Physics at a Linear Collider Facility

Direct Production of New Particles

Howard Baer, Sven Heinemeyer, Sabine Kraml,
Natsumi Nagata, **Aleksander Filip Żarnecki**

Linear Collider Vision Community Event 2025
January 8-10, 2025

Direct Production of New Particles

Outline:

1. Natural SUSY
2. Exotic scalars
3. Dark Matter
4. Conclusions

Selected from the current contents of the LCVision document section

Light, natural higgsinos at a LC

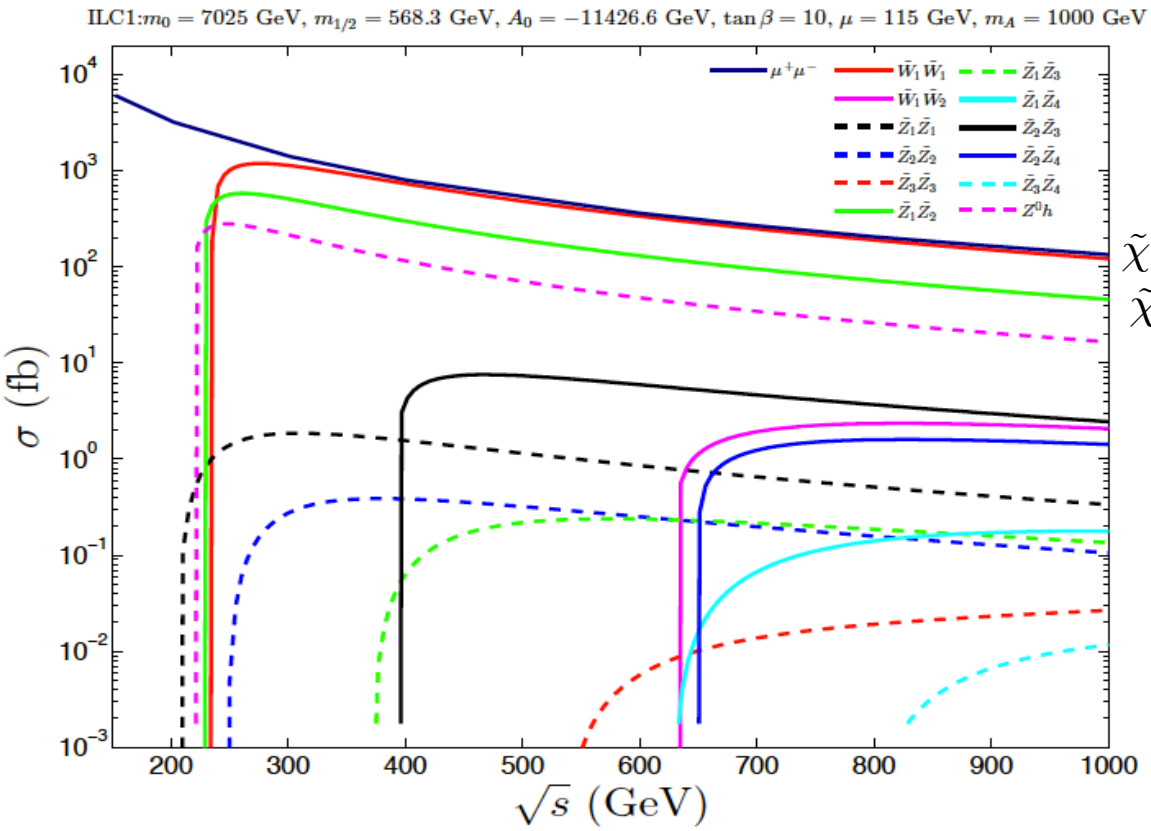
- In SUSY, minimization of scalar potential relates weak scale to parameters
- naturalness: SUSY preserving mu parameter ~100-350 GeV
- => W,Z,h, higgsinos~100-350 GeV
- other sparticle contributions suppressed by loop factor: can be much heavier

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$
$$\simeq -m_{H_u}^2 - \Sigma_u^u(\tilde{t}_{1,2}) - \mu^2.$$

for review, see: arXiv:2002.03013

Note: ATLAS/CMS each have 2-sigma excess in higgsino pair search channel!

Smoking gun signature: light higgsinos at ILC:
ILC is Higgs/higgsino factory!



$\sigma(higgsino) \gg \sigma(Zh)$

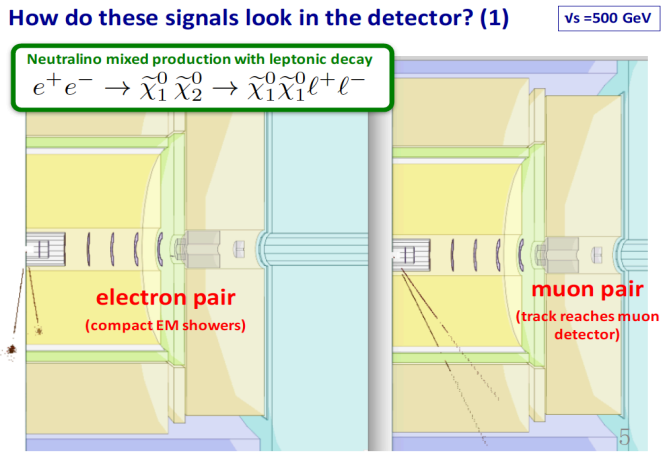
$\tilde{\chi}_1^+\tilde{\chi}_1^-$
$\tilde{\chi}_1^0\tilde{\chi}_2^0$

3-15 GeV higgsino mass gaps no problem in clean ILC environment

HB, Barger, Mickelson, Mustafayev, Tata
arXiv:1404:7510

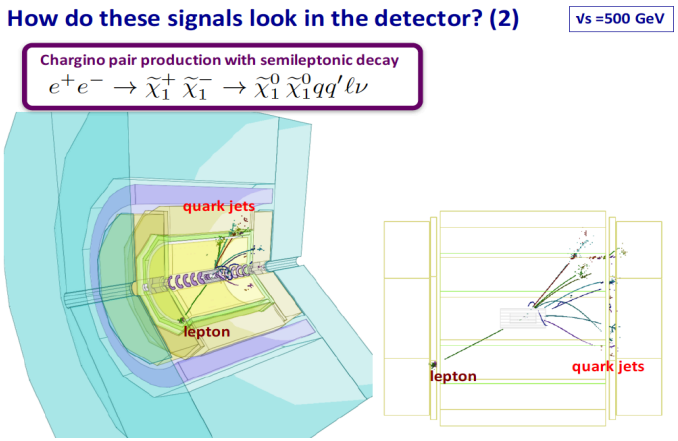
$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + (\ell^+\ell^-\tilde{\chi}_1^0)$$

measure $m(\ell^+\ell^-) < m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ and $E(\ell^+\ell^-)$



$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to (\ell\nu_\ell\tilde{\chi}_1^0) + (q\bar{q}'\tilde{\chi}_1^0)$$

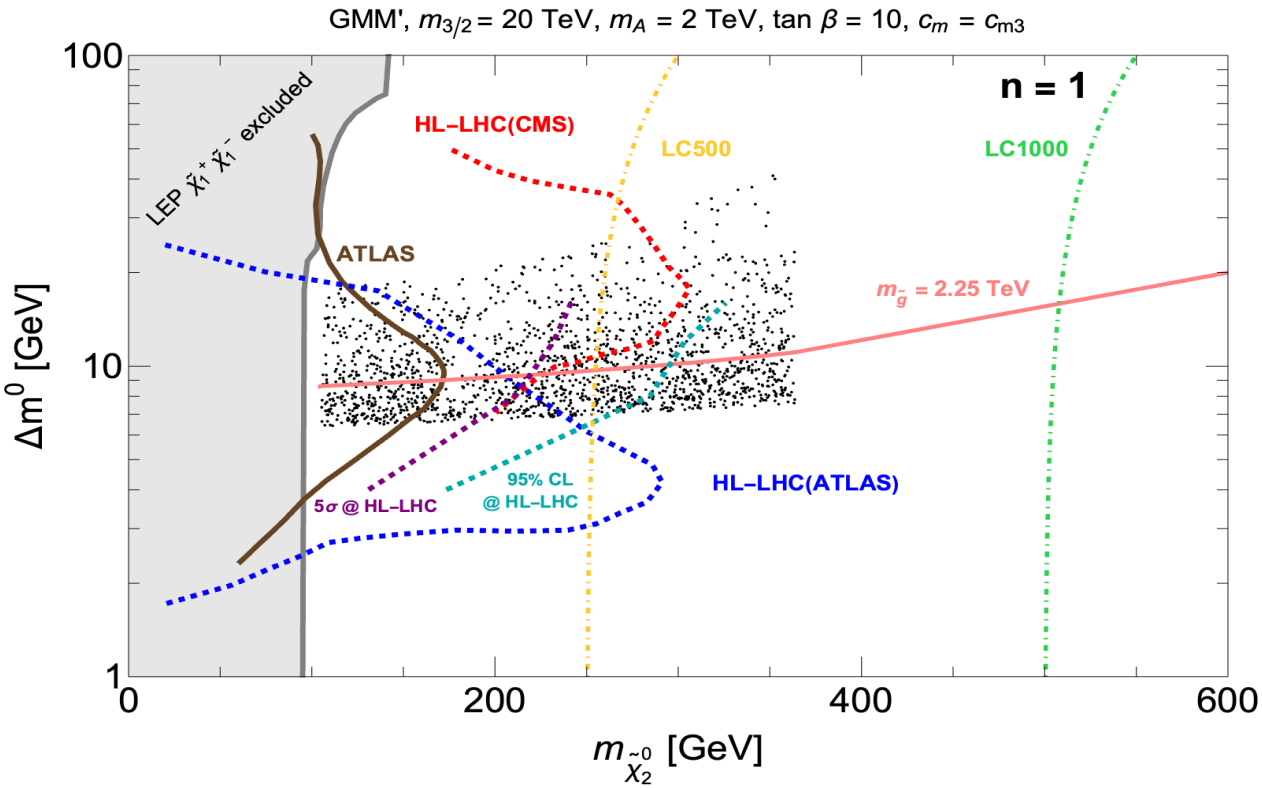
soft visible particles since small higgsino mass gaps



HB, Berggren, Fujii, List, Lehtinen, Tanabe, Yan, arXiv: 1912.06643

Natural higgsino discovery plane

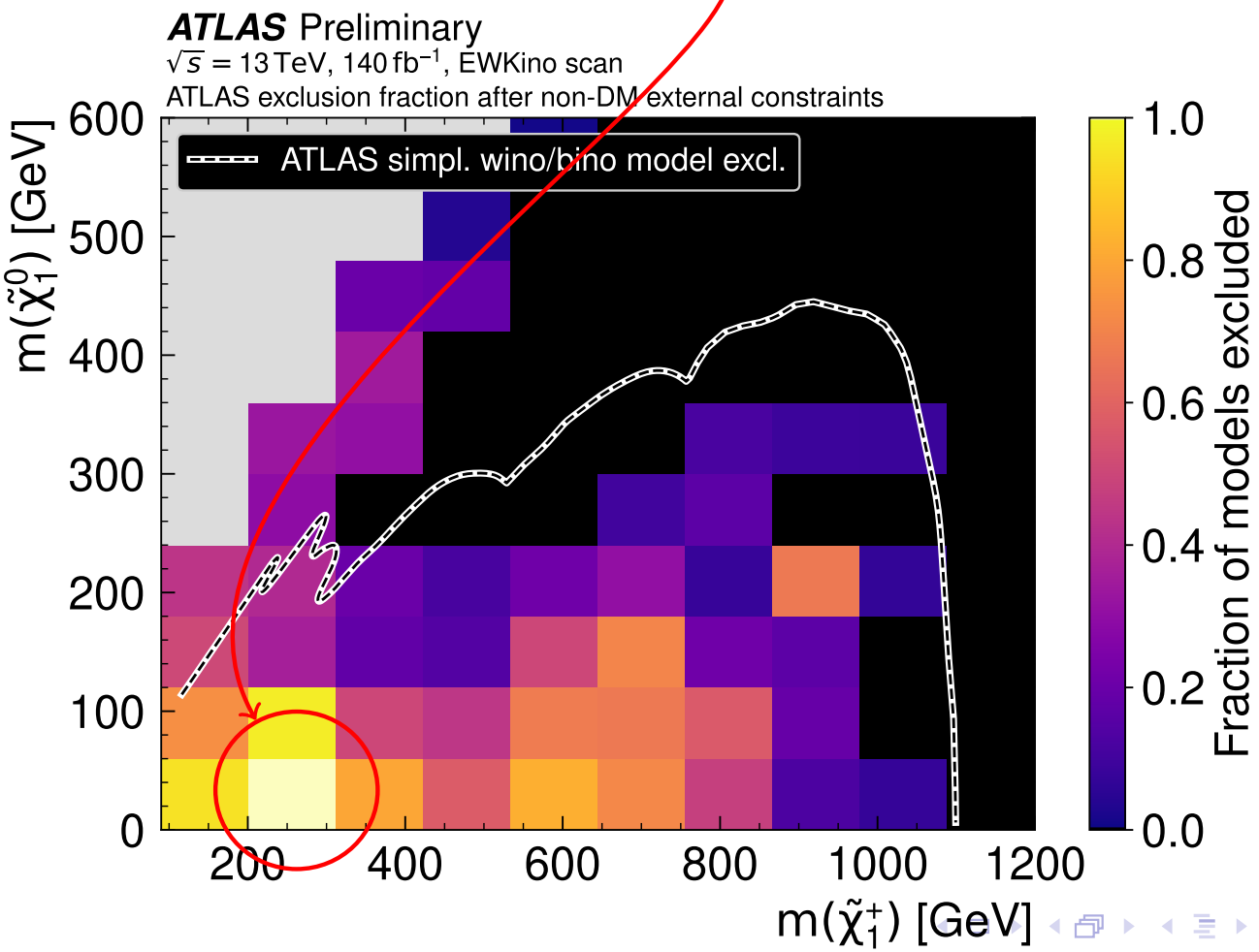
Whereas HL-LHC can see only a portion of higgsino discovery plane, a LC with rs>2m(higgsino) can see all of it!



(higher density of dots: more theoretically plausible) arXiv:2007.09252

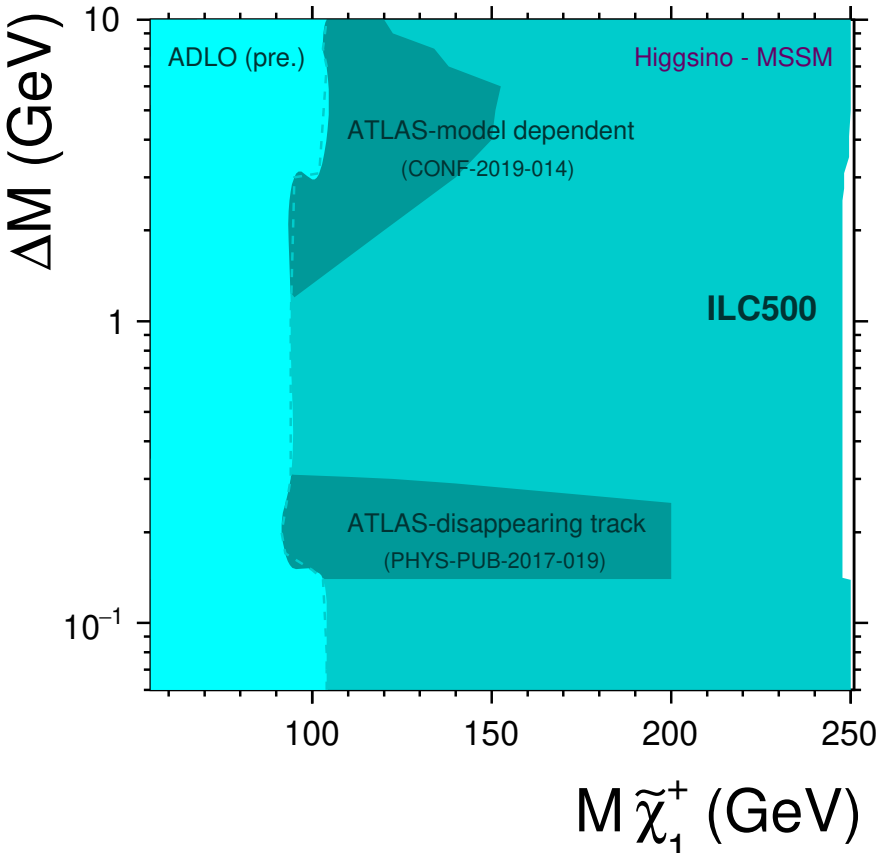
ATLAS pMSSM-19 (-7) scan in M_{LSP} vs. $M_{\chi_1^\pm}$ (ATLAS-CONF-2023-055)

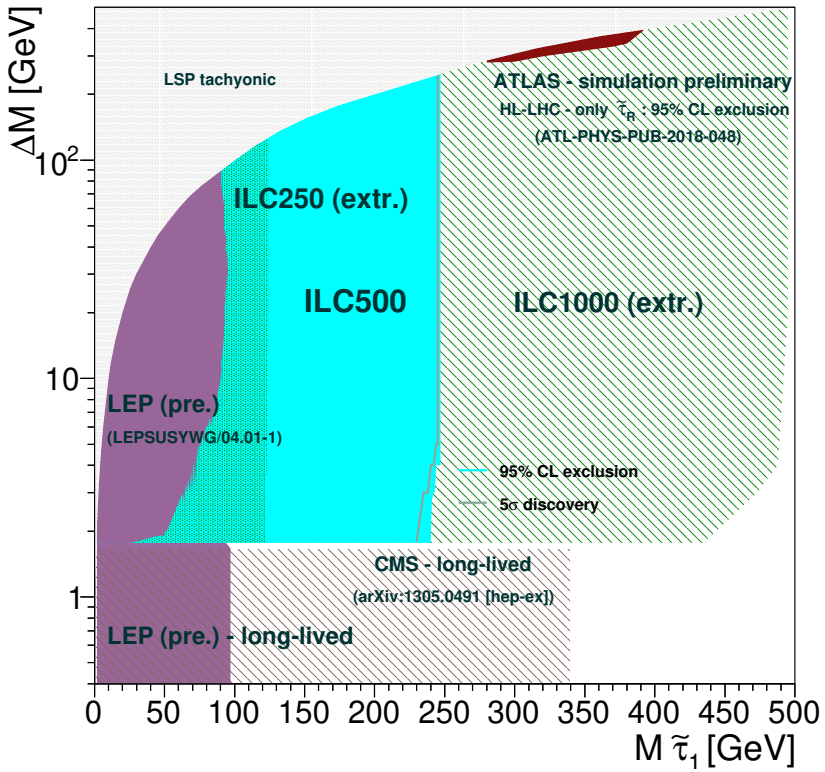
Only this one is actually excluded !



ILC projections on Higgsinos and $\tilde{\tau}$s

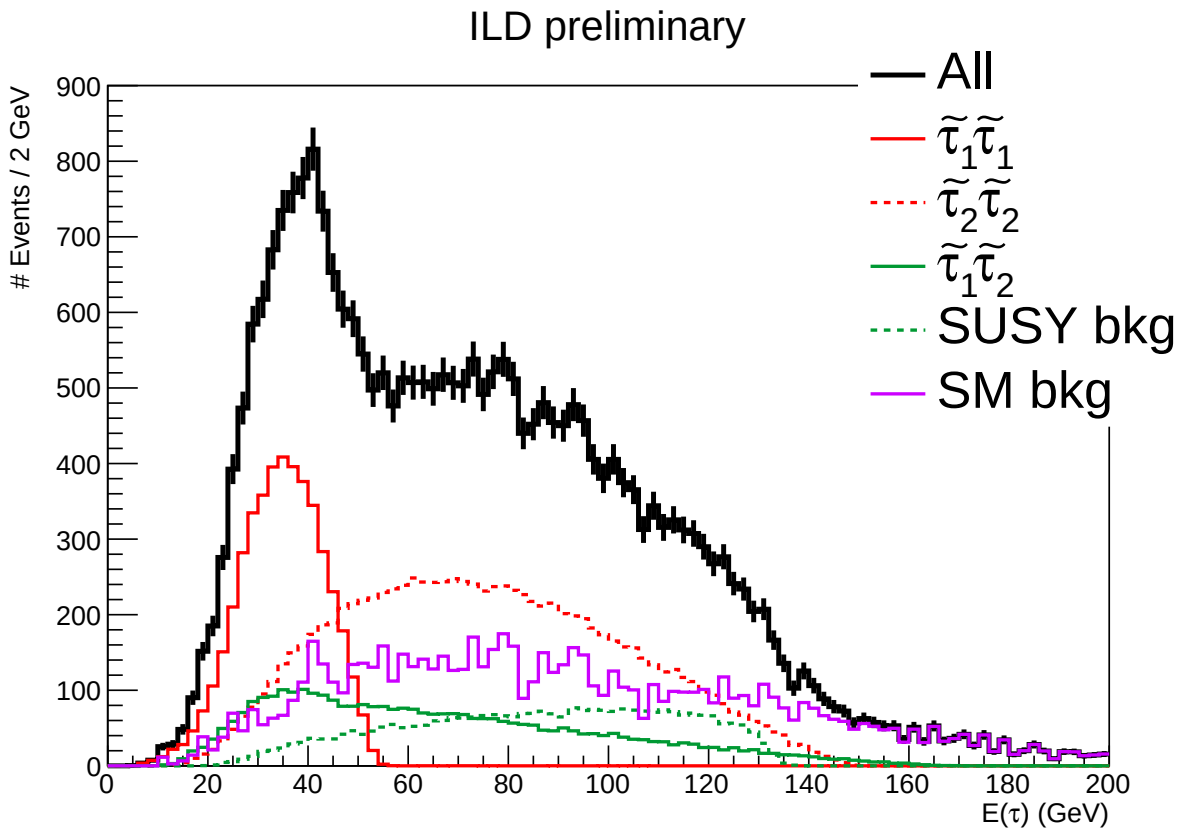
From `arXiv:2002.01239`





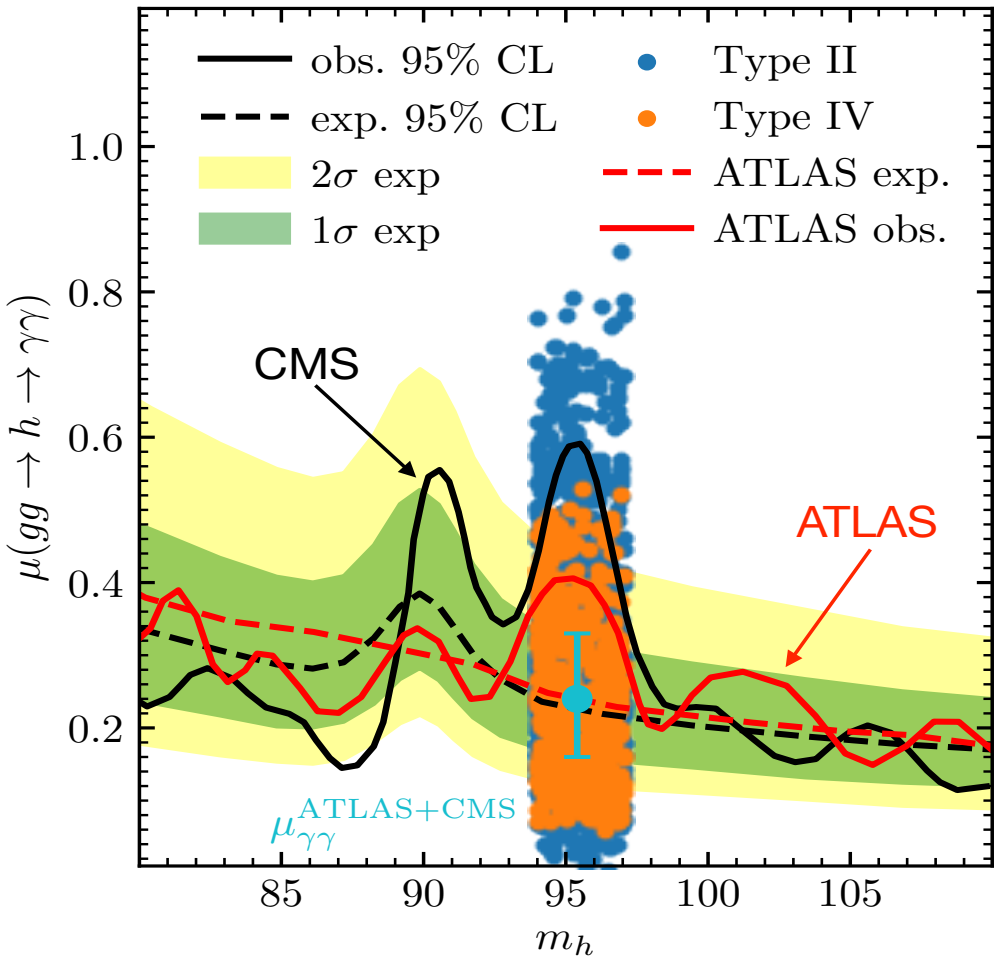
From `arXiv:2105.08616`

Example results from the $\tilde{\tau}$ study at the ILC



LHC: CMS + ATLAS excess in $\gamma\gamma$ channel at 95 GeV, interpretation in 2HDM + singlet (S2HDM)

CMS + ATLAS excess in $\gamma\gamma$ channel at 95 GeV:



[T. Biekötter, S. Heinemeyer, G. W. '23]

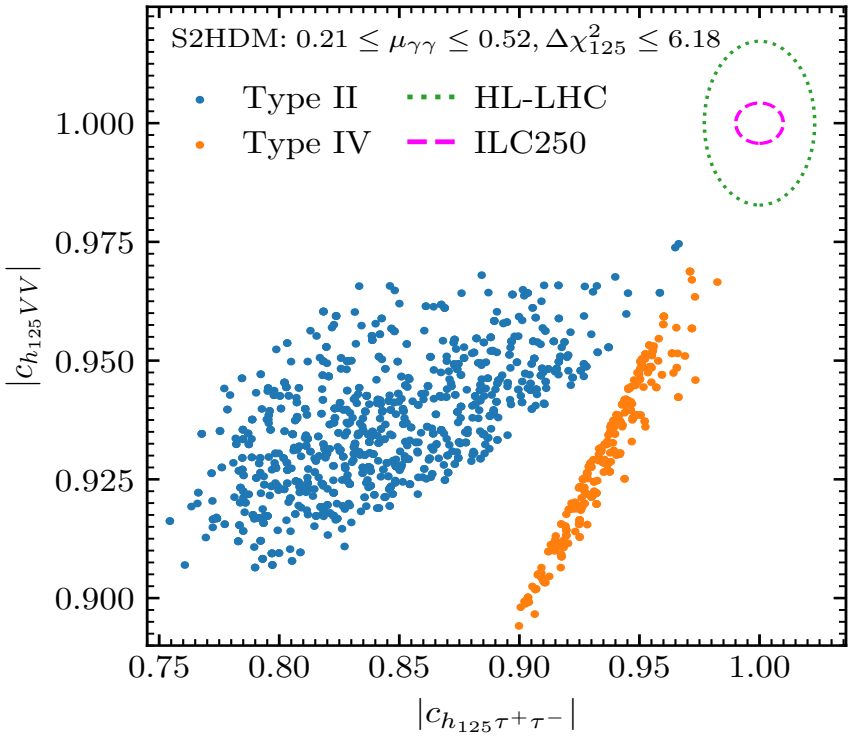
Example interpretation: S2HDM, type II and IV

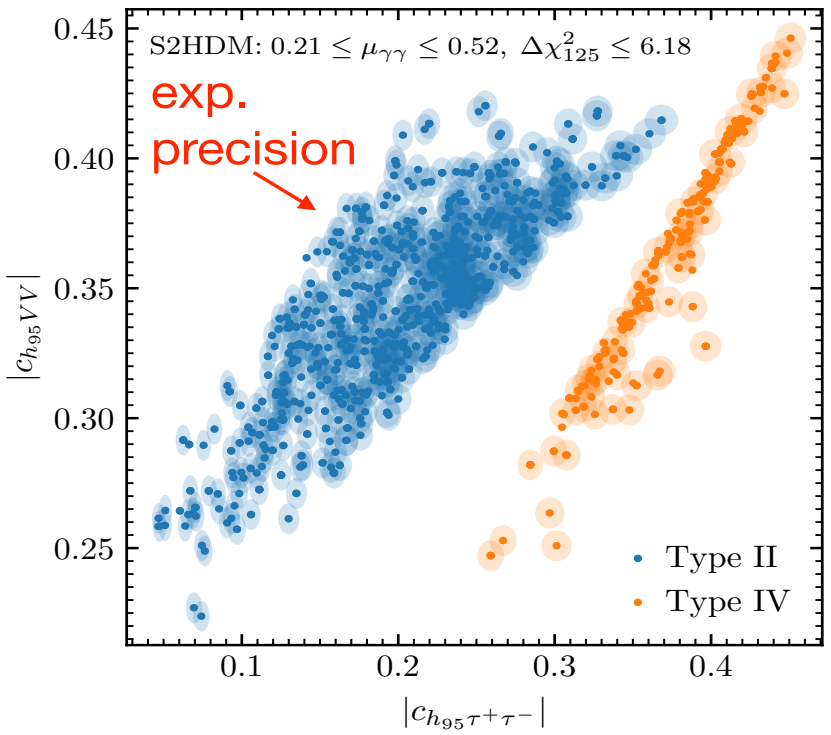
⇒Good description in extended Higgs sectors with an additional doublet and a singlet

Prospects for coupling measurements of h125 and h95 at an e⁺e⁻ Higgs factory

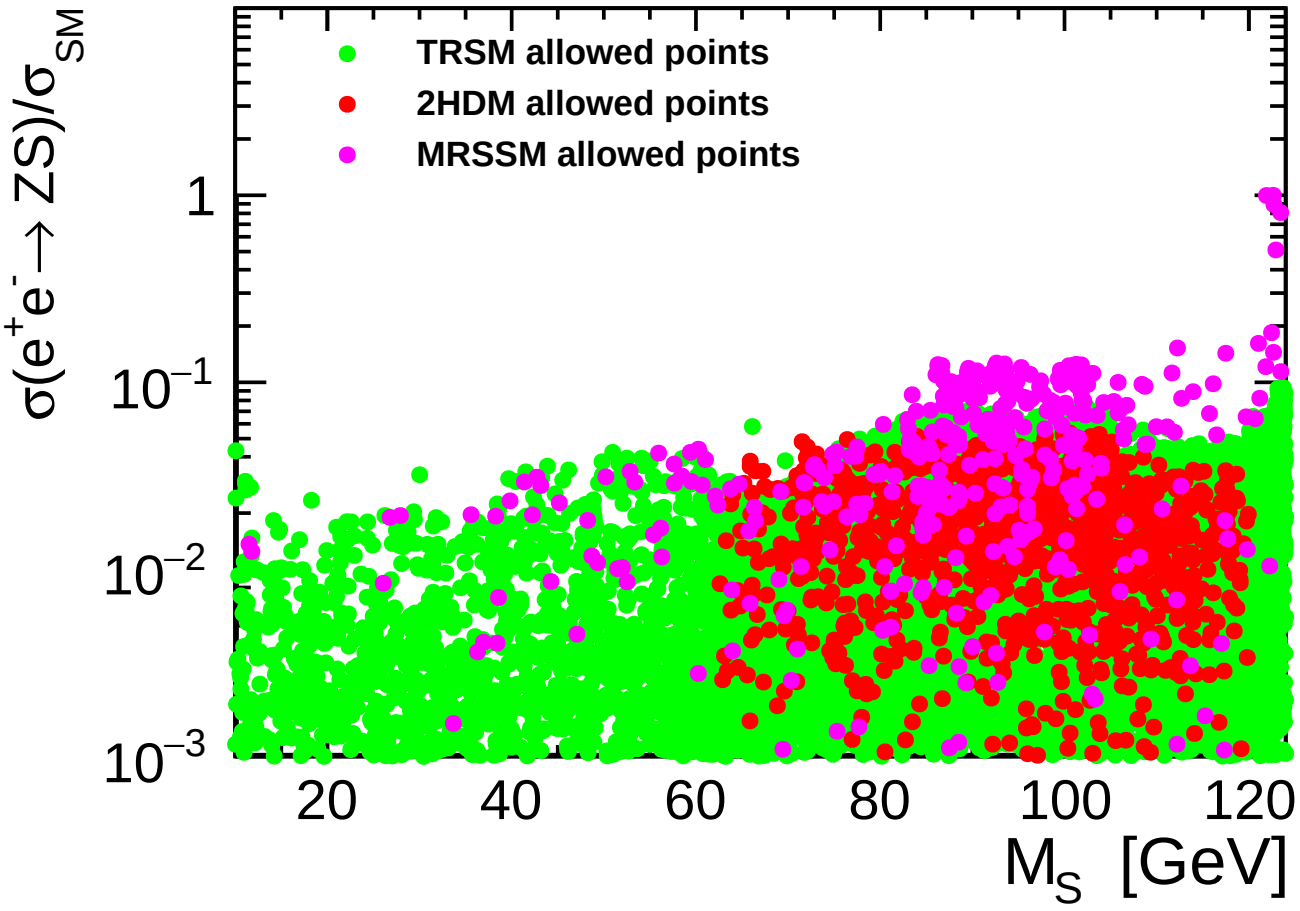
S2HDM, type II and IV:

[T. Biekötter, S. Heinemeyer, G. W. '23]

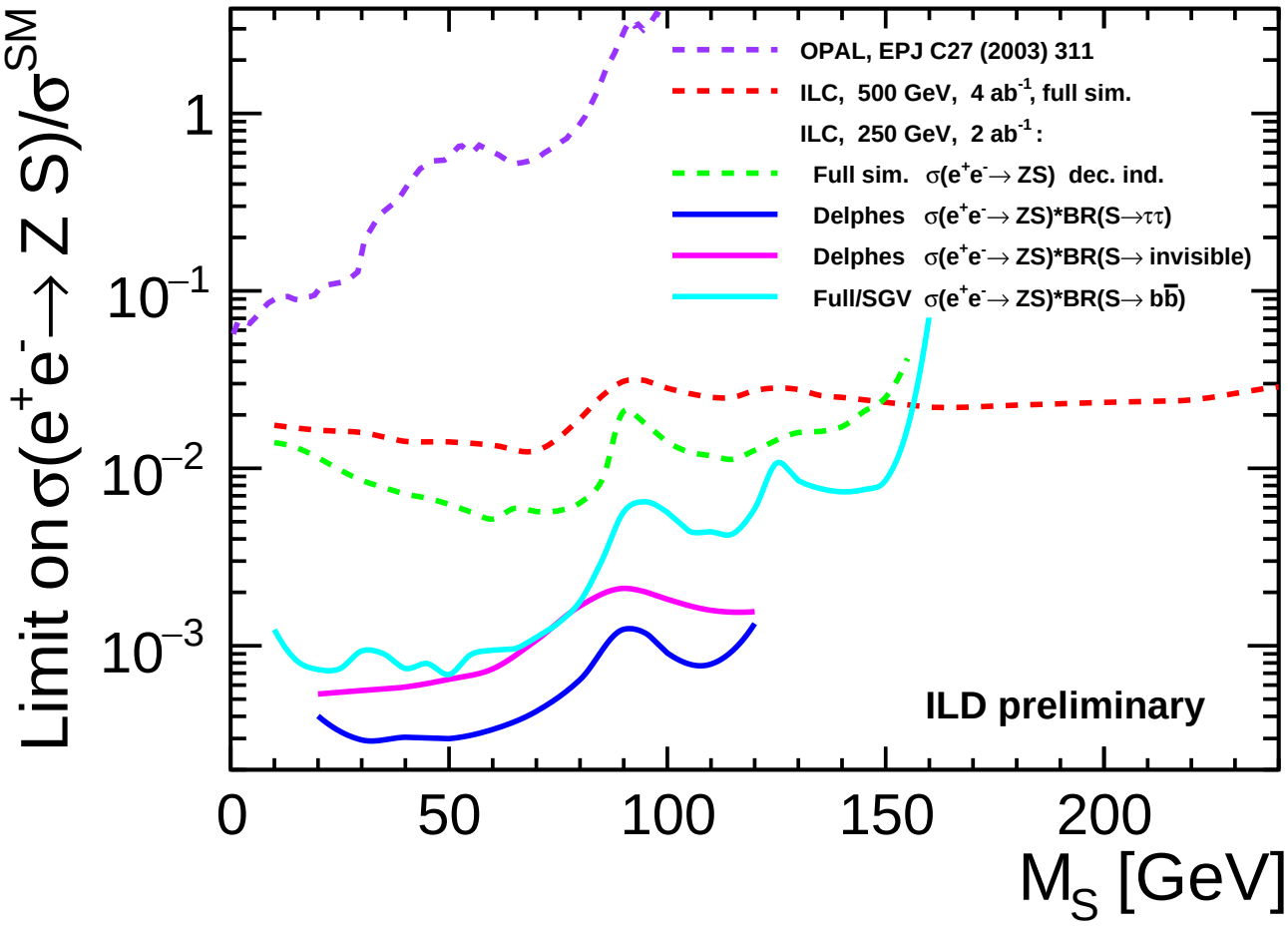




⇒ Precision measurements of the couplings of both h125 and h95
High sensitivity to the realised physics scenario (Yukawa type, …)


TRSM allowed points
2HDM allowed points
MRSSM allowed points
σ(e+e-→ ZS)/σSM
1
10−1
10−2
10−3
20
40
60
80
100
120
MS [GeV]

ILC/ILD results on the Exotic scalar sensitivity in different decay channels



Electroweak-charged dark matter

Quantum numbers $U(1)_Y$	$SU(2)_L$	$SU(3)_c$	Spin	DM could decay into	M_{DM} in TeV tree	non-pert	$M_{DM^\pm} - M_{DM}$ in MeV	σ_{SI} in $10^{-46}\,cm^2$
1/2	2	1	0	EL	0.54		350	$(0.4 \pm 0.6)\,10^{-3}$
1/2	2	1	1/2	EH	1.1		341	$(0.3 \pm 0.6)\,10^{-3}$
0	3	1	0	HH^*	2.0	2.5	166	0.23 ± 0.04
0	3	1	1/2	LH	2.4	2.6	166	0.23 ± 0.04
1	3	1	0	HH, LL	1.6	?	540	0.001 ± 0.001
1	3	1	1/2	LH	1.9	?	526	0.001 ± 0.001
1/2	4	1	0	HHH^*	2.4	?	353	0.27 ± 0.08
1/2	4	1	1/2	(LHH^*)	2.4	?	347	0.27 ± 0.08
3/2	4	1	0	HHH	2.9	?	729	0.15 ± 0.07
3/2	4	1	1/2	(LHH)	2.6	?	712	0.15 ± 0.07
0	5	1	0	(HHH^*H^*)	5.0	14	166	2.0 ± 0.5
0	5	1	1/2	none	4.4	14	166	2.0 ± 0.5

M. Cirelli, A. Strumia, J. Zupan, arXiv:2406.01705

(→: Sommerfeld enhancement)

The neutral component of an electroweak multiplet can be a DM candidate.

Thermal relic agrees with the observed DM density for a TeV-scale mass.

Lower masses are also allowed:

- Non-thermal production
- Rest of the DM density could be some other species

Electroweak-charged dark matter

Quantum numbers $\mathrm{U}(1)_Y$	$\mathrm{SU}(2)_L$	$\mathrm{SU}(3)_c$	Spin	DM could decay into	M_{DM} in TeV tree	non-pert	$M_{\mathrm{DM}^\pm} - M_{\mathrm{DM}}$ in MeV	σ_{SI} in $10^{-46}\,\mathrm{cm}^2$
1/2	2	1	0	EL	0.54		350	$(0.4 \pm 0.6)\,10^{-3}$
1/2	2	1	1/2	EH	1.1		341	$(0.3 \pm 0.6)\,10^{-3}$
0	3	1	0	HH^*	2.0	2.5	166	0.23 ± 0.04
0	3	1	1/2	LH	2.4	2.6	166	0.23 ± 0.04
1	3	1	0	HH, LL	1.6	?	540	0.001 ± 0.001
1	3	1	1/2	LH	1.9	?	526	0.001 ± 0.001
1/2	4	1	0	HHH^*	2.4	?	353	0.27 ± 0.08
1/2	4	1	1/2	(LHH^*)	2.4	?	347	0.27 ± 0.08
3/2	4	1	0	HHH	2.9	?	729	0.15 ± 0.07
3/2	4	1	1/2	(LHH)	2.6	?	712	0.15 ± 0.07
0	5	1	0	(HHH^*H^*)	5.0	14	166	2.0 ± 0.5
0	5	1	1/2	none	4.4	14	166	2.0 ± 0.5

M. Cirelli, A. Strumia, J. Zupan, arXiv:2406.01705

- Direct detection rate tends to be suppressed since the scattering is induced at loop level. Some of the candidates can be probed in future DM direct detection experiments.

  J. Hisano, K. Ishiwata, N. Nagata, JHEP **1506**, 097 (2015).

- Indirect detection is also promising, though it may suffer from uncertainty of DM profile.

  V. Lefranc, E. Moulin, P. Panci, F. Sala, and J. Silk, JCAP **1609**, 043 (2016).

Electroweak-charged dark matter

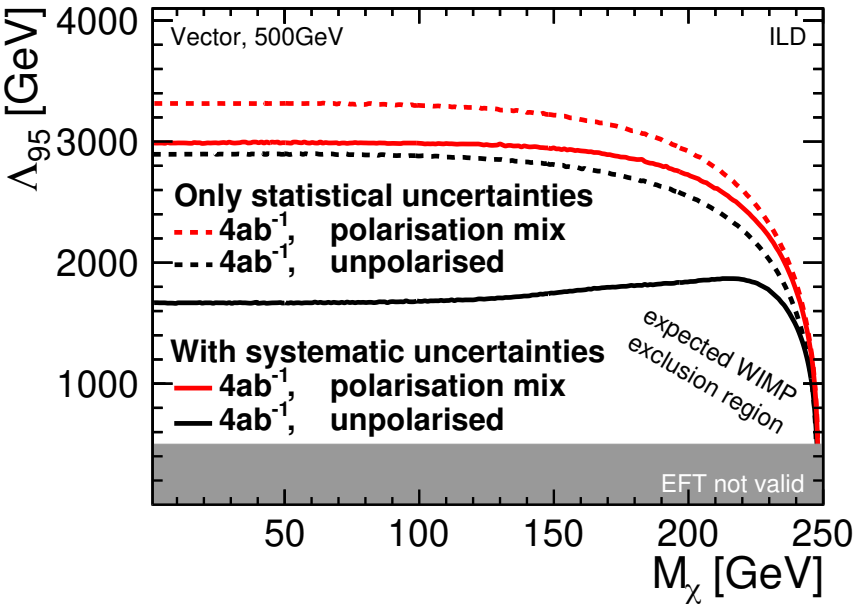
Quantum numbers $U(1)_Y$	$SU(2)_L$	$SU(3)_c$	Spin	DM could decay into	M_{DM} in TeV tree	non-pert	$M_{DM^\pm} - M_{DM}$ in MeV	σ_{SI} in $10^{-46}\,cm^2$
1/2	2	1	0	EL	0.54		350	$(0.4 \pm 0.6)\,10^{-3}$
1/2	2	1	1/2	EH	1.1		341	$(0.3 \pm 0.6)\,10^{-3}$
0	3	1	0	HH^*	2.0	2.5	166	0.23 ± 0.04
0	3	1	1/2	LH	2.4	2.6	166	0.23 ± 0.04
1	3	1	0	HH, LL	1.6	?	540	0.001 ± 0.001
1	3	1	1/2	LH	1.9	?	526	0.001 ± 0.001
1/2	4	1	0	HHH^*	2.4	?	353	0.27 ± 0.08
1/2	4	1	1/2	(LHH^*)	2.4	?	347	0.27 ± 0.08
3/2	4	1	0	HHH	2.9	?	729	0.15 ± 0.07
3/2	4	1	1/2	(LHH)	2.6	?	712	0.15 ± 0.07
0	5	1	0	(HHH^*H^*)	5.0	14	166	2.0 ± 0.5
0	5	1	1/2	none	4.4	14	166	2.0 ± 0.5

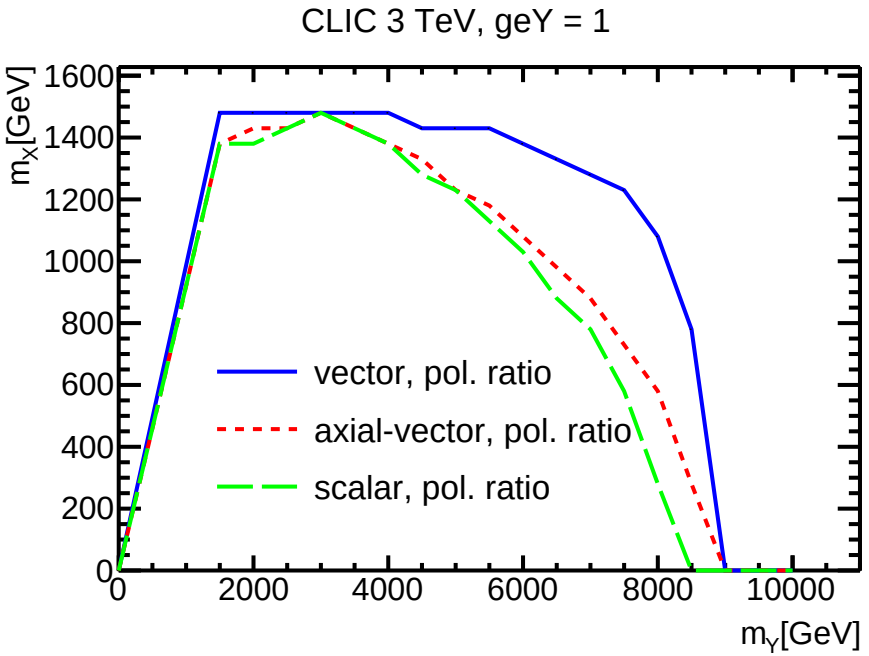
M. Cirelli, A. Strumia, J. Zupan, arXiv:2406.01705

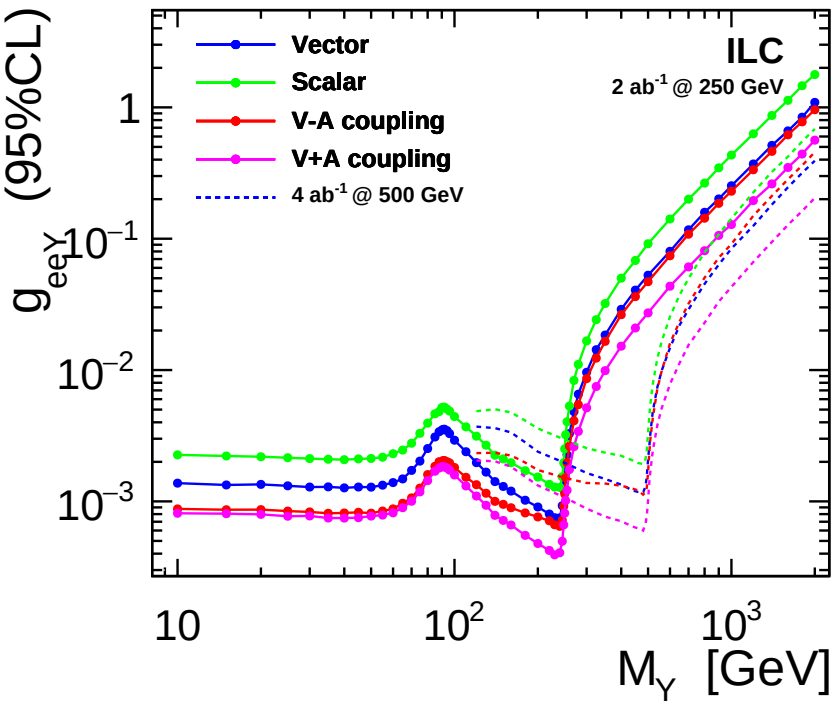
- The charged-neutral mass splitting is very small, as it is induced by electroweak loop diagrams. This makes it difficult to probe this DM candidate at the LHC.

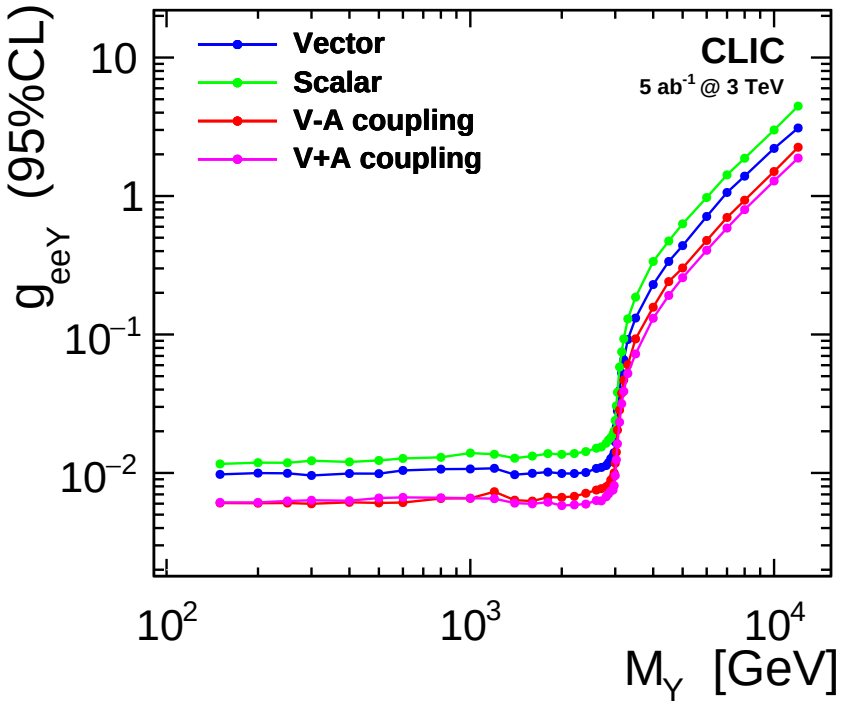
  Disappearing track searches can have sensitivities to some cases (e.g., triplet).

- Linear colliders can probe EW-charged DM up to $M_{DM} = \sqrt{s}/2$.


Vector, 500GeV
ILD
Only statistical uncertainties
4ab-1, polarisation mix
4ab-1, unpolarised
With systematic uncertainties
4ab-1, polarisation mix
4ab-1, unpolarised
expected WIMP exclusion region
EFT not valid
Λ95 [GeV]
Mχ [GeV]
4000
3000
2000
1000
50
100
150
200
250


CLIC 3 TeV, geY = 1
vector, pol. ratio
axial-vector, pol. ratio
scalar, pol. ratio
mX[GeV]
mY[GeV]
1600
1400
1200
1000
800
600
400
200
0
0
2000
4000
6000
8000
10000


Vector
Scalar
V-A coupling
V+A coupling
4 ab^{-1} @ 500 GeV
ILC
2 ab^{-1} @ 250 GeV
g_{eeY} (95%CL)
M_Y [GeV]


Vector
Scalar
V-A coupling
V+A coupling
CLIC
5 ab^{-1} @ 3 TeV
g_{eeY} (95%CL)
M_Y [GeV]

Conclusions