SI 2026

Probing Light Higgsinos with Electroweak Precision Measurements at Future e^+e^- Colliders

Natsumi Nagata (U. Tokyo)

August 7—13, 2026

Fuji Calm, Fuji-Yoshida

Outline

- Introduction

  Electroweak precision measurements at future e^+e^- colliders

- Current status of higgsino search
- Results
- Conclusion

Introduction

Next-generation e^+e^- colliders

Several future e^+e^- collider projects are now being discussed.

Linear

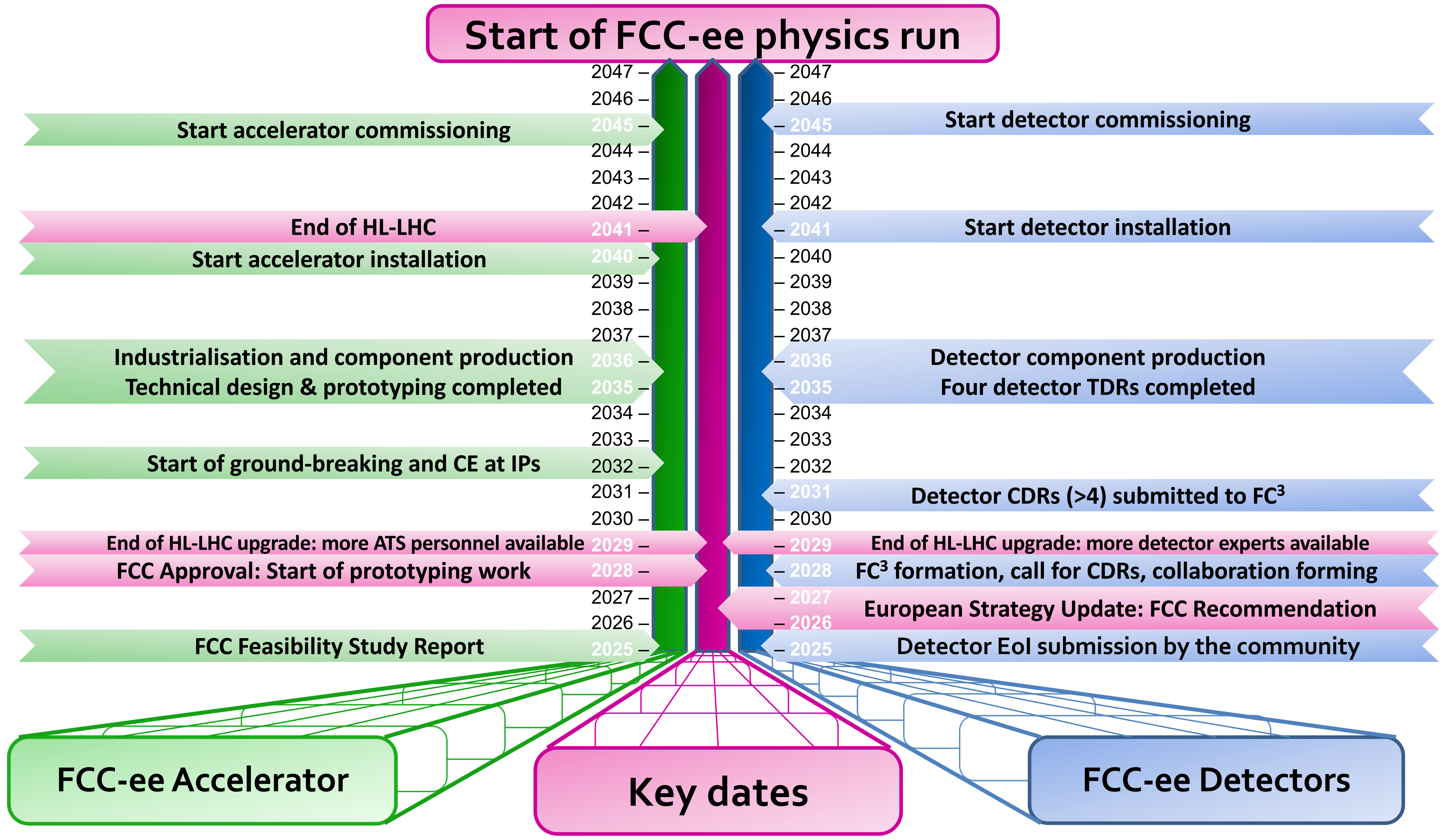
- ILC
- LCF

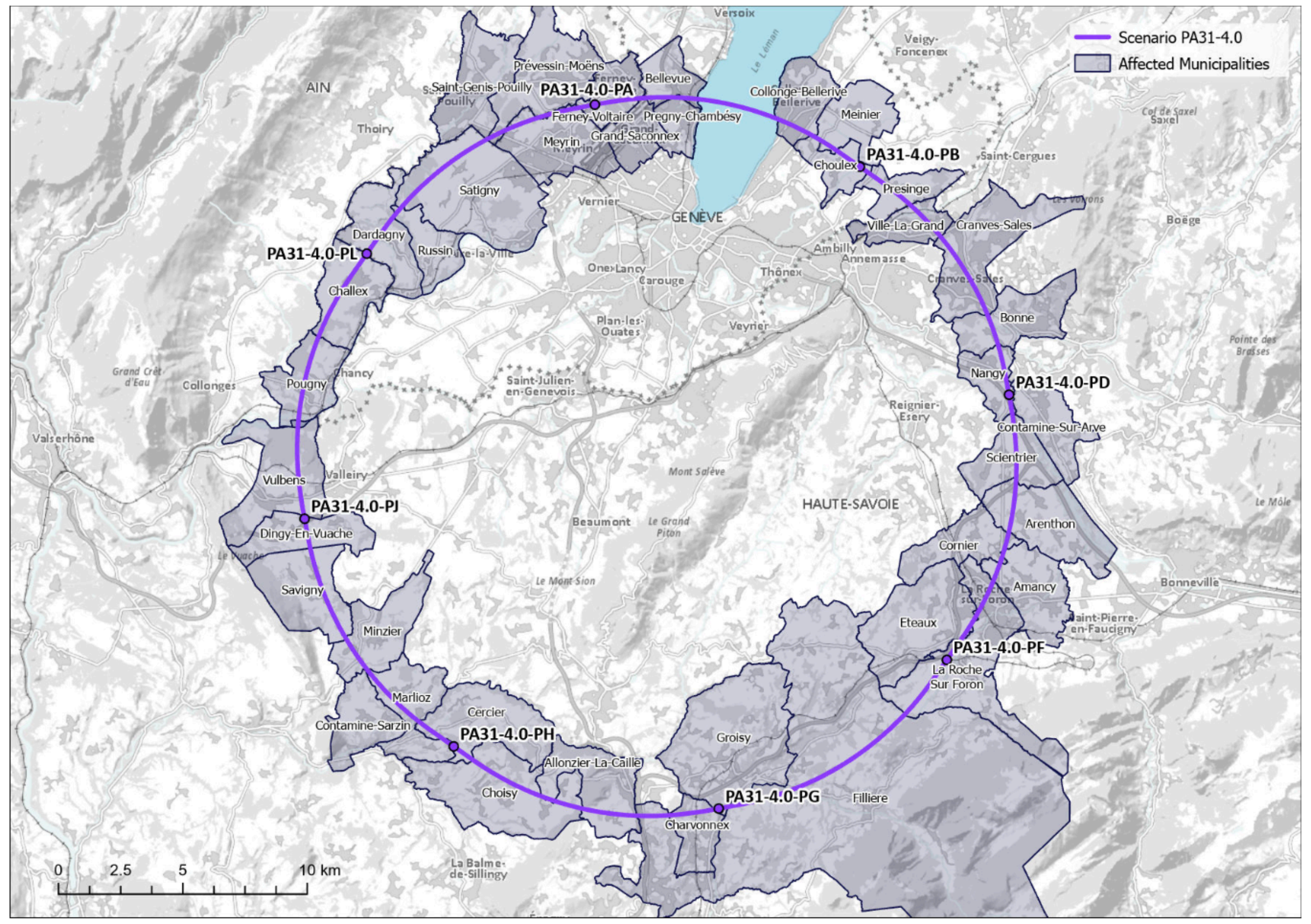
Circular

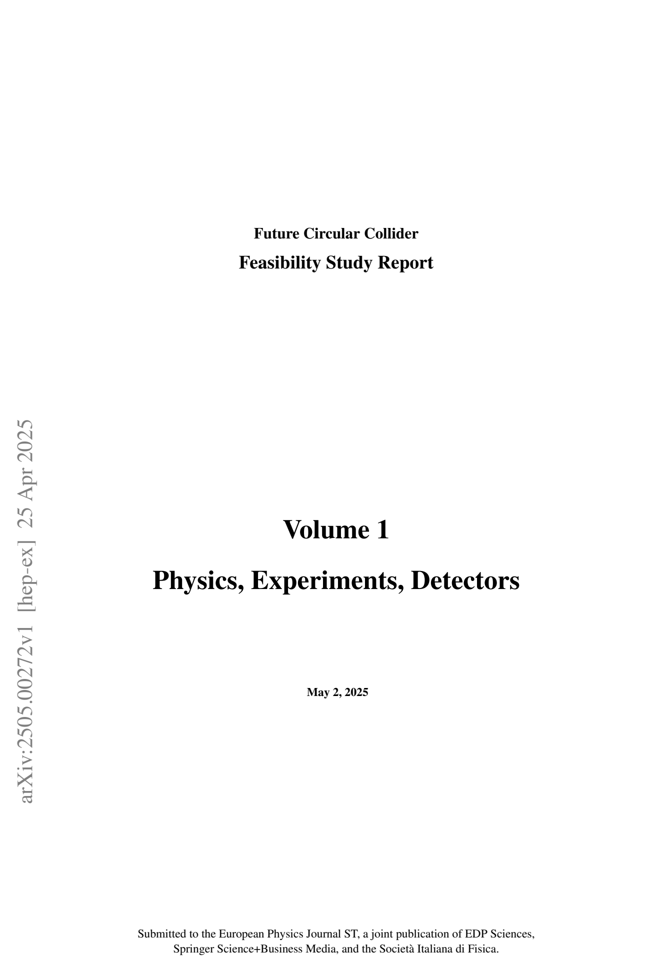
- FCC-ee
- CEPC

In particular, circular collider projects are attracting a lot of attention recently.

Future Circular Collider (FCC)







Future Circular Collider
Feasibility Study Report

Volume 1

Physics, Experiments, Detectors

May 2, 2025

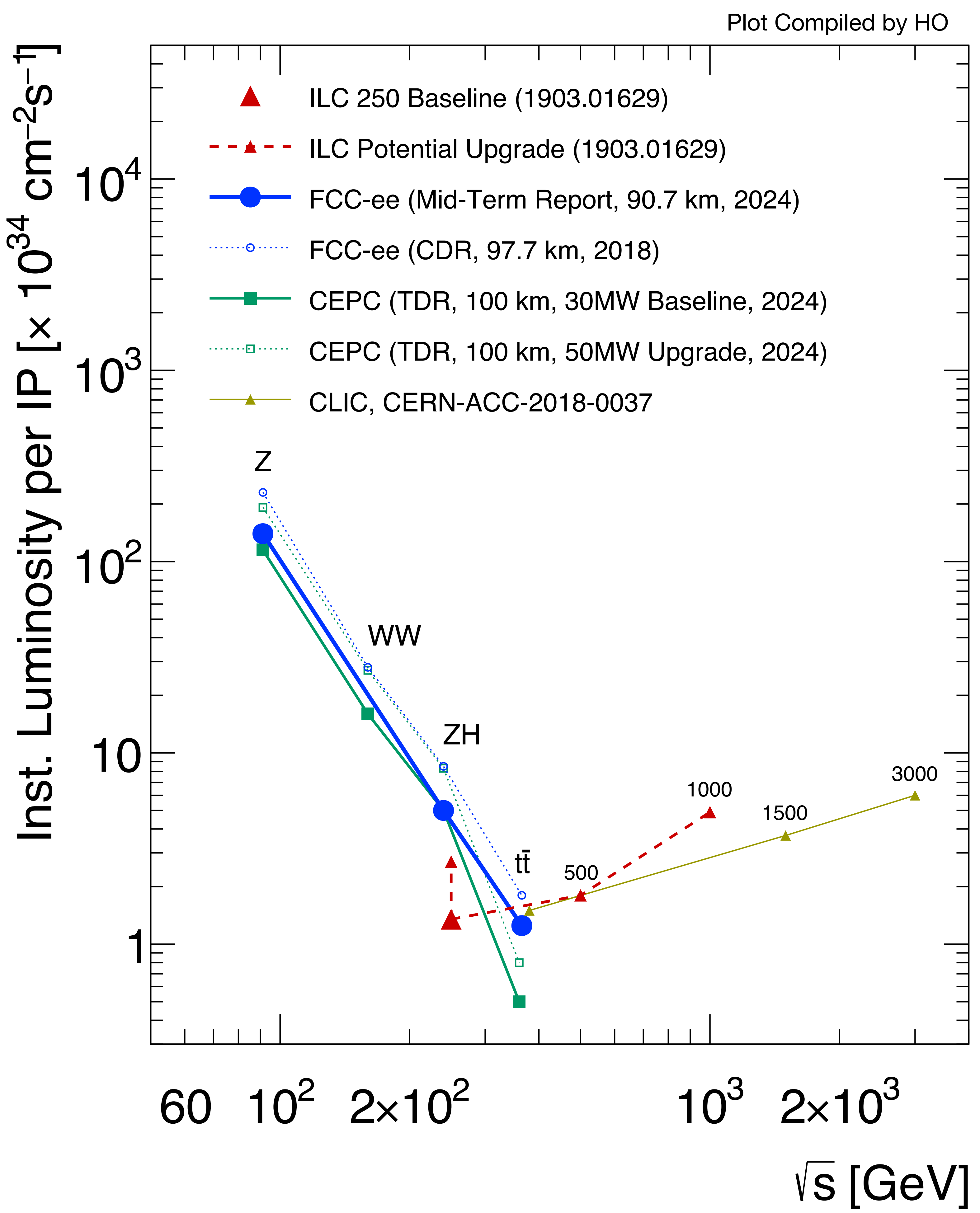
arXiv:2505.00272v1 [hep-ex] 25 Apr 2025

Submitted to the European Physics Journal ST, a joint publication of EDP Sciences, Springer Science+Business Media, and the Società Italiana di Fisica.

FCC Collaboration, arXiv:2505.00272

- Feasibility Study completed.
- Decision is expected ~2028.
- Physics run is planned to start ~2048.

Instantaneous luminosity

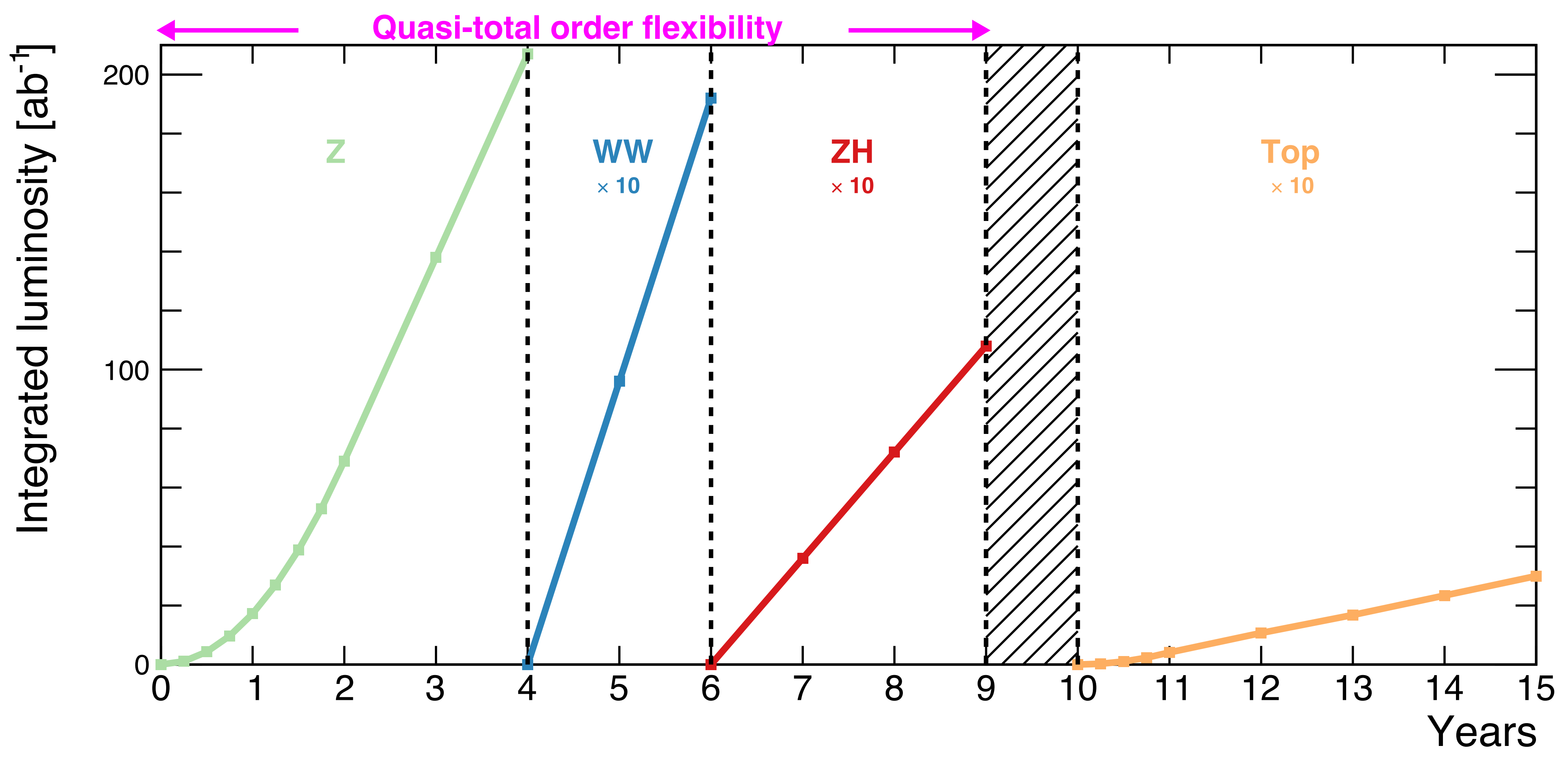


Circular colliders can achieve much higher luminosity at low energies.

➡ Electroweak precision measurements

Baseline operation plans

FCC-ee



FCC Collaboration, arXiv:2505.00272

Plan to start with electroweak precision measurements

CEPC

Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. per IP (10^{34}cm^{-2}s^{-1})	Integrated Lumi. per year (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H*	240	10	50	8.3	2.2	21.6	4.3×10^6
			30	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30	115**	30	60	2.5×10^{12}
W	160	1	50	26.7	6.9	6.9	2.1×10^8
			30	16	4.2	4.2	1.3×10^8
$t\bar{t}$	360	5	50	0.8	0.2	1.0	0.6×10^6
			30	0.5	0.13	0.65	0.4×10^6

* Higgs is the top priority. The CEPC will commence its operation with a focus on Higgs.

Jie Gao, LCWS2024, Jul 8, 2024

Higgs is the top priority

Electroweak precision comparison

Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$)	17.8*	17.8*		3.8 (1.2)	17.8*	
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*
Δm_H (MeV)	170*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*
ΔA_e ($\times 10^5$)	190*	14 (4.5)	1.5 (8)	0.7 (2)	1.5 (2)	60 (15)
ΔA_μ ($\times 10^5$)	1500*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	390 (14)
ΔA_τ ($\times 10^5$)	400*	86 (4.5)	3 (8)	0.5 (20)	1.2 (20)	550 (14)
ΔA_b ($\times 10^5$)	2000*	53 (35)	9 (50)	2.4 (21)	3 (21)	360 (92)
ΔA_c ($\times 10^5$)	2700*	140 (25)	20 (37)	20 (15)	6 (30)	190 (67)
$\Delta\sigma^0_{\text{had}}$ (pb)	37*			0.035 (4)	0.05 (2)	37*
δR_e ($\times 10^3$)	2.4*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.5 (1.0)
δR_μ ($\times 10^3$)	1.6*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.5 (1.0)
δR_τ ($\times 10^3$)	2.2*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	3.3 (5.0)
δR_b ($\times 10^3$)	3.1*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.5 (1.0)
δR_c($\times 10^3$)	17*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	2.4 (5.0)

Snowmass, arXiv:2209.08078

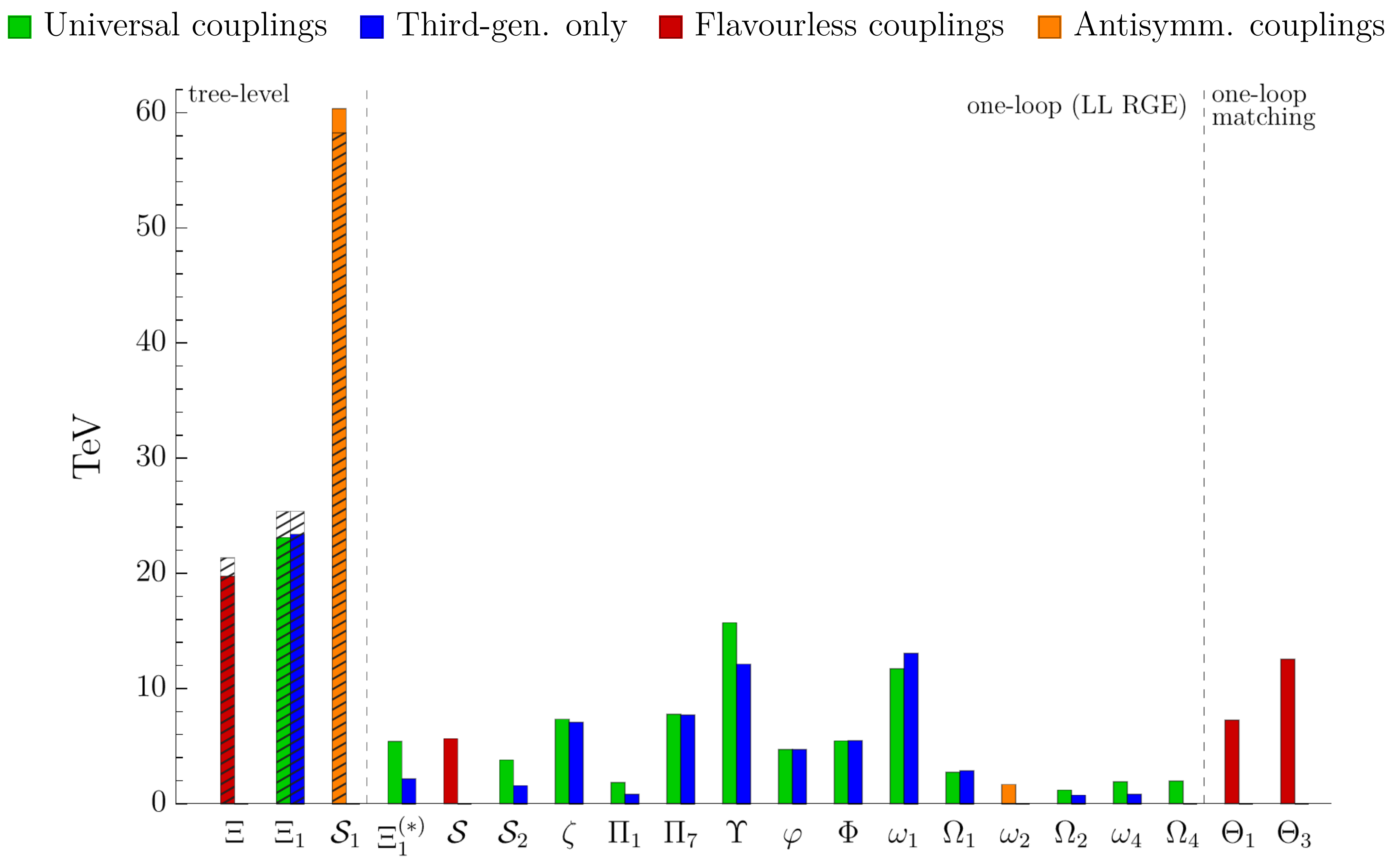
- Linear colliders can also provide high precision for some observables.
- Improvements of several orders of magnitude.

Beam polarization

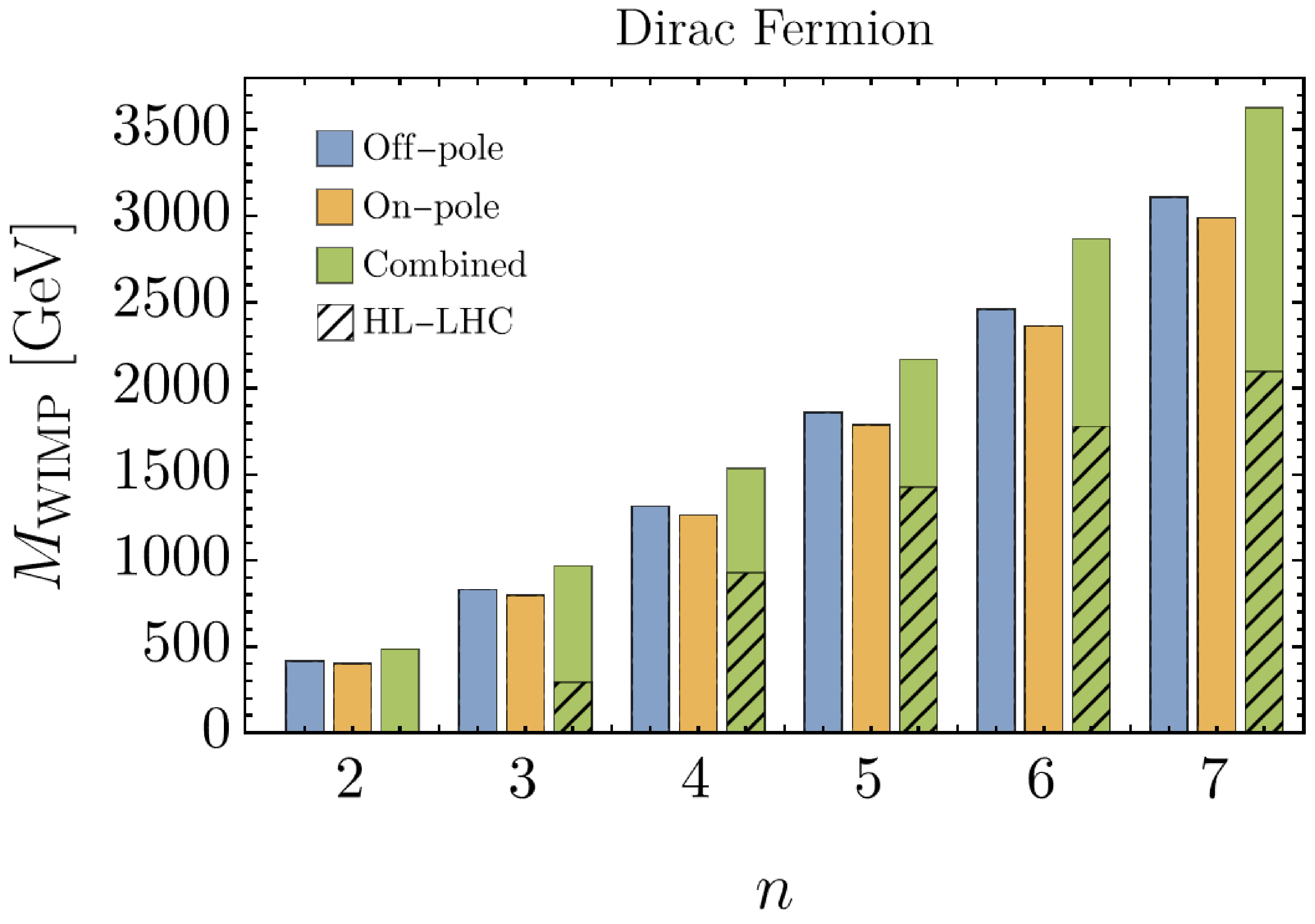
Prospects for new physics search

Future e^+e^- colliders can measure EW observables very precisely.

Implications for some simplified models have been studied in the literature.



L. Allwicher, M. McCullough, S. Renner, JHEP **02**, 164 (2025)



V. Maura, B. A. Stefanek, and T. You, JHEP **10**, 022 (2025)

Target in this talk

We consider a more realistic setup: light higgsinos in the MSSM.

Motivation

- Electroweak naturalness

$$m_H^2 \simeq |\mu|^2 + m_{H_u}^2 + \Delta m_H^2$$

Higgs mass Higgsino mass

Light higgsino is favored.

J. R. Ellis, et.al. (1986); R. Barbieri and G. F. Giudice, et.al. (1988); R. Kitano and Y. Nomura (2005); H. Baer, et.al. (2012).

- Higgsino dark matter
  - Thermal mass: 1 TeV
  - Lighter masses are also motivated: multi-component/non-thermal production

A. Ibarra's lecture

Current status of higgsino search

Higgsino search at LHC

It is quite difficult to probe higgsinos at hadron colliders.

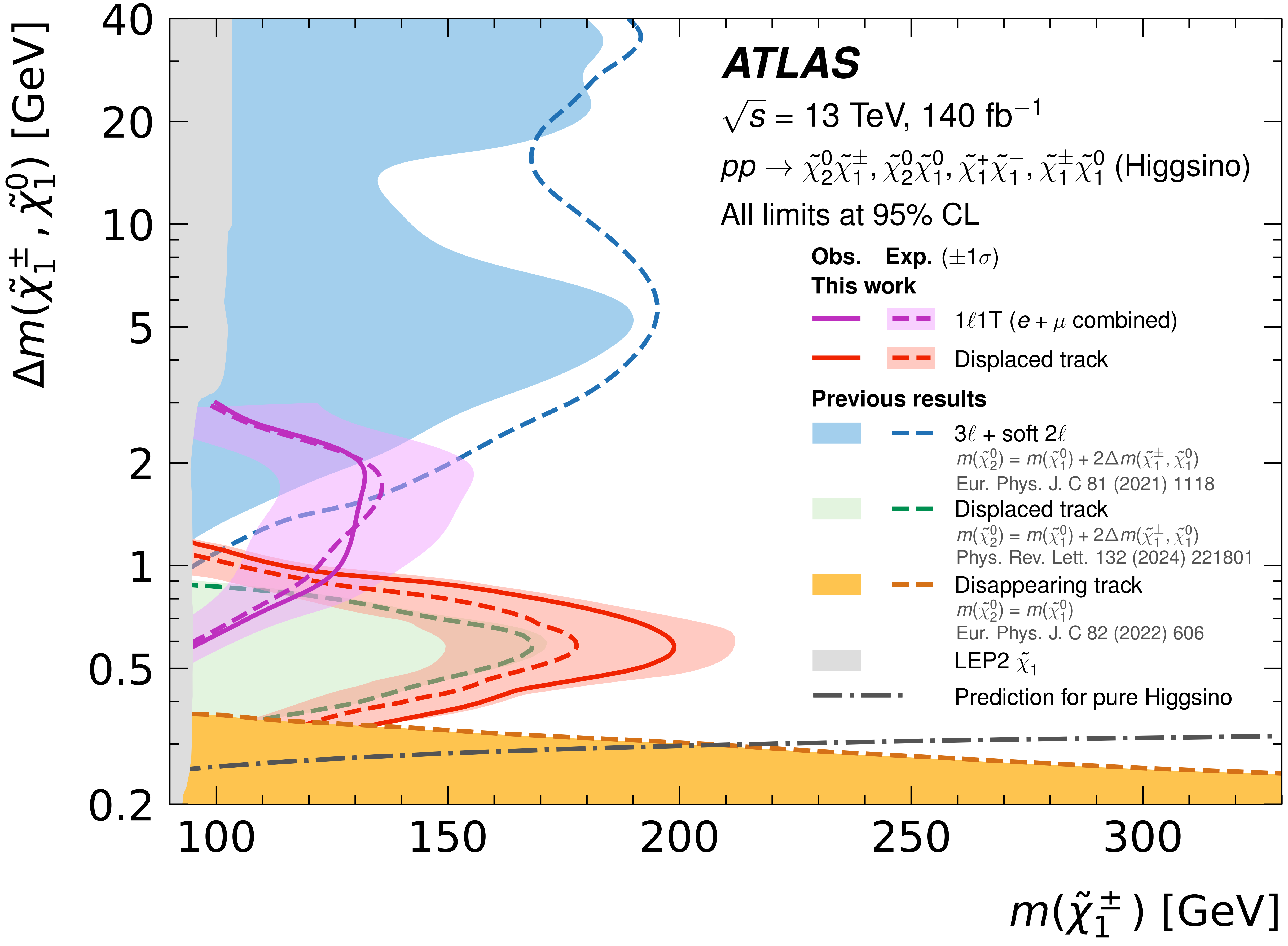
- Interact only through electroweak interactions.
- Mass splitting between the charged and neutral higgsinos is very small.

$$\Delta M_{+} \simeq \frac{v^2}{8}\left[\left|\frac{g'^2}{M_1}+\frac{g^2}{M_2}\right|+\left(\frac{g'^2}{M_1}-\frac{g^2}{M_2}\right)\sin 2\beta\,\mathrm{sgn}(\mu)\right] + \text{EW loop corrections}$$

$$\sim 355\ \mathrm{MeV}$$

Mass splitting becomes even smaller as the gaugino masses become larger.

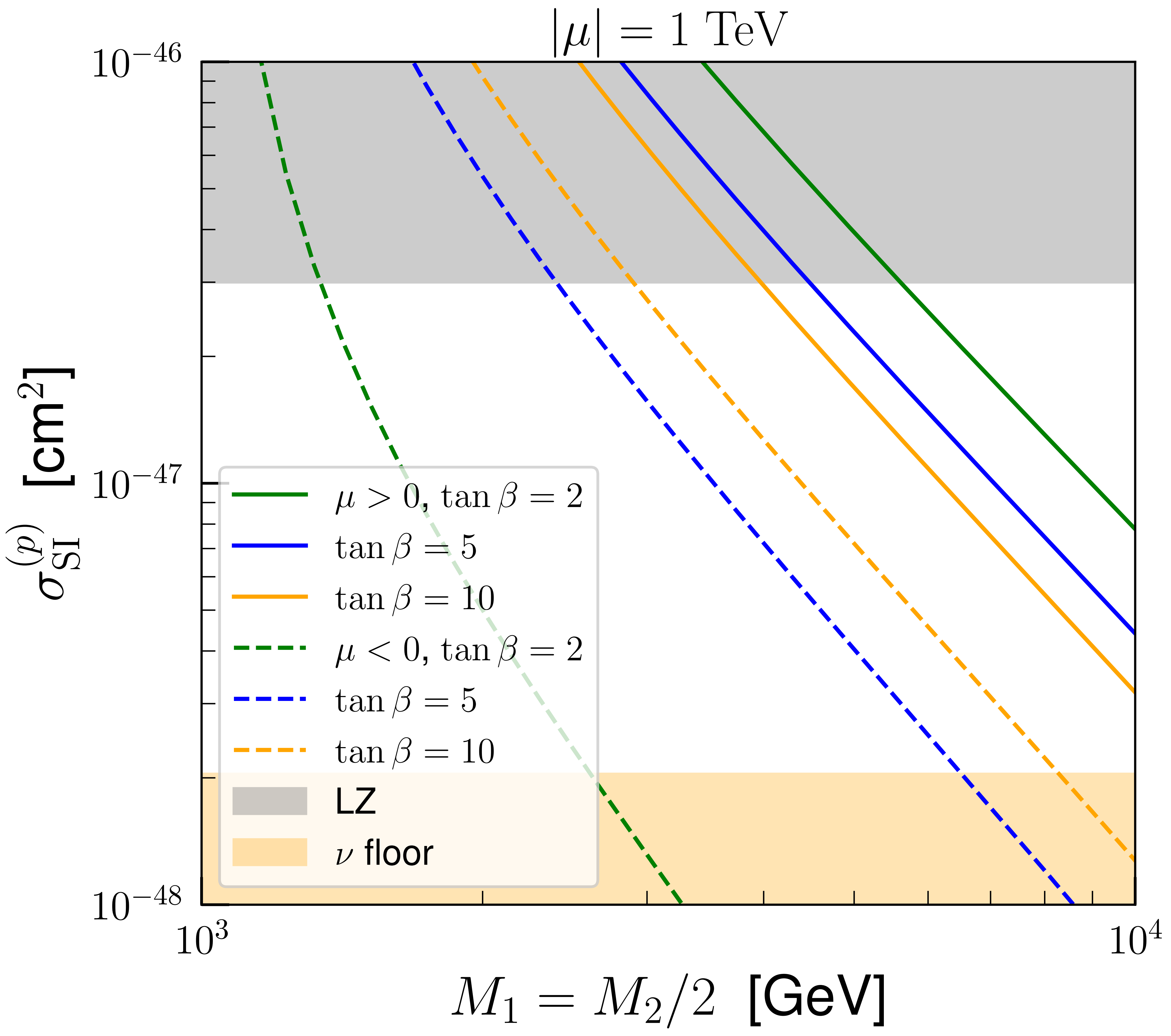
Higgsino search at LHC

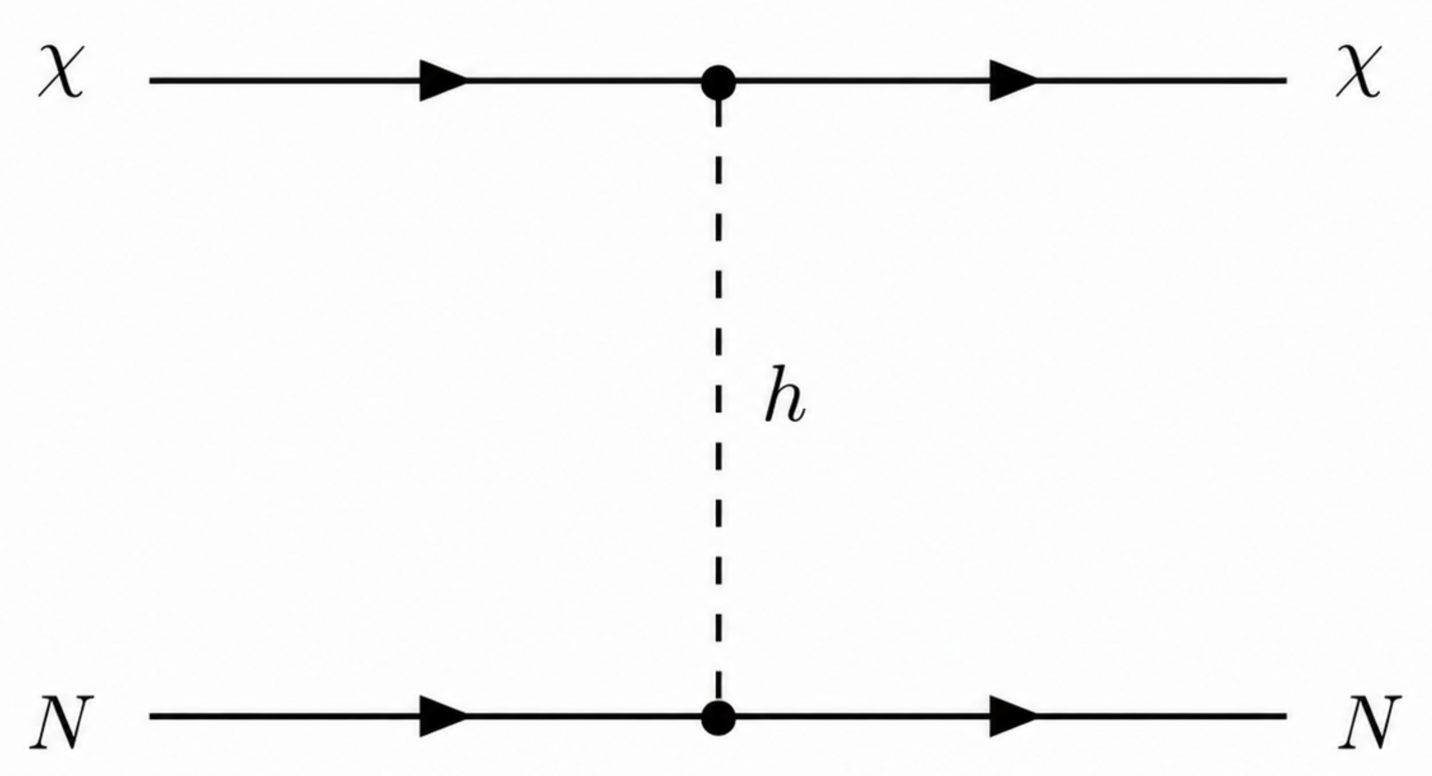


ATLAS, arXiv:2511.20042

Higgsinos with masses as low as ~ 150 GeV are still allowed.

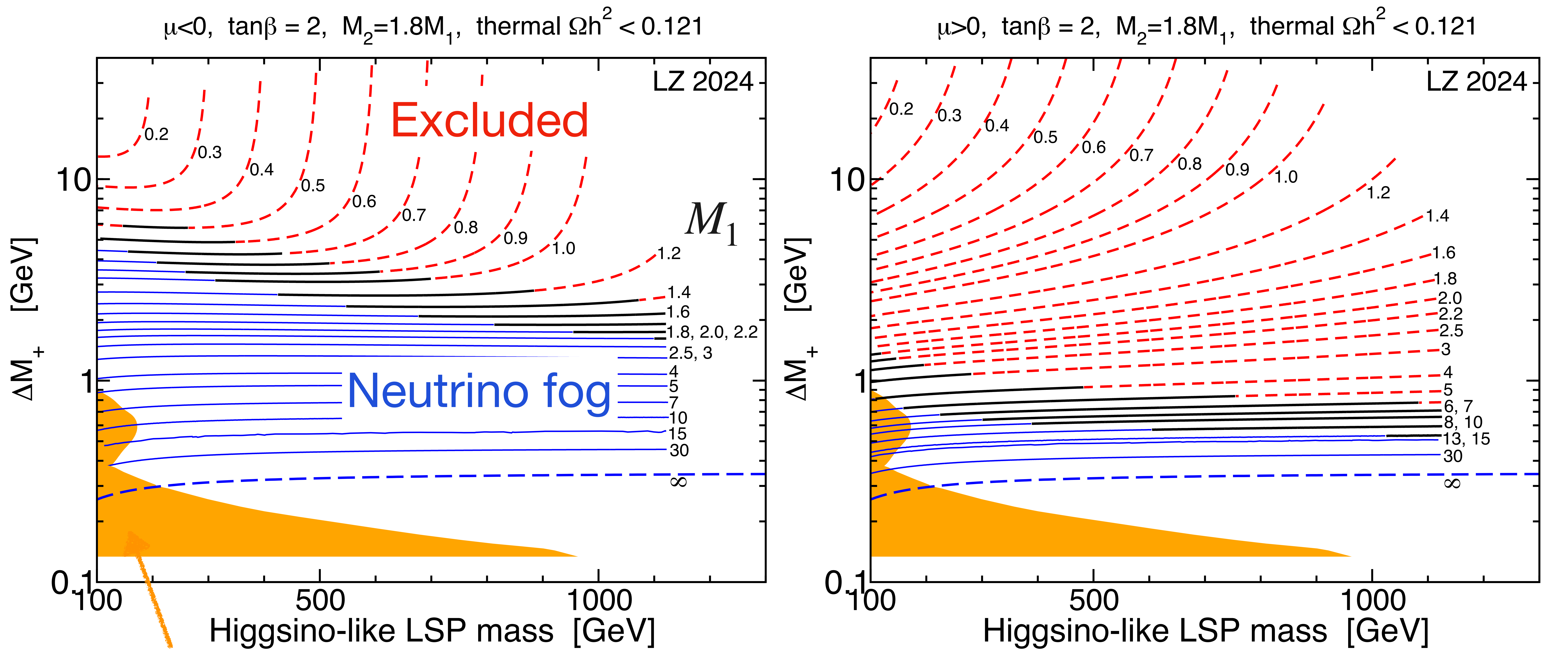
Dark matter direct detection





Scattering cross section becomes much smaller when the gaugino masses are large.

Current status of higgsino searches



LHC limits

S. P. Martin, Phys. Rev. **D111**, 075004 (2025)

A wide range of parameter space still remains unexplored.

Indirect search of higgsinos

We study indirect probes of higgsinos through radiative corrections at future e^+e^- colliders.

Previous studies

- Indirect searches for pure higgsinos at ILC through $e^+e^- \to f\bar{f}$.

  K. Harigaya, K. Ichikawa, A. Kundu, S. Matsumoto, S. Shirai, JHEP **1509**, 105 (2015).

- Electroweak precision measurements

  S. P. Martin, K. Tobe, and J. D. Wells, Phys. Rev. **D71**, 073014 (2005);
  G. Marandella, C. Schappacher, and A. Strumia, Nucl. Phys. **B715**, 173 (2005);
  S. Heinemeyer, W. Hollik, and G. Weiglein, Phys. Rept. **425**, 265 (2006);
  S. Heinemeyer, et.al., JHEP **08**, 052 (2006); JHEP **04**, 039 (2008).

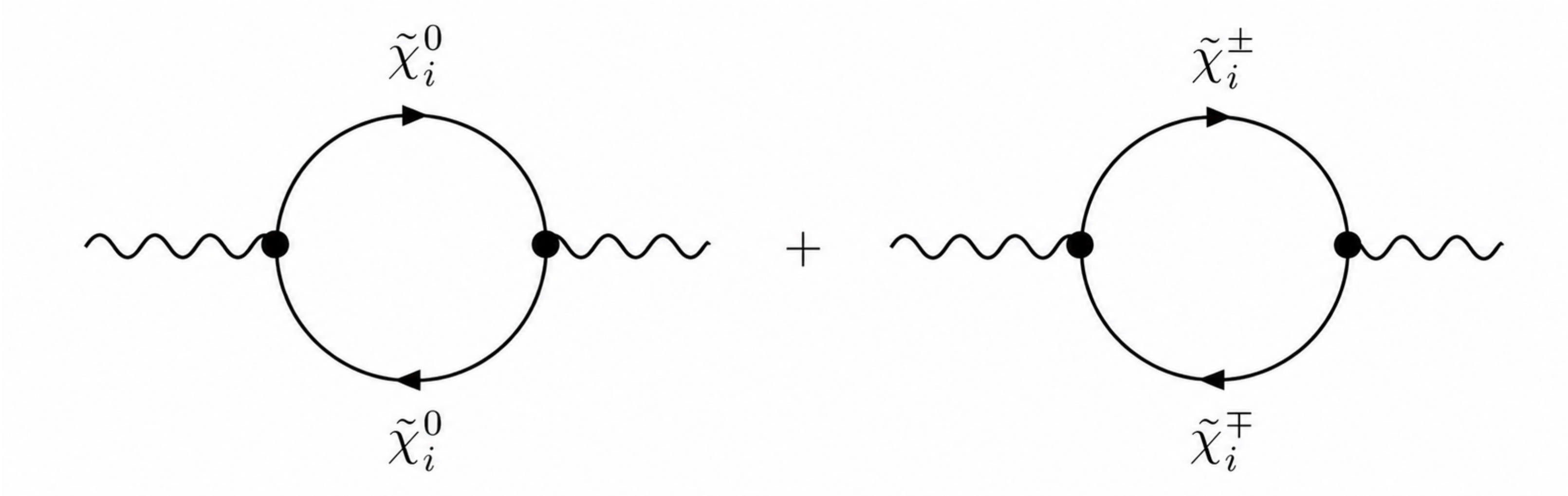
Results

Oblique parameters

Higgsinos affect electroweak observables through vacuum polarization diagrams of the electroweak gauge bosons.

This effect can be conveniently described by four oblique parameters:

$$\hat{S}, \hat{T}, W, Y$$



Effective operators

$$\mathcal{L}_{\text{eff}} = C_{WB} \left(H^\dagger \sigma^a H\right) W^a_{\mu\nu} B^{\mu\nu} + \frac{C_T}{2} \left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2 - \frac{C_{2W}}{2} \left(D^\mu W^a_{\mu\nu}\right)^2 - \frac{C_{2B}}{2} \left(\partial^\mu B_{\mu\nu}\right)^2$$

with

$$\hat{S} = \frac{\cos\theta_W}{\sin\theta_W} v^2 C_{WB} \ , \quad \hat{T} = v^2 C_T \ , \quad W = M_W^2 C_{2W} \ , \quad Y = M_W^2 C_{2B}$$

Higgsino properties in a nutshell

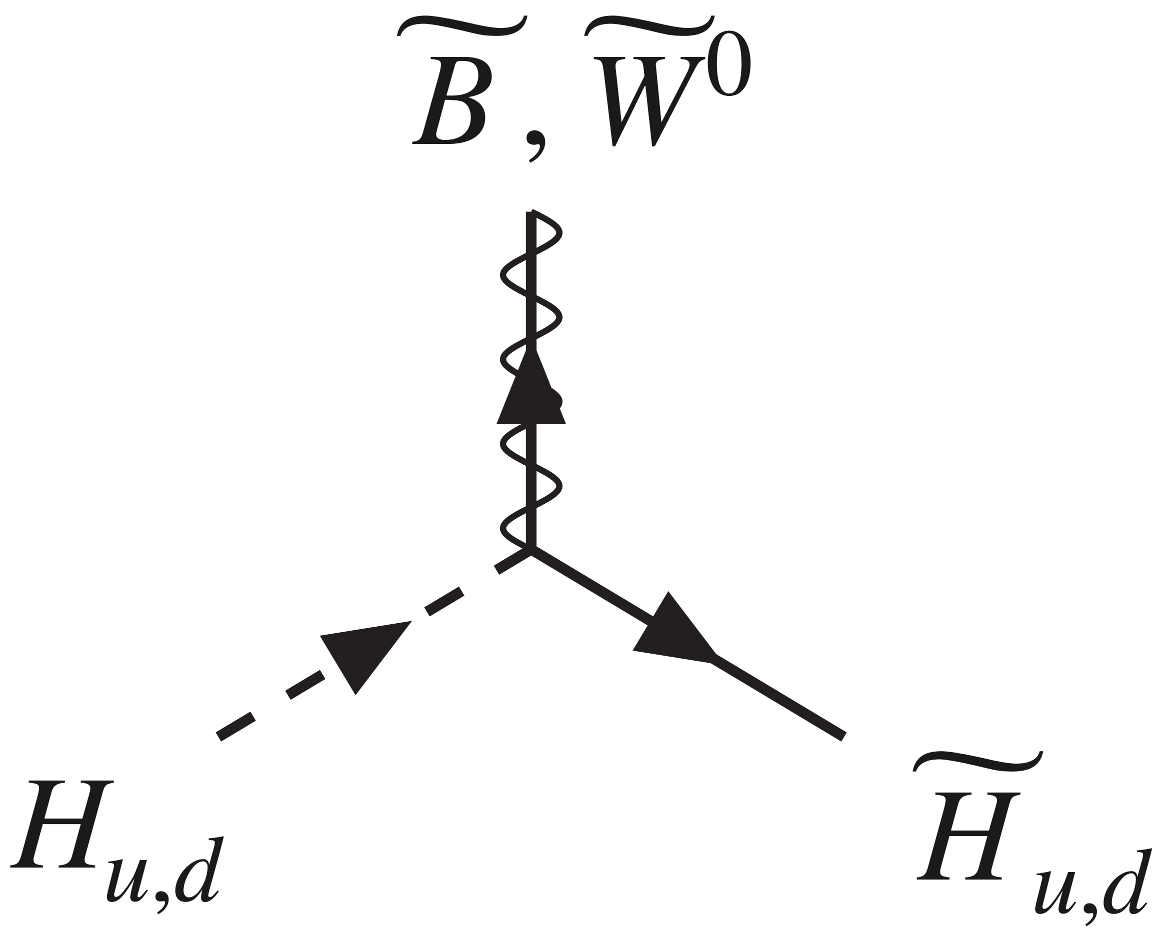
Higgsino properties are largely controlled by their mixing with gauginos.

Smaller $M_{1,2}$ → Larger gaugino-higgsino mixing

↓

Larger coupling with the Higgs boson

↓



- Larger direct detection rate
- Larger $\hat{S}, \hat{T}$
- Larger charged-neutral mass splitting

Parameter scan

We perform a parameter scan over the following ranges:

$$\begin{aligned} 150 \text{ GeV} &< |\mu| < 1000 \text{ GeV} \ , \\ 1.6 &< \tan\beta < 50 \ , \\ 0.5 \text{ TeV} &< M_1 < 10 \text{ TeV} \ , \\ \text{sgn}(\mu) &= \pm 1 \ . \end{aligned}$$

$$\begin{aligned} M_1 &> |\mu| \\ M_2 &= 2M_1 \end{aligned}$$

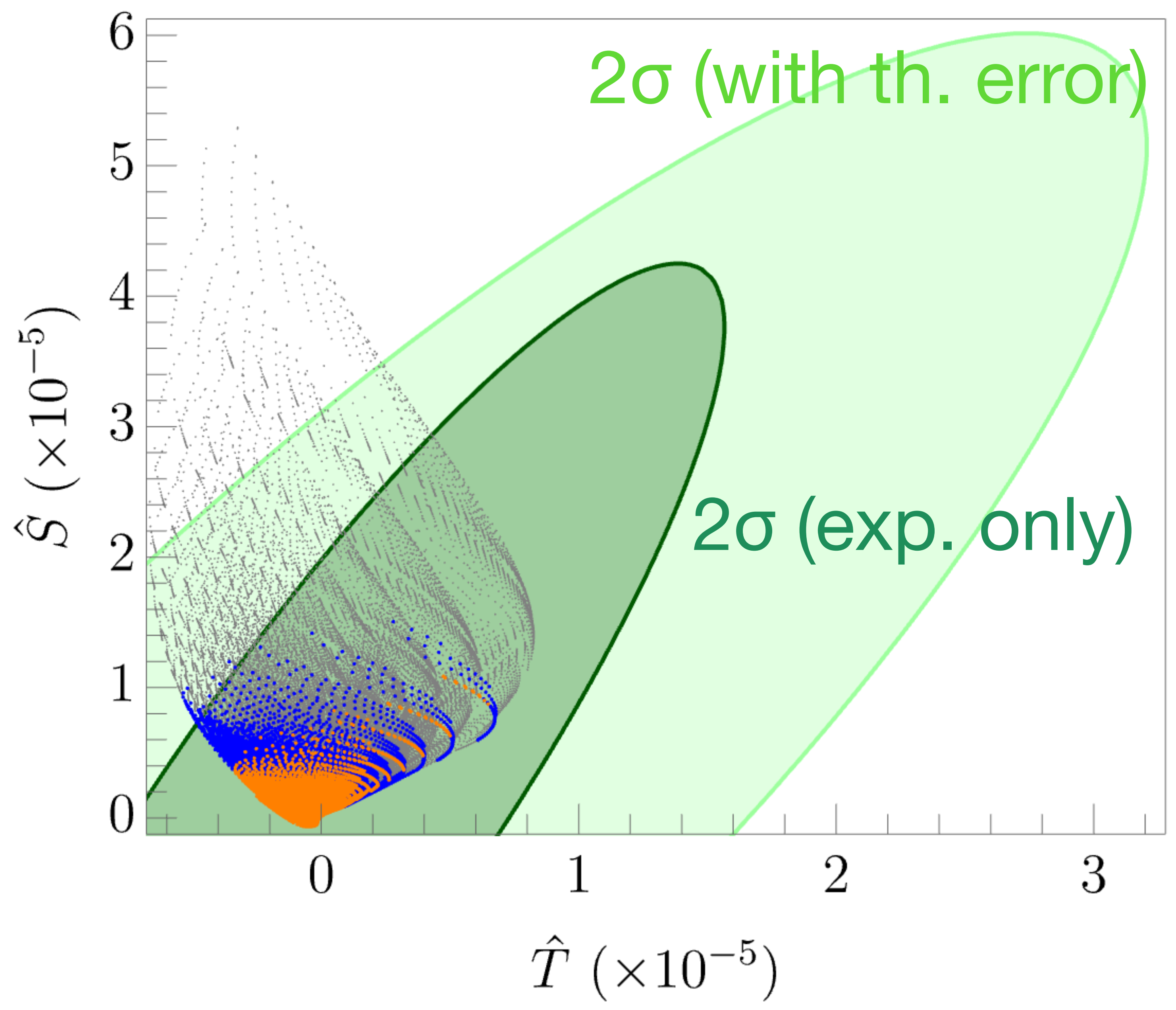
We assume that the higgsino abundance is determined by thermal freeze-out:

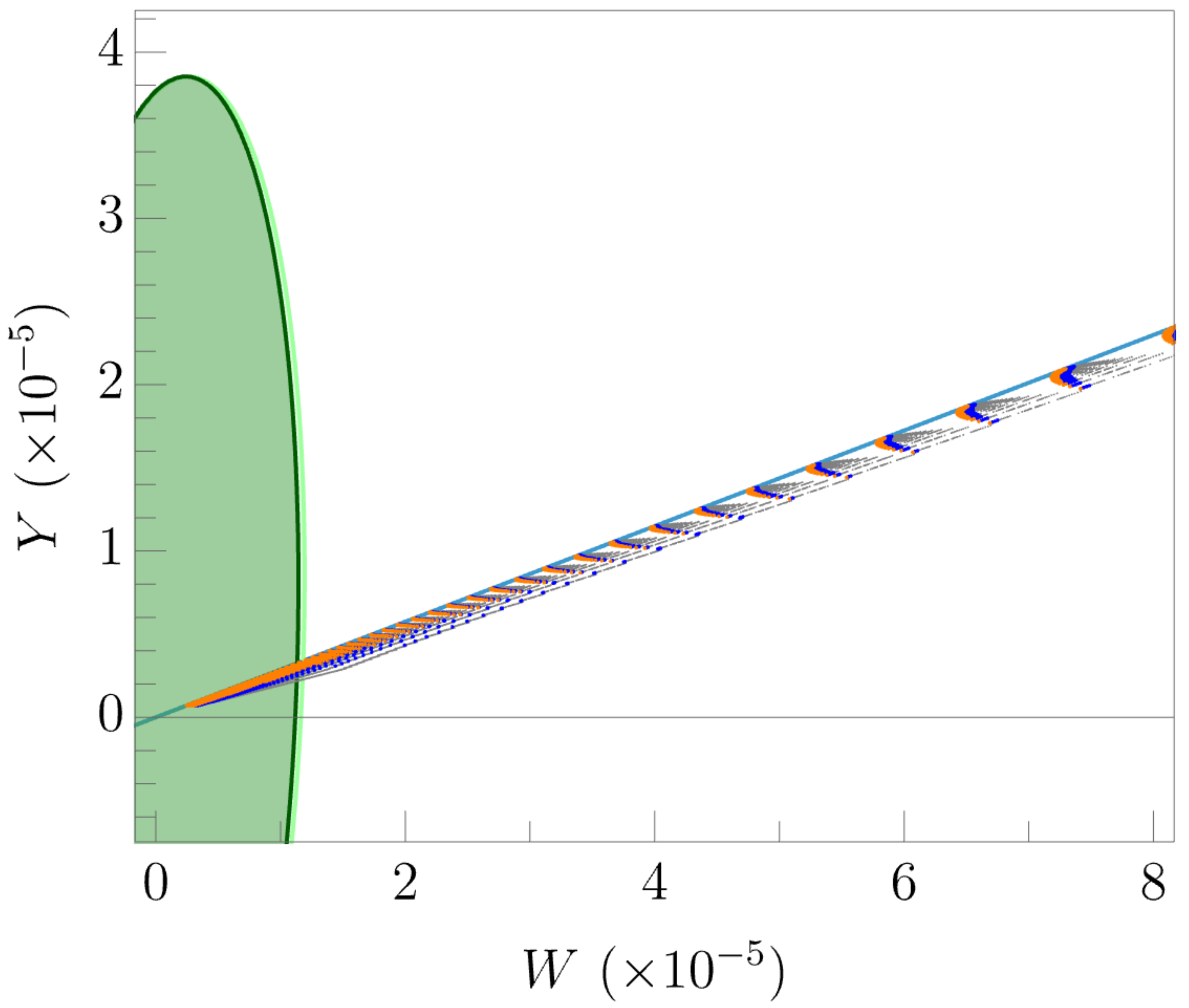
$$\sigma^{(N)}_{\text{SI/SD,eff}} = \frac{\Omega_{\widetilde{H}} h^2}{0.12} \sigma^{(N)}_{\text{SI/SD}}$$

χ^2-fit for EW precision measurements: we follow

A. Greljo, B. A. Stefanek, A. Valenti, Phys. Lett. B **871**, 140009 (2025)

Oblique parameters





Gray: excluded by LZ

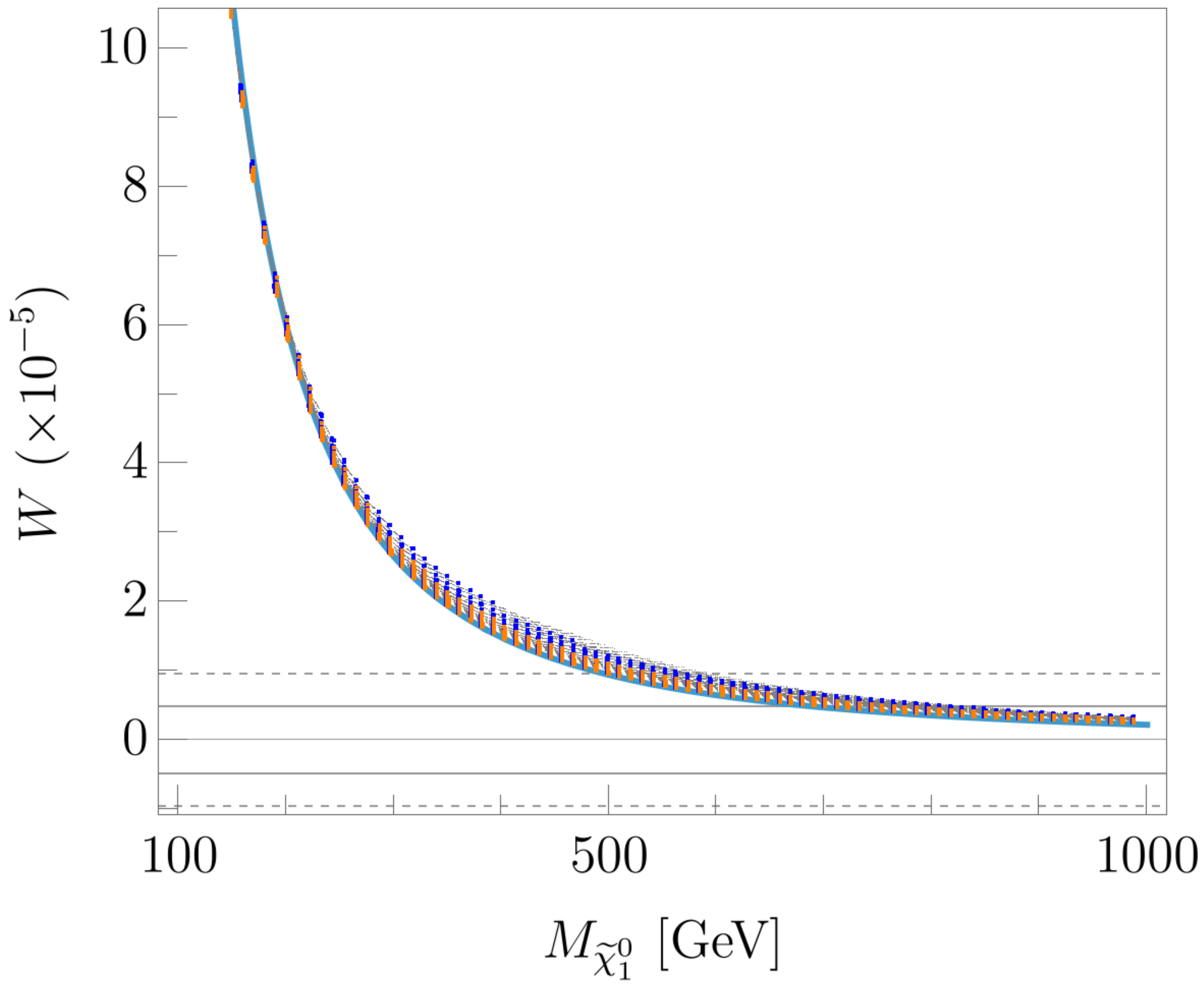
Blue: above ν-fog

Orange: below ν-fog

- Once the LZ limits are imposed, $\hat{S}$ and $\hat{T}$ are predicted to be small.
- W can be sufficiently large to be probed at FCC-ee.

K. Hamaguchi, N. Nagata, G. Osaki, arXiv:2606.31013.

Oblique parameters



Gray: excluded by LZ

Blue: above ν-fog

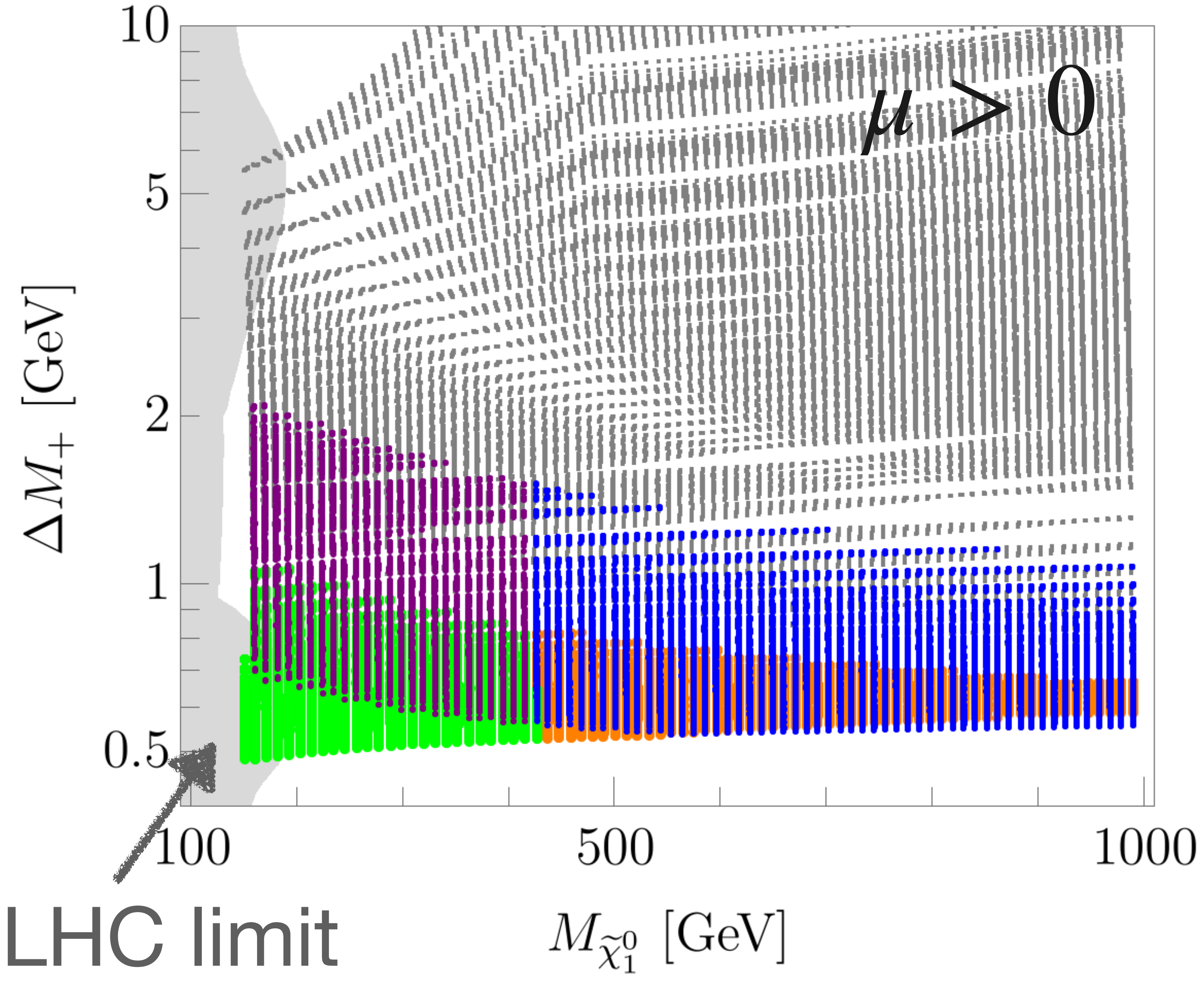
Orange: below ν-fog

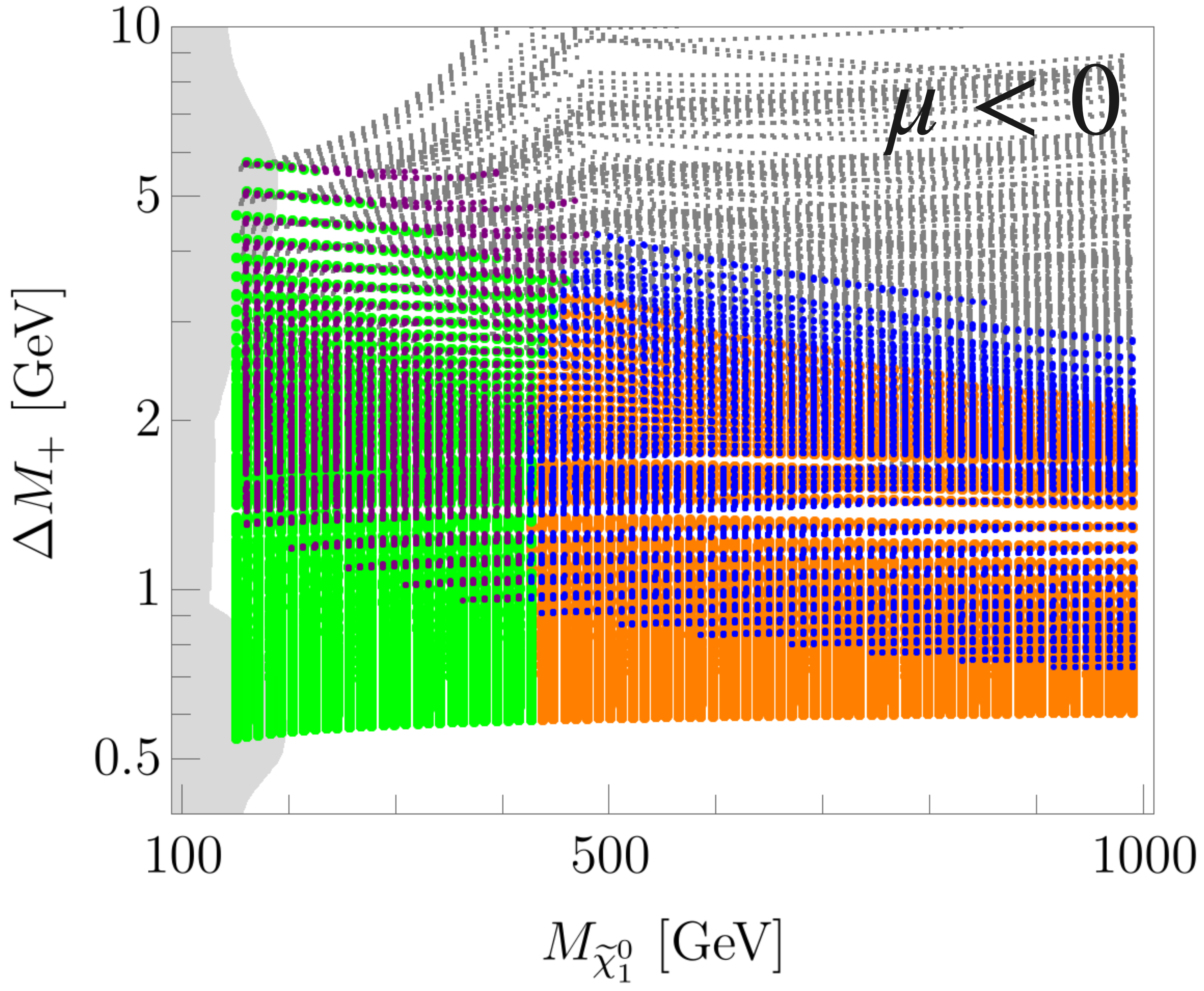
Solid (dashed): FCC-ee 1σ (2σ) sensitivity

Higgsinos with masses $\lesssim 500$ GeV can be probed.

K. Hamaguchi, N. Nagata, G. Osaki, arXiv:2606.31013.

Direct detection vs EW precision





Gray: excluded by LZ

Blue: above ν-fog

Green: > 2σ deviation at FCC-ee

Purple: Green & Blue

Orange: no sensitivity

- Complementarity between EW precision measurements and dark matter direct detection experiments.
- $M_{\tilde{\chi}^0} \lesssim 500\ \mathrm{GeV}, \Delta M_+ \gtrsim 1\ \mathrm{GeV}$ can be probed.

K. Hamaguchi, N. Nagata, G. Osaki, arXiv:2606.31013.

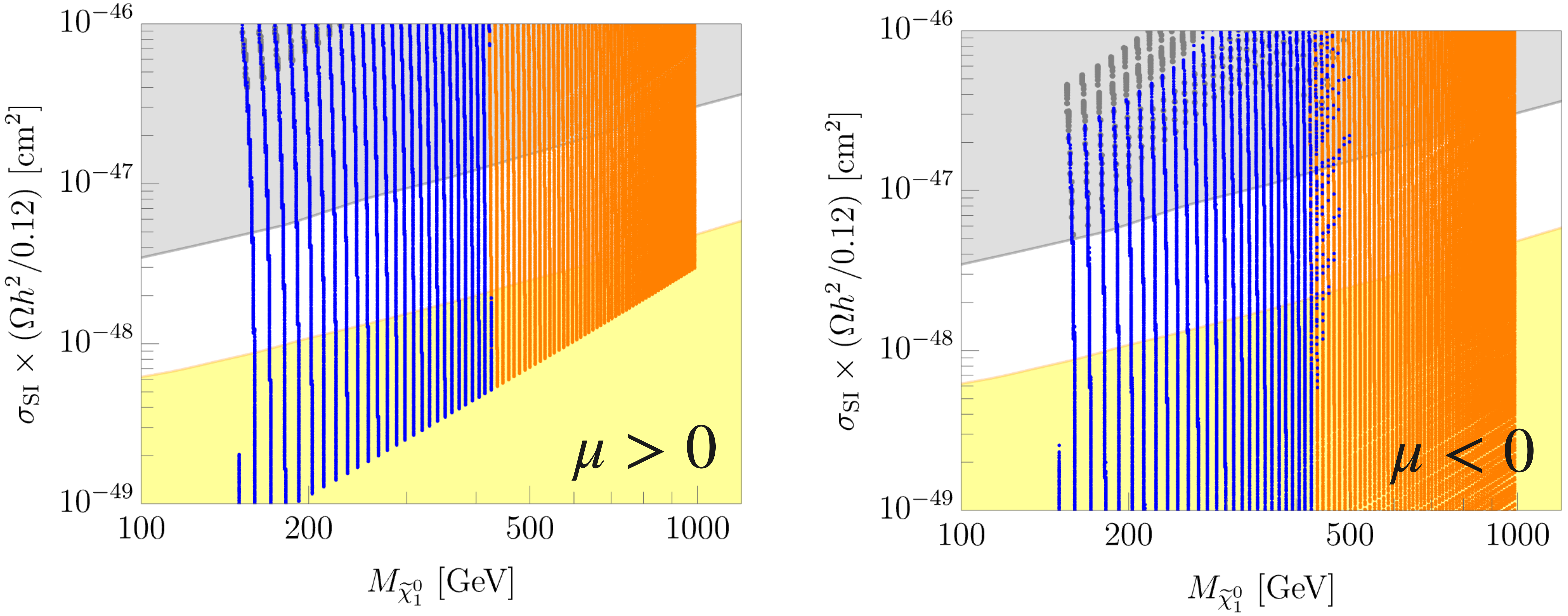
Conclusion

Conclusion

- Future e^+e^- circular colliders have recently attracted a lot of attention.
- These colliders can measure electroweak observables with very high precision.
- Electroweak precision measurements provide a powerful probe of light higgsinos and electroweak naturalness.
- Complementarity between electroweak precision measurements and dark matter direct detection experiments.

Backup

Direct detection vs EW precision



LZ limit

Blue: > 2σ deviation at FCC-ee

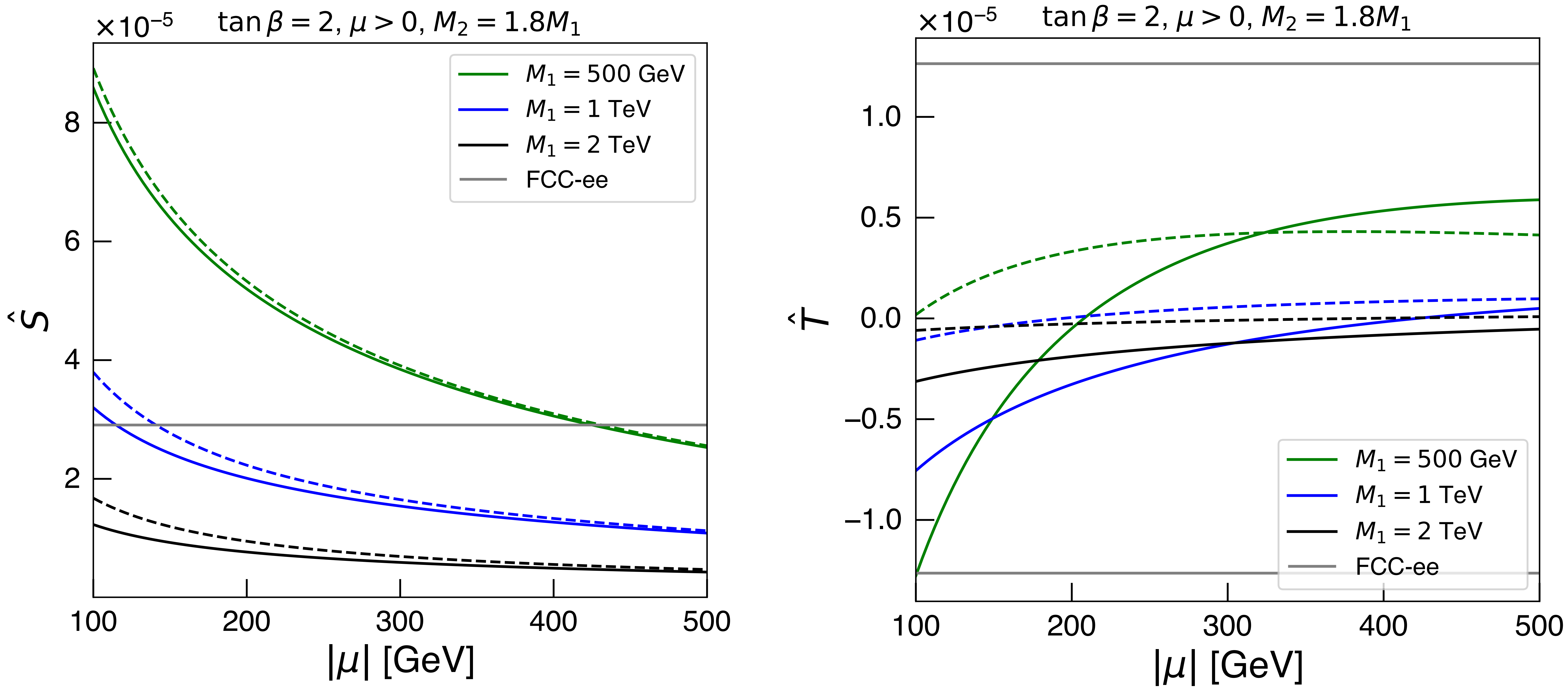
Orange: < 2σ

ν-fog

EW precision measurements can probe the parameter points that are difficult to access through direct detection experiments alone.

K. Hamaguchi, N. Nagata, G. Osaki, arXiv:2606.31013.

Oblique parameters

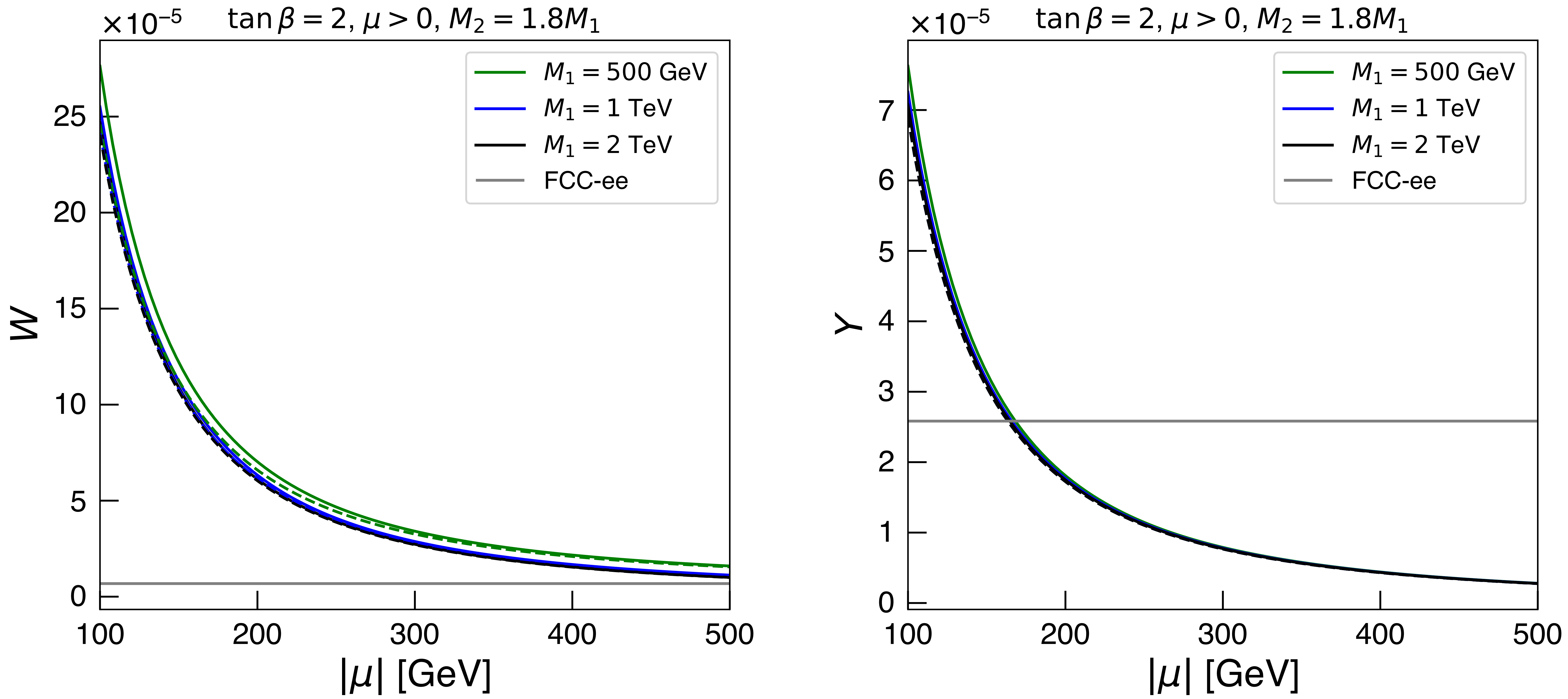


Dashed lines: approximated results obtained in arXiv:hep-ph/0502095

- $\hat{S}, \hat{T}$ strongly depend on the gaugino masses.
- Become very small in the pure higgsino limit.

N. Nagata, G. Osaki, JHEP **07**, 242 (2025)

Oblique parameters

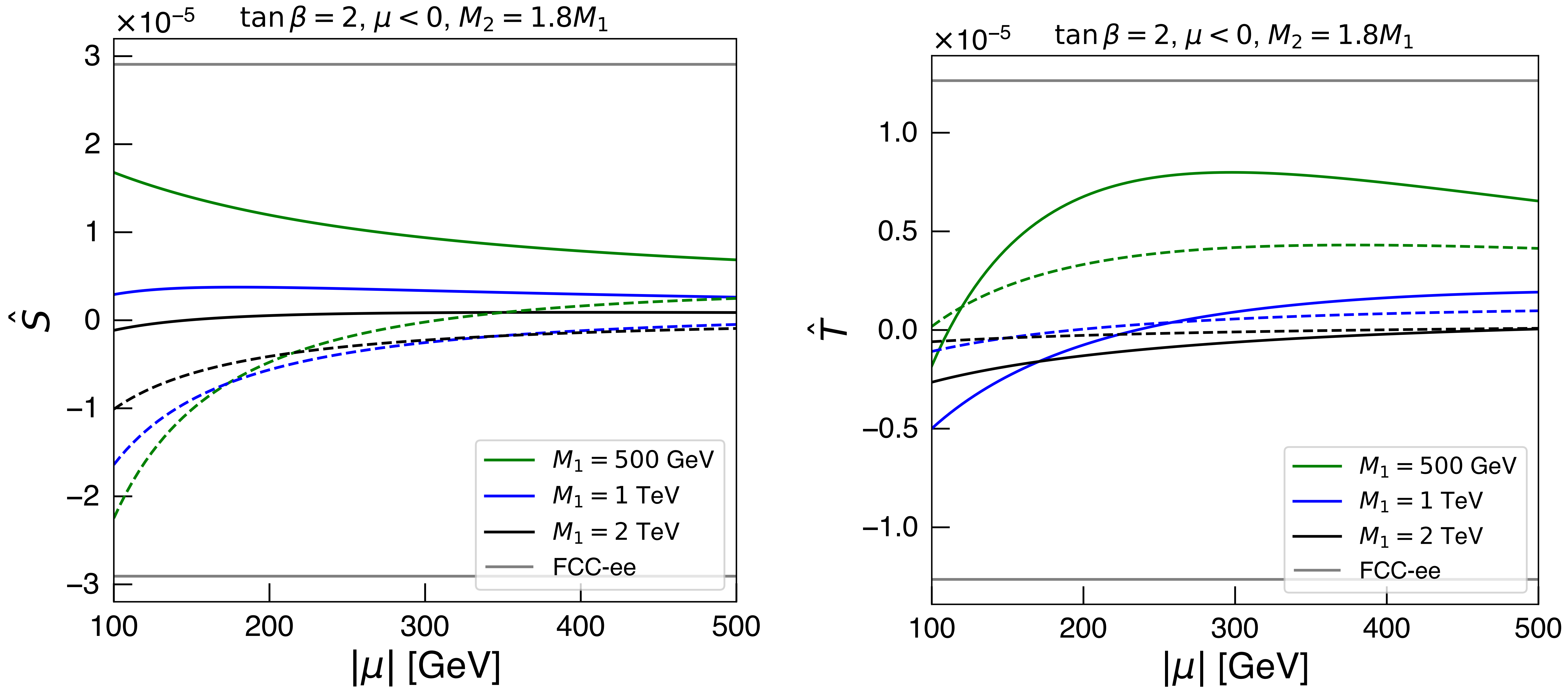


Dashed lines: approximated results obtained in arXiv:hep-ph/0502095

- W, Y depend only weakly on the gaugino masses.
- Can be sizable even in the pure higgsino limit.

N. Nagata, G. Osaki, JHEP **07**, 242 (2025)

Oblique parameters

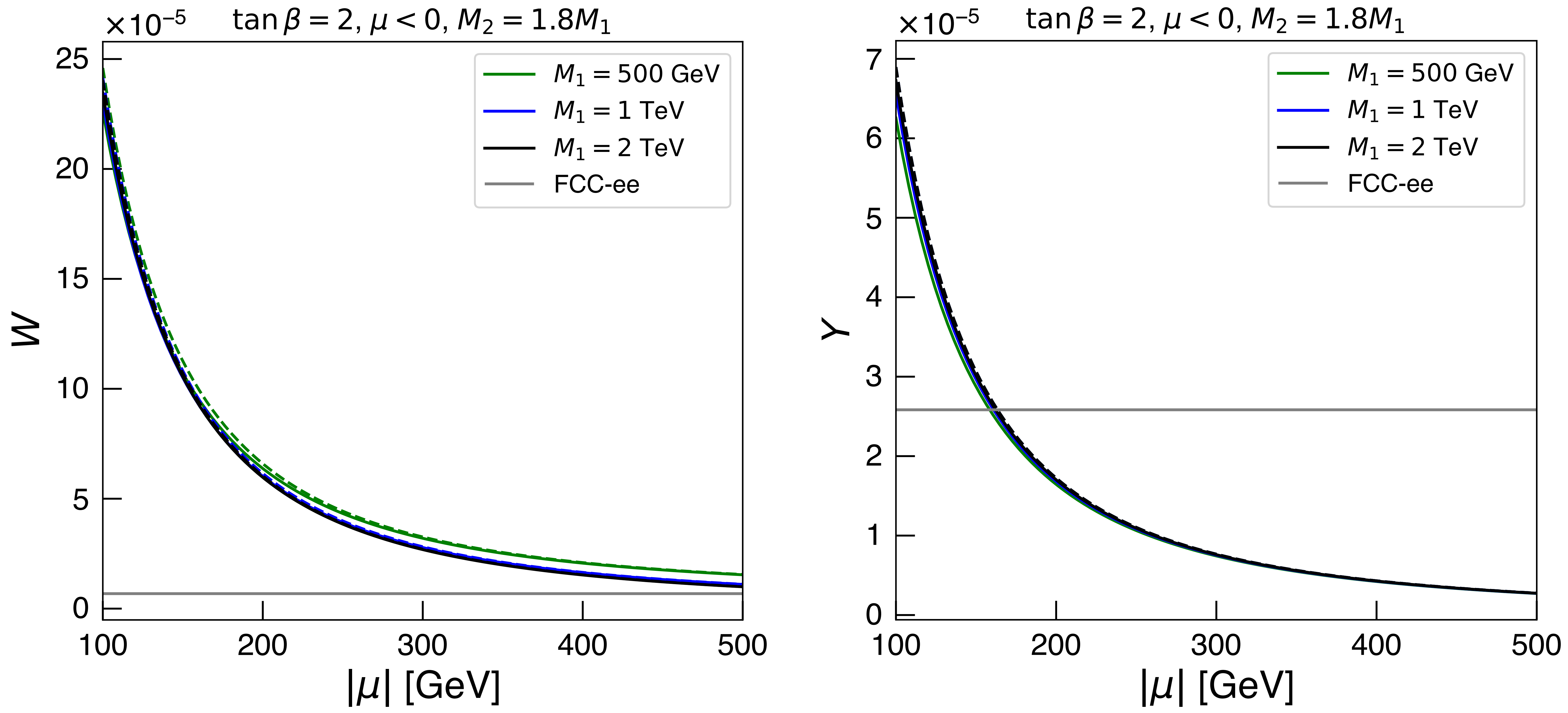


Dashed lines: approximated results obtained in arXiv:hep-ph/0502095

- $\hat{S}, \hat{T}$ depend highly on gaugino masses.
- Vanish in the pure higgsino limit.

N. Nagata, G. Osaki, JHEP **07**, 242 (2025)

Oblique parameters

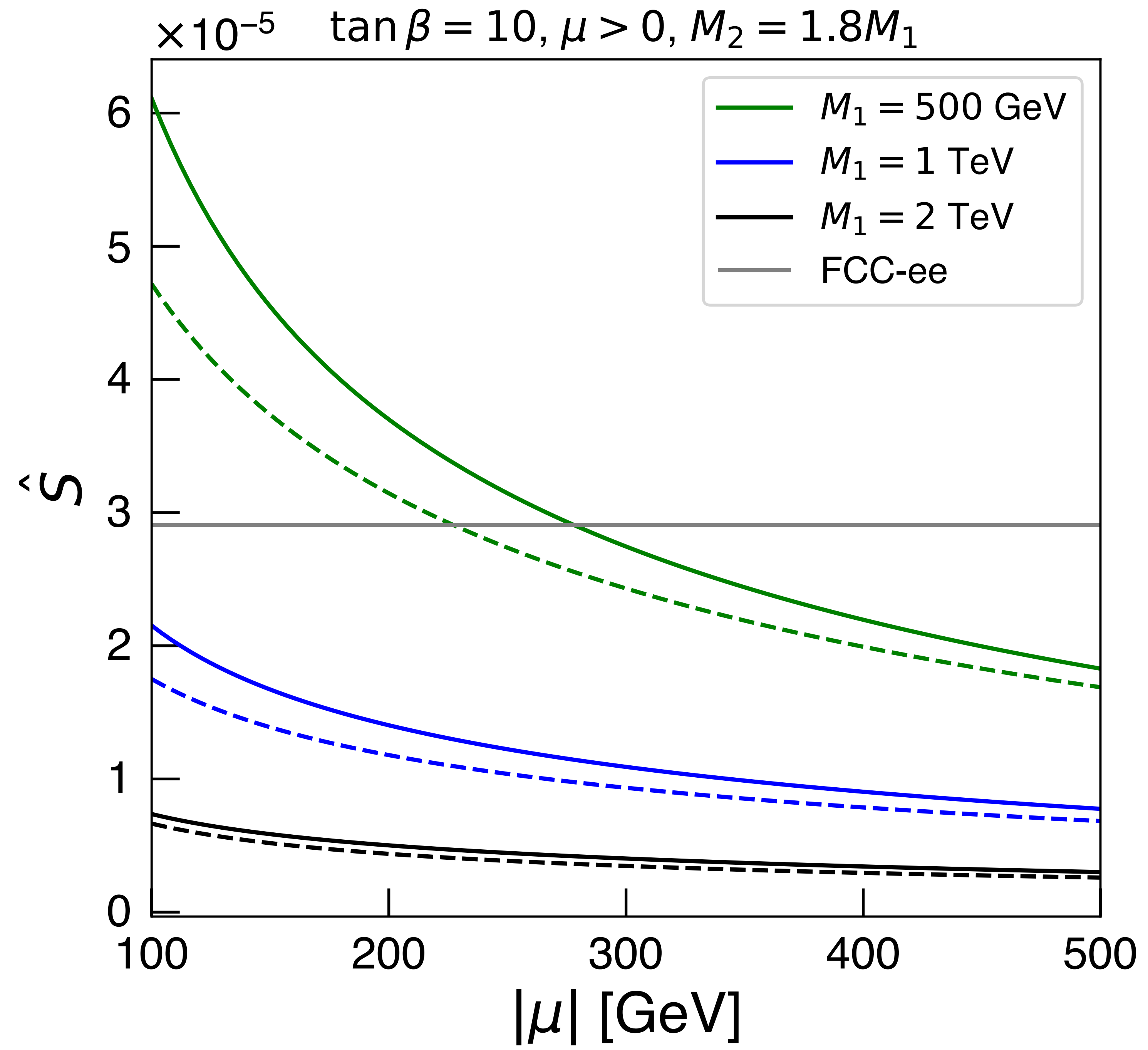


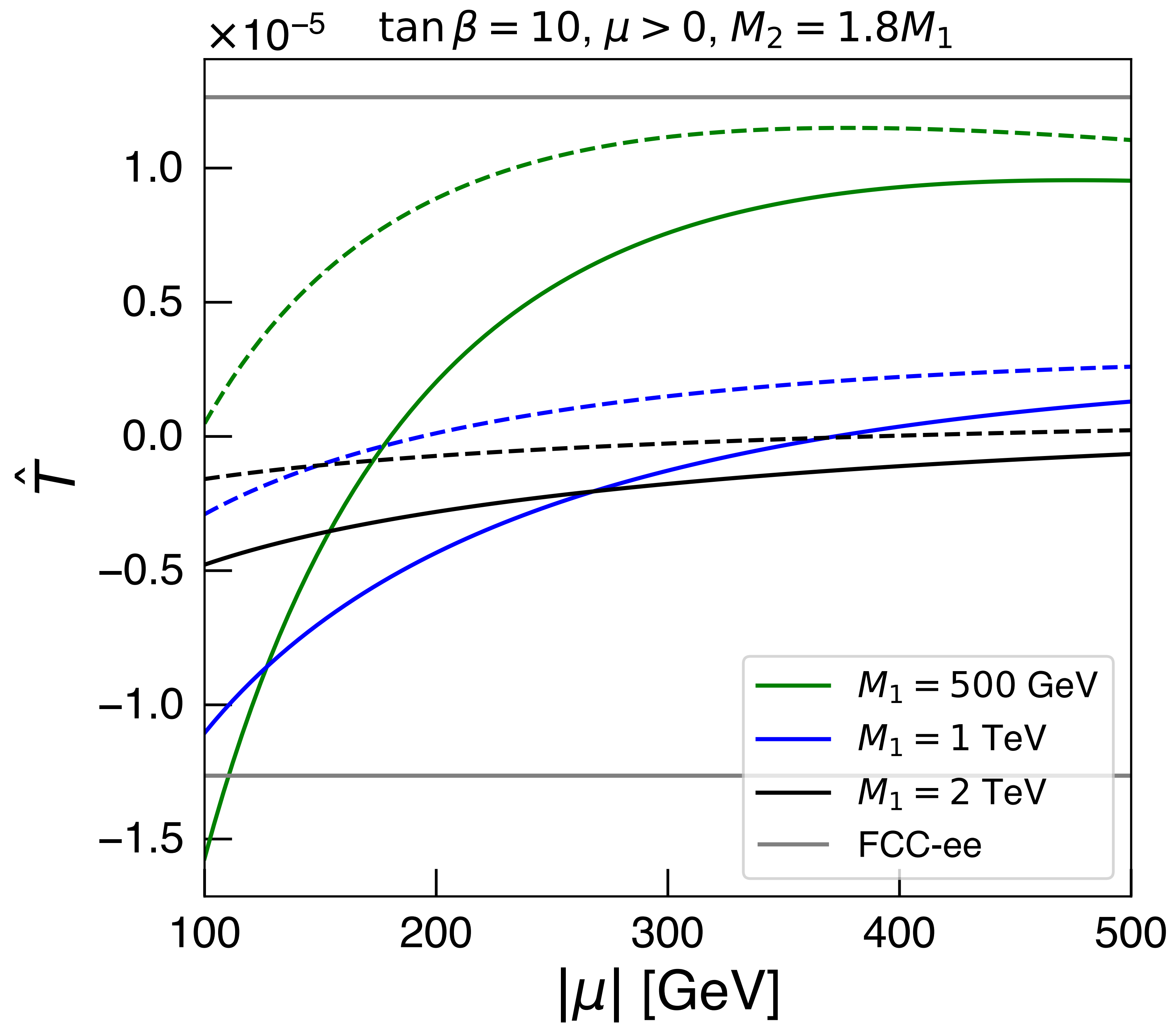
Dashed lines: approximated results obtained in arXiv:hep-ph/0502095

- W, Y depend rarely on gaugino masses.
- Do not vanish in the pure higgsino limit.

N. Nagata, G. Osaki, JHEP **07**, 242 (2025)

Oblique parameters





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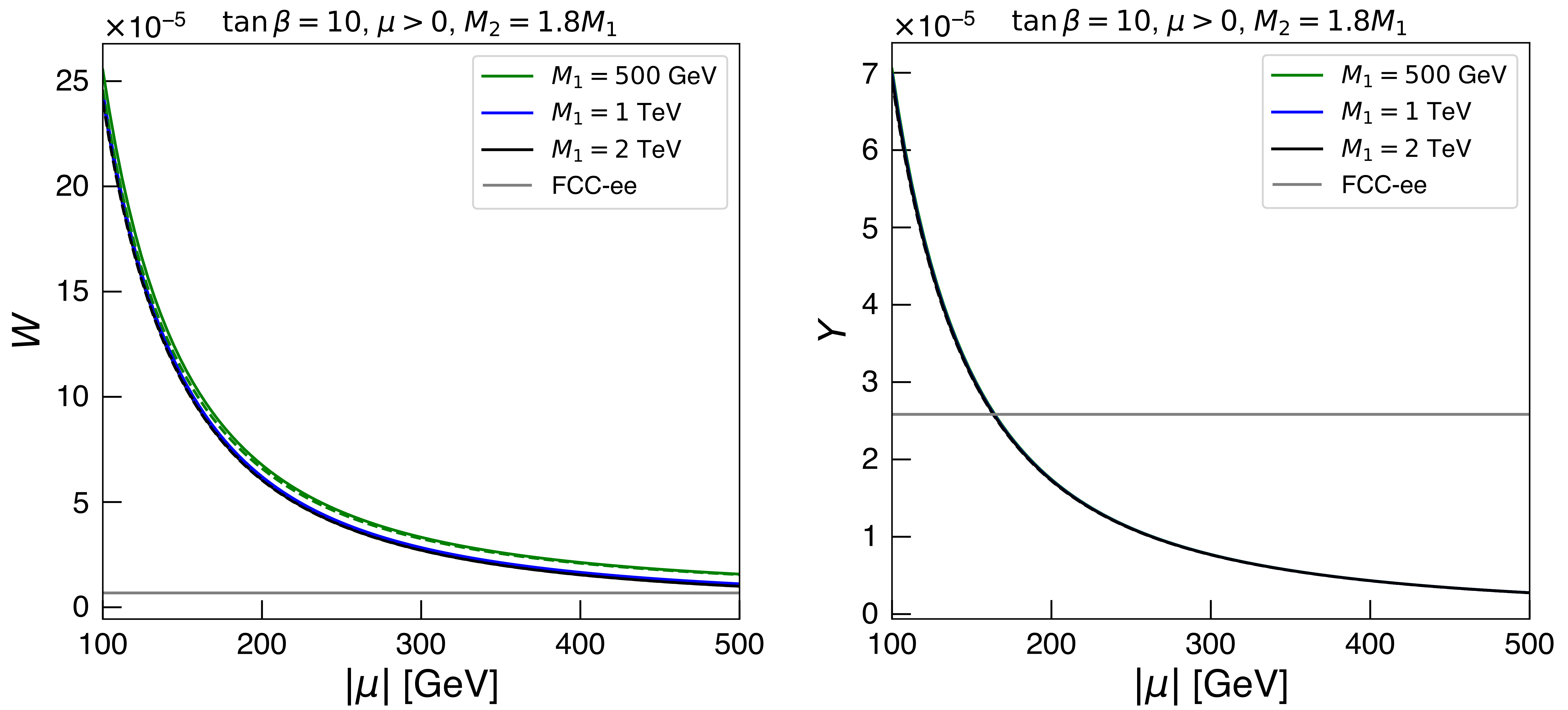
N. Nagata, G. Osaki, JHEP **07**, 242 (2025)

Oblique parameters



Dashed lines: approximated results obtained in arXiv:hep-ph/0502095

- W, Y depend rarely on gaugino masses.
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N. Nagata, G. Osaki, JHEP **07**, 242 (2025)

Electroweak precision observables

We also calculate the corrections to electroweak precision observables.

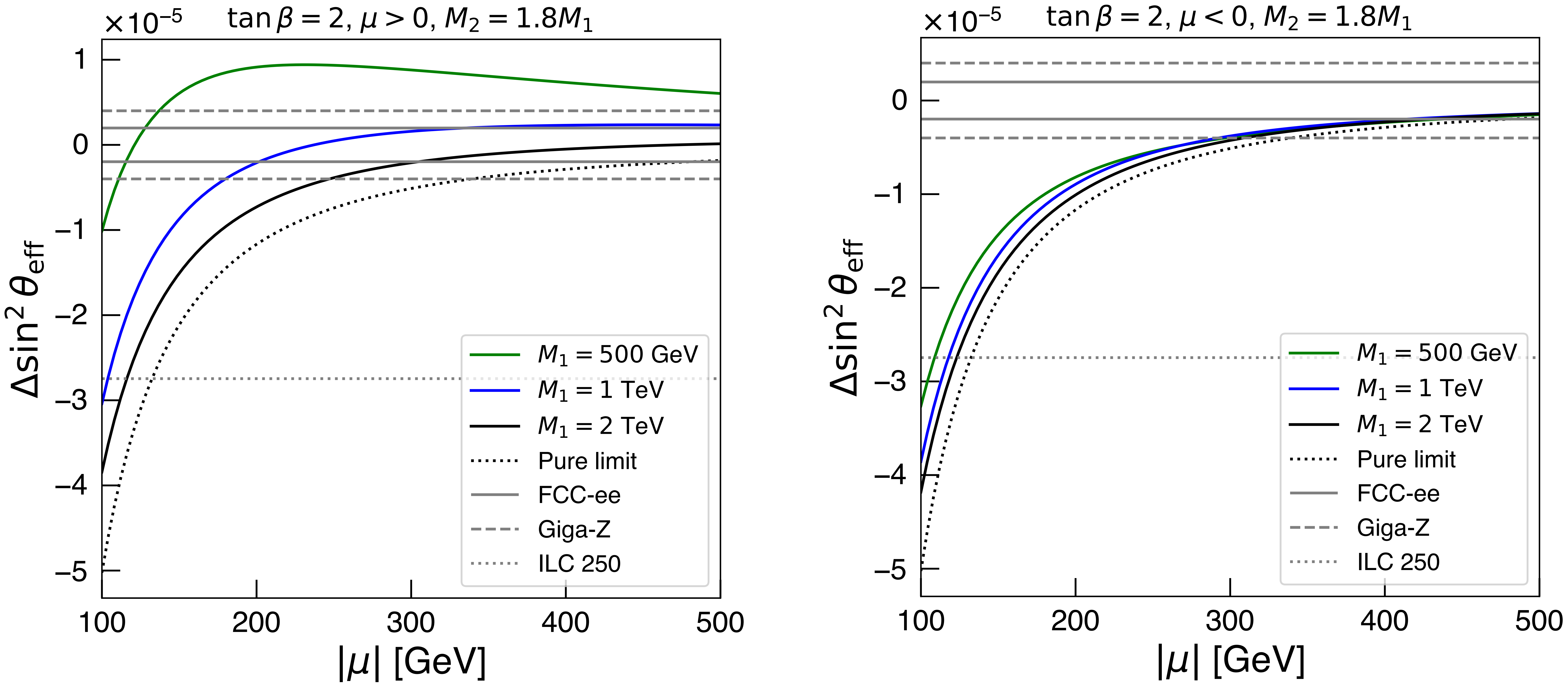
- Effective weak mixing angle Z-pole observable

$$\frac{\Delta \sin^2\theta_{\rm eff}}{\sin^2\theta_{\rm eff}} \simeq \frac{1}{\cos 2\theta_W}\hat{S} - \frac{\cos^2\theta_W}{\cos 2\theta_W}\hat{T} - \frac{\sin^2\theta_W}{\cos 2\theta_W}W - \frac{\cos^2\theta_W}{\cos 2\theta_W}Y$$

- W boson mass W-boson production

$$\frac{\Delta M_W^2}{M_W^2} \simeq -\frac{2\sin^2\theta_W}{\cos 2\theta_W}\hat{S} + \frac{\cos^2\theta_W}{\cos 2\theta_W}\hat{T} + \frac{\sin^2\theta_W}{\cos 2\theta_W}W + \frac{\sin^2\theta_W}{\cos 2\theta_W}Y$$

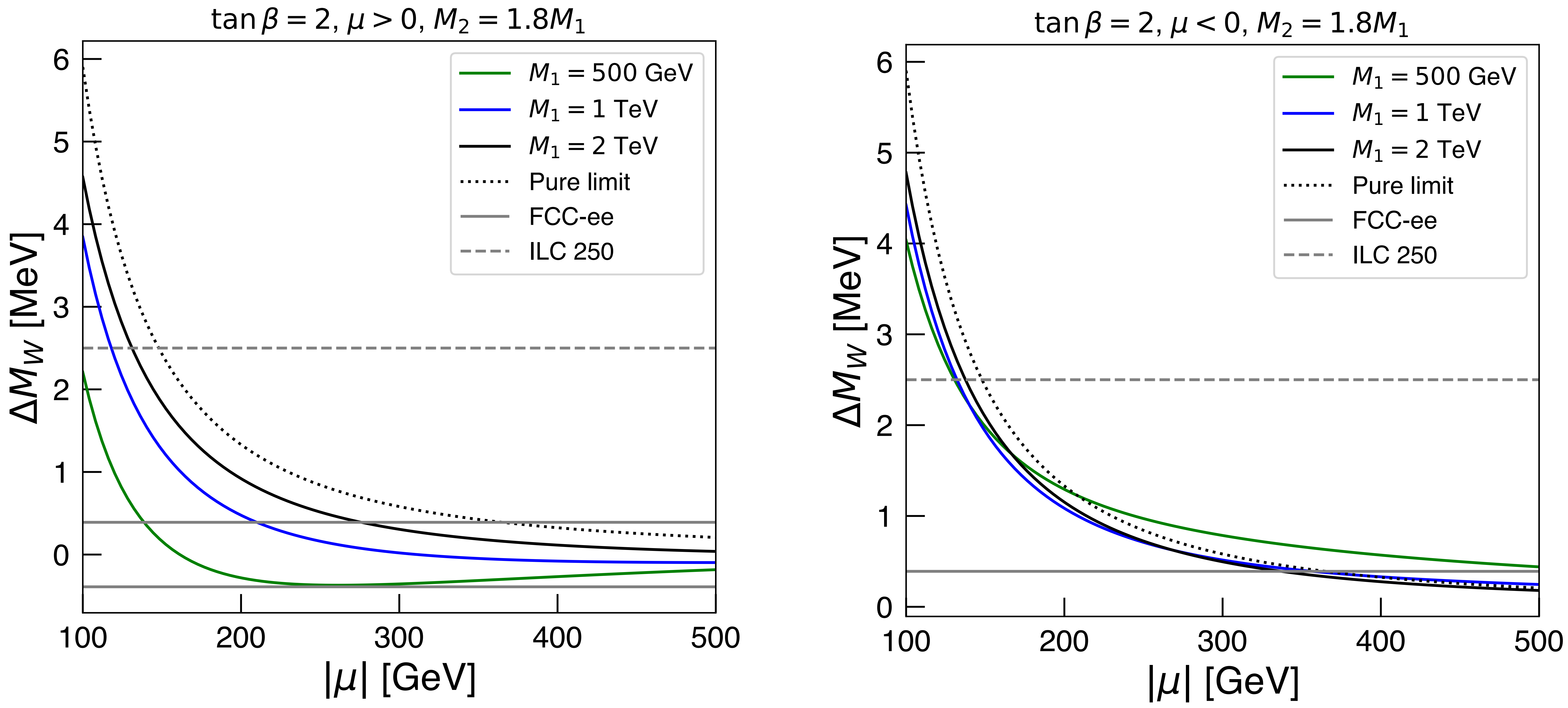
Effective weak mixing angle



- FCC-ee can probe higgsino masses up to ~ 500 GeV.
- Giga-Z program at ILC also has sensitivity.

N. Nagata, G. Osaki, JHEP **07**, 242 (2025)

W-boson mass



W-boson mass measurement at FCC-ee can probe higgsino masses up to ~ 500 GeV.

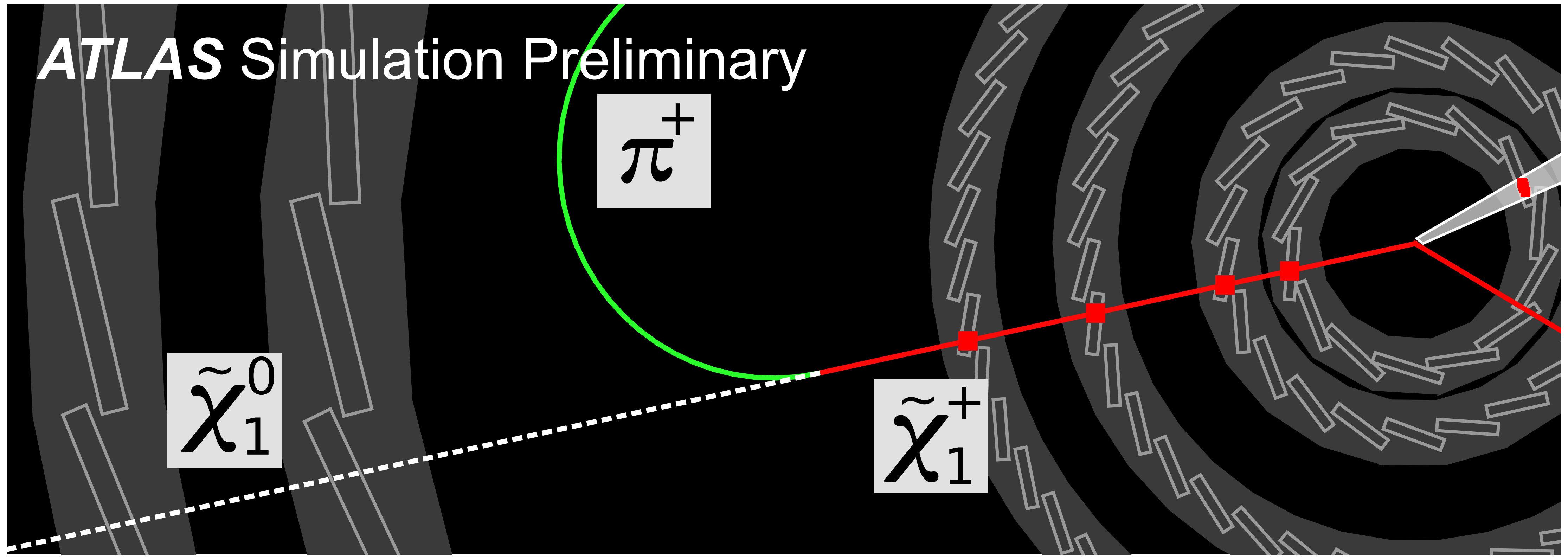
N. Nagata, G. Osaki, JHEP **07**, 242 (2025)

Higgsino search at LHC

Several sophisticated search strategies have been proposed.

Disappearing track

J. L. Feng, T. Moroi, L. Randall, M. Strassler, S. F. Su (1999);
M. Ibe, T. Moroi, T. T. Yanagida (2006), etc…

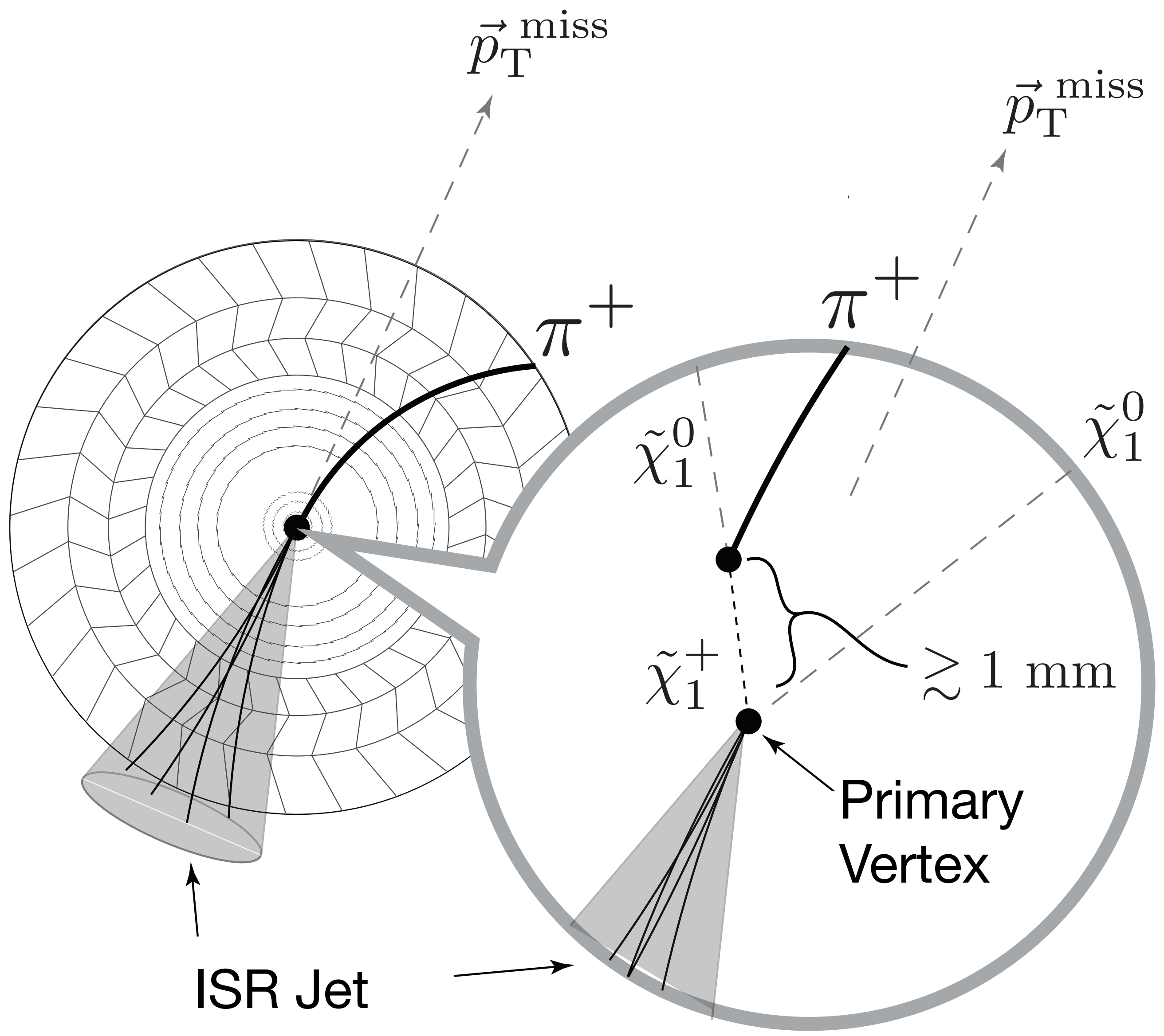


Strongly depend on higgsino lifetime

and thus the mass splitting

Displaced track

H. Fukuda, N. Nagata, H. Oide, H. Otono, S. Shirai (2020)

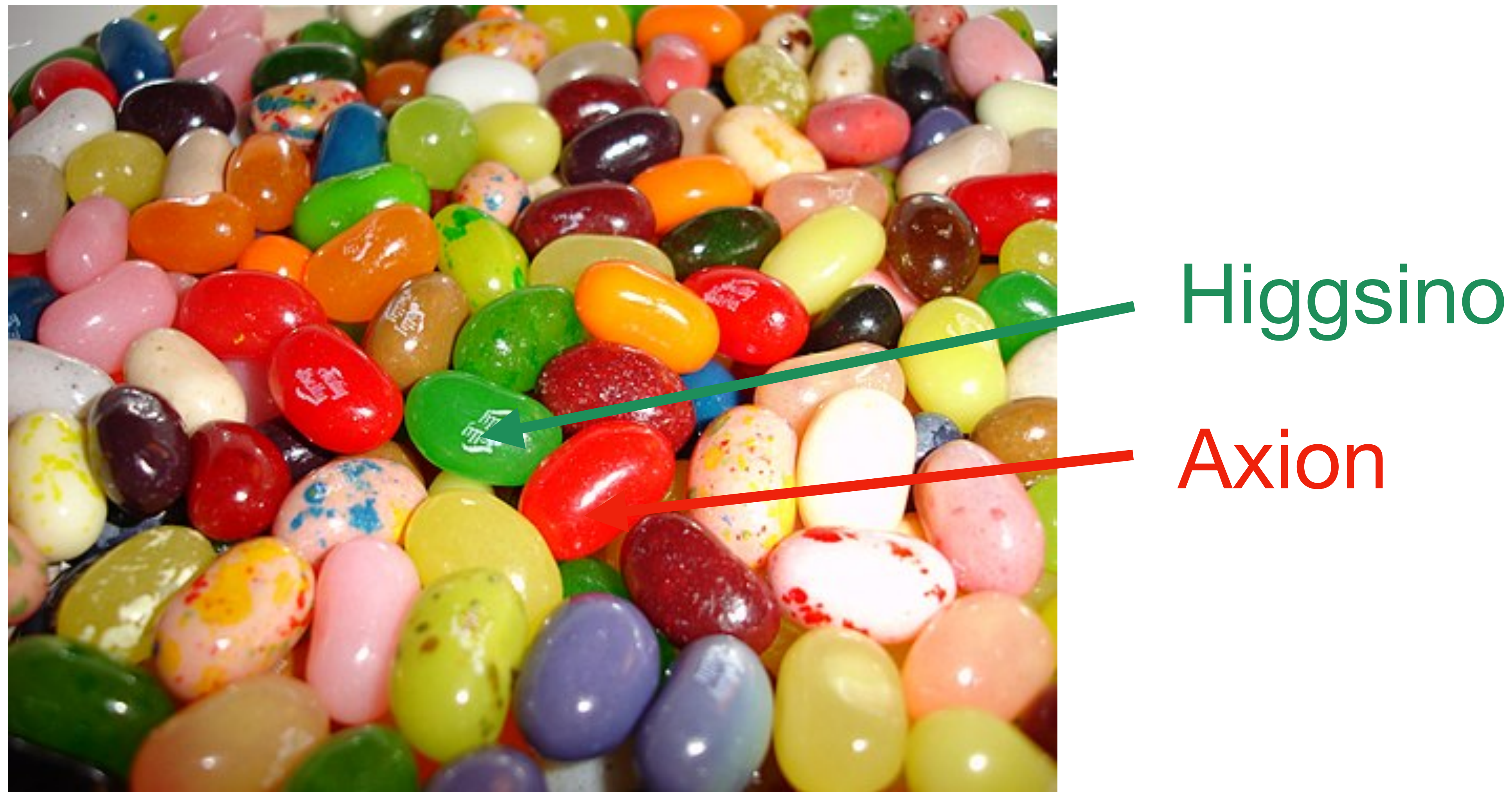


From talk slides by H. Oide @ LLP2024

Light higgsino dark matter

Thermal relic abundance of higgsino with mass less than 1 TeV is lower than the observed dark matter density.

Multi-component

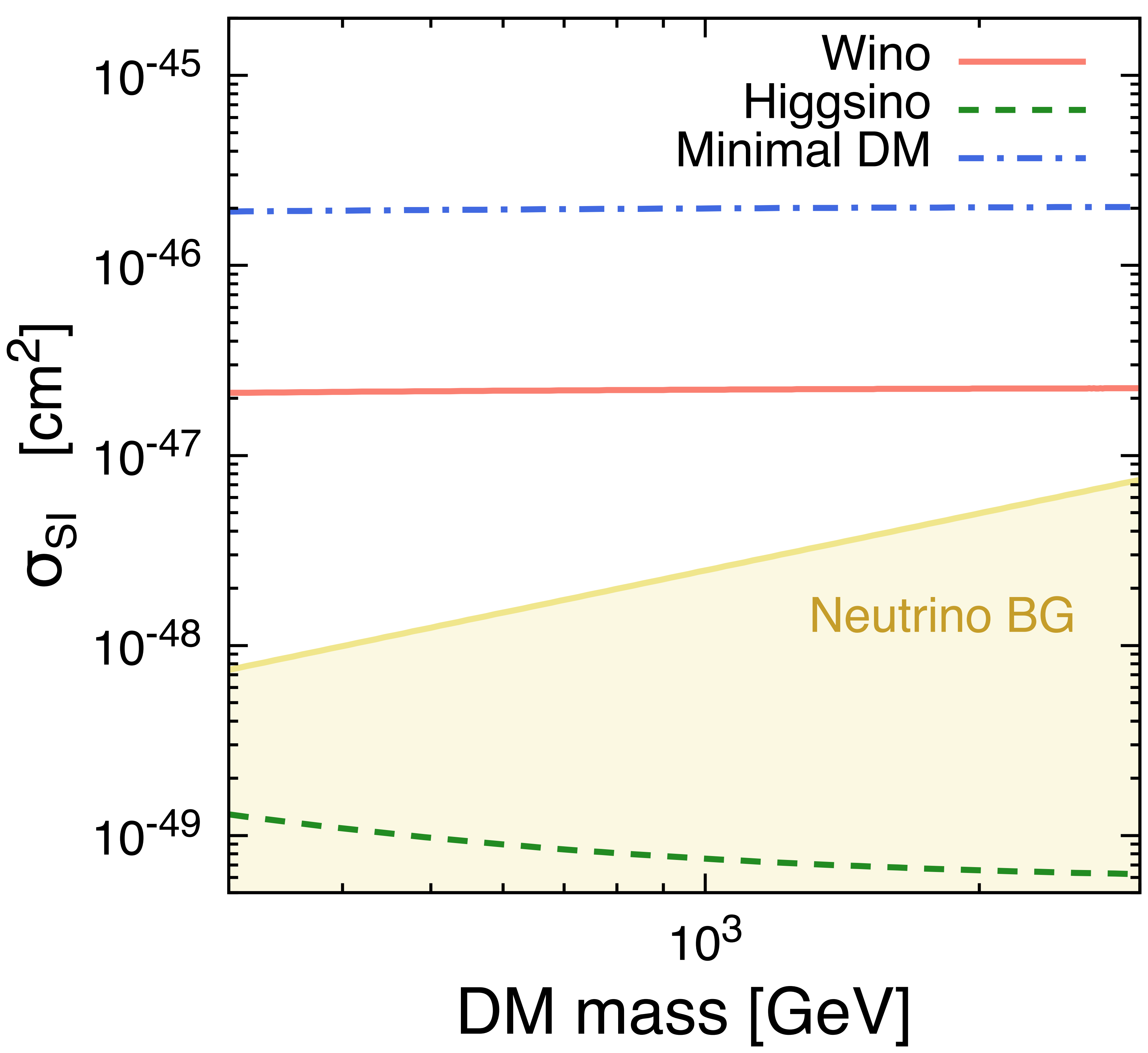


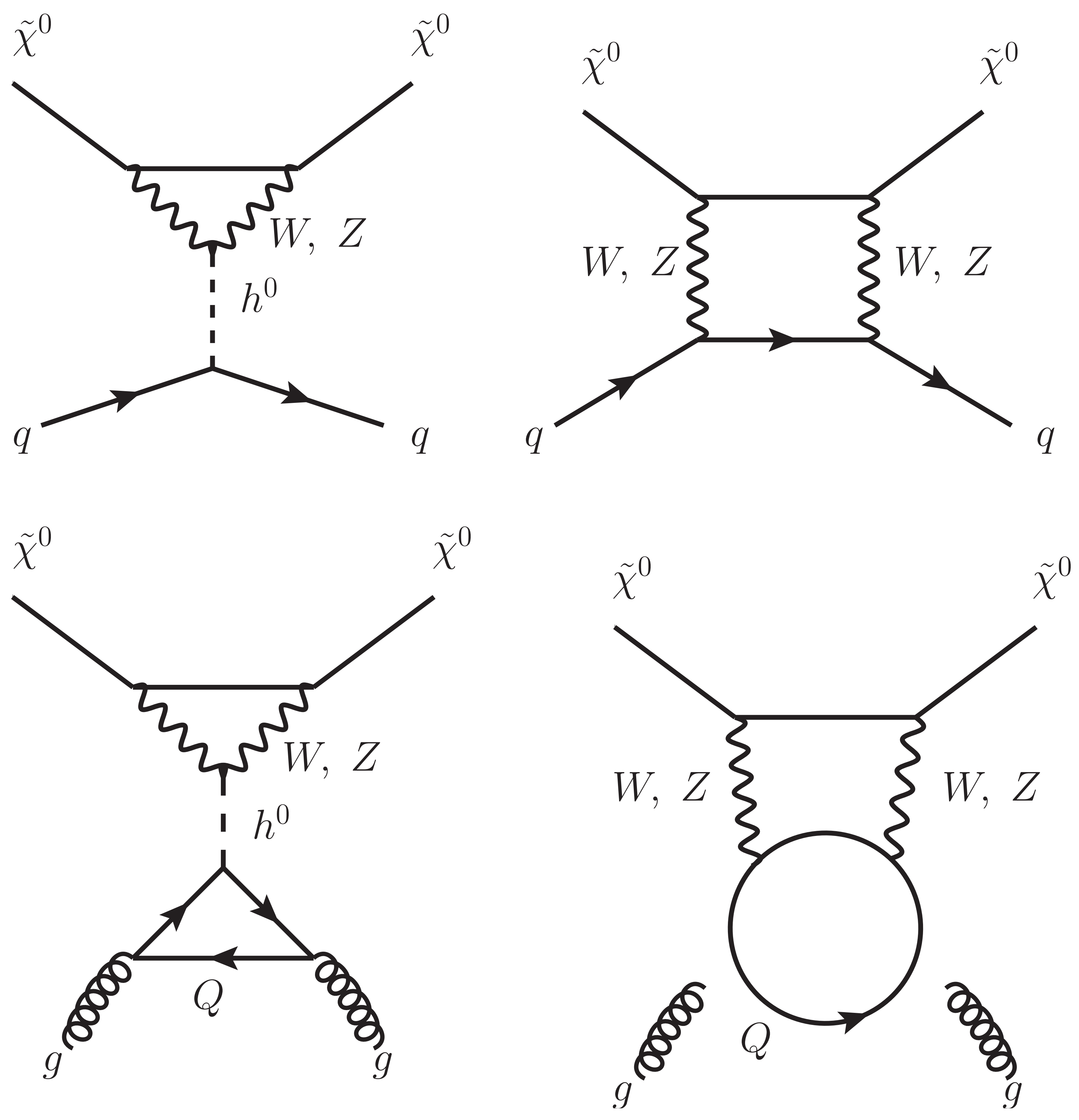
K. J. Bae, H. Baer, and E. J. Chun (2013)

Non-thermal production

These well-motivated scenarios can be realized with light higgsinos.

Dark matter direct detection





EW loop corrections for higgsino dark matter are found to be negligible.

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

Theoretical uncertainty

Projected sensitivities

- $\sin^2\theta_{\rm eff}$
  - FCC-ee: $\Delta\sin^2\theta_{\rm eff} = 1.2\,(1.2)\times 10^{-6}$
  - Giga-Z: $\Delta\sin^2\theta_{\rm eff} = 4.0\times 10^{-6}$
- M_W
  - FCC-ee: $\Delta M_W = 0.18\,(0.16)$ MeV
  - ILC250: $\Delta M_W = 2.5$ MeV

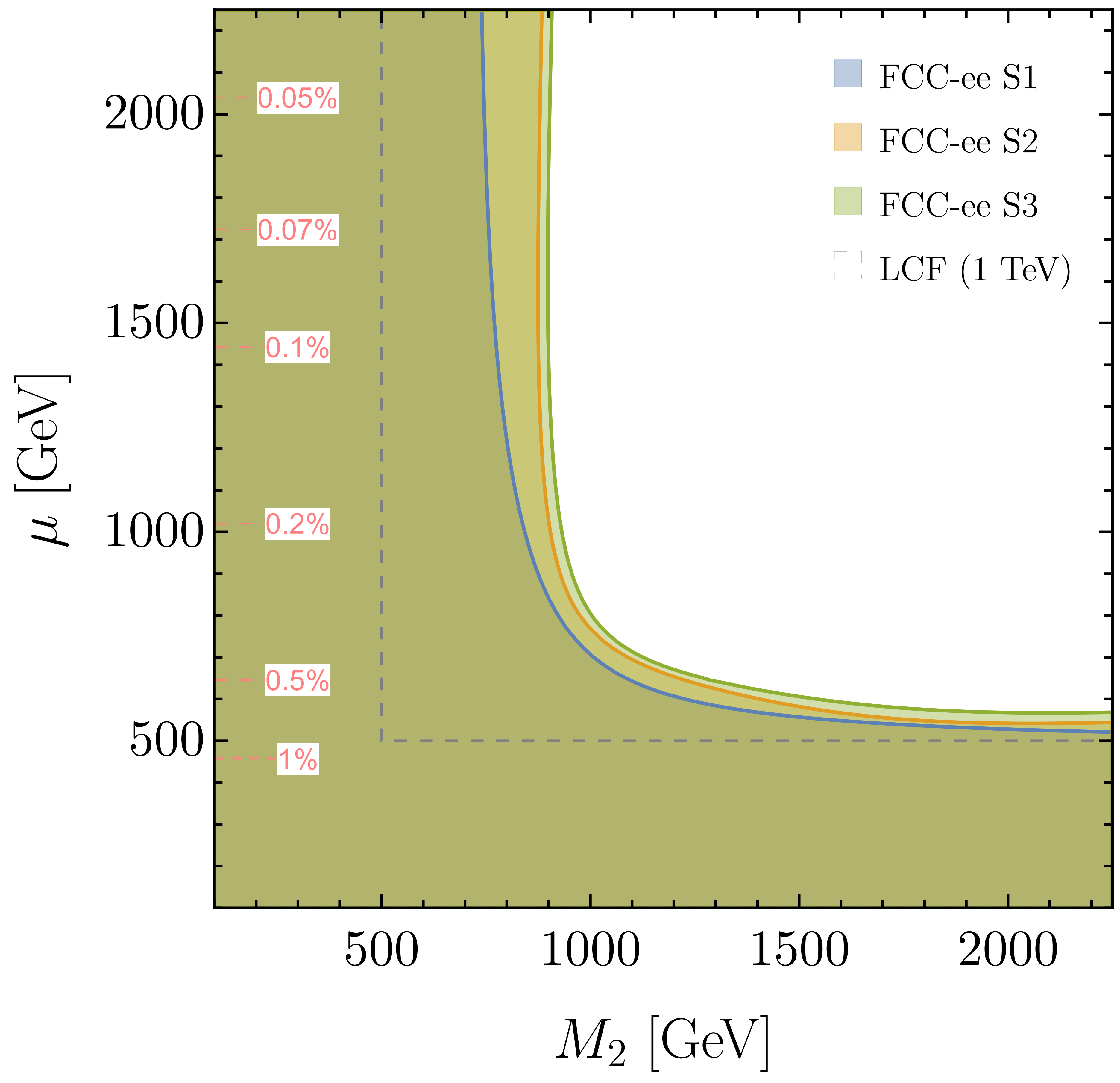
Current theoretical uncertainties

$$\Delta\sin^2\theta_{\rm eff}^{\rm th} \simeq 4.5\times 10^{-5}\ ,$$
$$\Delta M_W^{\rm th} \simeq 4.0\ \text{MeV}\ .$$

A. Freitas, et.al., arXiv:1906.05379

We need to reduce the theoretical uncertainties by 1—2 orders of magnitude to match the future experimental precision.

FCC-ee projected 2σ sensitivities



$M_1 = M_2/2$, $\tan\beta = 10$

S1: conservative theory progress

S2: aggressive theory progress

S3: experimental errors only

The bound does not vary much in these three scenarios.

The limits are entirely driven by W, which is best constrained by fermion pair-production above the Z-pole where theory errors are sub-leading.

A. Greljo, B. A. Stefanek, A. Valenti, Phys. Lett. B **871**, 140009 (2025)

Relative uncertainties for EWPOs

	Scenario S1	Scenario S2	Scenario S3
Observable	**TH PO+TH agg.+EXP** (10^{-5})	**TH agg.+EXP** (10^{-5})	**EXP Only** (10^{-5})
Γ_Z	1.55	0.820	0.510
σ_{had}	4.33	2.06	1.93
R_e	2.21	1.05	0.410
R_μ	2.20	1.02	0.330
R_τ	2.20	1.03	0.350
R_b	20.1	1.63	0.180
R_c	100	1.19	0.260
A_{FB}^e	126	25.7	25.2
A_{FB}^μ	125	21.1	20.6
A_{FB}^τ	126	23.3	22.8
A_{FB}^b	87.8	6.42	5.50
A_{FB}^c	89.1	10.2	9.62
A_{FB}^s	88.2	10.7	10.2
$\sin^2\theta_W$	6.87	0.780	0.730
A_e	87.9	9.78	9.20
A_μ	90.1	22.1	21.8
A_τ	90.5	23.4	23.2
A_b	11.7	10.5	10.5
A_c	16.9	9.00	8.99
A_s	14.2	13.2	13.2
M_W	0.490	0.320	0.300
Γ_W	16.1	16.1	16.1

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Theoretical uncertainty

Current and projected theoretical uncertainties

Quantity	FCC-ee	Current intrinsic error		Projected intrinsic error
M_W [MeV]	0.5–1 ‡	4	$(\alpha^3, \alpha^2\alpha_s)$	1
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	0.6	4.5	$(\alpha^3, \alpha^2\alpha_s)$	1.5
Γ_Z [MeV]	0.1	0.4	$(\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$	0.15
R_b [10^{-5}]	6	11	$(\alpha^3, \alpha^2\alpha_s)$	5
R_l [10^{-3}]	1	6	$(\alpha^3, \alpha^2\alpha_s)$	1.5

Uncertainties due to errors in input parameters

Quantity	FCC-ee	future parametric unc.	Main source
M_W [MeV]	0.5 – 1	1 (0.6)	$\delta(\Delta\alpha)$
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	0.6	2 (1)	$\delta(\Delta\alpha)$
Γ_Z [MeV]	0.1	0.1 (0.06)	$\delta\alpha_s$
R_b [10^{-5}]	6	< 1	$\delta\alpha_s$
R_ℓ [10^{-3}]	1	1.3 (0.7)	$\delta\alpha_s$

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