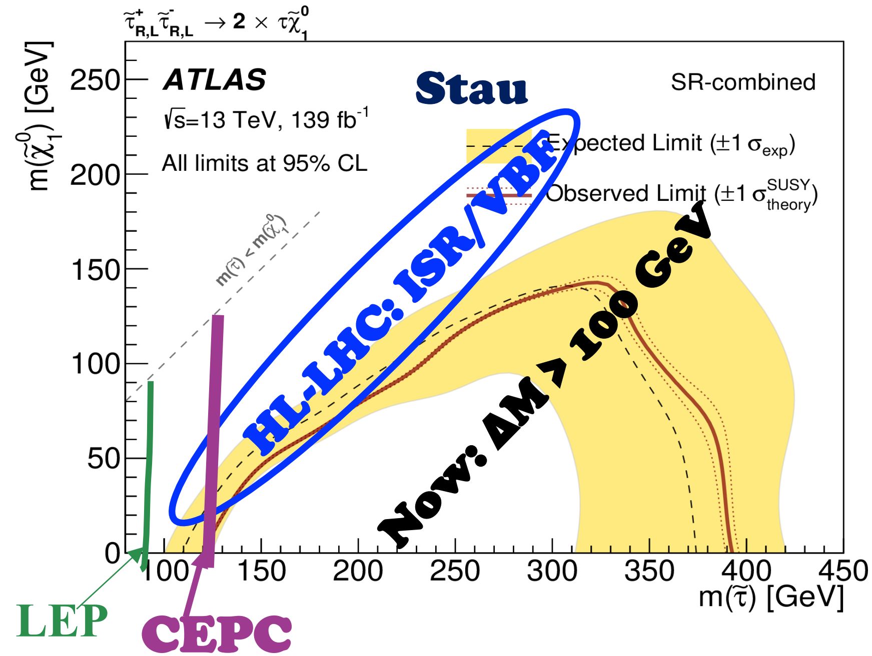


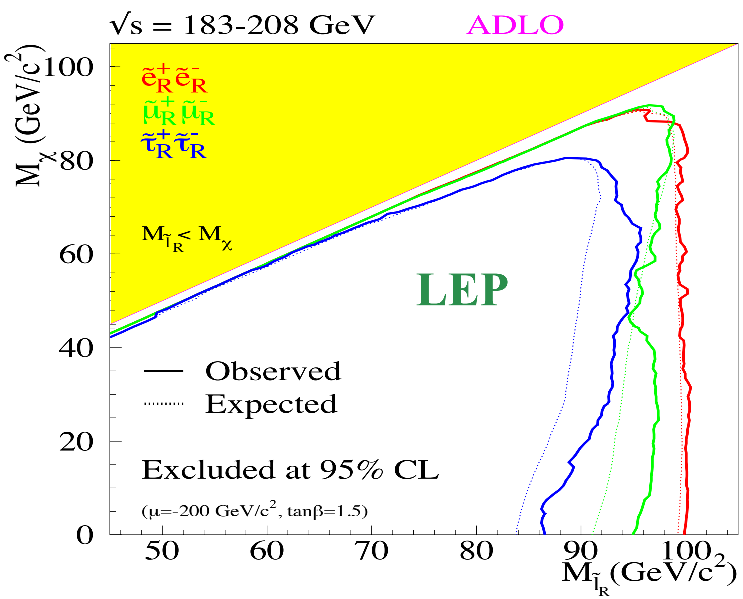


1. Phys. Lett. B 631, 58 (2005)
2. Phys. Rev. D 73, 095004 (2006)
3. arXiv:1212.2655

Stau & smuon

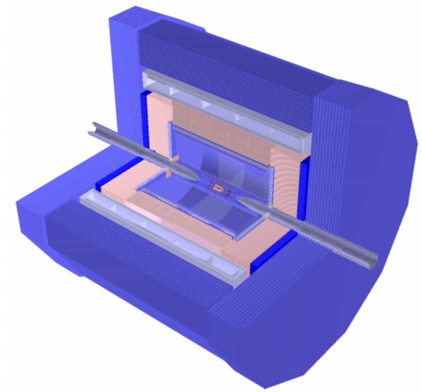






- **Smuon: muon g-2 excess**
- **Stau: dark matter**

TECHNICAL DETAIL



- About CEPC

  ECM=240GeV, higgs factory, 100 km circumference, 2 interaction points.

  ILD-like detector

- Software

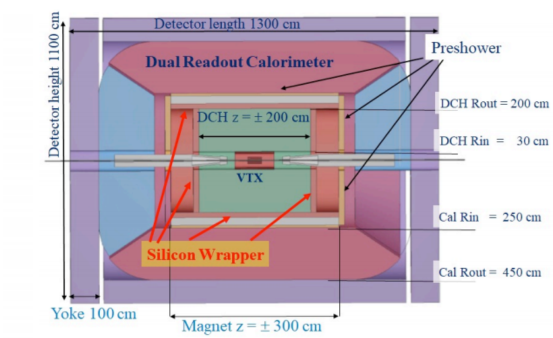
  Signal samples: MadGraph+Pythia8

  Simulation: Mokka

  Reconstruction: Marlin

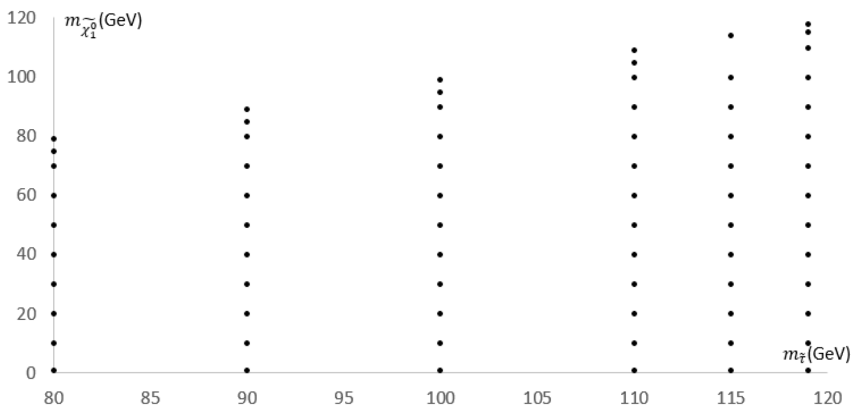
- Normalized to $5050\ \mathrm{fb}^{-1}$
- **Dominant backgrounds:**
  - **SM processes with two-e or two-μ or two-τ and large missing energy final states.**

process	Cross Section [fb]
$\mu\mu$	4967.58
$\tau\tau$	4374.94
$WW \to \ell\ell$	392.96
$ZZorWW \to \mu\mu vv$	214.81
$ZZorWW \to \tau\tau vv$	205.84
$vZ, Z \to \mu\mu$	43.33
$ZZ \to \mu\mu vv$	18.17
$vZ, Z \to \tau\tau$	14.57
$ZZ \to \tau\tau vv$	9.2
$vvH, H \to \tau\tau$	3.07
$evW, W \to \mu v$	429.2
$evW, W \to \tau v$	429.42
$eeZ, Z \to vv$	29.62
$eeZ, Z \to vv\ or\ evW, W \to ev$	249.34

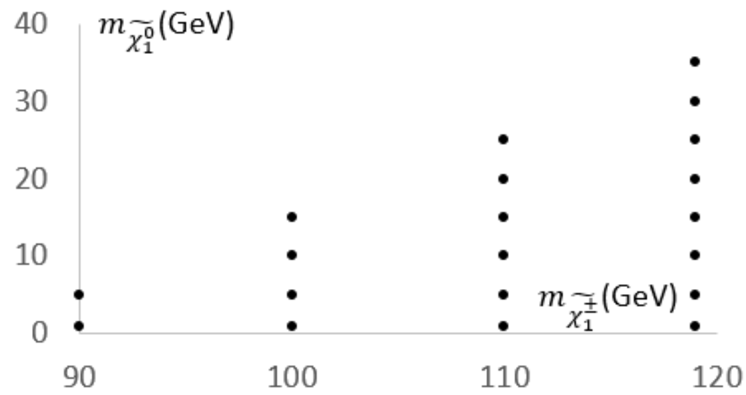


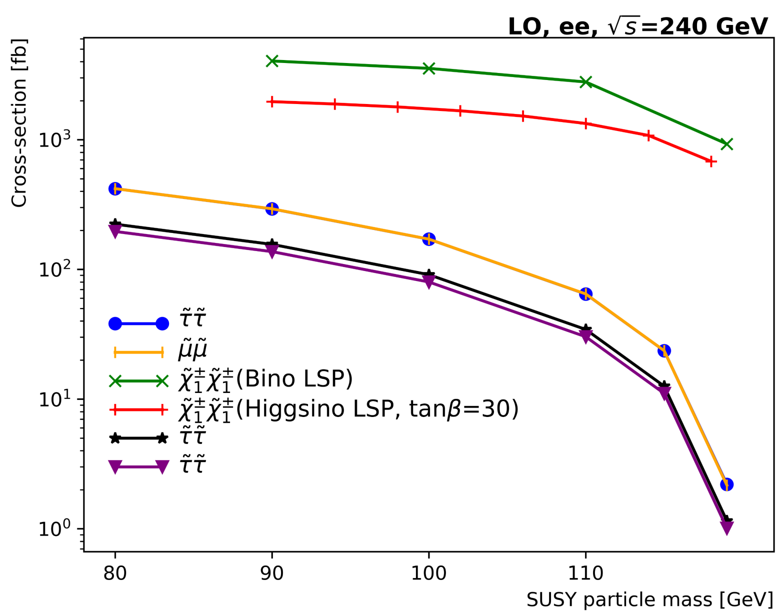
SIGNAL SAMPLES & CROSS SECTIONS

Direct stau/smuon

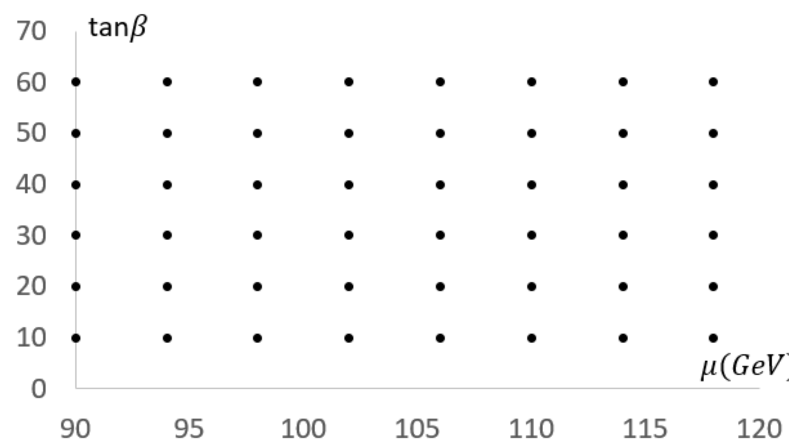


Chargino (Bino LSP)



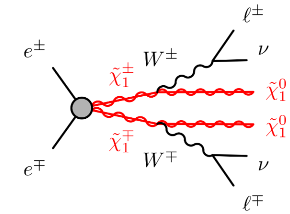


Chargino (Higgsino LSP)



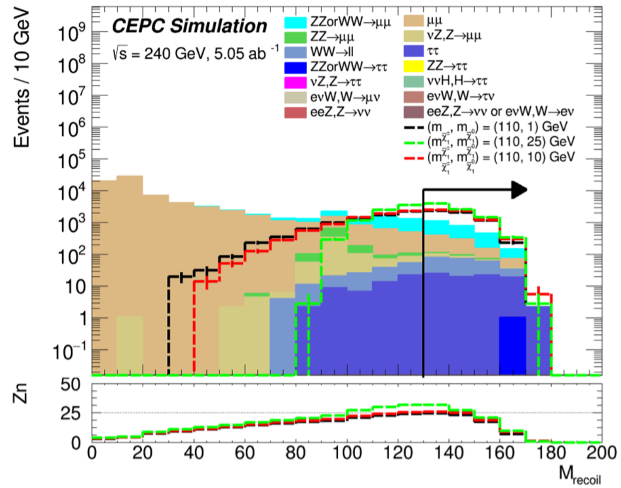
Cross-section based on Madgraph calculation

GAUGINO SEARCH

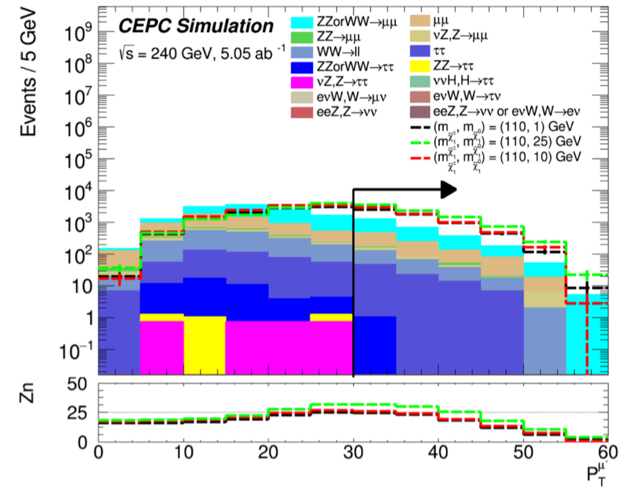


Bino LSP

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



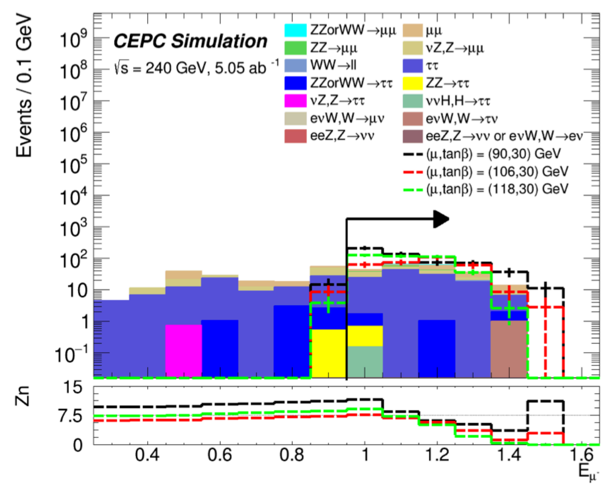
(a) M_{recoil} (M_{recoil} >130 GeV)



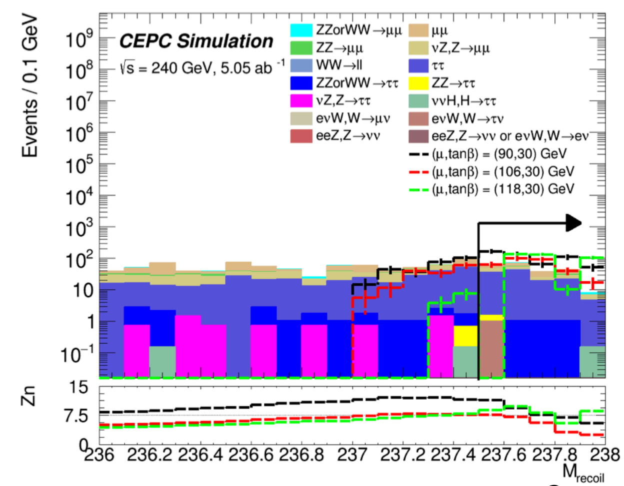
(b) $P_T^{\mu^-}$ ($P_T^{\mu^-}$ >30 GeV)

Higgsino LSP

Signal Region
== 2 muons (OS)
$E_{\mu^\pm} > 0.95$ GeV
$3.2 < \Delta R(\mu^\pm, recoil) < 4.6$
$\Delta\phi(\mu^\pm, recoil) < 2.9$
$M_{recoil} > 237.5$ GeV

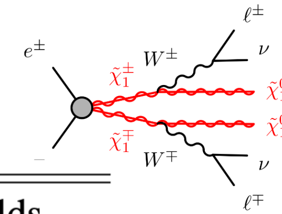


(a) E_{μ^-} ($E_{\mu^-} > 0.95$ GeV)



(b) M_{recoil} ($M_{recoil} > 237.5$ GeV)

GAUGINO SEARCH



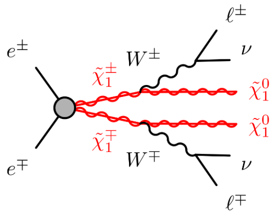
Bino LSP

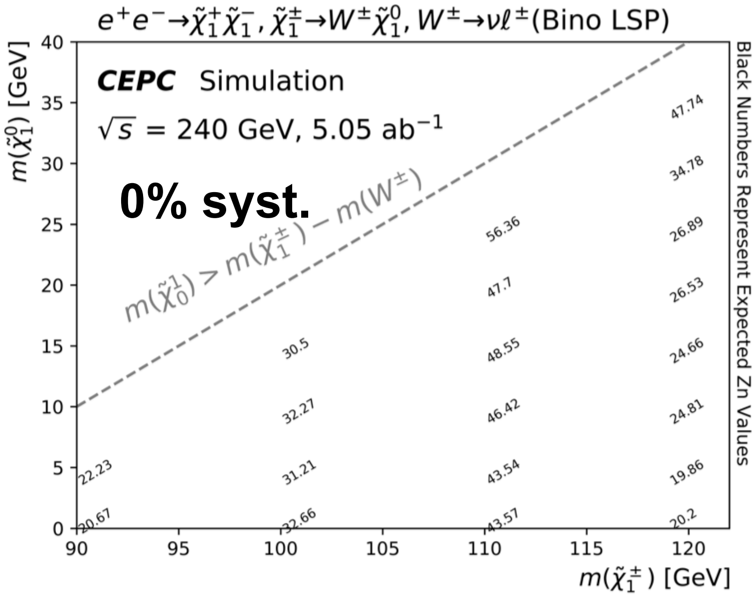
Process	Yields
ZZ or $WW \to \mu\mu\nu\nu$	1638 ± 42
$\mu\mu$	609 ± 61
$ZZ \to \mu\mu\nu\nu$	27.7 ± 6.2
$\nu Z, Z \to \mu\mu$	47.9 ± 7.3
$WW \to \ell\ell$	163 ± 13
$\tau\tau$	88 ± 14
ZZ or $WW \to \tau\tau\nu\nu$	0.74 ± 0.74
$ZZ \to \tau\tau\nu\nu$	-
$\nu Z, Z \to \tau\tau$	-
$\nu\nu H, H \to \tau\tau$	-
$e\nu W, W \to \mu\nu$	-
$e\nu W, W \to \tau\nu$	-
$eeZ, Z \to \nu\nu$	-
$eeZ, Z \to \nu\nu$ or $e\nu W, W \to e\nu$	-
Total background	2568 ± 77
m ($\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0$) = (110 , 1) GeV	5940 ± 130
m ($\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0$) = (110 , 10) GeV	6470 ± 140
m ($\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0$) = (110 , 25) GeV	8470 ± 160

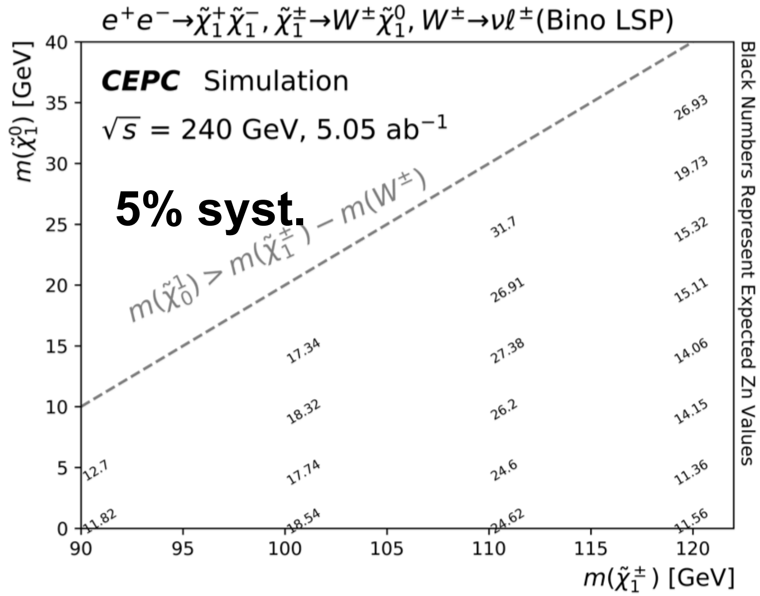
Higgsino LSP

Processes	Yields
ZZ or $WW \to \mu\mu\nu\nu$	4.3 ± 2.1
$\mu\mu$	49 ± 17
$ZZ \to \mu\mu\nu\nu$	5.5 ± 2.8
$\nu Z, Z \to \mu\mu$	36.7 ± 6.4
$WW \to \ell\ell$	1.0 ± 1.0
$\tau\tau$	118 ± 16
ZZ or $WW \to \tau\tau\nu\nu$	3.1 ± 1.8
$ZZ \to \tau\tau\nu\nu$	0.52 ± 0.52
$\nu Z, Z \to \tau\tau$	-
$\nu\nu H, H \to \tau\tau$	0.16 ± 0.16
$e\nu W, W \to \mu\nu$	-
$e\nu W, W \to \tau\nu$	1.0 ± 1.0
$eeZ, Z \to \nu\nu$	-
$eeZ, Z \to \nu\nu$ or $e\nu W, W \to e\nu$	-
Total background	219 ± 25
(μ , tanβ) = (90 GeV , 30)	546 ± 45
(μ , tanβ) = (106 GeV , 30)	319 ± 30
(μ , tanβ) = (118 GeV , 30)	400 ± 23

GAUGINO SEARCH

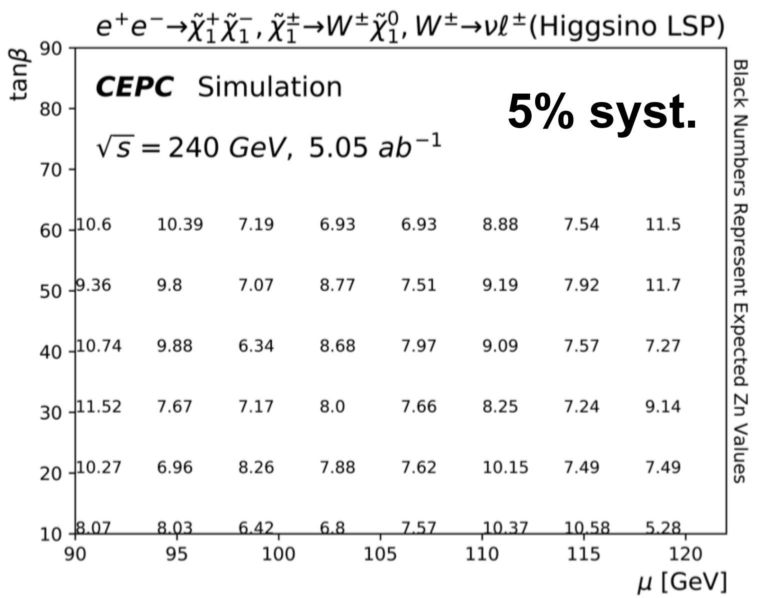


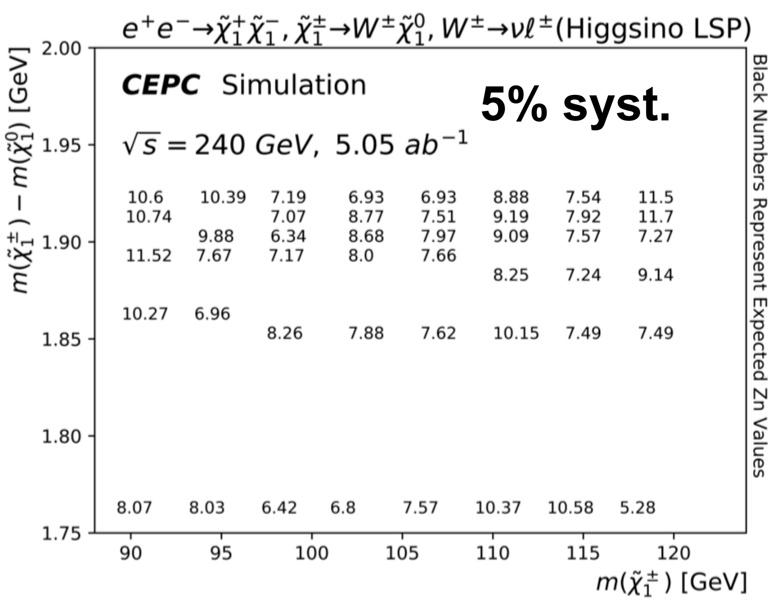




Bino LSP

CEPC240(FCCee/ILC): discovery for gauginos up to kinematic limit: √s/2

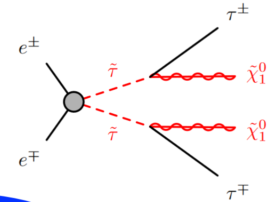




Higgsino LSP

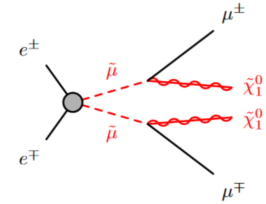
SLEPTON SEARCH

stau

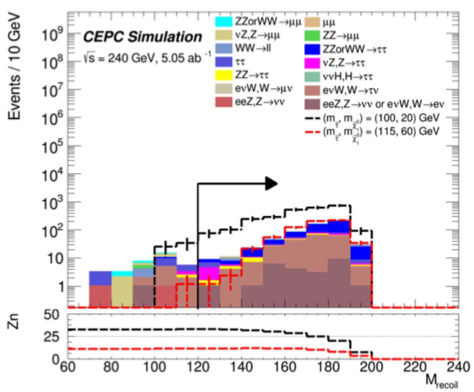


SR-highDeltaM	SR-midDeltaM	SR-lowDeltaM
$\Delta R(\tau^{\pm}, recoil) < 3.1$		$\Delta R(\tau^{\pm}, recoil) < 2.9$
$2.4 < \lvert\Delta\phi(\tau^{\pm}, recoil)\rvert < 3$		$\lvert\Delta\phi(\tau^{\pm}, recoil)\rvert > 2.3$
$0.4 < \Delta R(\tau,\tau) < 1$	$0.4 < \Delta R(\tau,\tau) < 1.6$	-
	$0.2 < \lvert\Delta\phi(\tau,\tau)\rvert < 1.2$	$\lvert\Delta\phi(\tau,\tau)\rvert > 0.6$
$E_{\tau^{\pm}} < 34$ GeV	$E_{\tau^{\pm}} < 15$ GeV	
sum$P_T > 70$ GeV	sum$P_T > 40$ GeV	-
$M_{recoil} > 95$ GeV	$M_{recoil} > 120$ GeV	$M_{recoil} > 205$ GeV
-	$M_{\tau\tau} < 40$ GeV	$M_{\tau\tau} < 18$ GeV

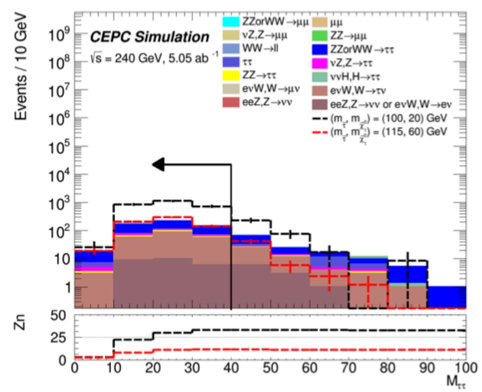
smuon



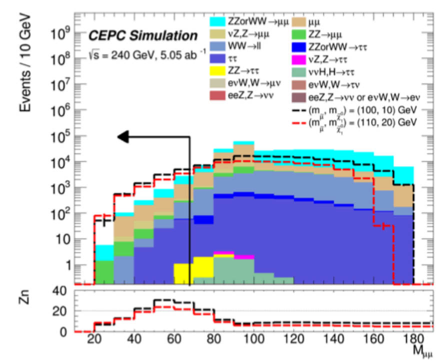
SR-highDeltaM	SR-midDeltaM	SR-lowDeltaM
== 2 muons(OS, both energy >0.5 GeV)		
$\Delta R(\mu, recoil) < 2.9$	$1.5 < \Delta R(\mu, recoil) < 2.8$	
$E_{\mu} > 40$ GeV	9 GeV$< E_{\mu} < 48$ GeV	-
$M_{\mu\mu} < 68$ GeV	$M_{\mu\mu} < 80$ GeV	-
$M_{recoil} > 60$ GeV	-	$M_{recoil} > 220$ GeV



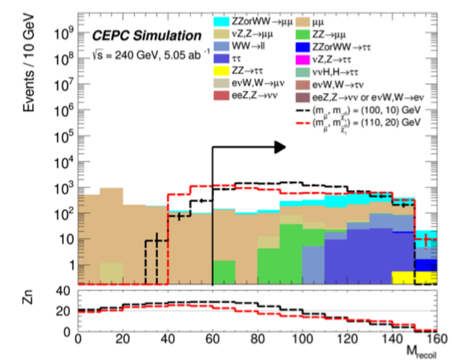
(c) SR-midDeltaM: M_{recoil}



(d) SR-midDeltaM: $M_{\tau\tau}$

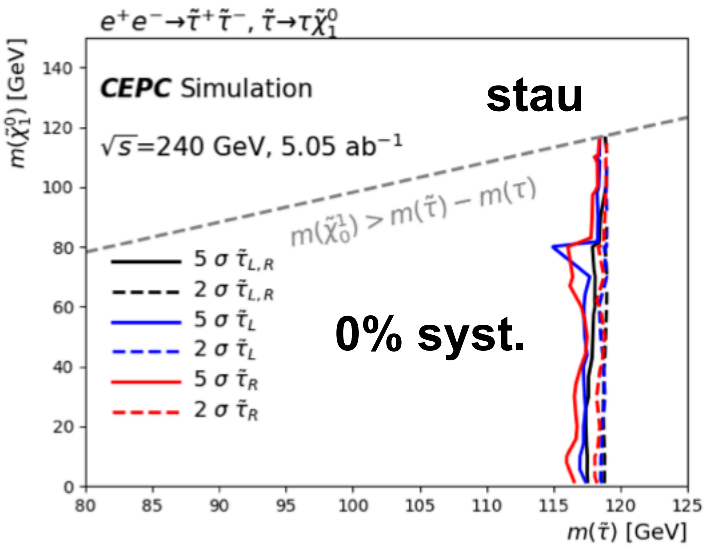


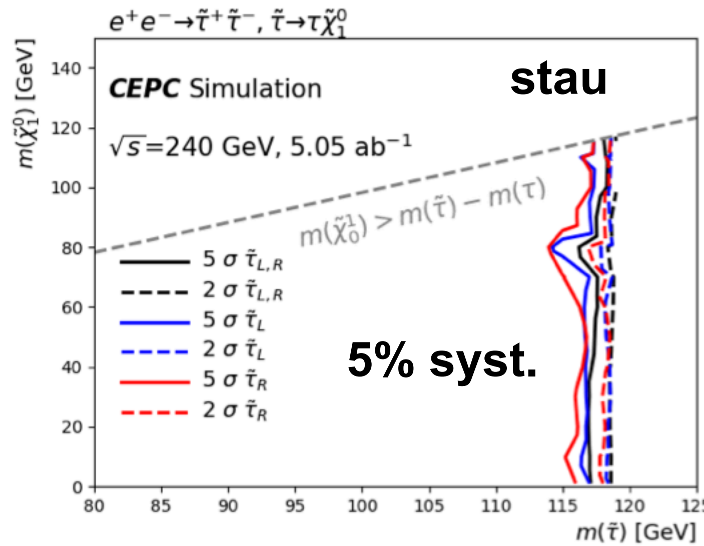
(a) SR-highDeltaM:$M_{\mu\mu}$

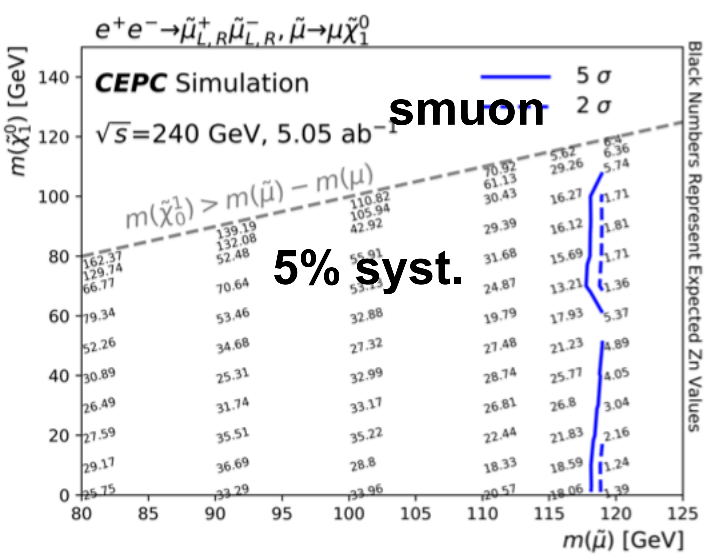


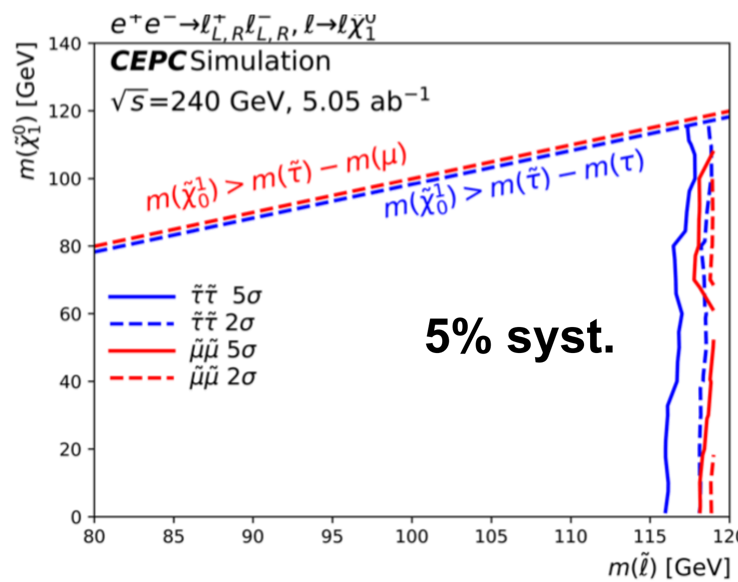
(b) SR-highDeltaM:M_{recoil}

SLEPTON SEARCH









CEPC240(FCCee/ILC): discovery for slepton nearly up to kinematic limit: √s/2

Paper drafts

Prospects for chargino pair production at CEPC

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To be submitted to CPC

ABSTRACT

The proposed Circular Electron Positron Collider (CEPC) with a center-of-mass energy $\sqrt{s} = 240$ GeV will serve as a Higgs factory, while it can offer good opportunity for new physics search at low energy, which is challenging in hadron colliders but motivated by some theory model such as dark matter. This paper presents the sensitivity study of chargino pair production with both Bino $\tilde{\chi}_1^0$ and Higgsino $\tilde{\chi}_1^0$ cases at CEPC using full Monte Carlo (MC) simulation. With the assumption of flat 5% systematic uncertainty, the CEPC has the ability to discover chargino pair production for both Bino $\tilde{\chi}_1^0$ and Higgsino $\tilde{\chi}_1^0$ cases up to kinematic limit $\sqrt{s}/2$. Because of the conserved assumption of systematic uncertainty and limited reliance on the reconstruction and detector geometry in this study, the results can be used as reference for similar searches in other electron positron colliders at a central-of-mass energy close to 240 GeV, such as FCC-ee and ILC.

Keywords: CEPC; chargino; Bino; Higgsino

CONTENTS

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(will be inserted by the editor)

Prospects for slepton pair production in the future e^-e^+ Higgs factories

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Abstract The Circular Electron Positron Collider (CEPC) with a center-of-mass energy $\sqrt{s} = 240$ GeV is proposed to serve as a Higgs factory, while it can also provide good opportunity for new physics searches at lower energy, which are difficult in hadron collider but well-motivated by some theories, such as dark matter. This paper presents the sensitivity study of direct stau/smuon production searches in CEPC with full Monte Carlo (MC) simulation. With the assumption of a conserved systematic uncertainty at 5%, the CEPC has the potential to discover the production of combined LH and RH stau up to 116 GeV with 5 sigma if existed, or up to 113 GeV for the production of pure LH/RH stau; the discovery potential of direct smuon reaches up to 117 GeV with the same assumption. The results can also provide reference to similar searches in other electron-positron colliders with a close central-of-mass energy, such as the ILC and FCC-ee, due to the conserved systematic uncertainty and small dependence on the detector geometry and reconstruction in the analysis.

Declarations

This study was supported by the National Key Programme (Grant NO.: 2018YFA0404000). The data used in this study won't be deposited, because this study is a simulation study without any experiment data.

1 Introduction

Spuersymmetry (SUSY) [1–7] proposes that there is a superpartner, known as sparticle, for every Standard Model (SM) particle, whose spin is different by a half from the corresponding SM particle. With R-parity [8] conserved, SUSY particles are produced in pair, and the lightest supersymmetric particle (LSP) is stable and weakly interacting, which makes LSP can't be detected directly and a dark matter candidate [9, 10].

The linear superpositions of charged and neutral Higgs bosons and electroweak gauge bosons formed two charged mass eigenstates called charginos and four neutral mass eigenstates called neutralinos. The superpartner of a lepton is a slepton whose chirality is the same as the lepton's chirality. The slepton mass eigenstates formed from superpositions of left-handed sleptons and right-handed sleptons.

Models with light sleptons satisfies the dark matter relic density measurements [11]. And lightlight sleptons can take part in the coannihilation of neutralinos [12, 13]. Models with light smuons can explain $(g-2)_\mu$ excess [14]. In gauge-mediated [15–17] and anomaly-mediated [18, 19] SUSY breaking models, the mass of sleptons are expected to be of the order of magnitude of 100 GeV.

LEP set lower mass limit on $\tilde{\mu}_R$ of 94.9 GeV with $m_{\tilde{\mu}_R} - m_{\tilde{\chi}_1^0}$ above 10 GeV and set a lower mass limit on $\tilde{\tau}$ of 87 - 93 GeV depending on the $\tilde{\chi}_1^0$ mass, for $m_{\tilde{\tau}} - m_{\tilde{\chi}_1^0} > 7$ GeV [20]. ATLAS and CMS have excluded the smuon/stau mass up to 700 / 300 GeV with massless LSP for simplified model, however, for the cases with massive LSP, especially when the mass split of slepton and LSP is very small, the sensitivity from LHC is limited by the trigger requirement [21–24].

Comparing to LHC, CEPC has very clean collision environment, which means less backgrounds. Comparing to LEP, CEPC has higher center-of-mass energy. And there is no trigger requirement for CEPC, so CEPC should have excellent sensitivity in compressed region. Reconstruction and identification efficiencies for tracks and single particles (e.g. muon) are very high in CEPC, which ensures sufficient sensitivities for the scenarios with very soft objects [25].

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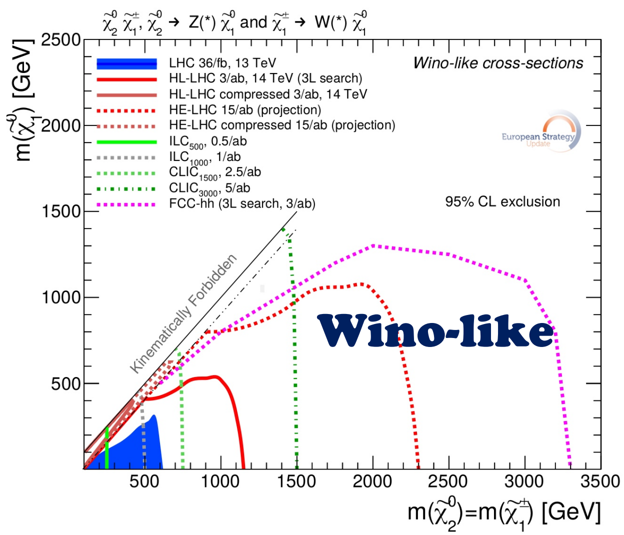
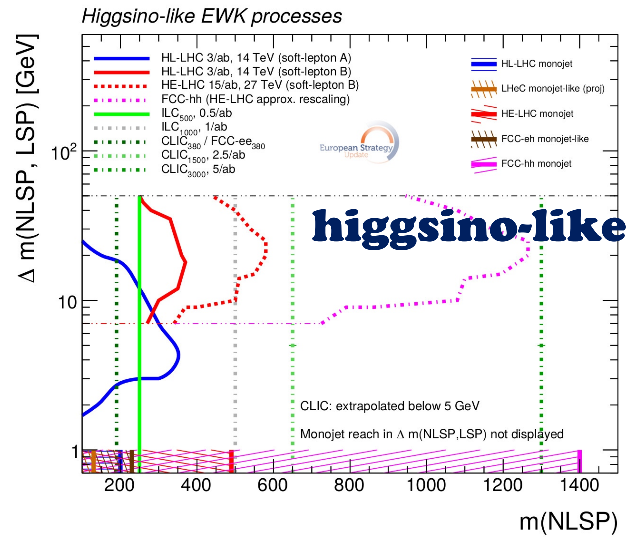
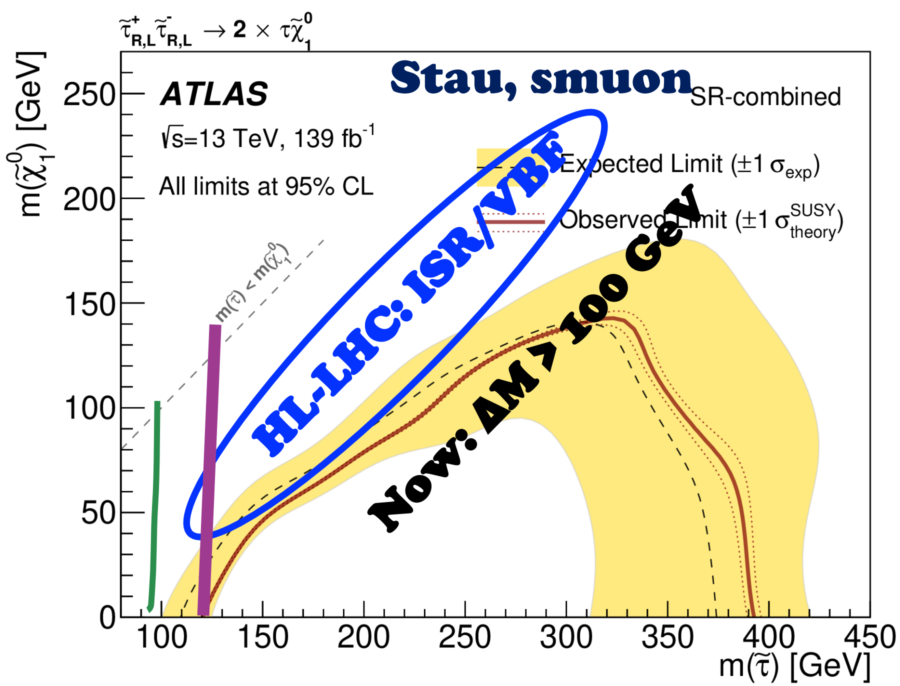
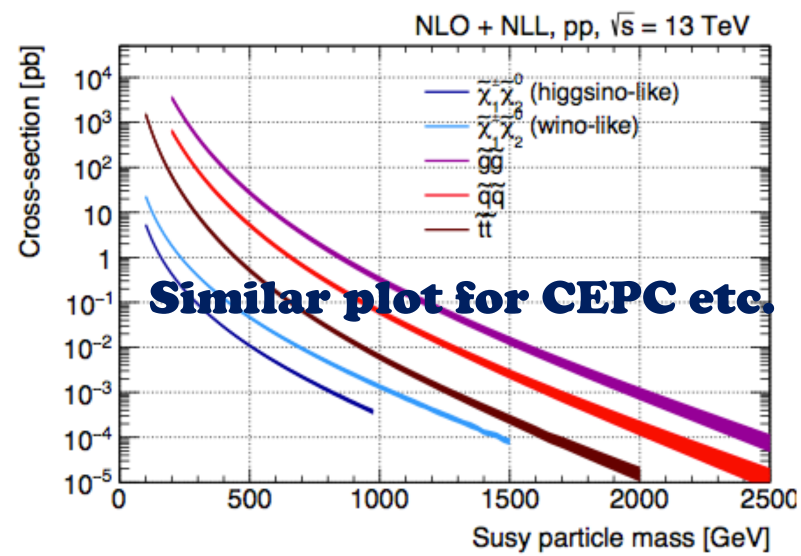
Curves contributed to a Snowmass report summary plot









Summary and Outlook

- Search for sleptons and electroweakinos were performed at CEPC.
  - The discovery potential for electroweakinos (wino-like & higgsino-like) is up to kinematic limit: $\sqrt{s}/2$.
  - The discovery potential for smuon and stau are nearly up to kinematic limit (up to ~116-117 GeV)
- The results can also be used as reference for other lepton colliders like ILC and FCC-ee etc.
- Paper drafts are almost done and to be provided as inputs for snowmass white paper.

Backup

STAU SEARCH

Table 2 The number of events in the signal regions for signal and SM backgrounds with statistical uncertainty for direct stau production

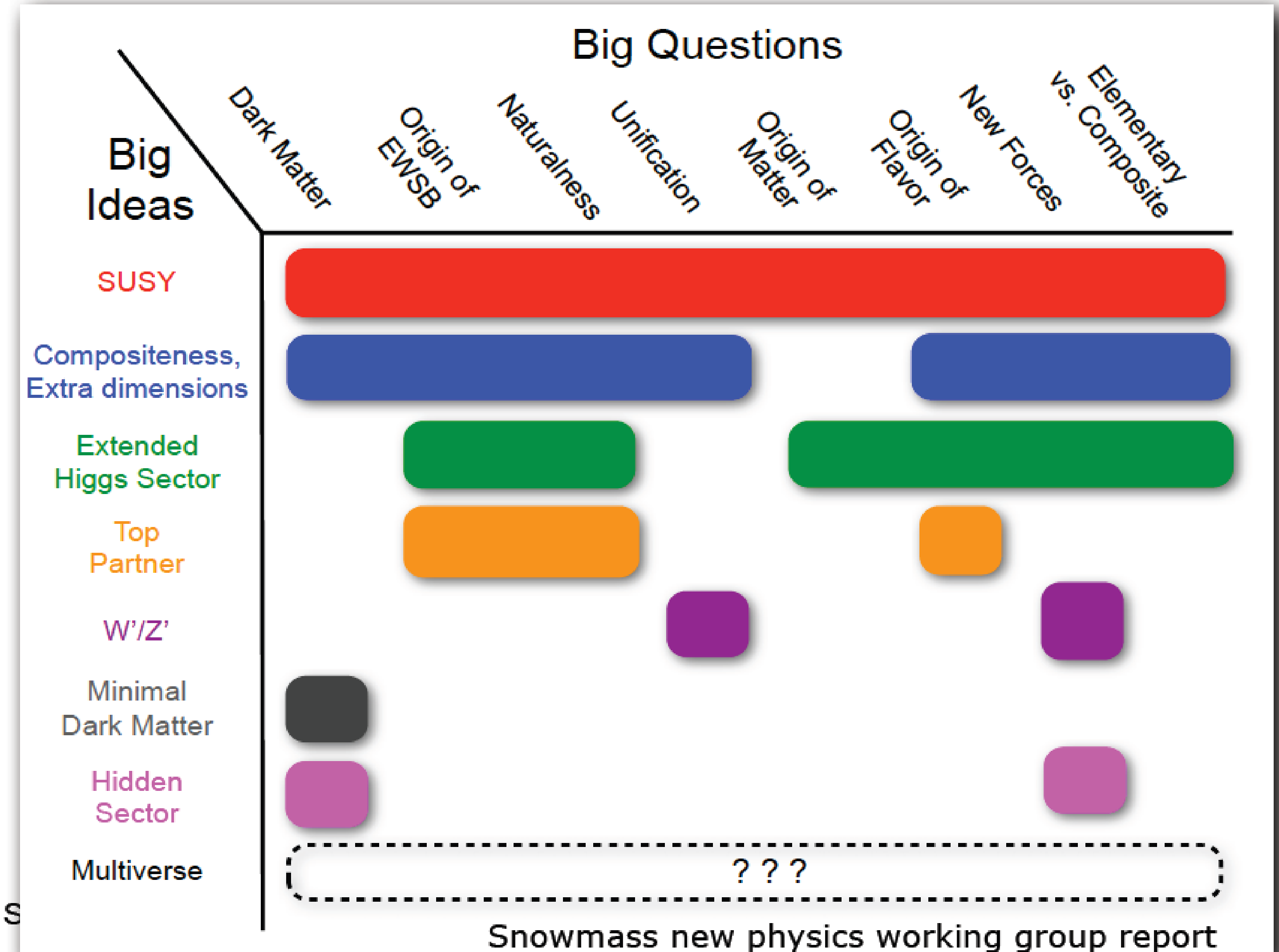
process	SR-highDeltaM	SR-midDeltaM	SR-lowDeltaM
ZZ or $WW \to \mu\mu\nu\nu$	8.5 ±3.0	1.1 ±1.1	74.8±8.9
$\mu\mu$	-	-	408 ±50
$\nu Z, Z \to \mu\mu$	3.3±1.9	2.2±1.6	698±28
$ZZ \to \mu\mu\nu\nu$	1.4 ±1.4	-	54.0±8.6
$WW \to \ell\ell$	91.0 ±9.6	38.9±6.3	284±17
ZZ or $WW \to \tau\tau\nu\nu$	41.2±6.5	275±17	1247±36
$\tau\tau$	15.9±6.0	15.9±6.0	497±34
$\nu Z, Z \to \tau\tau$	15.6 ±3.4	25.2±4.3	232 ±13
$ZZ \to \tau\tau\nu\nu$	17.7 ±3.1	19.3±3.2	49.3 ±5.1
$\nu\nu H, H \to \tau\tau$	-	-	-
$e\nu W, W \to \mu\nu$	39±20	-	9.8±9.8
$e\nu W, W \to \tau\nu$	147±12	185 ±14	139 ±12
$eeZ, Z \to \nu\nu$	9.2±3.1	-	8.2 ±2.9
$eeZ, Z \to \nu\nu$ or $e\nu W, W \to e\nu$	98±10	25.7±5.1	54.5±7.5
Total background	488 ±29	589 ±25	3756±81
m($\tilde{\tau}_{L,R}$,$\tilde{\chi}_1^0$) = (115,20) GeV	3400±170	3070±160	2110±140
m($\tilde{\tau}_{L,R}$,$\tilde{\chi}_1^0$) = (100,20) GeV	200±15	377 ±21	374 ±21
m($\tilde{\tau}_{L,R}$,$\tilde{\chi}_1^0$) = (100,80) GeV	-	1.2 ±1.2	3143±61

SMUON SEARCH

Table 4 The number of events in the signal regions for signal and SM backgrounds with statistical uncertainty for direct smuon production

process	SR-highDeltaM	SR-midDeltaM	SR-lowDeltaM
$ZZorWW \to \mu\mu\nu\nu$	1561±41	18020±140	168±13
$\mu\mu$	1096±82	8000±220	2180±120
$\nu Z, Z \to \mu\mu$	97±10	423±22	468±23
$ZZ \to \mu\mu\nu\nu$	69.2±9.8	160±15	52.6±8.5
$WW \to \ell\ell$	164±13	7672±89	282±17
$ZZorWW \to \tau\tau\nu\nu$	3.1±1.8	2128±47	326±18
$\tau\tau$	73±13	3748±92	1782±64
$ZZ \to \tau\tau\nu\nu$	1.07±0.76	69.1±6.1	19.8±3.3
$\nu Z, Z \to \tau\tau$	-	83.7±7.9	51.9±6.2
$\nu\nu H, H \to \tau\tau$	-	47.9±2.7	5.12±0.89
$e\nu W, W \to \mu\nu$	-	-	-
$e\nu W, W \to \tau\nu$	-	-	-
$eeZ, Z \to \nu\nu$	-	-	-
$eeZ, Z \to \nu\nu$ or $e\nu W, W \to e\nu$	-	-	-
Total background	3064±94	40350±300	5340±140
m($\tilde{\mu}$,$\tilde{\chi}_1^0$) = (100,10) GeV	8820±280	19450±410	190±40
m($\tilde{\mu}$,$\tilde{\chi}_1^0$) = (100,50) GeV	8190±270	58680±710	104±30
m($\tilde{\mu}$,$\tilde{\chi}_1^0$) = (100,95) GeV	-	17±12	114360±990

New Physics beyond the SM



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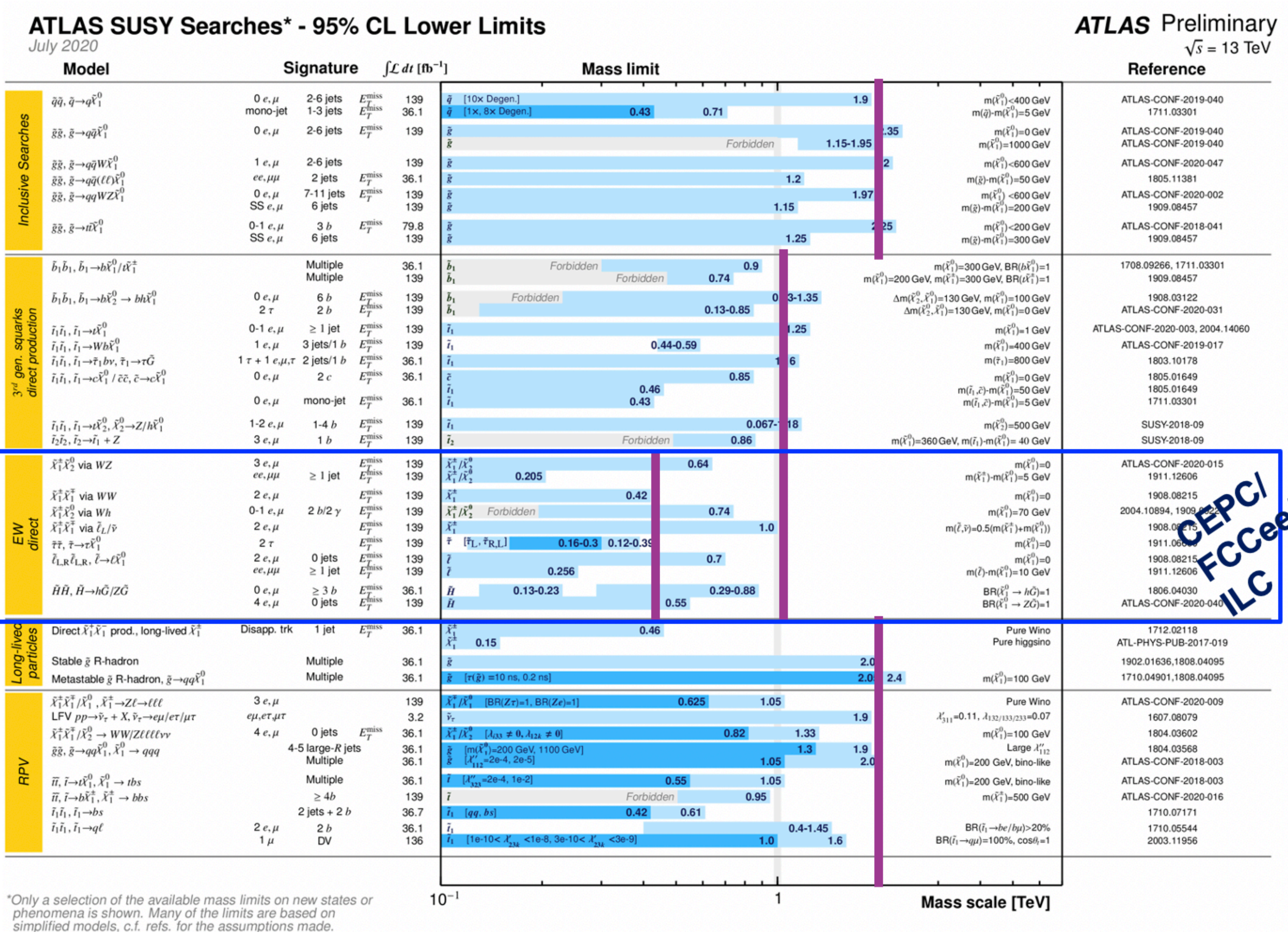


ATLAS SUSY Searches* - 95% CL Lower Limits
July 2020
ATLAS Preliminary
√s = 13 TeV
Model
Signature
∫L dt [fb⁻¹]
Mass limit
Reference
Inclusive Searches
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Forbidden
CEPC/
FCCee/
ILC
10⁻¹
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

EU Strategy- SUSY: ~g

https://arxiv.org/pdf/1910.11775.pdf

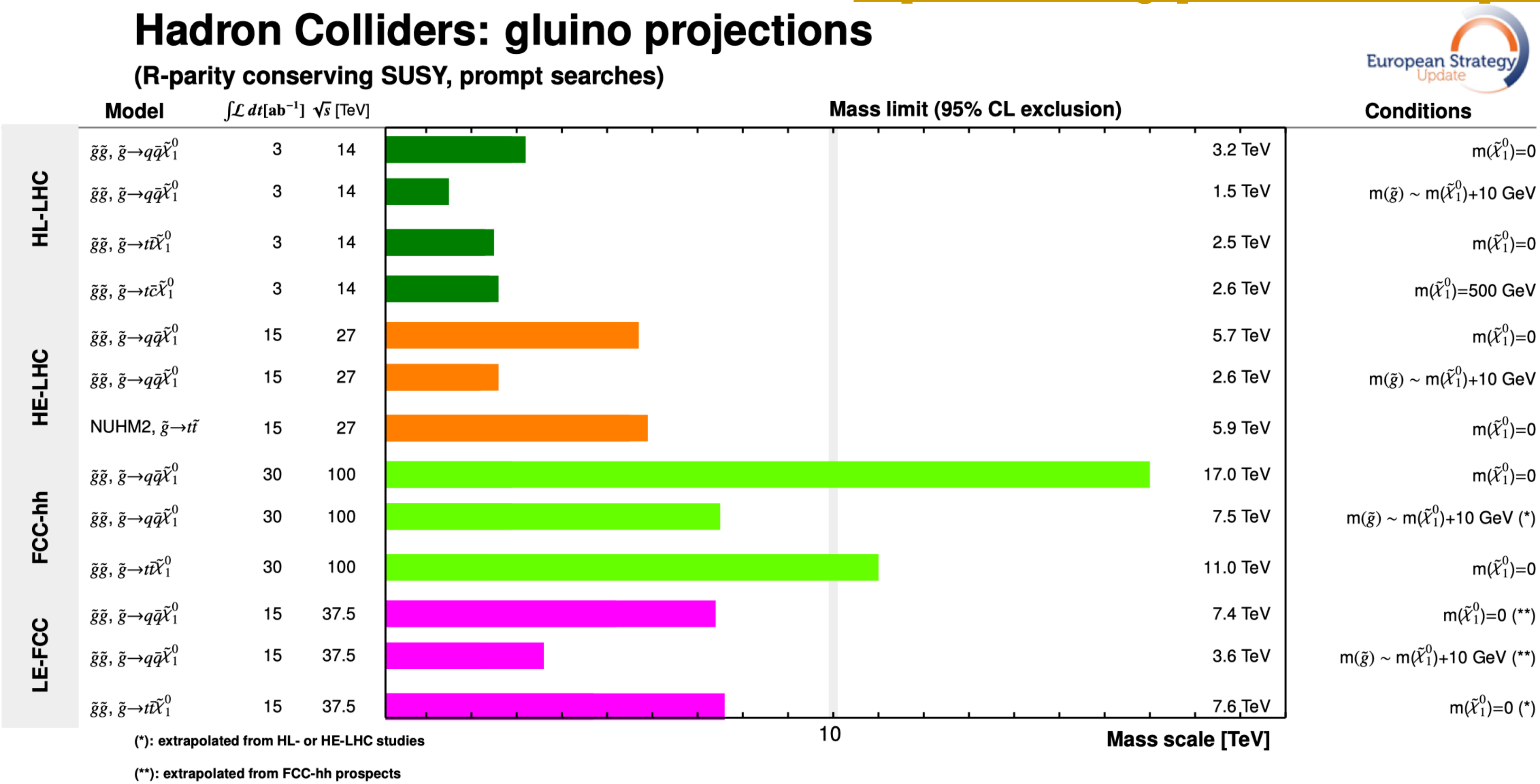


Fig. 8.6: Gluino exclusion reach of different hadron colliders: HL- and HE-LHC [443], and FCC-hh [139, 448]. Results for low-energy FCC-hh are obtained with a simple extrapolation.

EU Strategy- SUSY: ~q

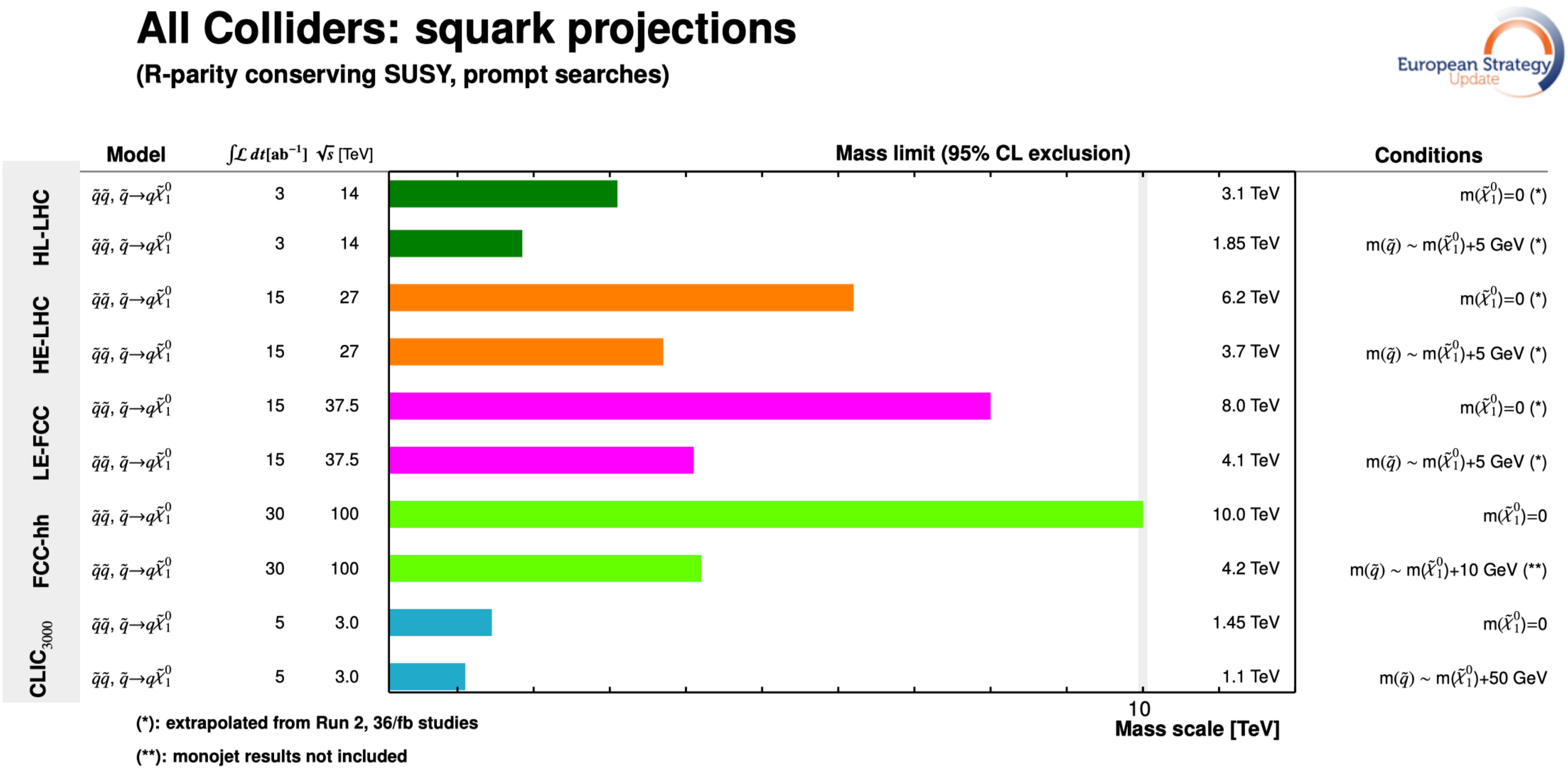


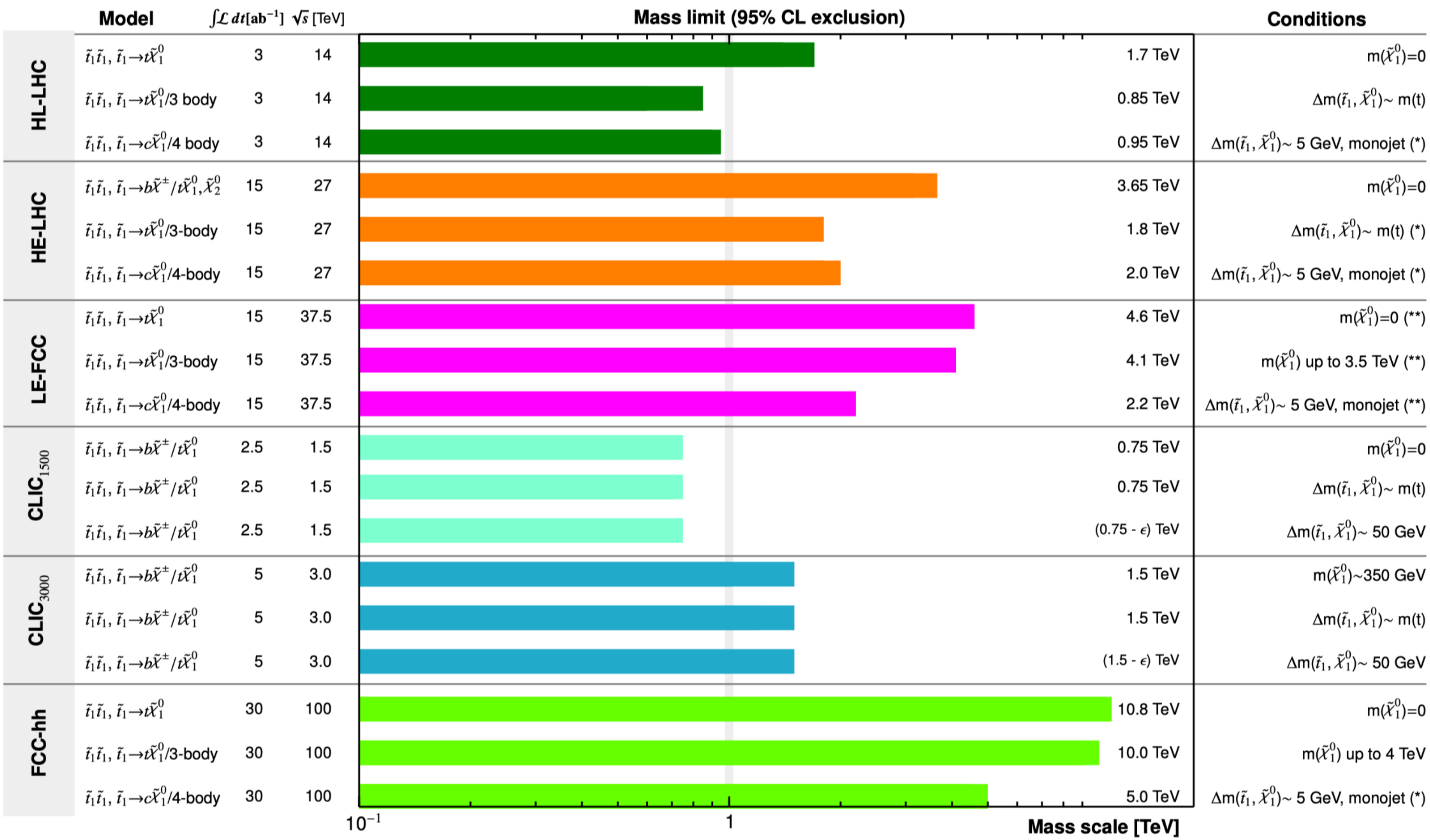
Fig. 8.7: Exclusion reach of different hadron and lepton colliders for first- and second-generation squarks.

EU Strategy- SUSY: ~t

All Colliders: Top squark projections

(R-parity conserving SUSY, prompt searches)

European Strategy Update



(*) indicates projection of existing experimental searches

(**) extrapolated from FCC-hh prospects

ϵ indicates a possible non-evaluated loss in sensitivity

ILC 500: discovery in all scenarios up to kinematic limit $\sqrt{s}/2$

MSSM charginos and neutralinos

Mass matrices

charginos

in $(\tilde{W}^-, \tilde{H}^-)$ basis

$$\begin{pmatrix} M_2 & \sqrt{2} m_W c_\beta \\ \sqrt{2} m_W s_\beta & \mu \end{pmatrix}$$

neutralinos

in $(\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0)$ basis

$$\begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_w & m_Z s_\beta s_w \\ 0 & M_2 & m_Z c_\beta c_w & -m_Z s_\beta c_w \\ -m_Z c_\beta s_w & m_Z c_\beta c_w & 0 & -\mu \\ m_Z s_\beta s_w & -m_Z s_\beta c_w & -\mu & 0 \end{pmatrix}$$

$$M_2 \text{ real}, \qquad M_1 = |M_1| e^{i\Phi_1}, \qquad \mu = |\mu| e^{i\Phi_\mu}$$

At tree level:

charginos $M_2, \mu, \tan\beta$

neutralinos $+M_1$

Φ_μ, Φ_1

CP phases

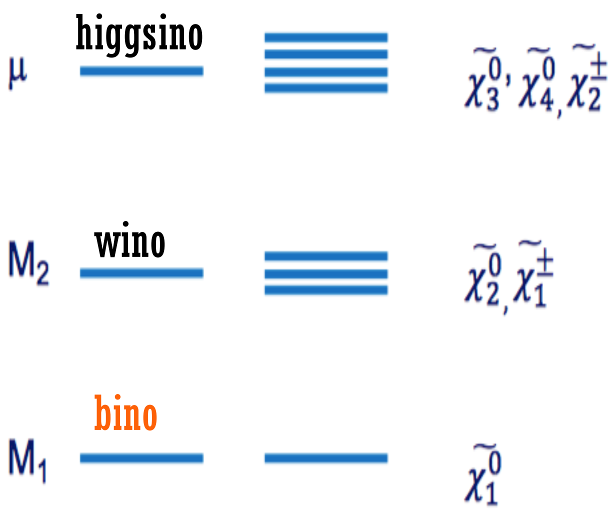
Expected to be among the lightest sparticles

→ A good starting point towards SUSY parameter determination

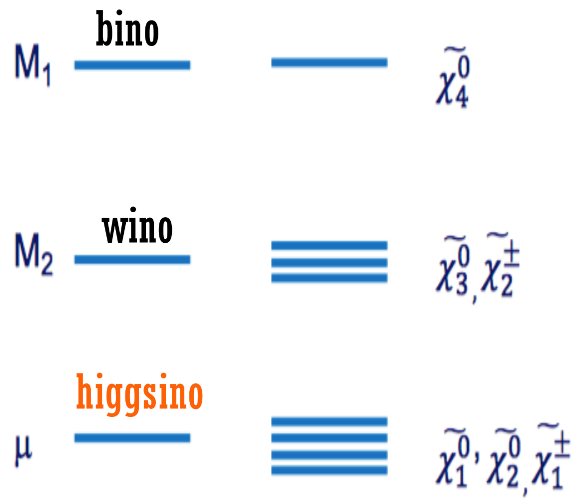
EWK-ino production

Mass splitting of the EWKinos depends on M1, M2, μ and tanβ

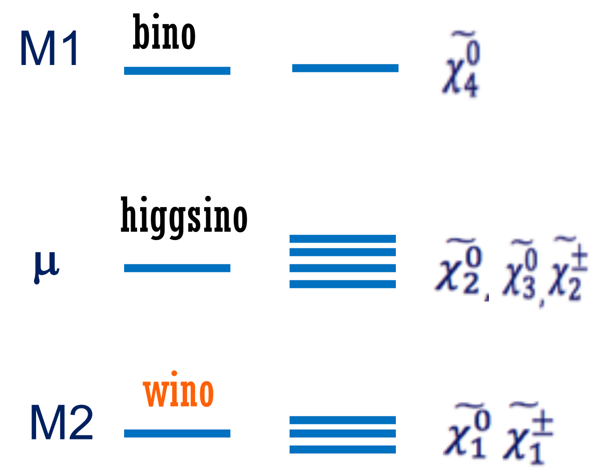
Bino LSP



Higgsino LSP



Wino LSP



Standard wino-bino case: large Δm between N1 and C1/N2;

➔ **MET + hard leptons**

N1,N2,C1 almost degenerate: experimental challenging;

➔ **MET + soft leptons**

➔ **Lower xsec than higgsino LSP;**

➔ **WW+MET dominant;**

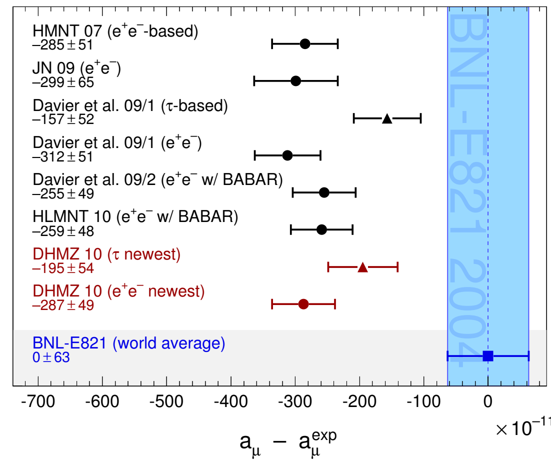
https://indico.cern.ch/event/687651/contributions/3400865/attachments/1850992/3038683/Wagner-LHCP2019.pdf

Muon Anomalous Magnetic Moment

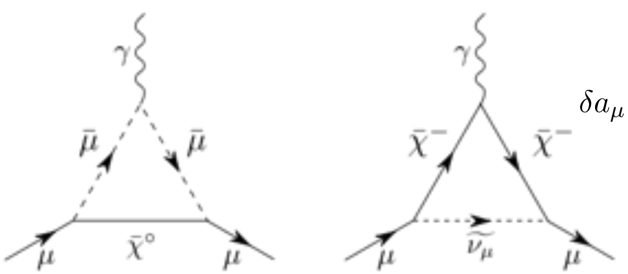
Present status: Discrepancy between Theory and Experiment at more than three Standard Deviation level

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

3.6σ Discrepancy



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



$$\delta a_\mu \simeq \frac{\alpha}{8\pi s_W^2} \frac{m_\mu^2}{\widetilde{m}^2} {\rm Sgn}(\mu M_2) \tan\beta \simeq 130 \times 10^{-11} \left(\frac{100 \text{ GeV}}{\widetilde{m}}\right)^2 {\rm Sgn}(\mu M_2) \tan\beta$$

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 !