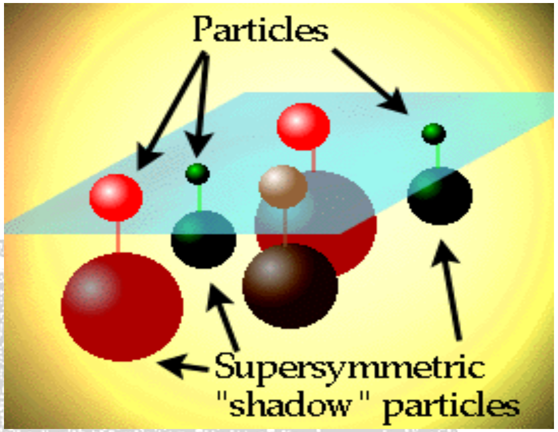


BSM @ CEPC

Xuai Zhuang

zhuangxa@ihep.ac.cn

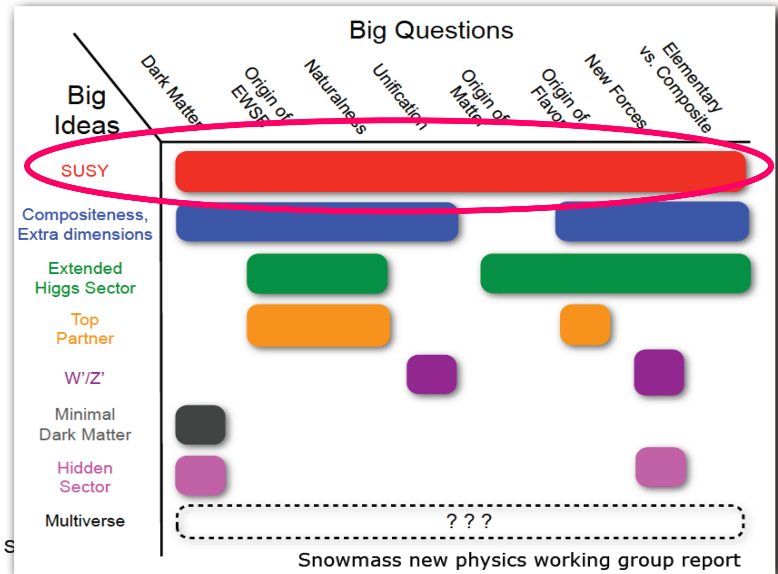
24/07/2020

1

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

SUSY Introduction (I)

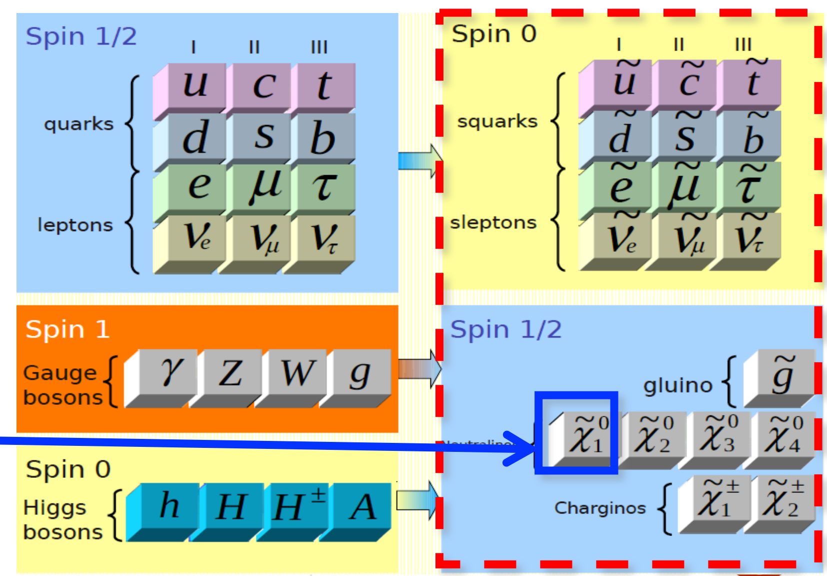
New Physics beyond the SM



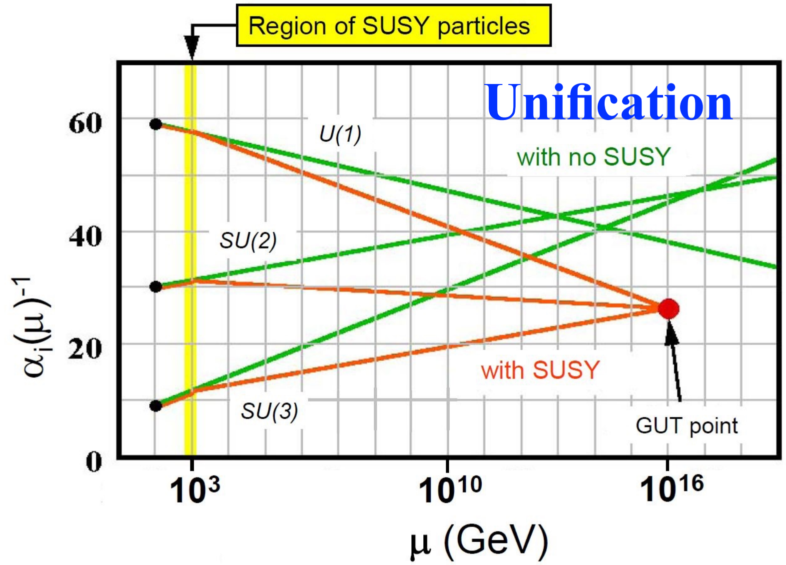
- **SUSY is one of the most favorite candidate for New Physics.**

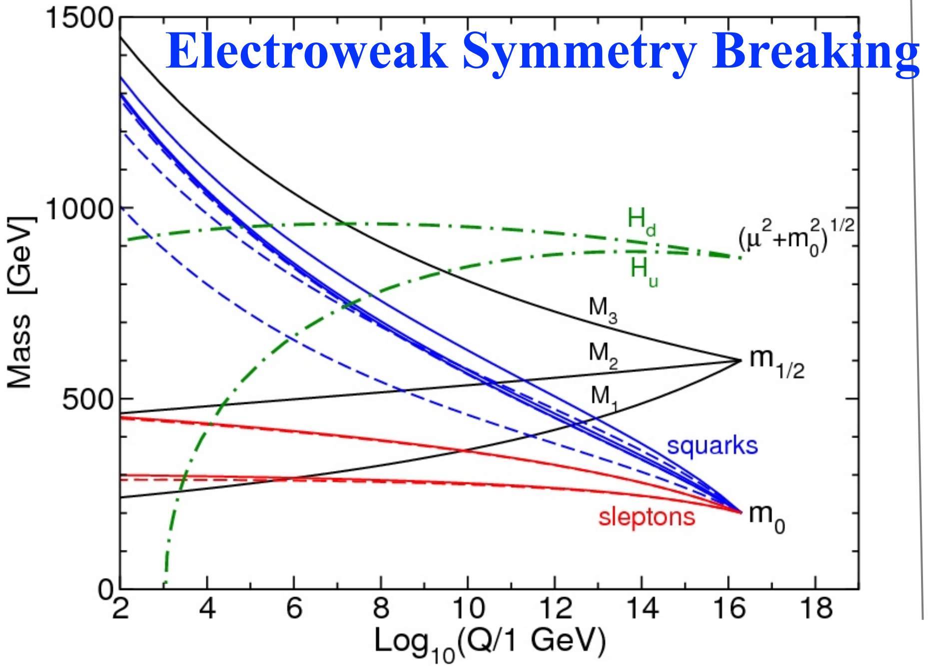
- **SUSY establishes a symmetry between fermions (matter) and bosons (forces)**
  - Unification
  - Solves deep problems of the SM
  - Provide Dark Matter candidate
  - …

OUR WORLD… NEW WORLD

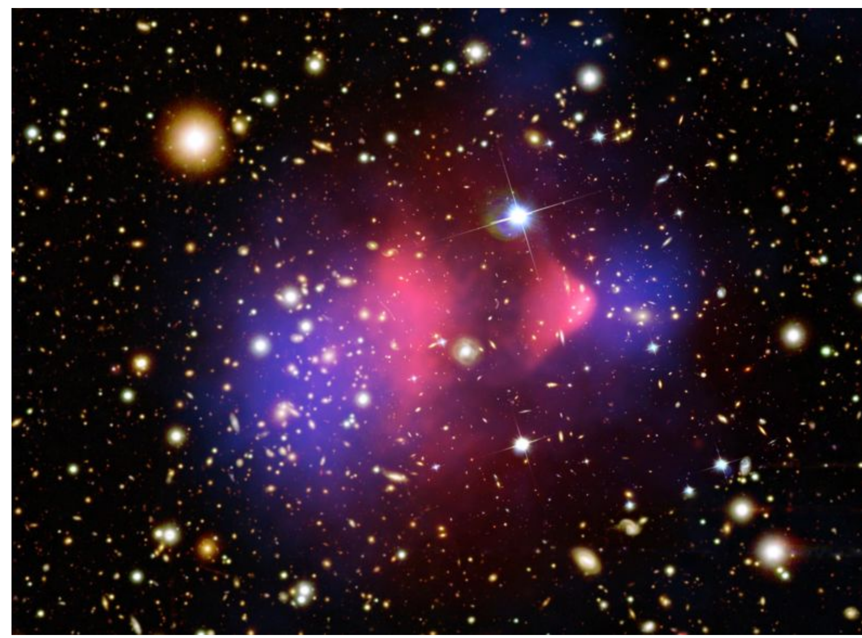


SUSY Introduction (II)

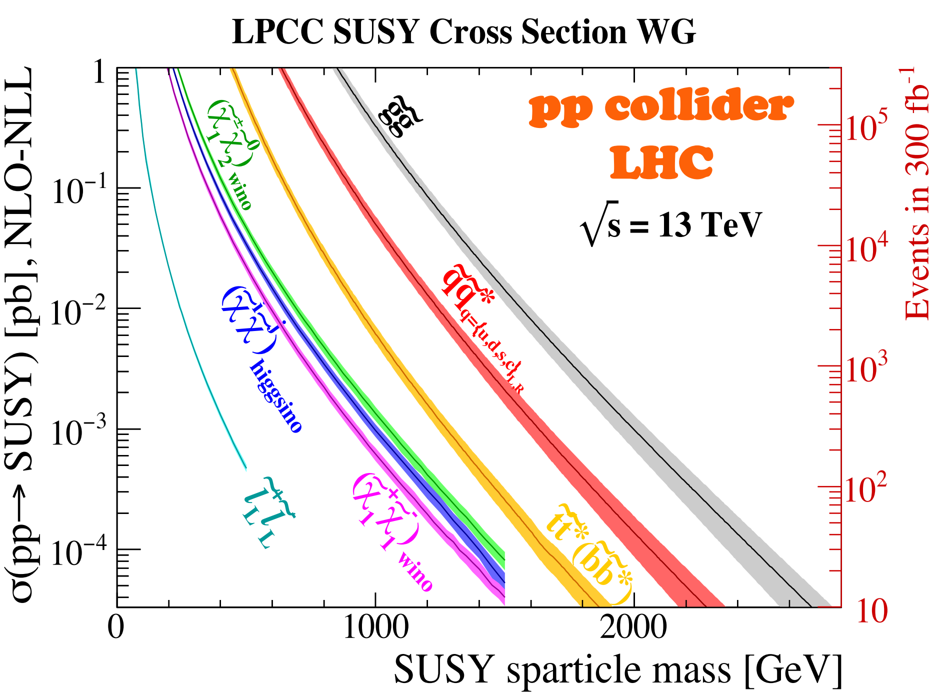


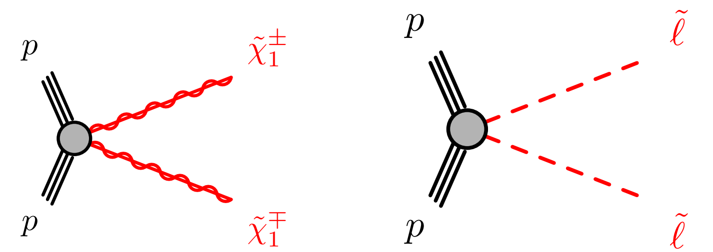


If R-Parity is Conserved the Lightest SUSY particle is a good Dark Matter candidate

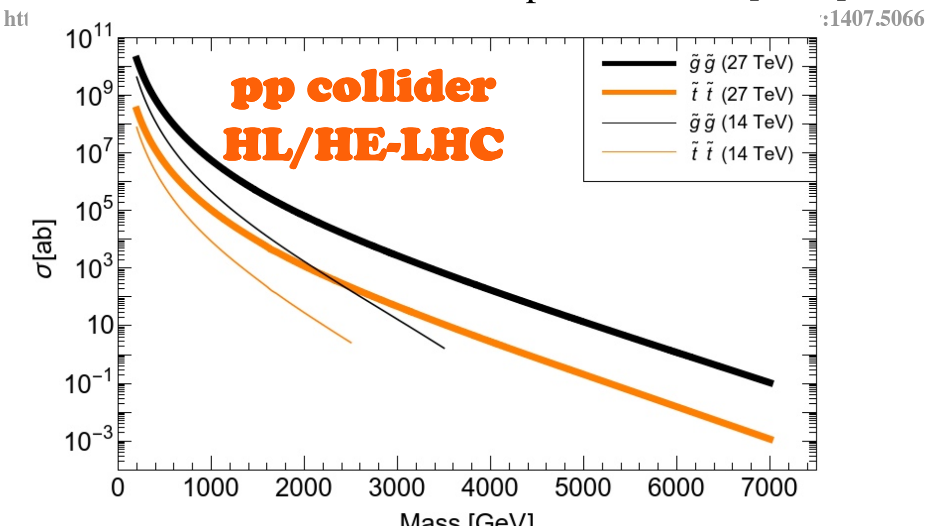


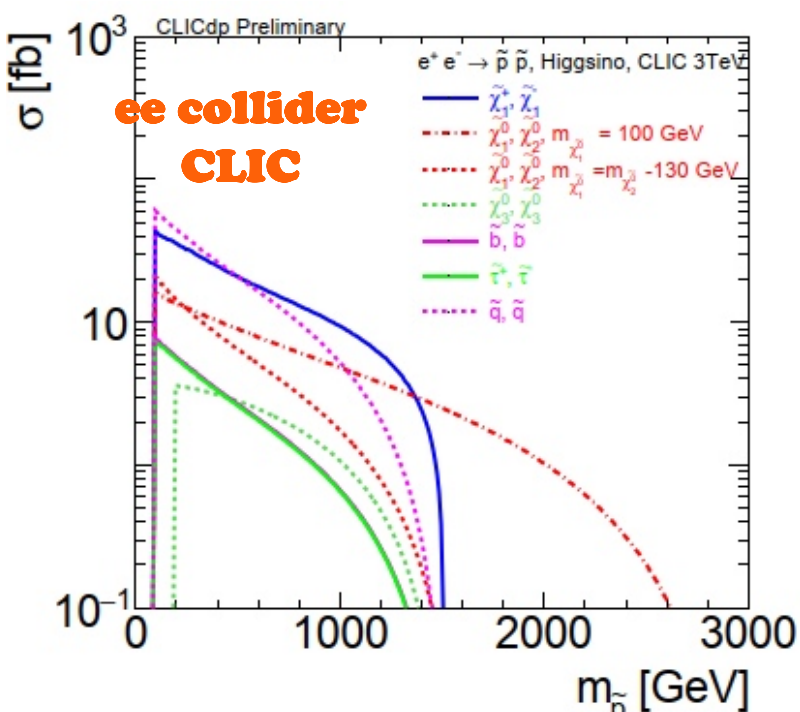
SUSY cross section





The dominant production is from <u>EWK and slepton</u> at lepton collider





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 real, $\quad M_1 = |M_1| e^{i\Phi_1}, \quad \mu = |\mu| e^{i\Phi_\mu}$

At tree level:

charginos $\quad M_2, \mu, \tan\beta$
neutralinos $\quad +M_1$

Expected to be among the lightest sparticles

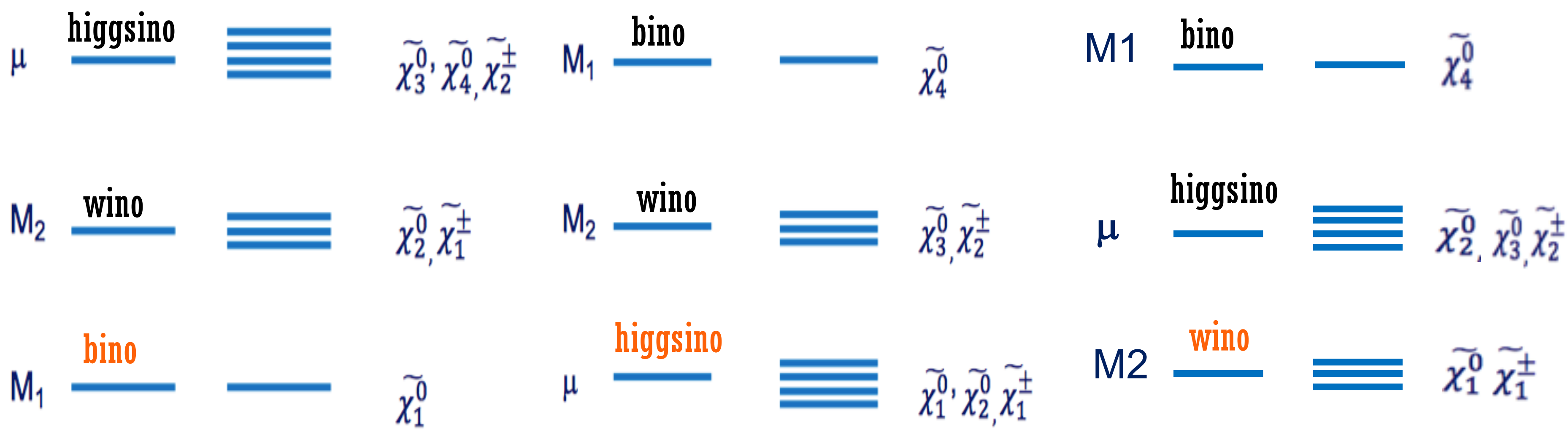
Φ_μ, Φ_1
CP phases

→ 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;

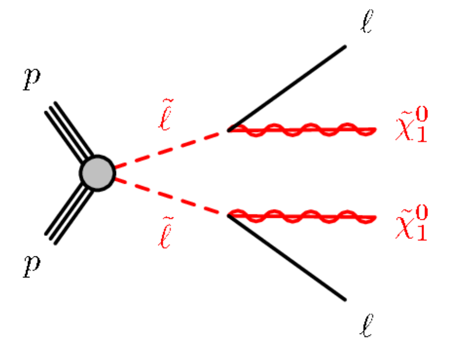
Interested Topics @ CEPC

Mainly for sleptons, electroweakinos, long-lived particles, RPV, DM …

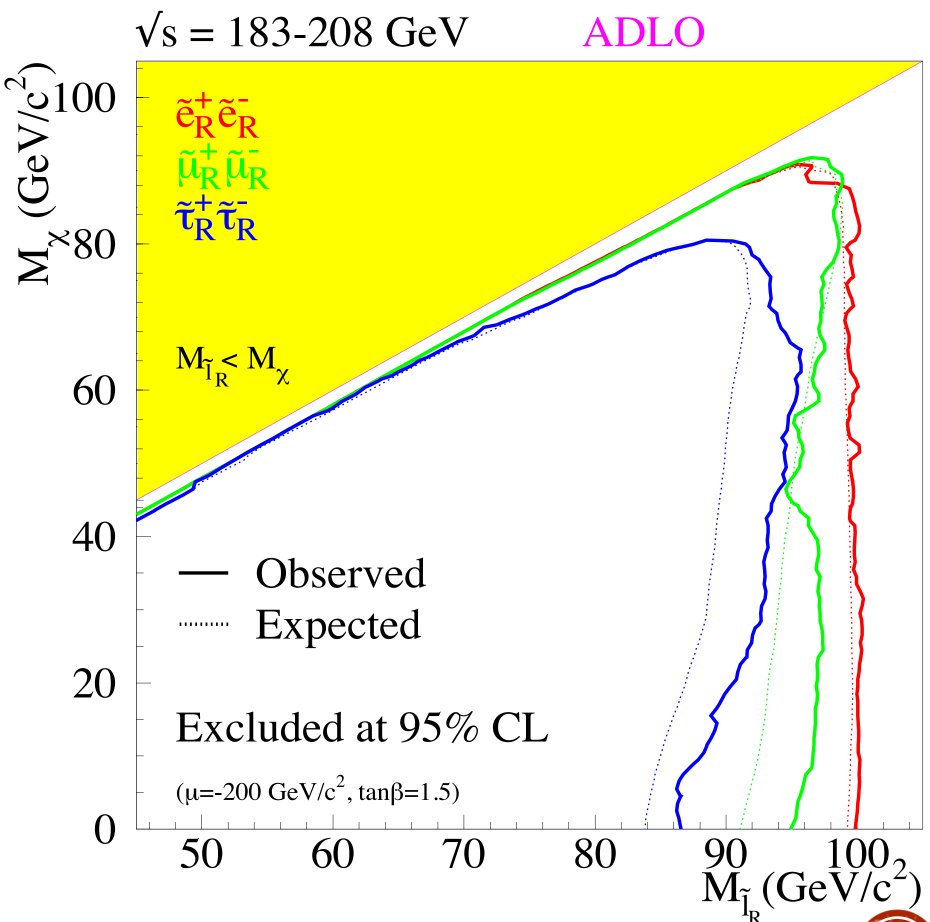
1. **Sleptons search (prefer stau, smuon)**
2. **Gaugino & higgsino search**
3. **Long-lived particles**
4. **RPV with LLE couplings**
5. **Mono-photon events (SUSY, ED, DM)**

➔ Top priority: stau, smuon, higgsino

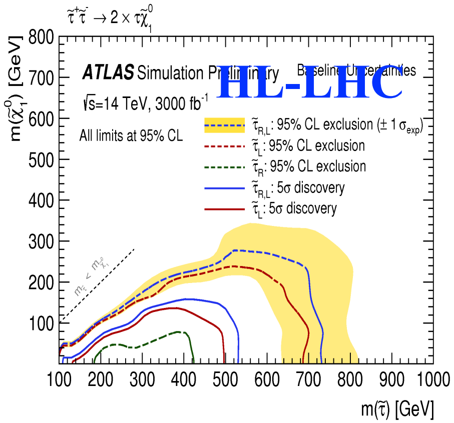
SUSY at LEP



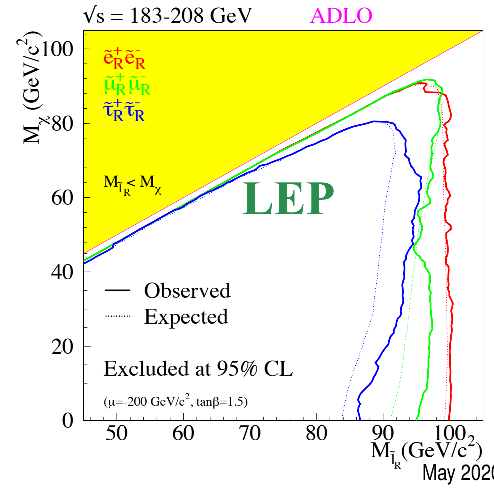
- Exclusion (dashed) is very close to Discovery (solid)
- Very good stau_R sensitivity (no discovery potential for stau_R at HL-LHC)
- Full discovery and exclusion potential up to the kinematic limit → Model independent exclusion/ discovery reach in M_NLSP – M_LSP plane.

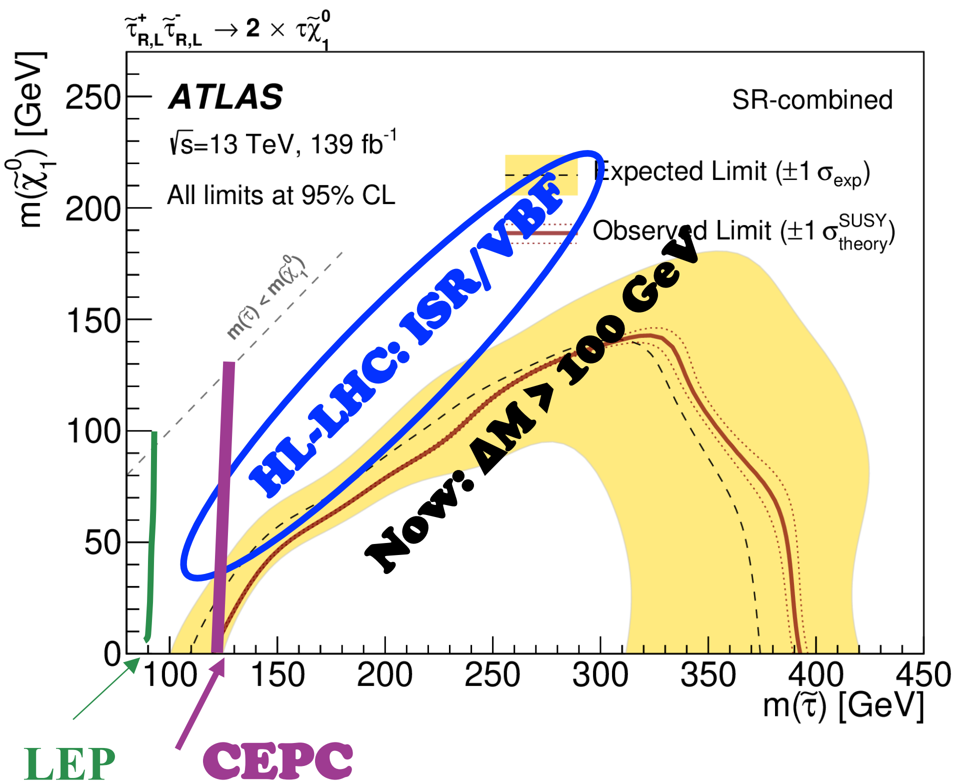


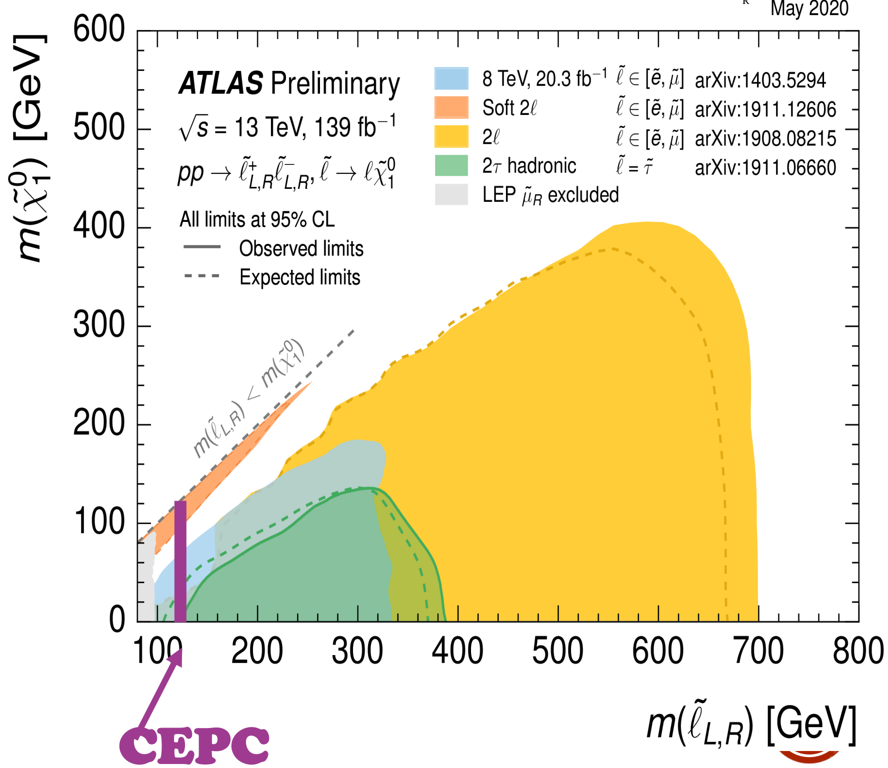
Stau & smuon



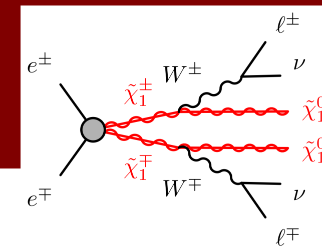
- **Stau: DM relic density consistent with cosmology observation**
- **Smuon: explain mu g-2 excess**

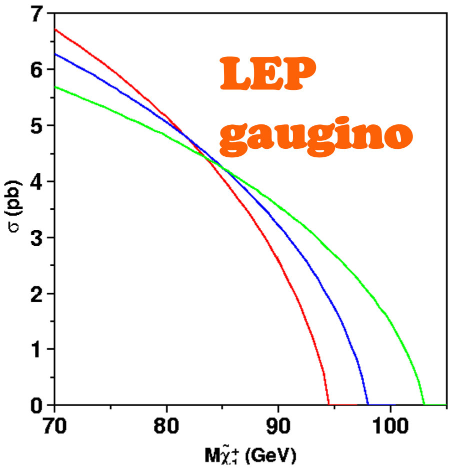


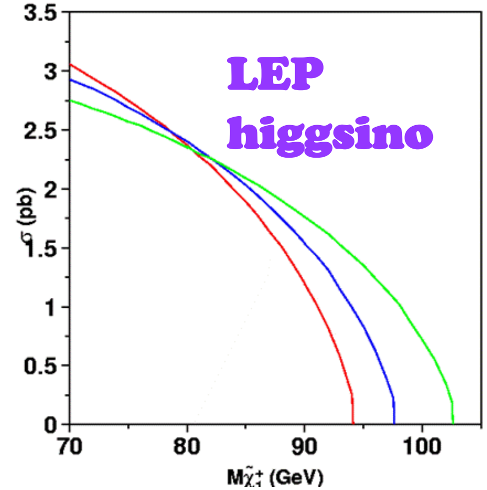


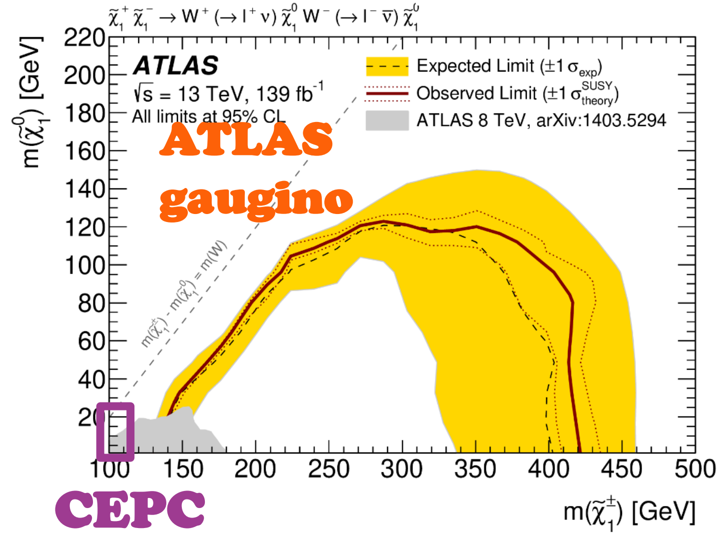


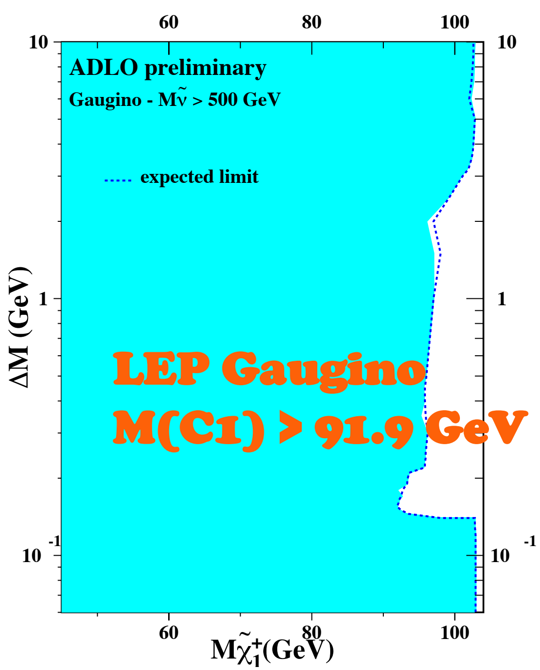
Gaugino & higgsino

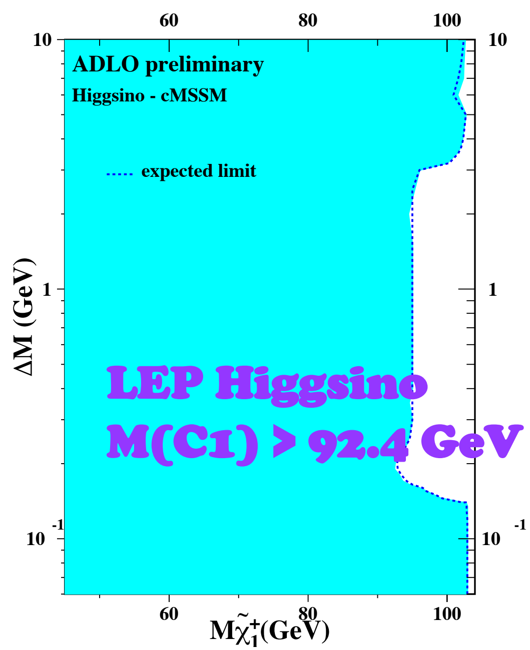


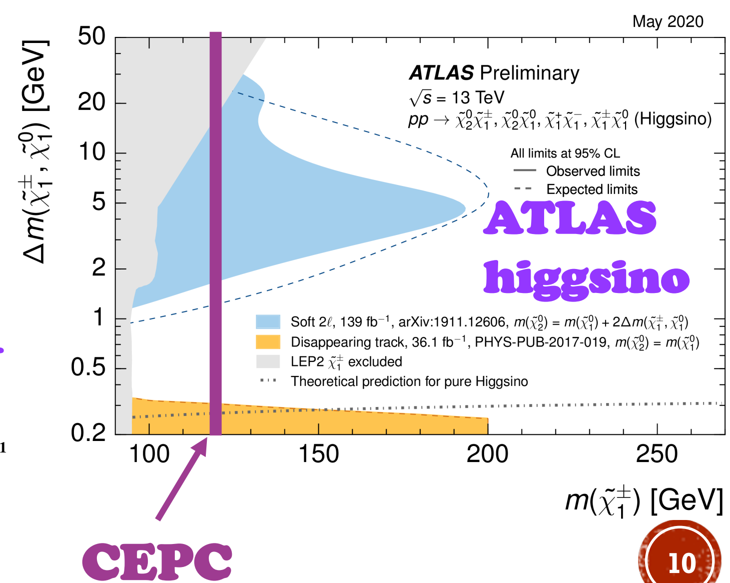






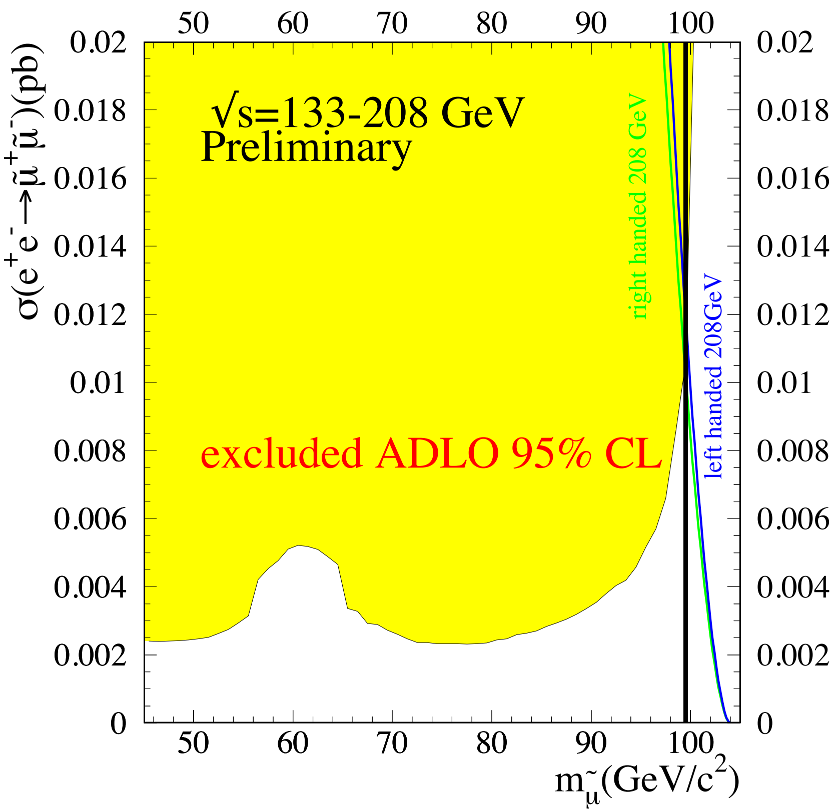






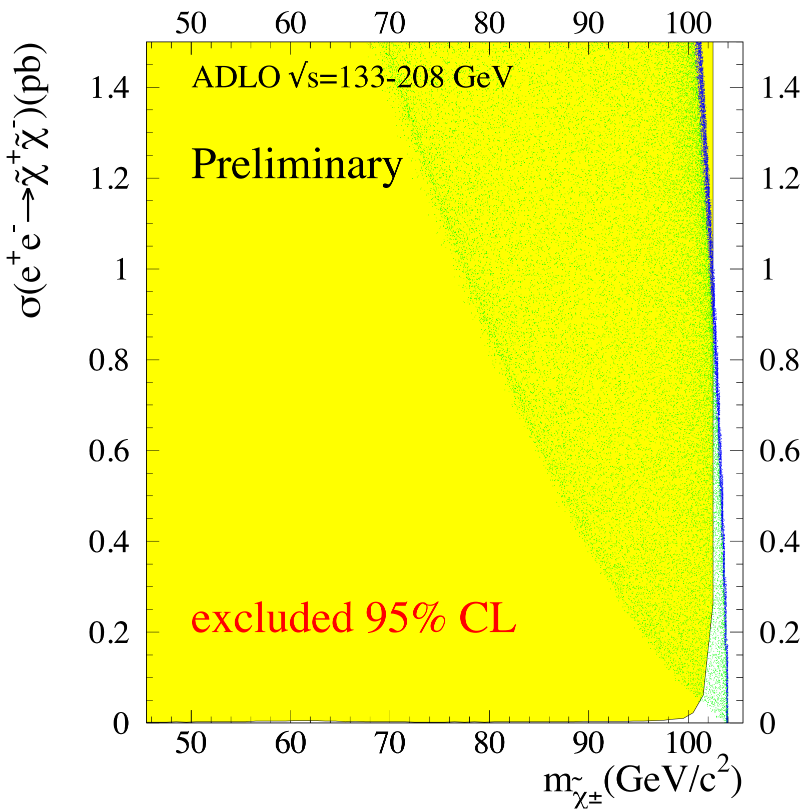
Long-lived particles

LEP
~tau, ~muon (GMSB)



M(~l_L): 45 - 99.6 GeV
M(~l_R): 45 - 99.4 GeV

LEP
Stable chargino (low dM)

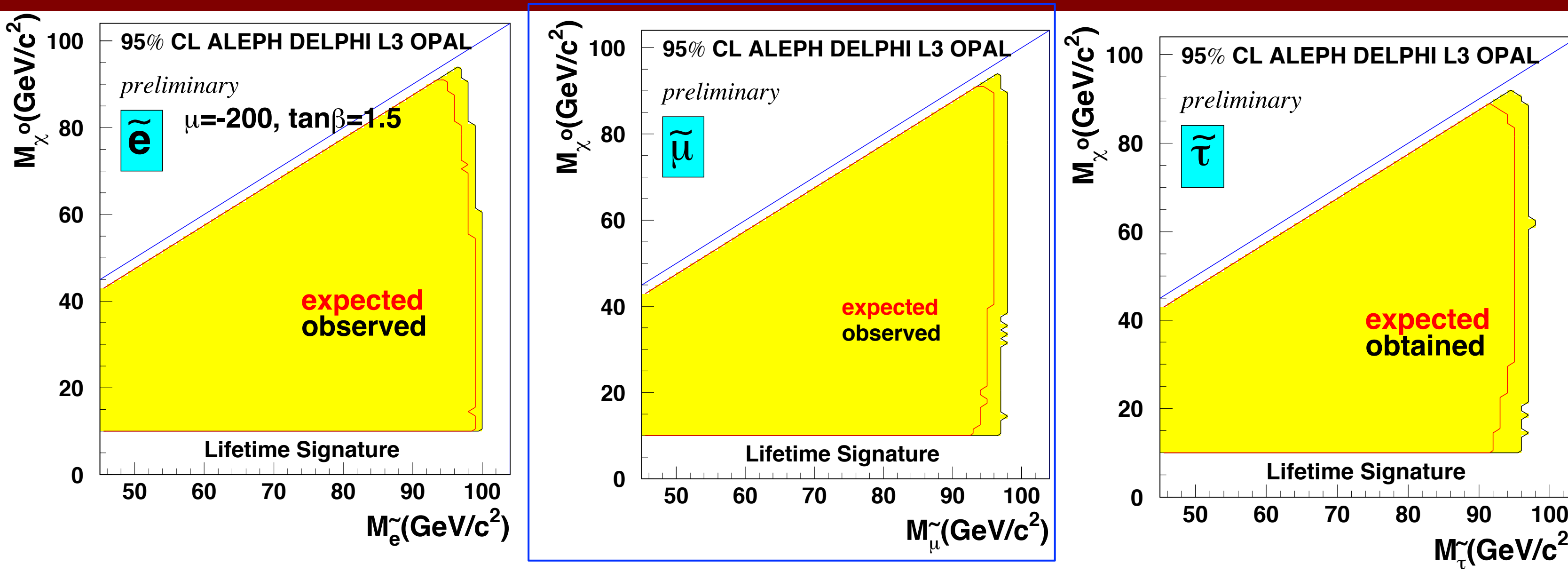


M(C1): 45 - 101.2 GeV (45<M_C1<500)
M(C1): 45 - 99.4 GeV (M_C1>500)

CEPC: ~muon

RPV with LLE coupling

LEP Mass excl.



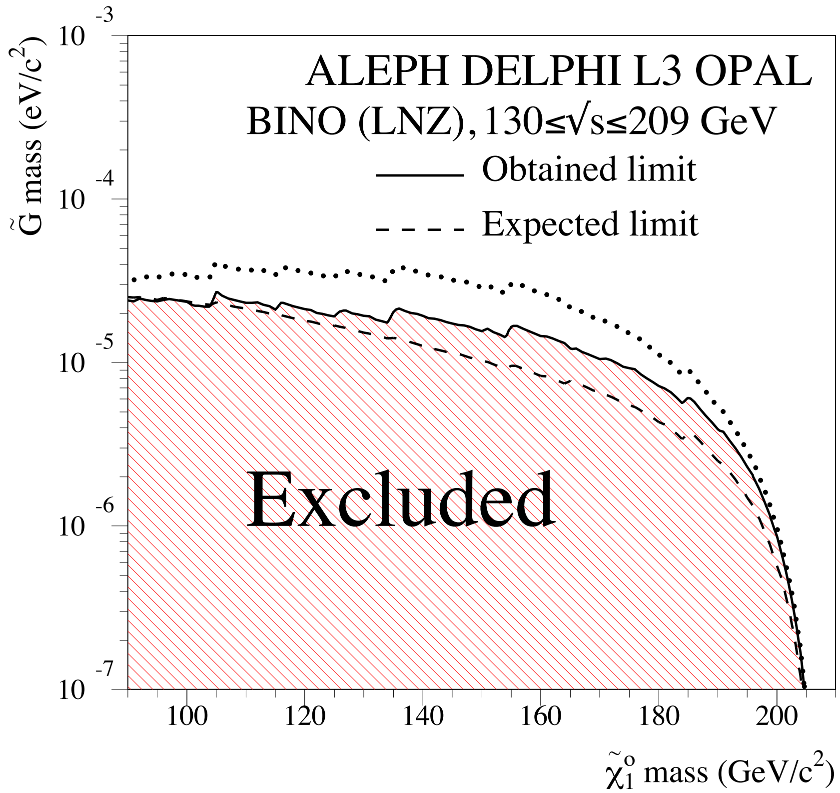
Cross-sections and corresponding branching ratios were calculated in the framework of the MSSM using SUSYGEN version 3.19.

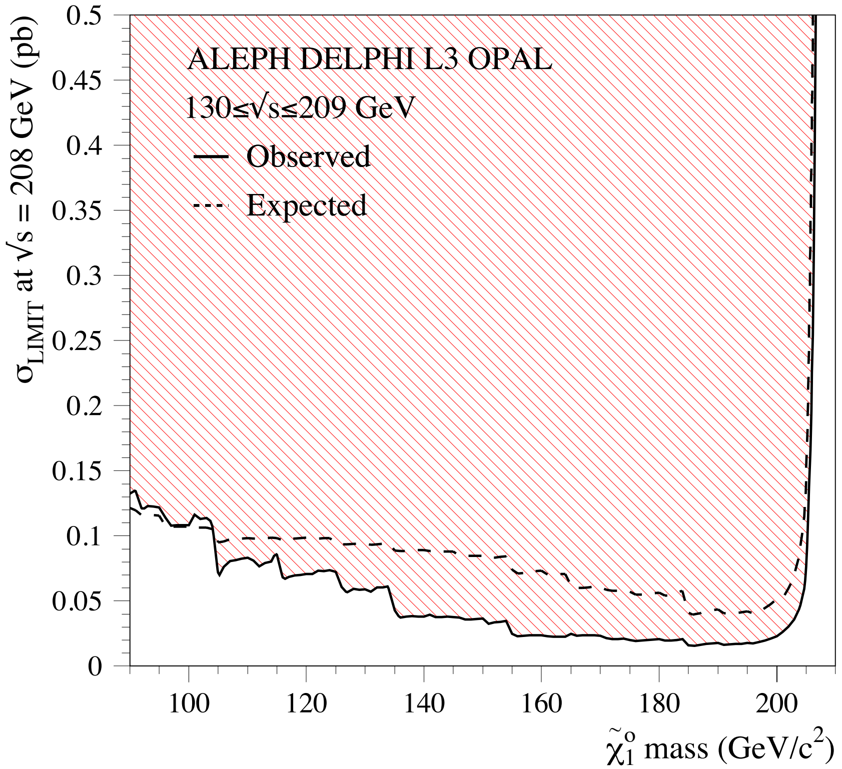
M_0 from 0 to 250 GeV
M_2 from 0 to 400 GeV
μ = -200 GeV
tanß = 0.7, 1.0, 1.5, 3.0, 10., 35.

Channel	M(obtained) >	M(expected) >	M(obtained) >	M(expected) >
	M(Chi0) = 40 GeV		DeltaM > 3 GeV	
selectron	100.3 GeV	98.9 GeV	96.6 GeV	92.9 GeV
smuon	98.0 GeV	95.9 GeV	96.9 GeV	92.9 GeV
stau	96.9 GeV	95.0 GeV	95.9 GeV	92.0 GeV
snu_el	100.1 GeV	99.8 GeV	98.9 GeV	99.1 GeV
snu_mu	87.1 GeV	90.7 GeV	84.5 GeV	86.0 GeV

CEPC: ~muon

Mono-photon (SUSY, ED,DM)

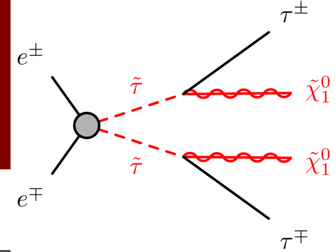


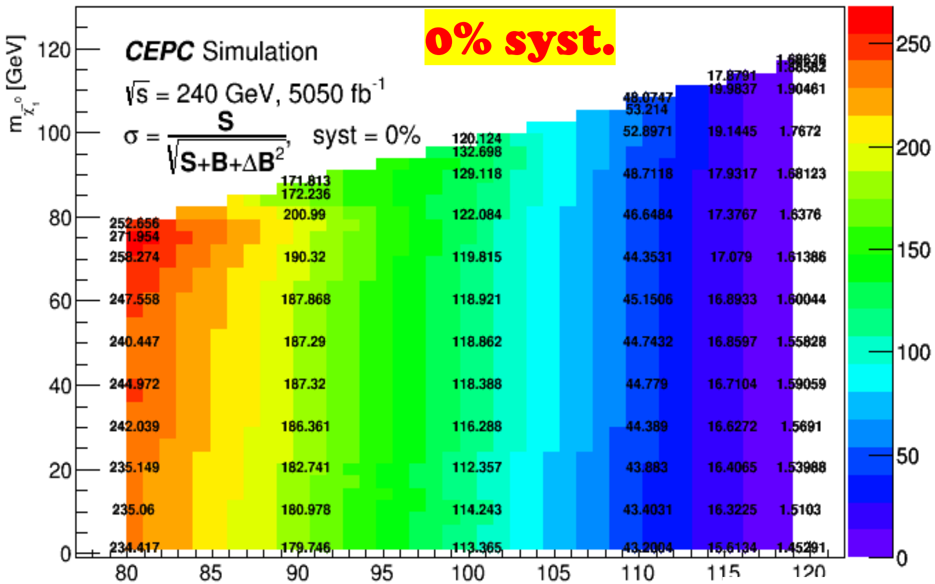


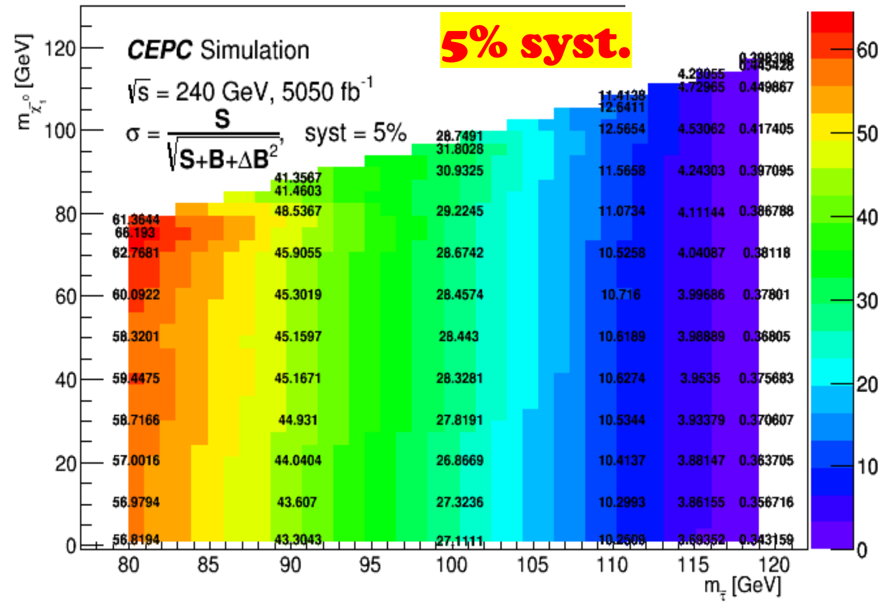
e+e- → chi_1 grav → grav grav gamma
grav: gravitino

Current results from SUSY@CEPC

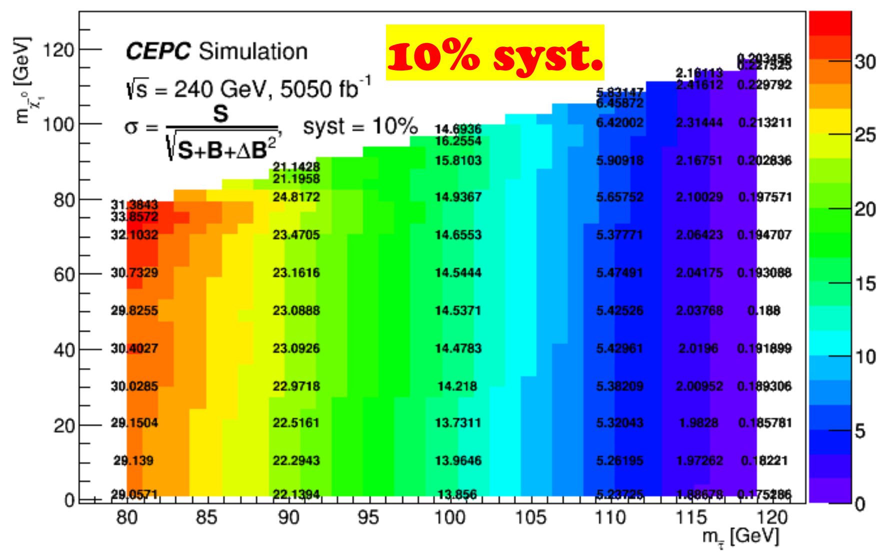
Stau search



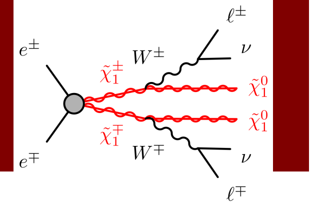




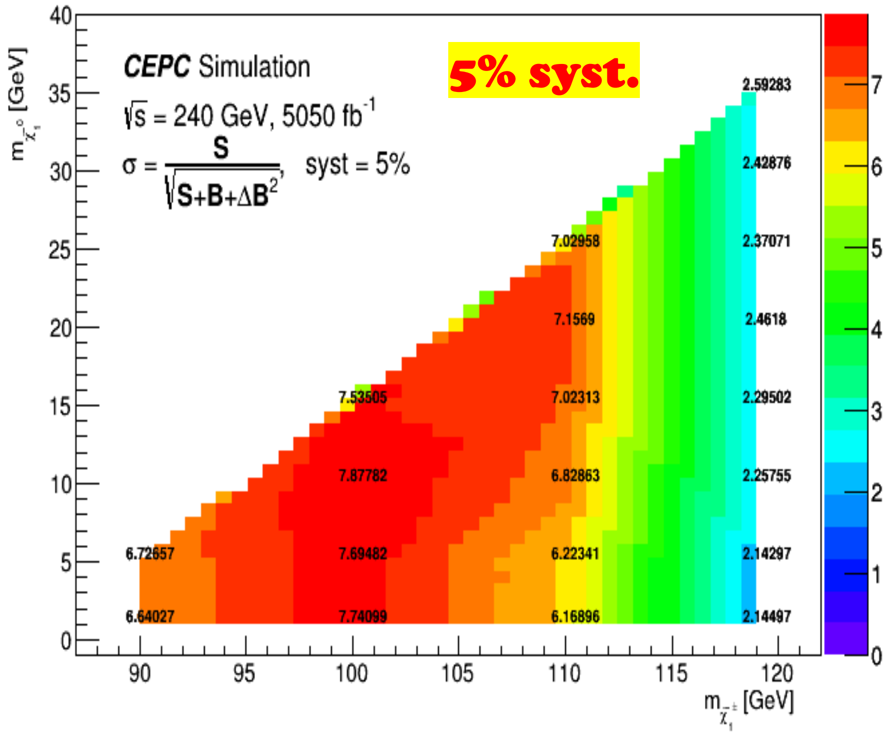
The map use $\frac{S}{\sqrt{S+B+dB^2}}$ as the sensitivity (stat + 0-10% syst)

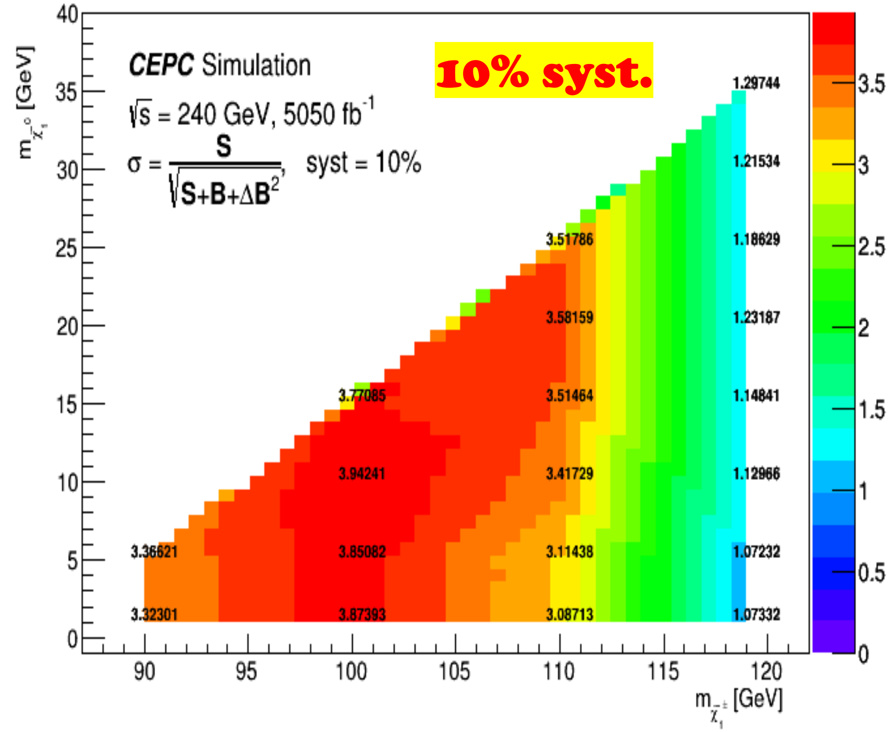


Gaugino search (only mu channel)



The map use $\frac{S}{\sqrt{S+B+dB^2}}$ as the sensitivity (stat + 5-10% syst)





To Do

1. **Stau:**
   - Signal and BG sample are ready; using track replacing tau, missing e, muon related BG
   - Should check the missing BG contribution
   - Or use rec tau instead of track
2. **Smuon:**
   - Bg samples are ready, signal samples are missing
   - Should produce signal samples
3. **Higgsino (muon final states)**
   - Bg samples are ready (same as smuon); signal samples are missing
   - Should produce signal samples
4. **Gaugino (muon final states)**
   - BG/Signal samples are ready; pre-liminary results (truth) are done
   - Should repeat with rec, and summarized for a paper

Backup

EU Strategy- SUSY: ~g

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

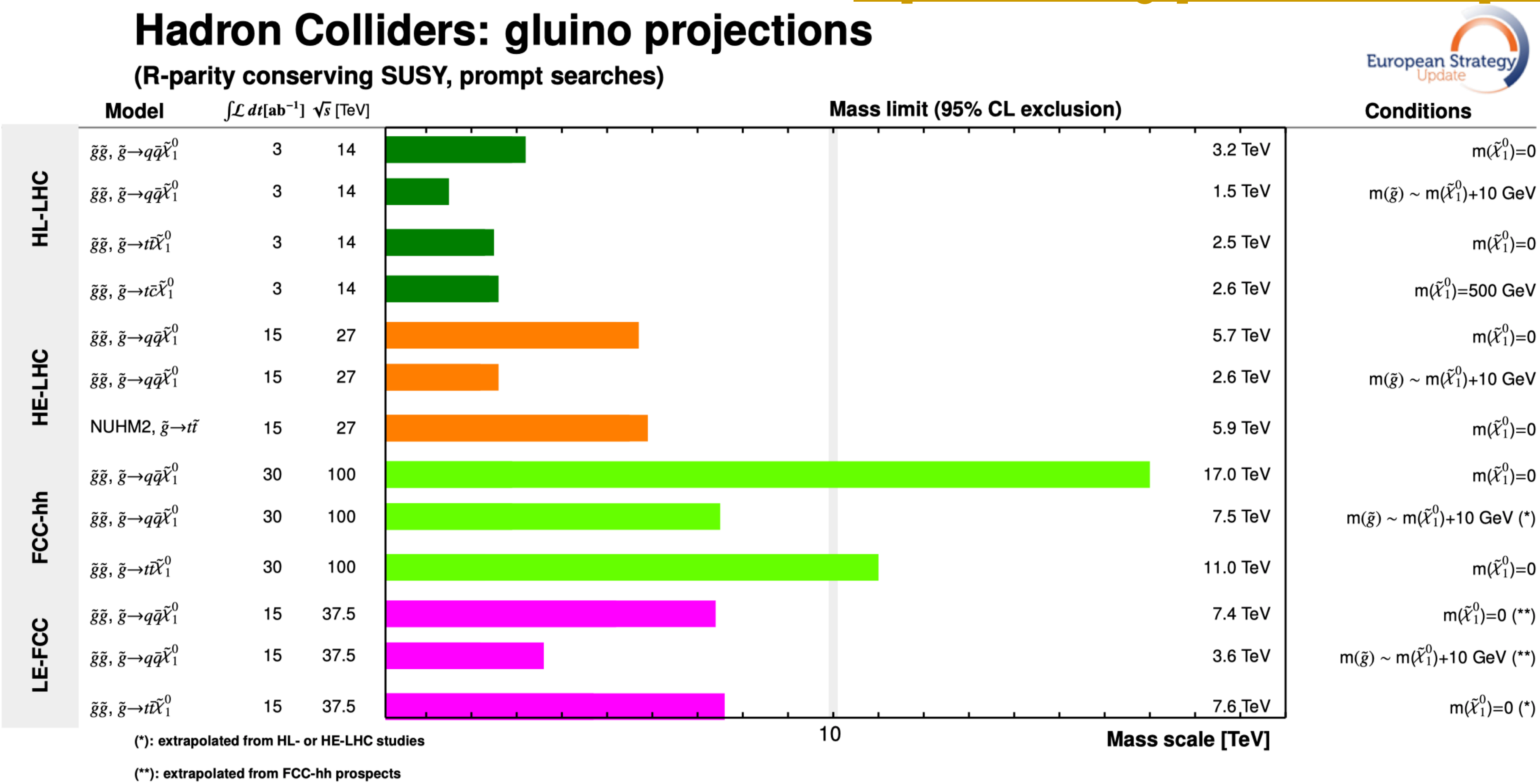


Fig. 8.6: Gluino exclusion reach of different hadron colliders: HL- and HE-LHC [443], and FCC-hh [139, 448]. Results for low-energy FCC-hh are obtained with a simple extrapolation.

EU Strategy- SUSY: ~q

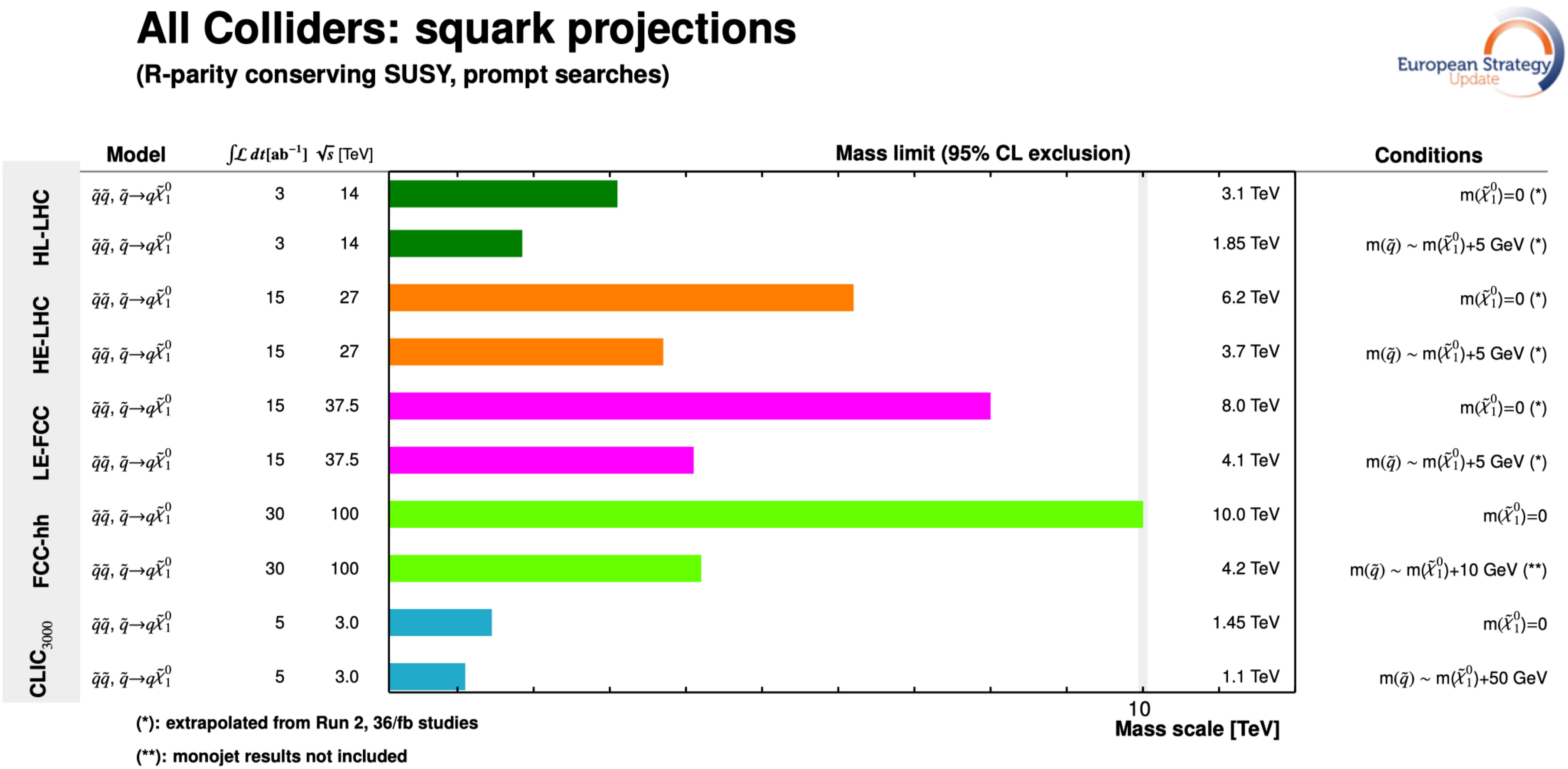
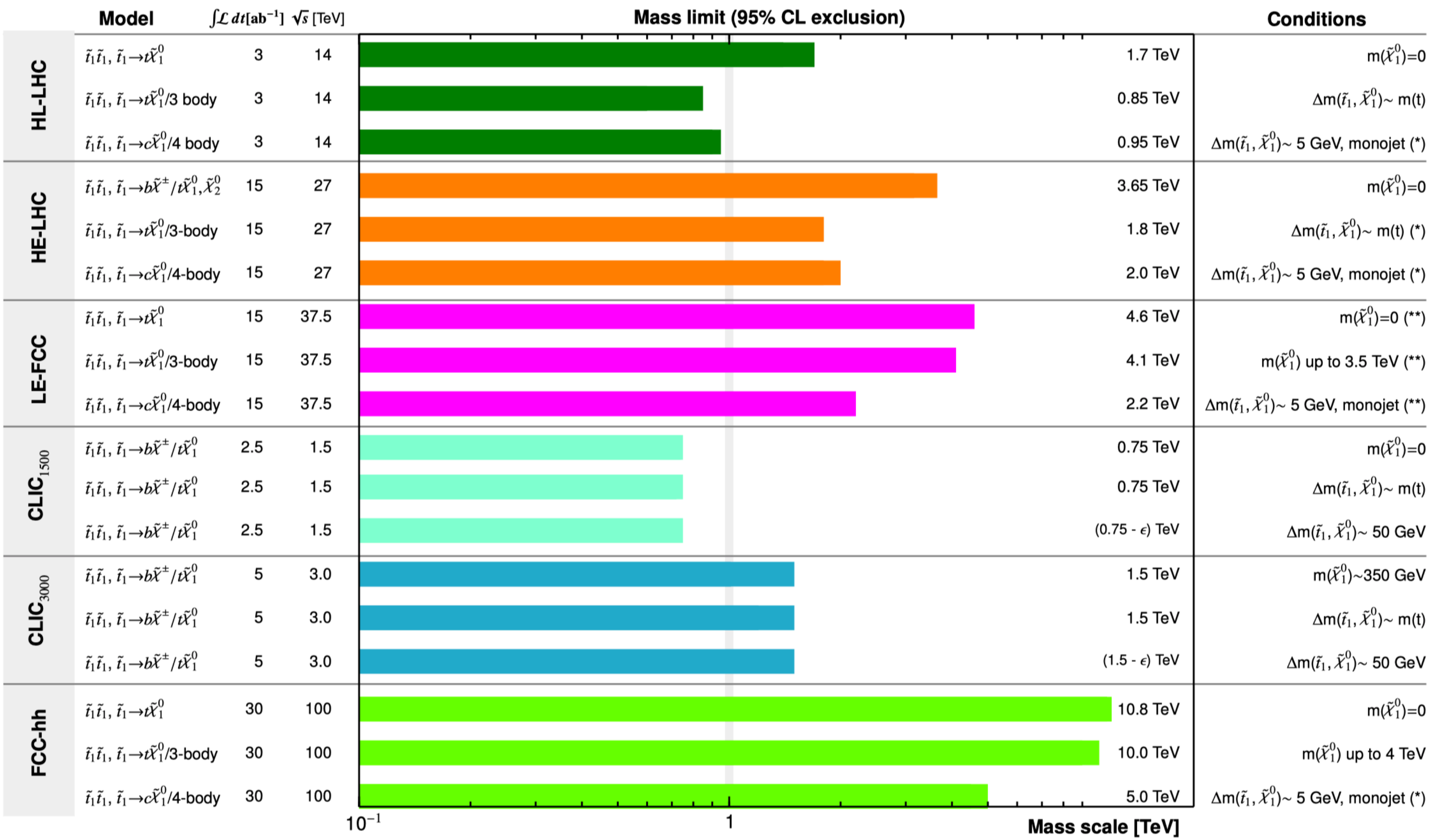


Fig. 8.7: Exclusion reach of different hadron and lepton colliders for first- and second-generation squarks.

EU Strategy- SUSY: ~t

All Colliders: Top squark projections

(R-parity conserving SUSY, prompt searches)



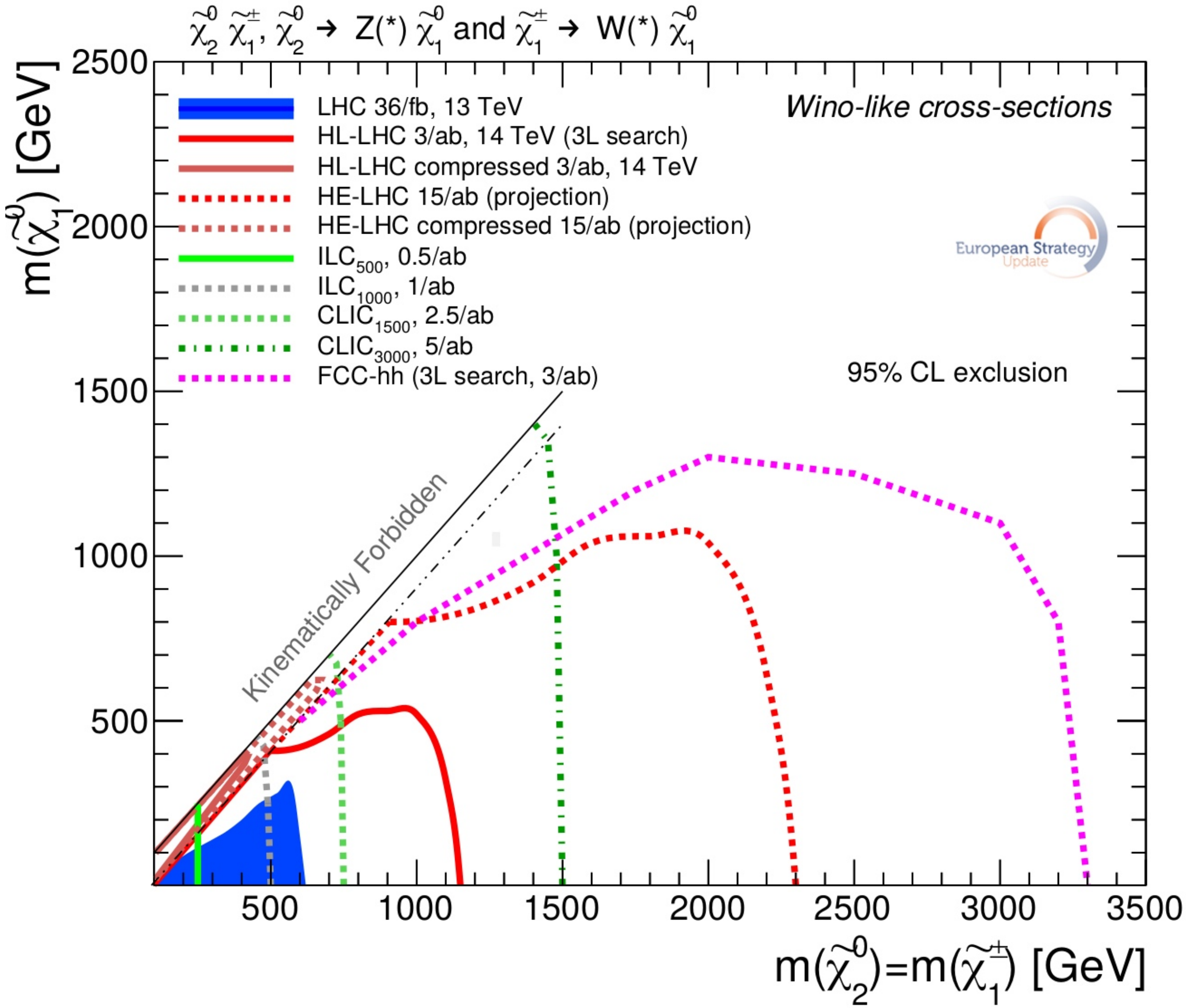
(*) indicates projection of existing experimental searches

(**) extrapolated from FCC-hh prospects

ϵ indicates a possible non-evaluated loss in sensitivity

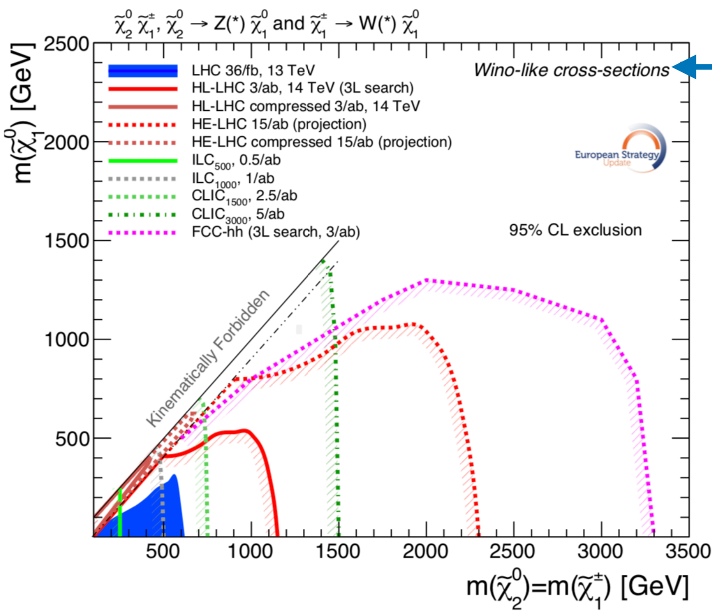
ILC 500: discovery in all scenarios up to kinematic limit $\sqrt{s}/2$

EU Strategy- SUSY: gaugino



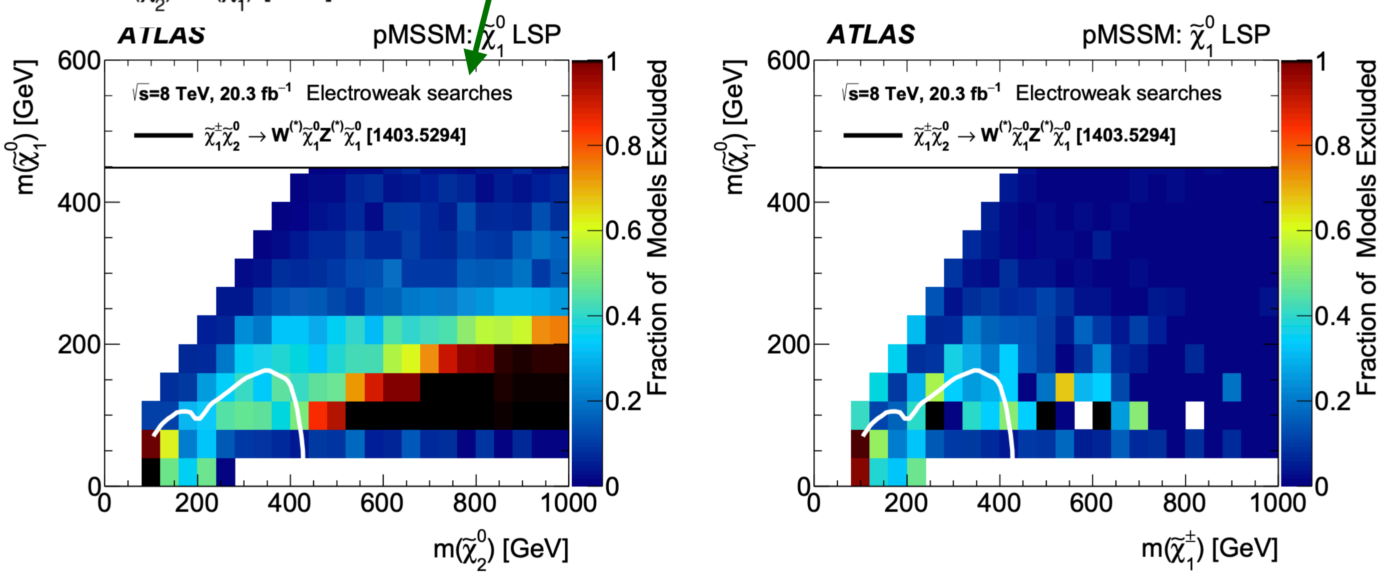
ILC 500/CEPC240: discovery in all scenarios up to kinematic limit: √s/2

European Strategy Example: SUSY (II)



Assumptions are important. Simplified models plots have limitations

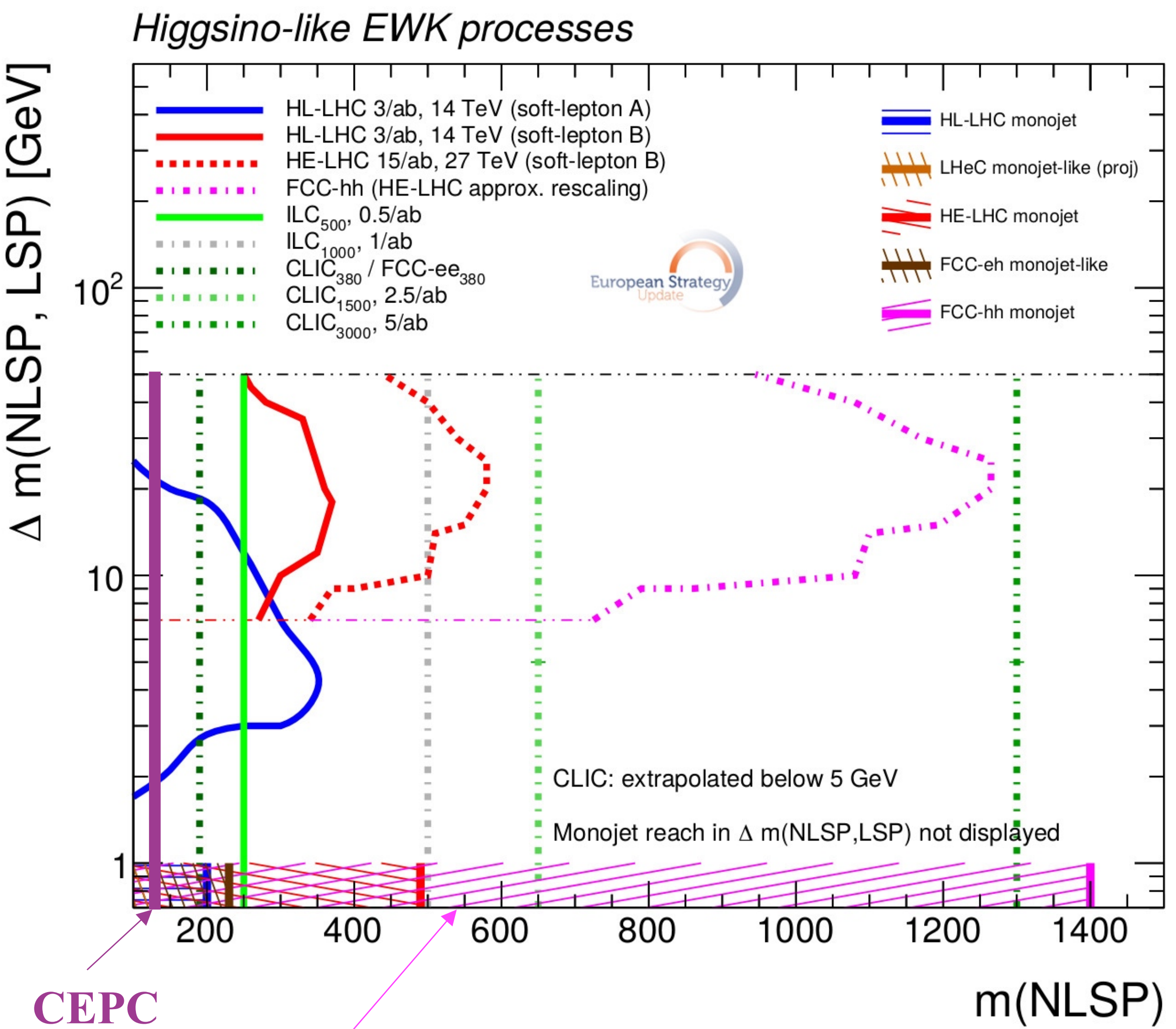
pMSSM scan → Very little of simplified model region actually excluded. How far should we go?



(a) Neutralinos

(b) Chargino–neutralino

EU Strategy- SUSY: higgsino

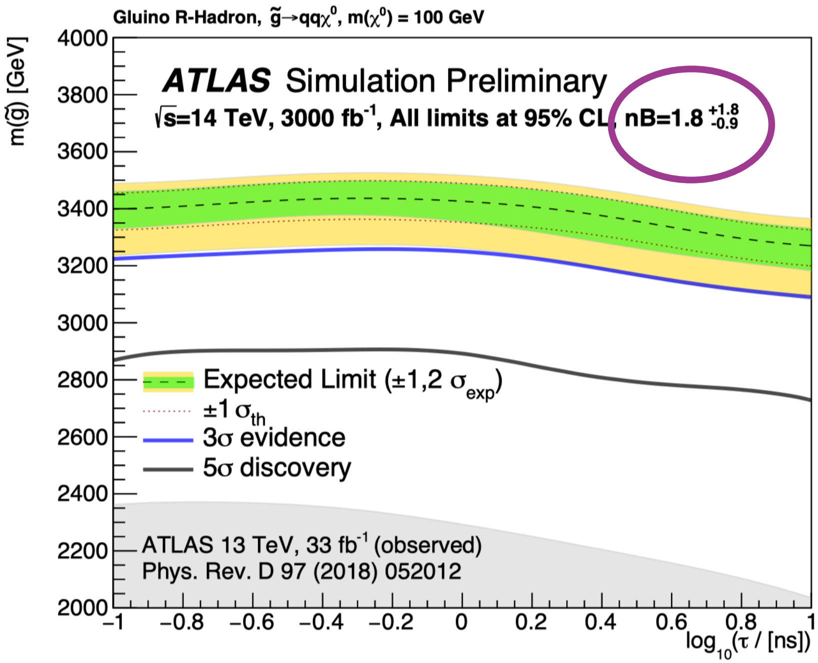


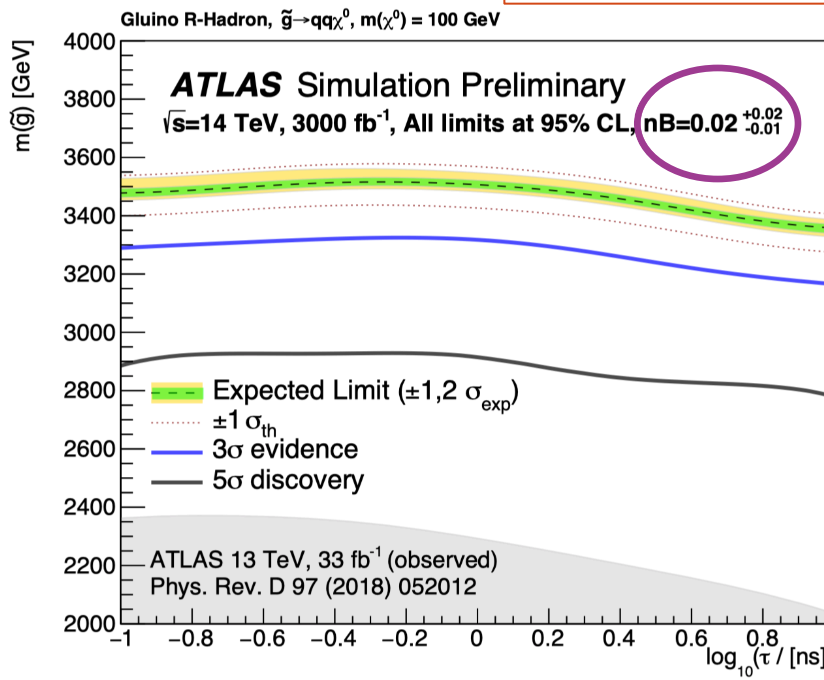
Disappearing tracks exclusion is actually off the scale

EU Strategy- SUSY: LLP

ATL-PHYS-PUB-2018-033

~1, RPV missing





- Only shows results using displaced vertex at HL-LHC
- Exclusion limits on gluinos with lifetimes $\tau > 0.1$ ns can reach about 3.4-3.5 TeV, using reconstructed massive displaced vertices.
- Muons displaced from the interaction point, such as found in SUSY models with ˜μ lifetimes of $c\tau > 25$ cm, can be excluded at 95% CL at the HL-LHC. **New fast timing detectors** will also be sensitive to displaced photon signatures arising from long-lived particles in the $0.1 < c\tau < 300$ cm range.

HL-LHC: DM

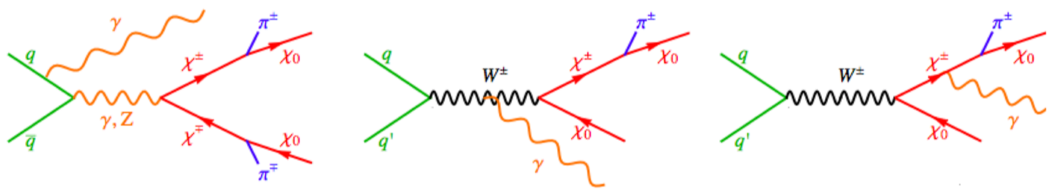
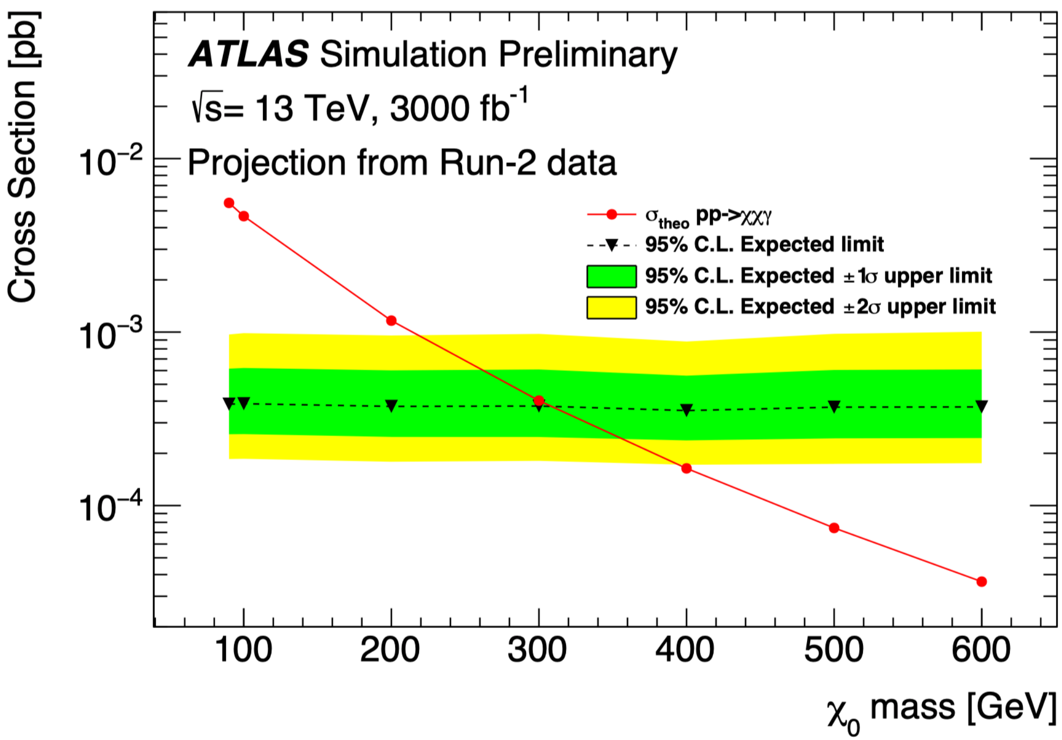
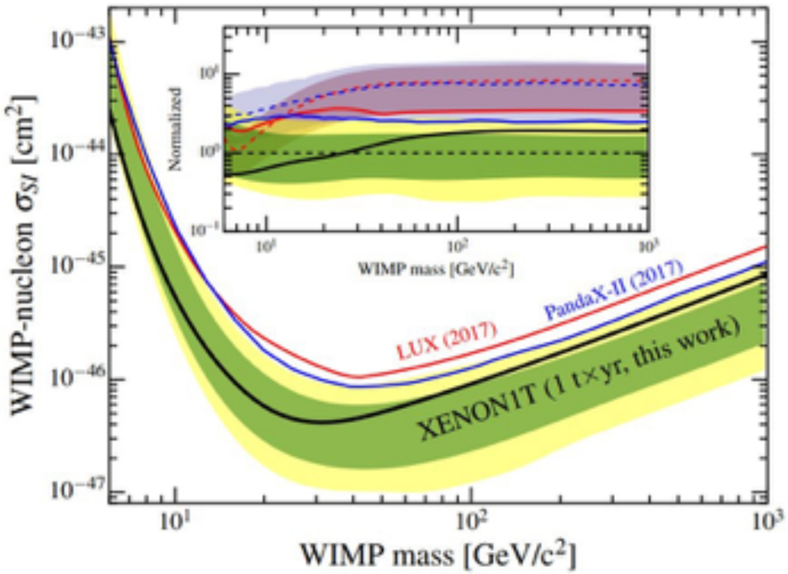


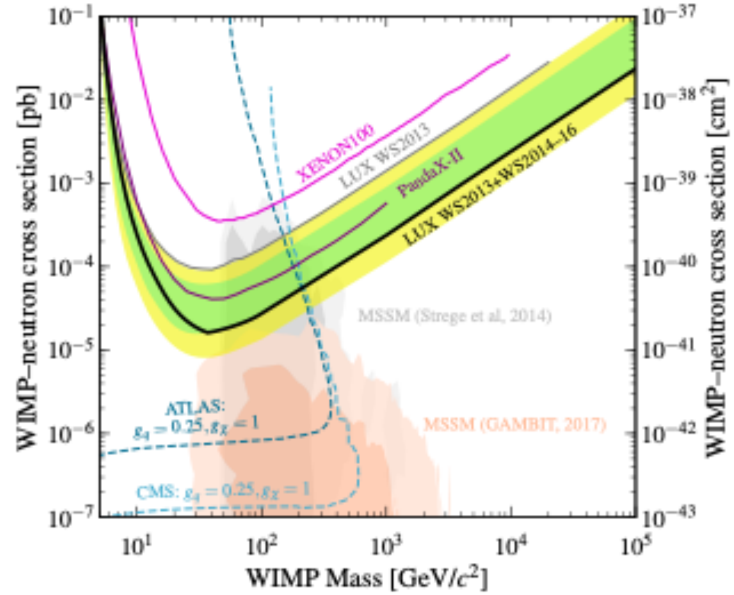
Figure 1: Some representative diagrams for the pure WIMP triplet in $\gamma + E_T^{miss}$ final states. The $\chi^{\pm}$ particles decay into the stable χ_0 DM candidate and soft pions which are not reconstructed [3].



ATL-PHYS-PUB-2018-038

DM : Direct Detection Bounds





$$\sigma_p^{\rm SI} \propto \frac{m_Z^4}{\mu^4}\left[2(m_{\tilde{\chi}_1^0} + 2\mu/\tan\beta)\frac{1}{m_h^2} + \mu\tan\beta\frac{1}{m_H^2} + (m_{\tilde{\chi}_1^0} + \mu\tan\beta/2)\frac{1}{m_{\tilde{Q}}^2}\right]^2$$

Blind Spot :

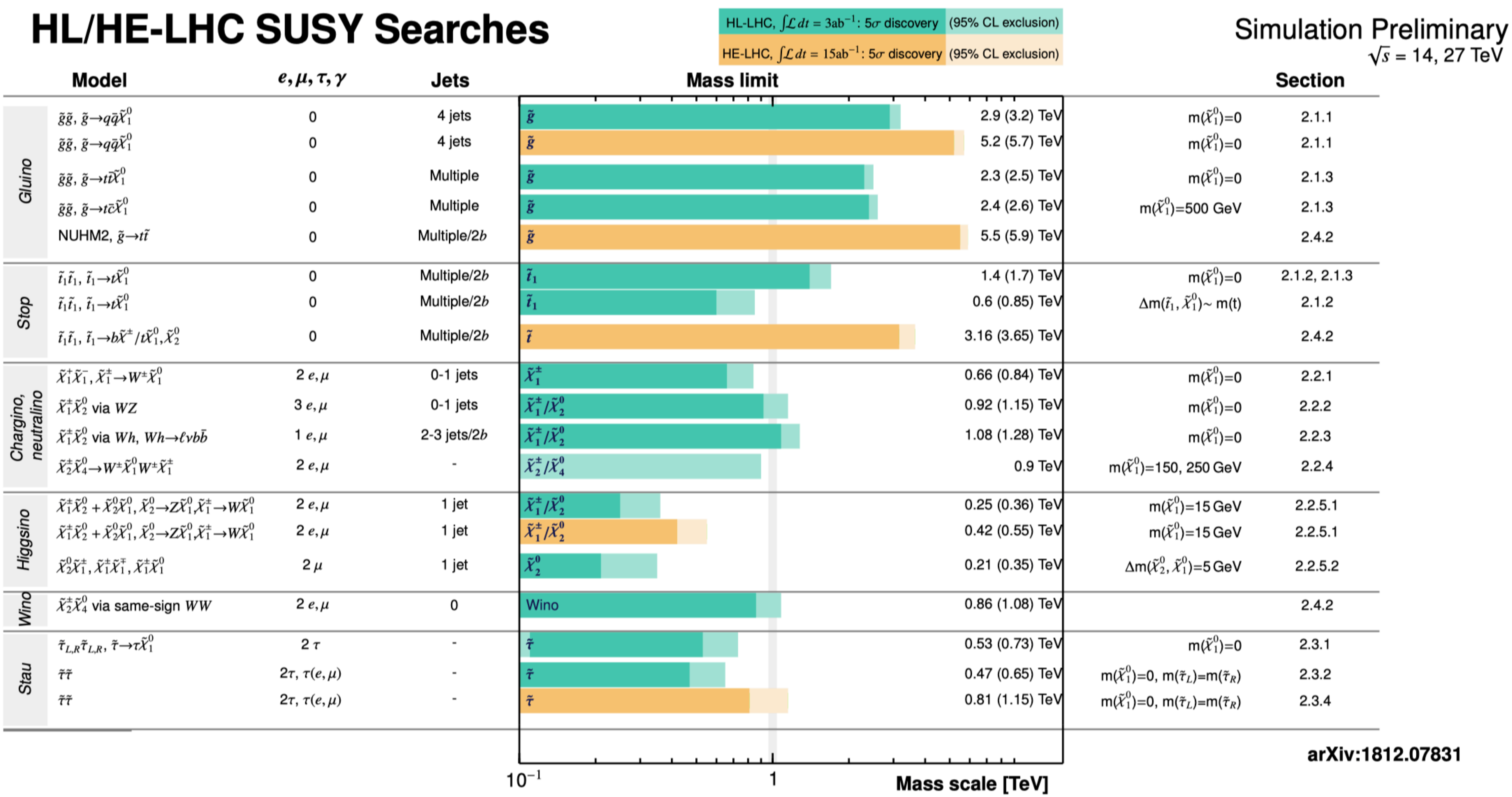
$$2\left(m_{\tilde{\chi}_1^0} + 2\frac{\mu}{\tan\beta}\right)\frac{1}{m_h^2} \simeq -\mu\tan\beta\left(\frac{1}{m_H^2} + \frac{1}{2m_{\tilde{Q}}^2}\right)$$

$$\mu \times m_{\tilde{\chi}^0} < 0$$
$$m_{\tilde{\chi}^0} \simeq M_1$$

Cheung, Hall, Pinner, Ruderman'12, Huang, C.W.'14, Cheung, Papucci, Shah, Stanford,Zurek'14, Han,Liu,Mukhopadhyay,Wang'18

$$\sigma^{\rm SD} \propto \frac{m_Z^4}{\mu^4}\cos^2(2\beta)$$

Prospects at HL/HE-LHC (summary)

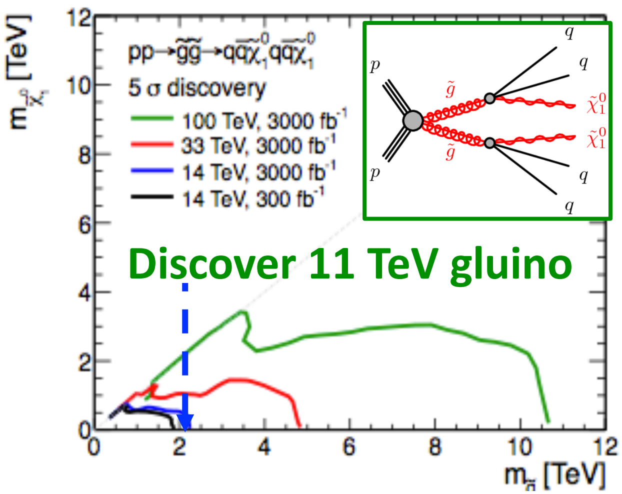


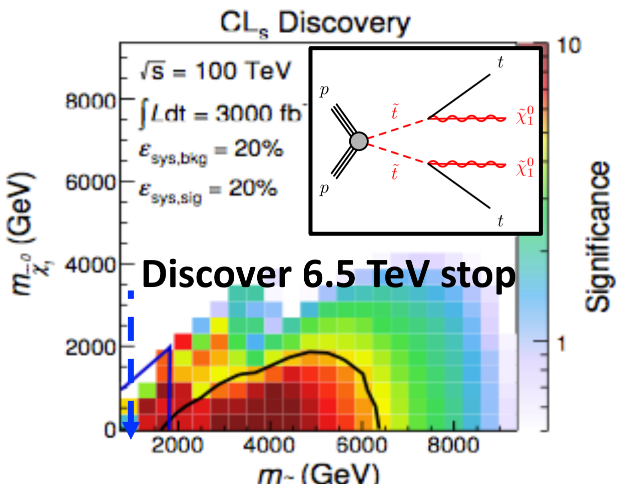
- In most BSM scenarios, we expect the HL-LHC will increase the present reach in mass and coupling by 20 – 50% (half Run-2 data)
- HE-LHC will allow for exclusion of almost all SUSY natural scenarios in case of null observation

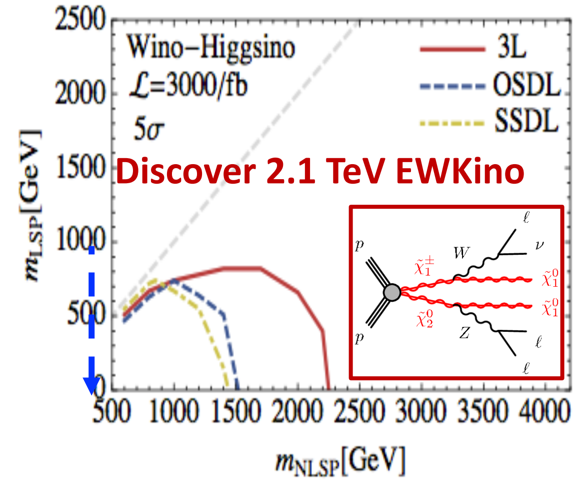
Prospects at FCC/SPPC (100 TeV)

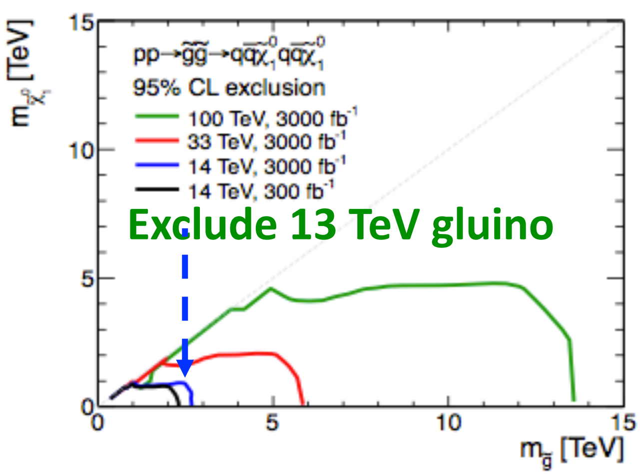
arXiv:1311.6480, 1406.4512, 1410.6287

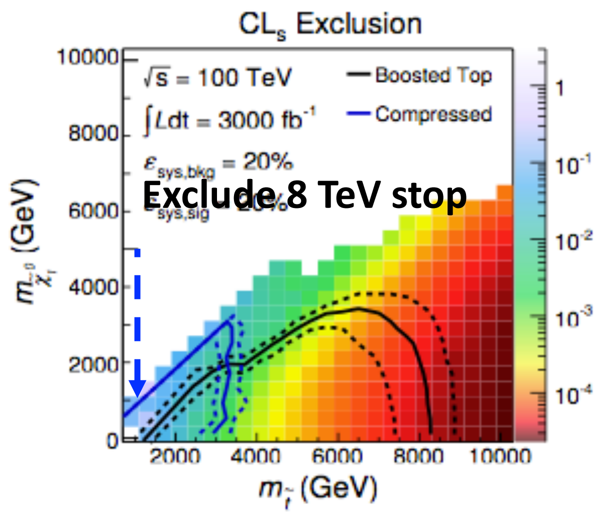
Gluinos ~ 11 (13) TeV | **Stop ~ 6.5 (8) TeV** | **EWKinos ~ 2.1 (3.2) TeV**

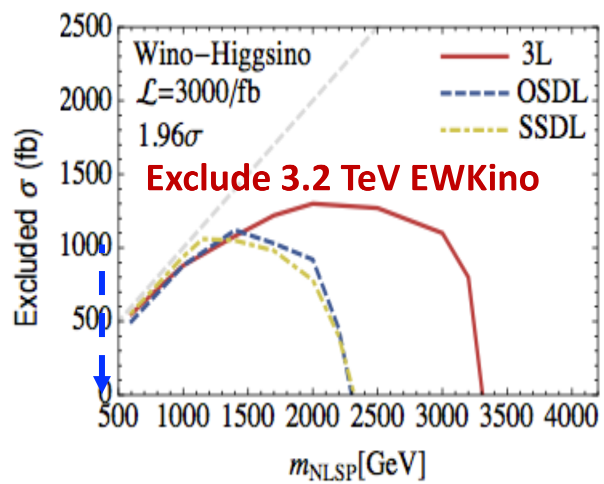






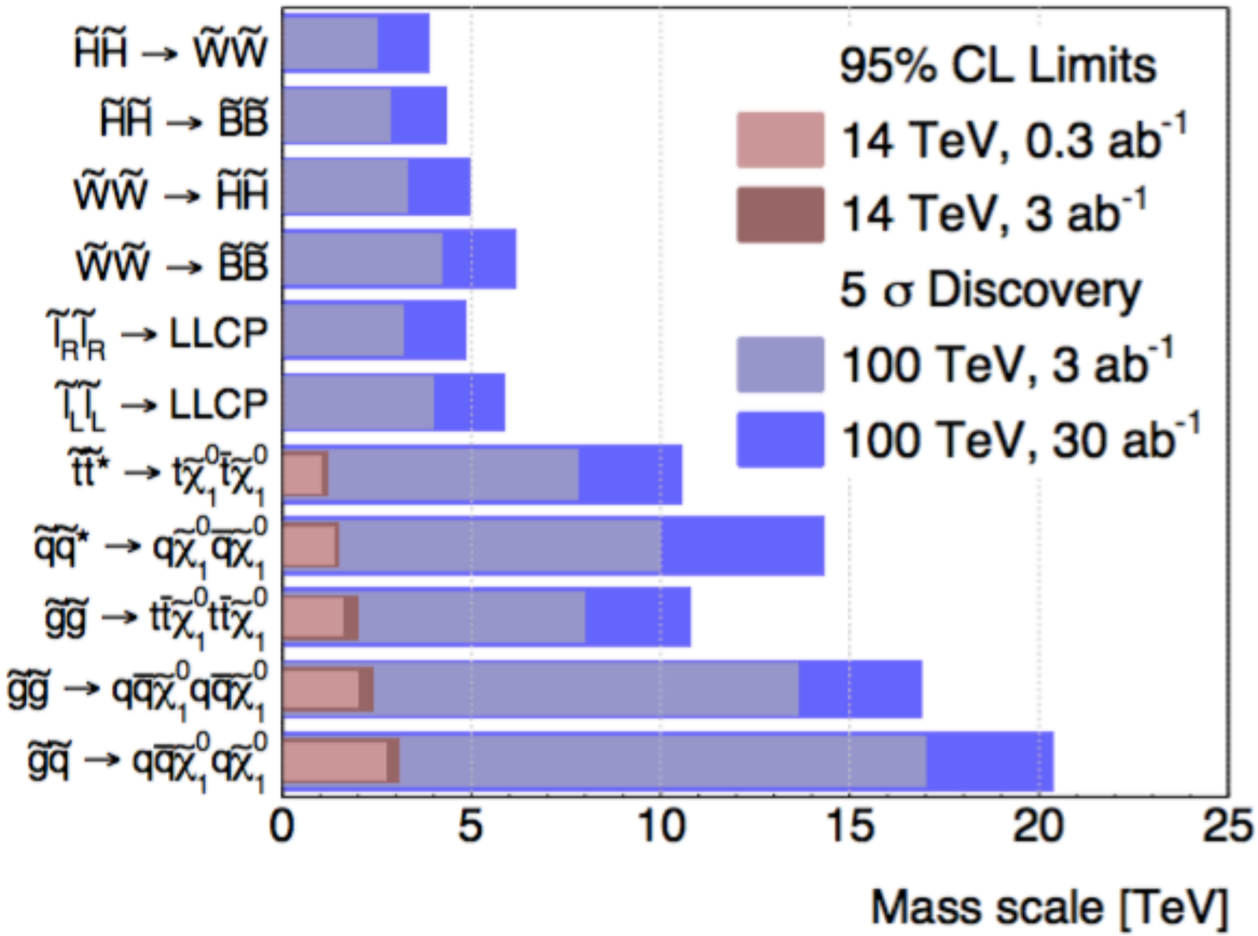




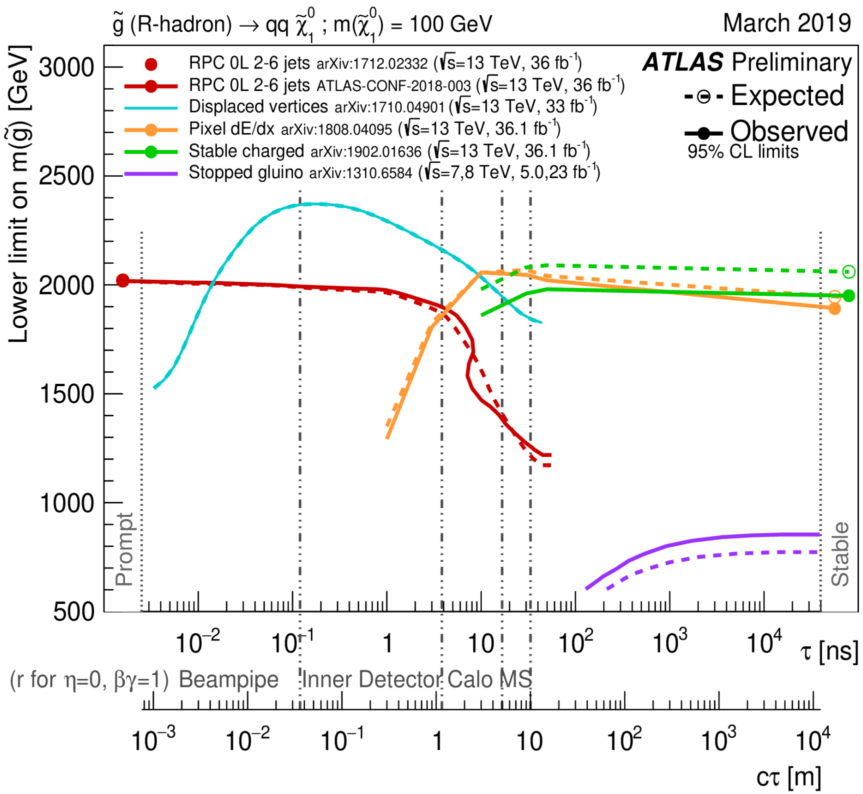


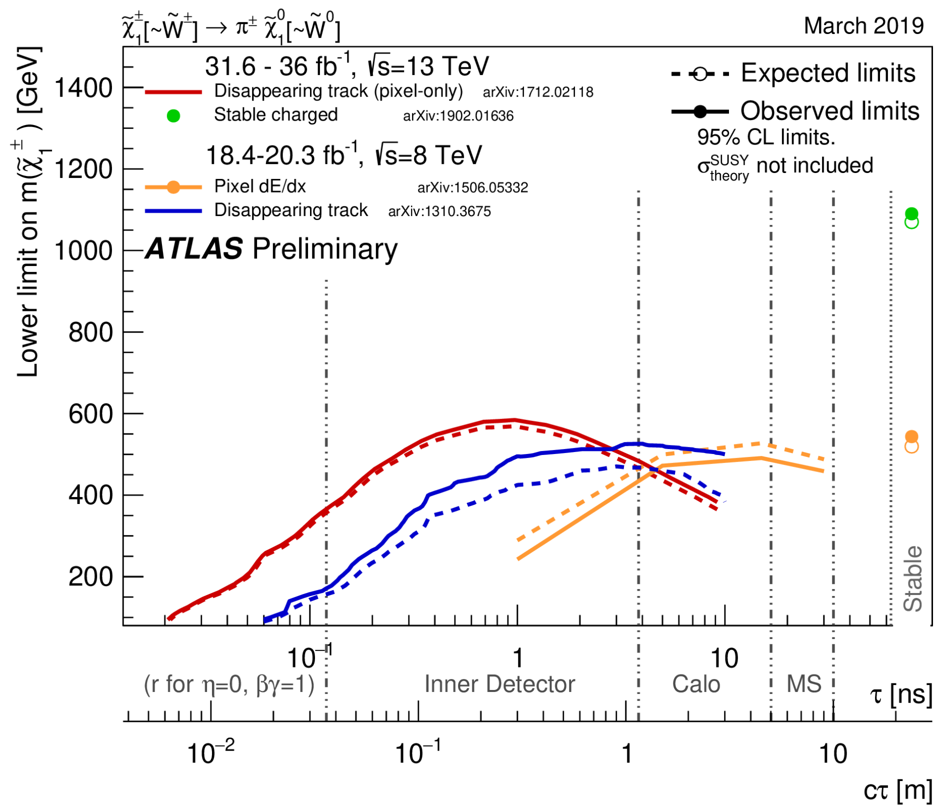
The reach of HE-LHC is generically more than double of HL-LHC

Prospects at FCC/SPPC 100 TeV



Long-lived Particles (LLP)





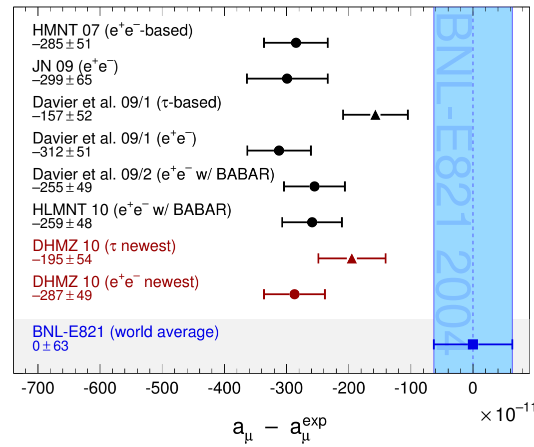
Long-lived R-hadron production **Long-lived chargino**

Muon Anomalous Magnetic Moment

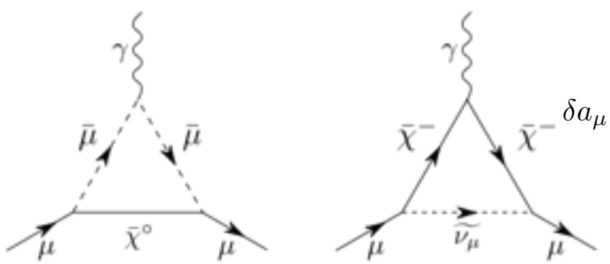
Present status: Discrepancy between Theory and Experiment at more than three Standard Deviation level

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

3.6σ Discrepancy



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



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

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.

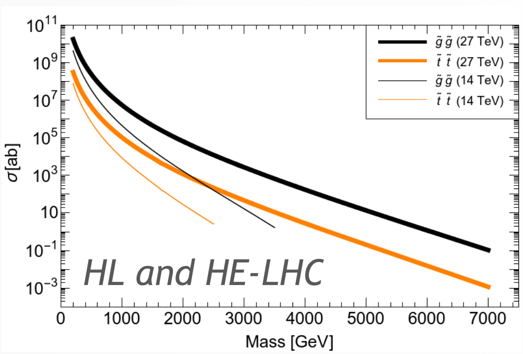
If Winos are heavy, one would need larger values of tanβ to explain the current anomaly.

Facilities and assumptions

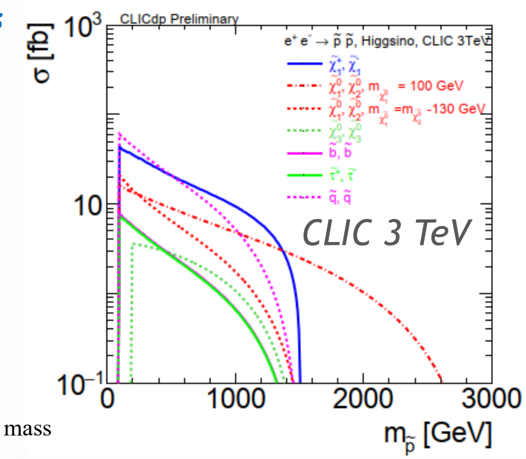
(arXiV:1905.03764)

- Studies from: HL-LHC, HE-LHC, FCC (ee/eh/hh), LHeC, ILC500, CLIC (1.5 and 3 TeV), MATHUSLA
  - Potential of muon / very high-energy lepton colliders outlined separately as more speculative
- e+e- facilities with c.o.m. below ~350 GeV not directly considered
  - Limited potential for discovery of low-mass SUSY given current LHC results

Examples of production x-sections



uncertainties on PDF as high as 60% for gluinos at high mass



Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]$ $\text{cm}^{-2}\text{s}^{-1}$	$\mathscr{L}$ $[\text{ab}^{-1}]$	Time [years]
HL-LHC	pp	14 TeV	-	2	5	6.0	12
HE-LHC	pp	27 TeV	-	2	16	15.0	20
FCC-hh	pp	100 TeV	-	2	30	30.0	25
FCC-ee	ee	M_Z	0/0	2	100/200	150	4
		$2M_W$	0/0	2	25	10	1-2
		240 GeV	0/0	2	7	5	3
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5
							(+1)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5
		350 GeV	±80/±30	1	1.6	0.2	1
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5
							(+1)
CEPC	ee	M_Z	0/0	2	17/32	16	2
		$2M_W$	0/0	2	10	2.6	1
		240 GeV	0/0	2	3	5.6	7
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8
		1.5 TeV	±80/0	1	3.7	2.5	7
		3.0 TeV	±80/0	1	6.0	5.0	8
							(+4)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25

+MATHUSLA: to be matched with HL-LHC

NOTE(1): In some cases, results with a reduced datasets wrt benchmarks are used

NOTE(2): HL/HE/FCC-hh results refer to a **single experiment** unless differently stated