Current status of the light neutralino thermal dark matter in the pMSSM

based on PRL 131 (2023) 1, 011802 and arXiv:2312.xxxxx

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Dark Matter

Multiple evidences

Galaxy Rotation Curves

Bullet Cluster

Gravitational Lensing

Cosmic Microwave Background

No idea about mass, spin and couplings

One possible DM candidate:
the **lightest neutralino** in the
Minimal Supersymmetric Standard Model (MSSM) ← a well-motivated BSM model

How does this very conventional dark matter candidate stand against the recent experimental results?

Lightest Neutralino in the MSSM

Extending SM to MSSM

Higgs sector: 2 Higgs doublets in MSSM: H_u, H_d

5 Higgs bosons: $h, H, A, H^{\pm}$

Supersymmetry (SUSY):

Weyl fermion ↔ complex scalar   fermions ↔ sfermions

complex scalar ↔ Weyl fermion   Higgs bosons ↔ higgsinos

gauge bosons ↔ Weyl fermion   gauge bosons ↔ gauginos

Electroweakino sector:

$\tilde{B}, \tilde{W}, \tilde{H}_u, \tilde{H}_d$ → $\tilde{B}, \tilde{W}^0, \tilde{H}_u{}^0, \tilde{H}_d{}^0$ → 4 neutralinos: $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$

Lightest neutralino ($\tilde{\chi}_1^0$)

mixing

$\tilde{B}, \tilde{W}, \tilde{H}_u, \tilde{H}_d$ → $\tilde{W}^+, \tilde{H}_u{}^+, \tilde{W}^-, \tilde{H}_d{}^-$ → 4 charginos: $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$

Lightest Neutralino dark matter in the MSSM

R-parity

R-parity is defined as

$$R = (-1)^{3(B-L)+2s}$$

B: baryon number

L: lepton number

s: spin

SM particles: even under R-parity

Superpartners: odd under R-parity

In R-parity conserving (RPC) scenario

Lightest Supersymmetric Particle (LSP) is stable

can be dark matter if neutral

Lightest Neutralino dark matter in the MSSM

✱ LSP in RPC SUSY?

Focus on parameter space where the LSP contributes to the invisible decay of SM Higgs Boson

Light neutralino, where $M_{\tilde{\chi}_1^0} \lesssim M_h/2$

Dominantly **Bino** due to LEP limit on chargino mass

$$M_{\tilde{\chi}_1^\pm} \gtrsim 103\,\mathrm{GeV}$$

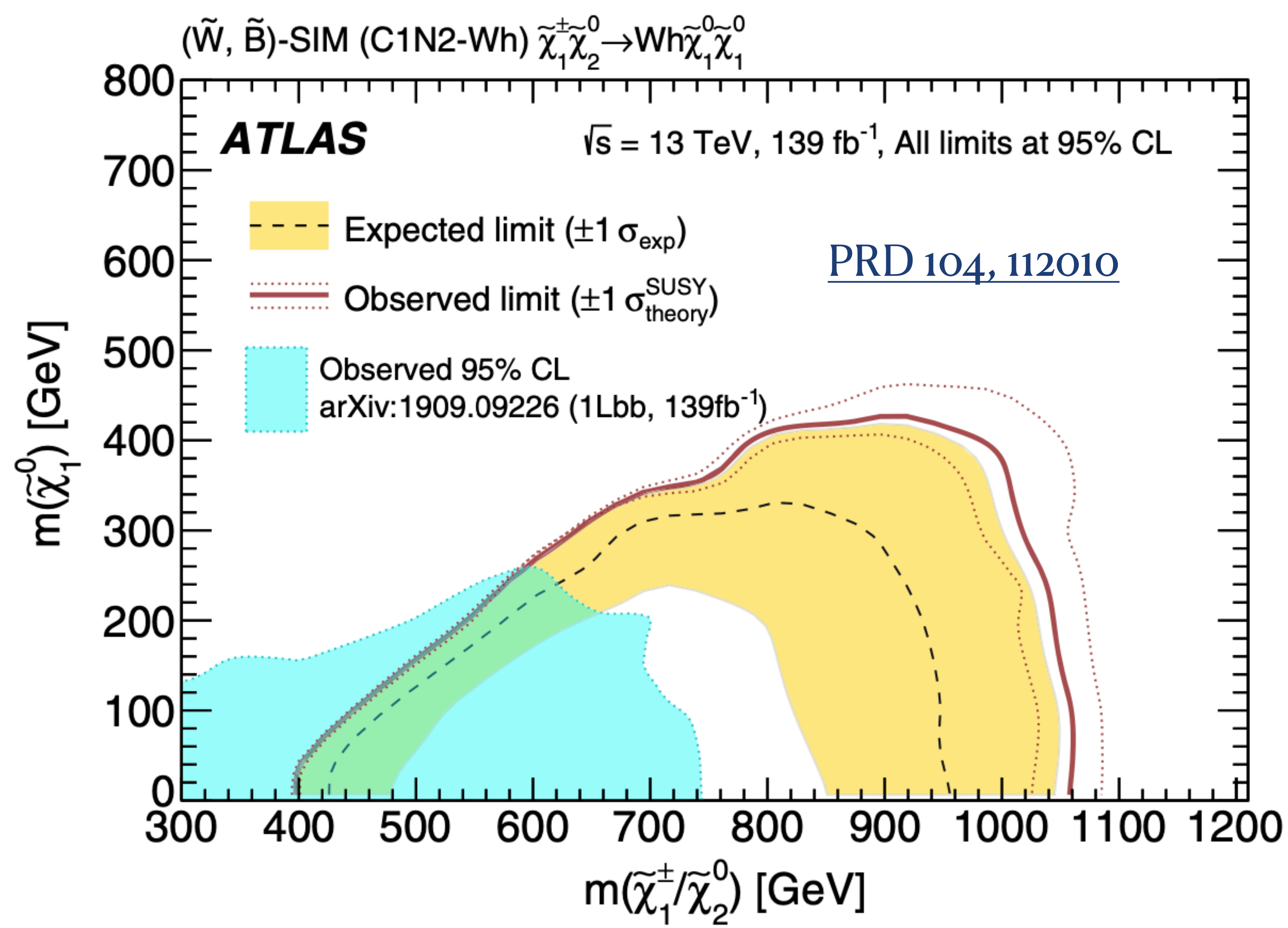
arXiv:hep-ex/0401026

Lightest Neutralino dark matter in the MSSM

✱ NLSP?

NLSP: Next-to Lightest Supersymmetric Particle

Mostly **Higgsino** due to strong limits for Wino NLSP



Lightest Neutralino dark matter in the MSSM

✱ NLSP?

NLSP: Next-to Lightest Supersymmetric Particle

Mostly **Higgsino** due to strong limits for Wino NLSP

*coupling of the LSP with Z and h bosons depends on the **Bino, Wino, and Higgsino components** in it*

$$g_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0} = \frac{g}{2\cos\theta_W}\left(|N_{13}|^2 - |N_{14}|^2\right)$$

$$g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} = -g\left(N_{12} - \tan\theta_W N_{11}\right)\underbrace{\left(\sin\alpha N_{13} + \cos\alpha N_{14}\right)}$$

$\left(\sin\beta N_{14} - \cos\beta N_{13}\right),\quad M_A \gg M_Z$

N_{1i} : ith component in $\tilde{\chi}_1^0$, where

$i = \tilde{B}, \tilde{W}^0, \tilde{H}_u^{\ 0}, \tilde{H}_d^{\ 0}$

Higgsino component required in the LSP for its coupling to Z and h bosons

Lightest Neutralino dark matter in the MSSM

- NLSP?

NLSP: Next-to Lig

Mostly Hig … o NLSP

coupling of the LS … no, Wino,

$g_{h\tilde{\chi}^0_1\tilde{\chi}^0_1}$

${}_{14} - \cos\beta N_{13}), \quad M_A \gg M_Z$

Previous works

Chattopadhyay, et al., PRD 82, 075013 (2010)

Barman, et al., PRD 95, 095018 (2017)

Pozzo, Zhang, PLB 789 (2019) 582–591

Barman, et al., Eur. Phys. J. Spec. Top. 229, 3159–3185 (2020)

Beekveld, et al., SciPost Phys. 11, 049 (2021)

and many more...

New data!

Higgsino component required in the LSP for its coupling to Z and h bosons

The pMSSM Parameter Space

10 parameters scanned

Slepton masses fixed at 2 TeV

1st and 2nd generation squark masses fixed at 5 TeV

M_1 bino mass

M_2 wino mass

μ higgsino mass

$\tan\beta$ ratio of vevs

M_A pseudoscalar mass

$$
\begin{aligned}
30\ \text{GeV} < M_1 < 100\ \text{GeV},\ 1\ \text{TeV} < M_2 < 3\ \text{TeV},\\
100\ \text{GeV} < |\mu| < \ 2\ \text{TeV},\ 2 < \tan\beta < 50,\\
100\ \text{GeV} < M_A < 5\ \text{TeV},\ 3\ \text{TeV} < M_{\tilde{Q}_{3L}} < 20\ \text{TeV},\\
3\ \text{TeV} < M_{\tilde{t}_R} < 20\ \text{TeV},\ 3\ \text{TeV} < M_{\tilde{b}_R} < 20\ \text{TeV},\\
-20\ \text{TeV} < A_t < 20\ \text{TeV},\ 2\ \text{TeV} < M_3 < 5\ \text{TeV},\\
M_{\tilde{Q}_{1,2L}} = M_{\tilde{u}_{1,2R}} = M_{\tilde{d}_{1,2R}} = 5\,\text{TeV},\ A_{u/d/c/s/b} = 0,\\
M_{\tilde{L}_{1,2,3L}} = M_{\tilde{e}_{1,2,3R}} = 2\,\text{TeV},\ A_{e/\mu/\tau} = 0.
\end{aligned}
$$

$M_{\tilde{Q}_{3L}}$, $M_{\tilde{t}_R}$, $M_{\tilde{b}_R}$ 3rd generation squark mass

A_t stop trilinear coupling

M_3 gluino mass

Both $\mu > 0$ and $\mu < 0$ scenarios studied separately

Particle spectrum generated using `FeynHiggs 2.18.1`

Current Constraints on the Parameter Space

MicrOMEGAS 5.2.13

LEP, Flavor

LEP constraints

invisible decay of Z-boson from new physics

$$\Gamma_{\rm inv}^{\rm new} < 2 \text{ MeV}$$

ALEPH, DELPHI, L3, OPAL, Phys. Rept. 427 (2006) 257–454

chargino mass

$$m_{\chi_1^\pm} > 103 \text{ GeV}$$

OPAL, EPJC 35, 1–20 (2004)

cross-section of associated production of neutralinos in final states with jets

$$\begin{aligned}&\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0) \times \text{Br}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + \text{jets})\\ &+\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_3^0) \times \text{Br}(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 + \text{jets}) < 0.1 \text{ pb}\end{aligned}$$

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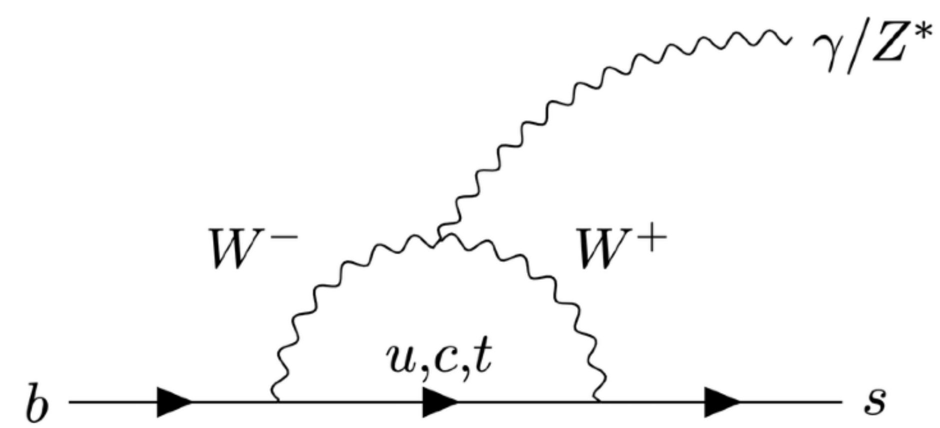
$$\sigma(e^+e^- \to \tilde\chi_1^0\tilde\chi_2^0) \times \text{Br}(\tilde\chi_2^0 \to \tilde\chi_1^0 + \text{jets}) + \sigma(e^+e^- \to \tilde\chi_1^0\tilde\chi_3^0) \times \text{Br}(\tilde\chi_3^0 \to \tilde\chi_1^0 + \text{jets}) < 0.1 \text{ pb}$$

OPAL, EPJC 35, 1–20 (2004)

Flavor observables

- Rare processes in SM
- Might receive contribution from MSSM
- Precise measurement of the branching of these processes constrain the MSSM parameter space



$$3.00 \times 10^{-4} < \text{Br}(b \to s\gamma) < 3.64 \times 10^{-4}$$

HFLAV, Eur. Phys. J. C 77, 895 (2017)

$$1.66 \times 10^{-9} < \text{Br}(B_s \to \mu^+\mu^-) < 4.34 \times 10^{-9}$$

CMS & LHCb, Nature 522, 68–72 (2015)

$$0.78 < (\text{Br}(B \to \tau\nu))_{\rm obs}/(\text{Br}(B \to \tau\nu))_{\rm SM} < 1.78$$

Belle, PRD 82, 071101(R)

Current Constraints on the Parameter Space

Higgs constraints

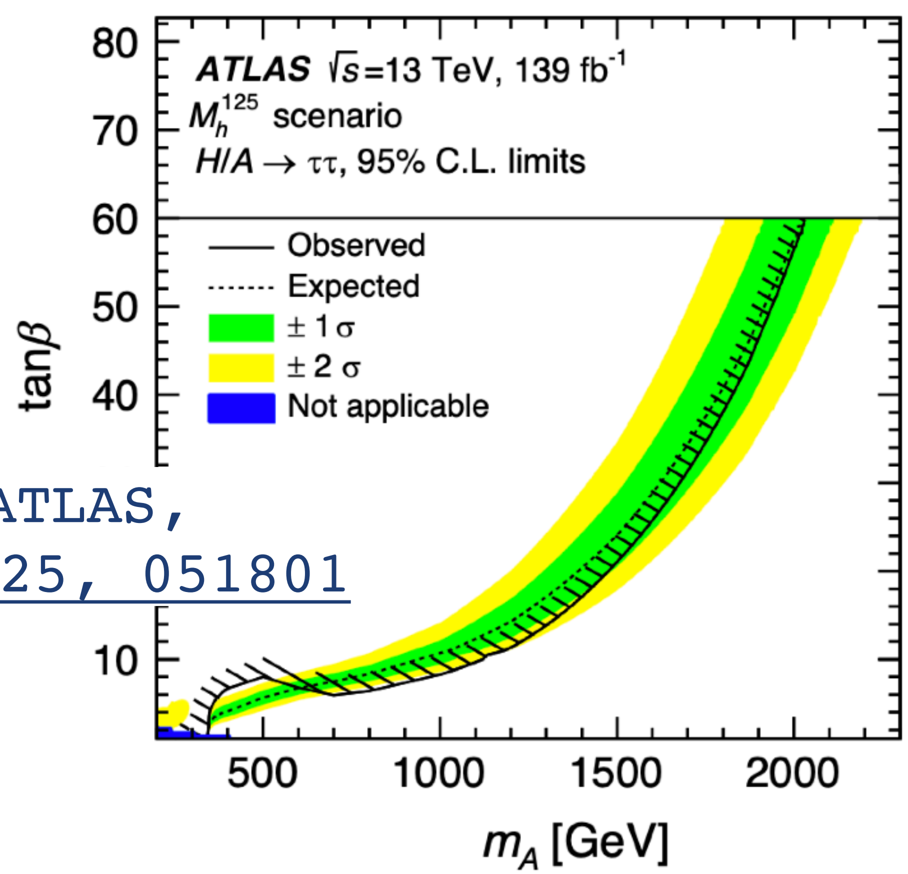
Observed Higgs mass

$$122\ \text{GeV} < m_h < 128\ \text{GeV}$$

`FeynHiggs 2.18.1`

Heavy Higgs searches

`HiggsBounds 5.10.0`



ATLAS, PRL 125, 051801

Higgs signal strength

$$\mu = \frac{(\text{Production}_{\text{mode}} \times \text{Branching}_{\text{mode}})_{\text{obs}}}{(\text{Production}_{\text{mode}} \times \text{Branching}_{\text{mode}})_{\text{SM}}}$$

`HiggsSignal 2.6.2`

Invisible decay of the Higgs Boson

$$\text{Br}(h \to \text{invisible}) < 0.11$$

ATLAS, ATLAS-CONF-2020-052

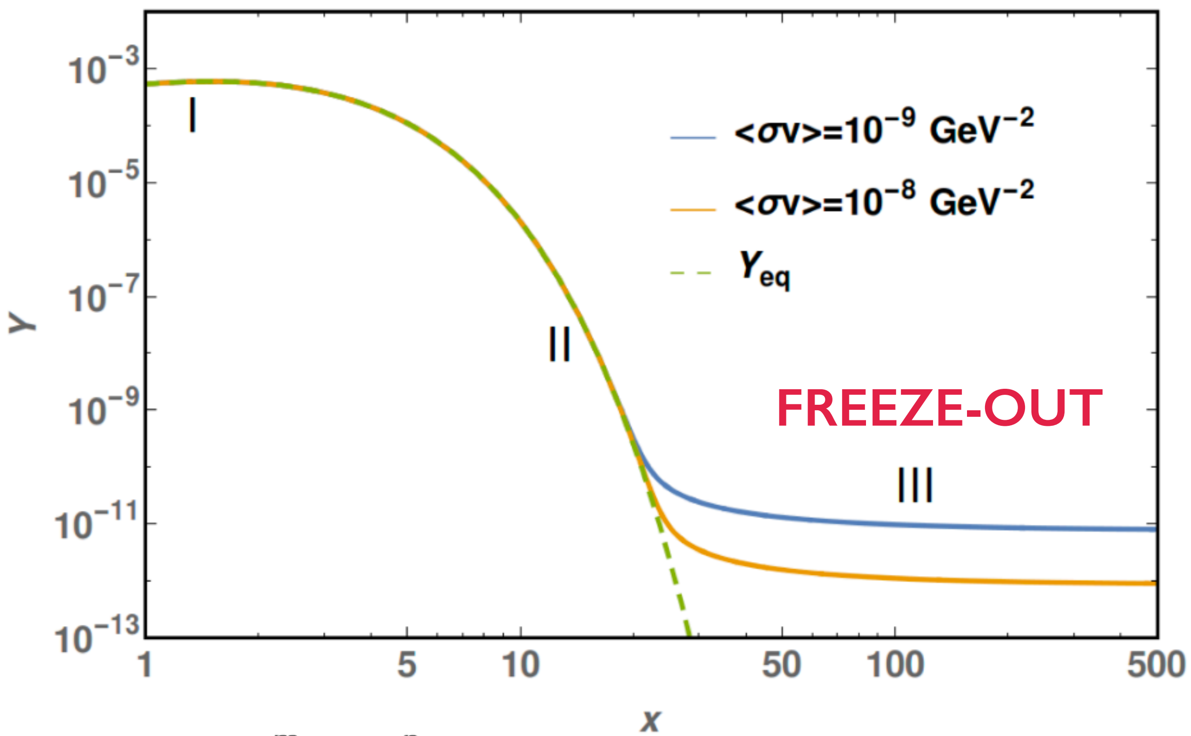
Current Constraints on the Parameter Space

Dark matter constraints

MicrOMEGAS 5.2.13

Relic Density

DM in thermal equilibrium with other SM particles in the early Universe



$x = \frac{m}{T}, Y = \frac{n}{s}$

$s = \frac{2\pi^2}{45} g_{*s} T^3$

m : mass of the particle
T : temperature of the thermal bath
n : number density of the particle
s : entropy density of the thermal bath

Observed relic density of Dark Matter:

$$\Omega^{\rm obs}_{\rm DM} h^2 = 0.120 \pm 0.001$$ PLANCK collaboration

$$\Omega_{\rm LSP} h^2 \lesssim 0.122$$

If underabundant, multi-component DM

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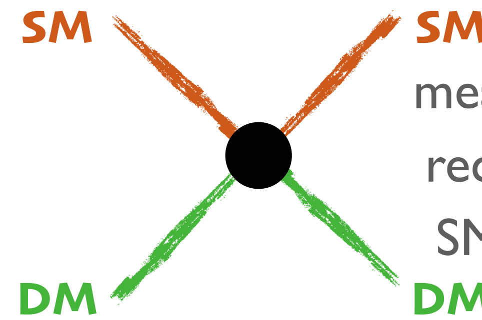
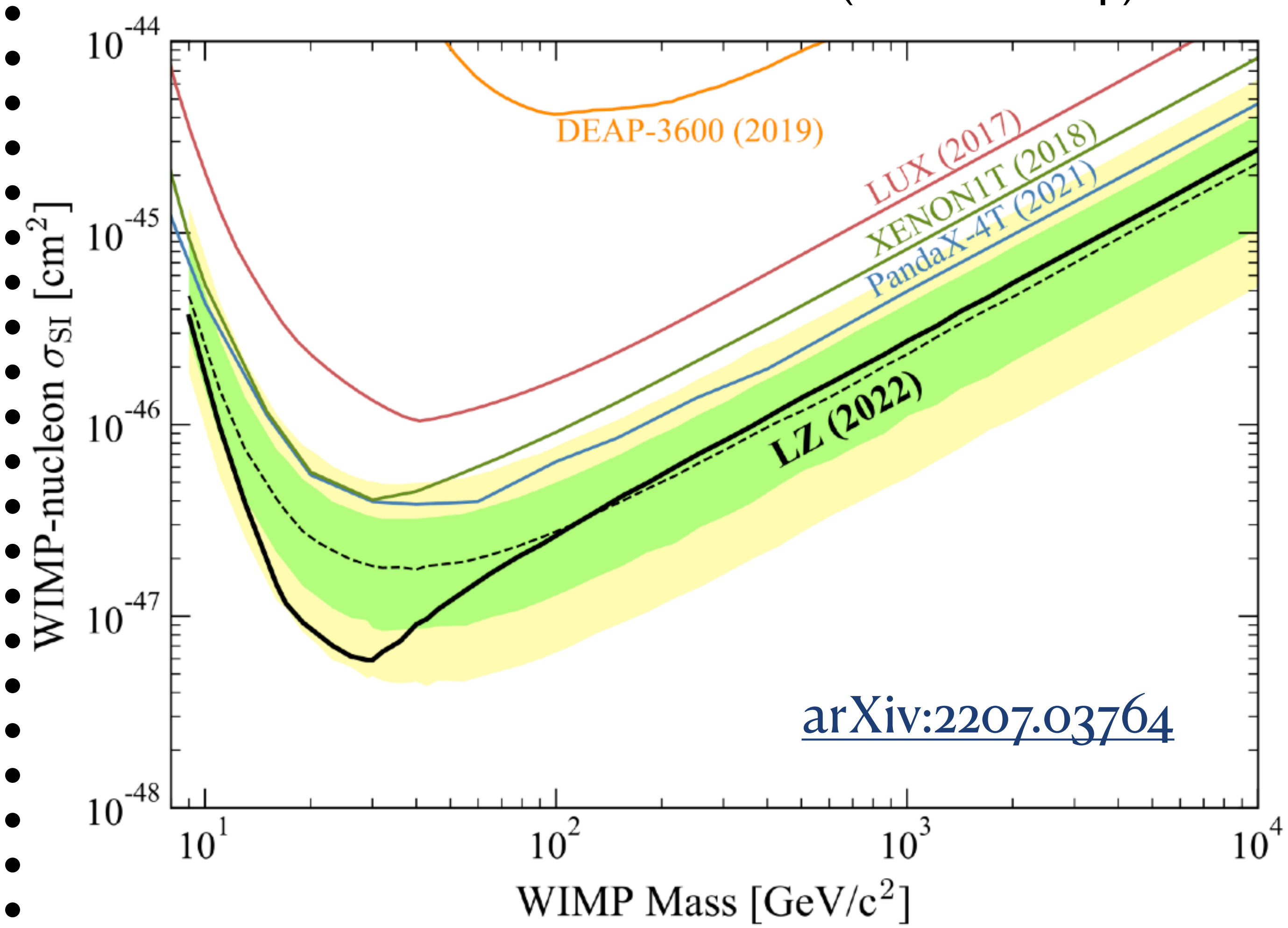


measures the recoil of the SM particle

Direct Detection

Spin-independent limits (SI)
Spin-dependent limits (SDn and SDp)



arXiv:2207.03764

$m_{\tilde{\chi}^0_1}$

If underabundant,

$$\sigma_{\rm DD} \to \sigma_{\rm DD} \times \xi \qquad \xi = \frac{\Omega_{\rm LSP}}{0.120}$$

Current Constraints on the Parameter Space

Electroweakino constraints

results of direct searches for chargino and neutralino at the ATLAS and CMS experiments of the LHC

$$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0/\chi_1^{\pm}\tilde{\chi}_3^0$$

$$\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0$$

$$\tilde{\chi}_2^0/\tilde{\chi}_3^0 \to (Z/h)\tilde{\chi}_1^0$$

Leptonic decay modes of $W/Z/h$: being cleaner have been used in the past, like $3l + \mathrm{MET}$ analysis

Low branching - sensitive to lighter NLSPs

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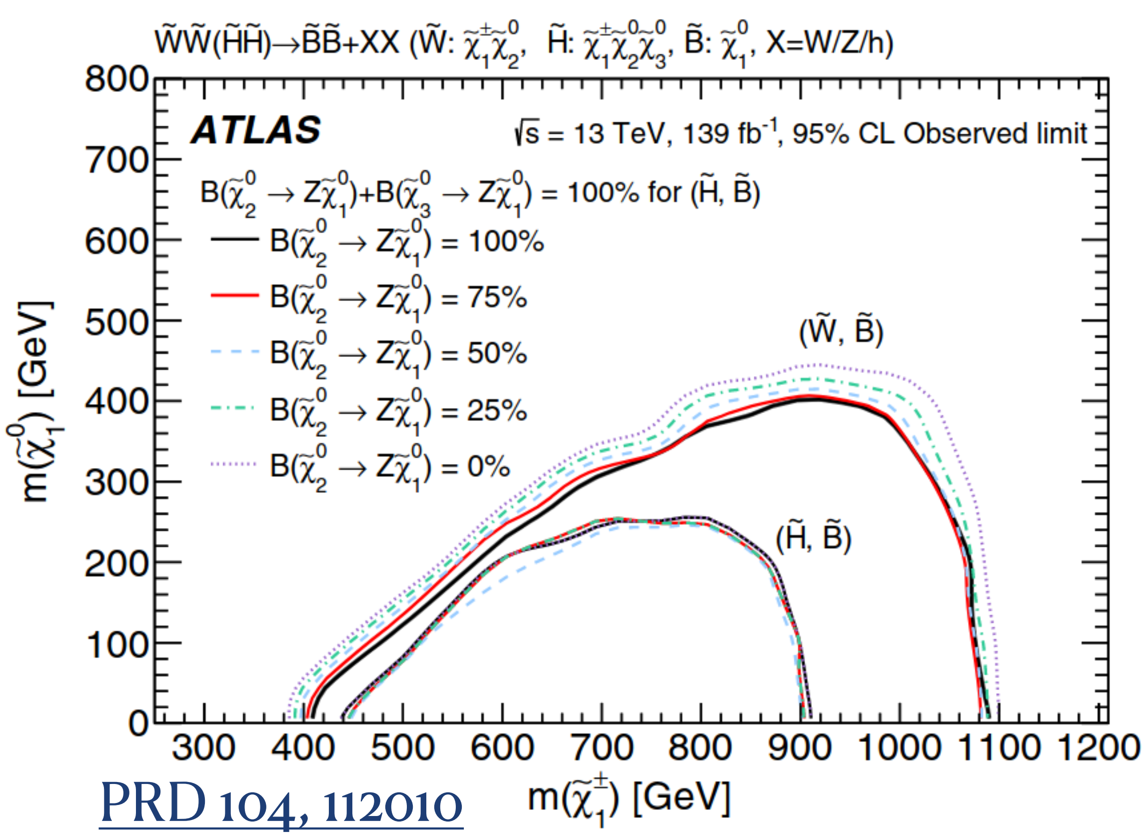
Leptonic decay modes of $W/Z/h$: being cleaner have been used in the past, like $3l + \mathrm{MET}$ analysis

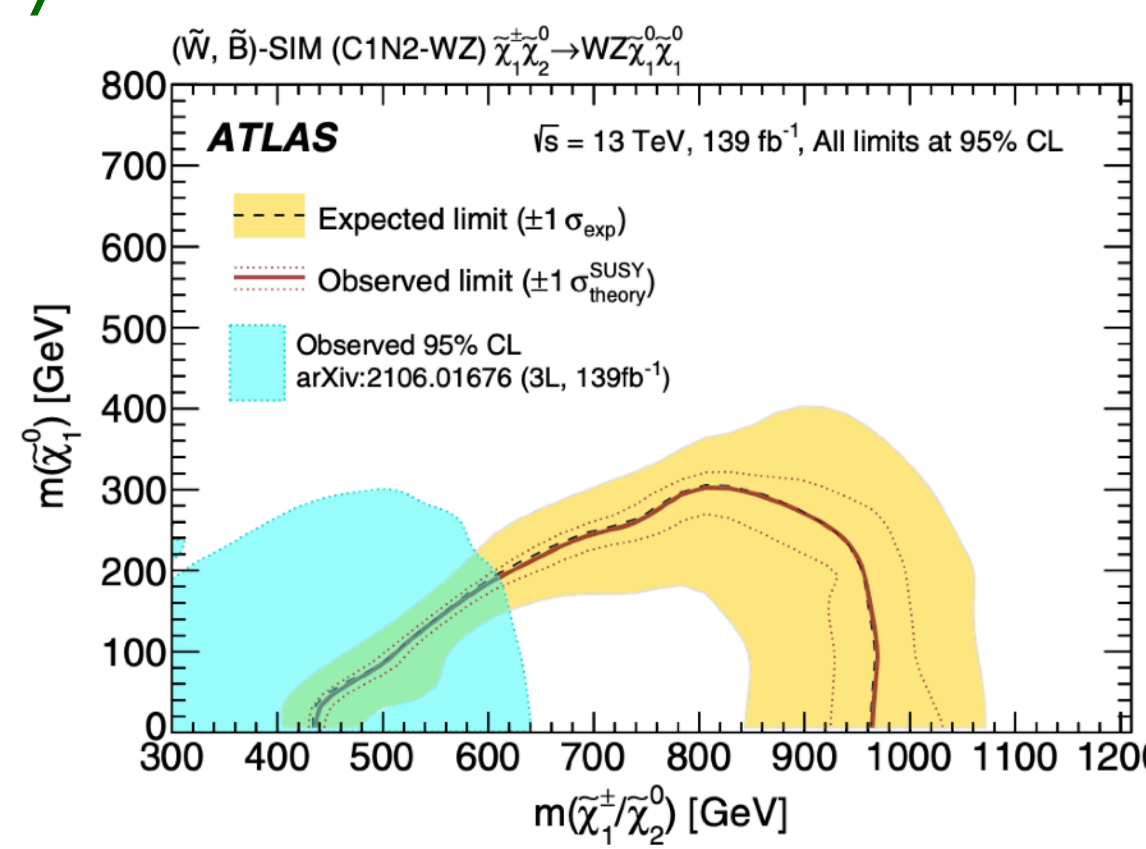
Low branching - sensitive to lighter NLSPs

Recently, hadronic final states are also being analysed

$\Rightarrow$ increase sensitivity to heavier NLSPs



PRD 104, 112010



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$$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 / \chi_1^{\pm}\tilde{\chi}_3^0$$

$$\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0$$

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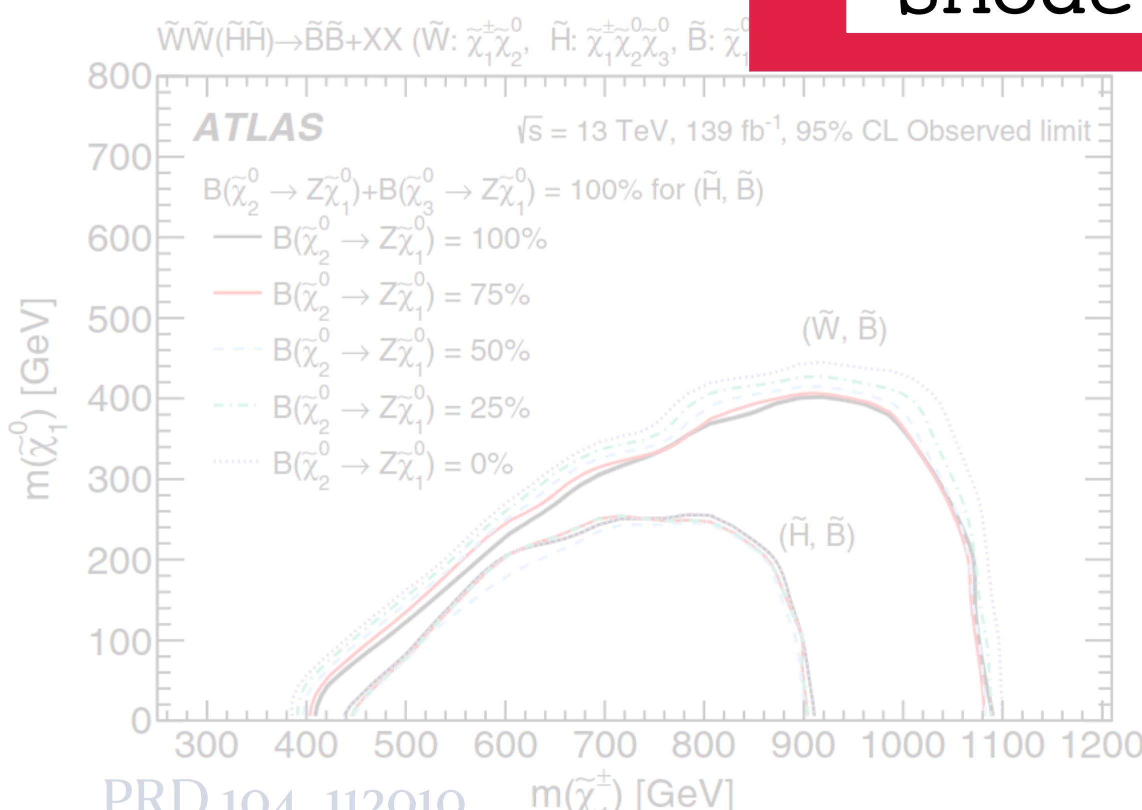
Leptonic decay modes of $W/Z/h$: being cleaner have been used in the past, like $3l + \mathrm{MET}$ analysis

Low branching - sensitive to lighter NLSPs

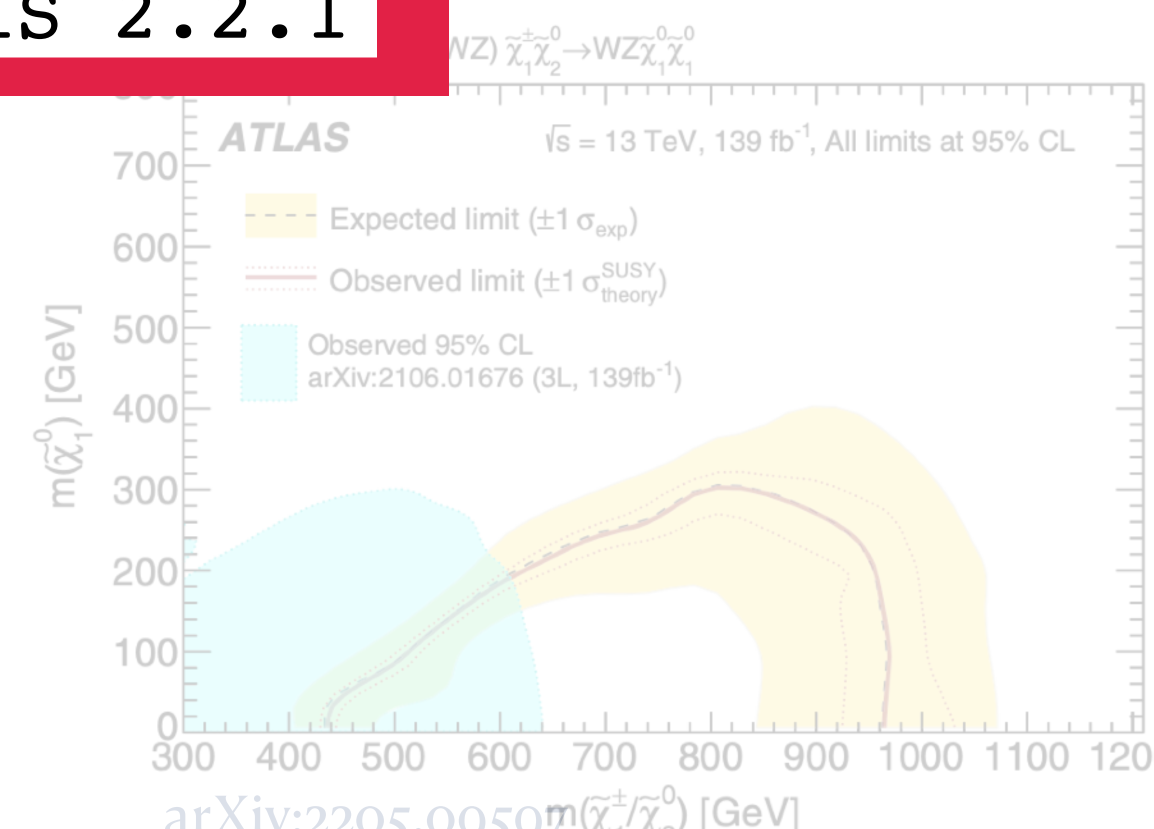
Recently, had ... eing analysed

⇒ inc ... NLSPs

Implemented using
`SModelS 2.2.1`



PRD 104, 112010

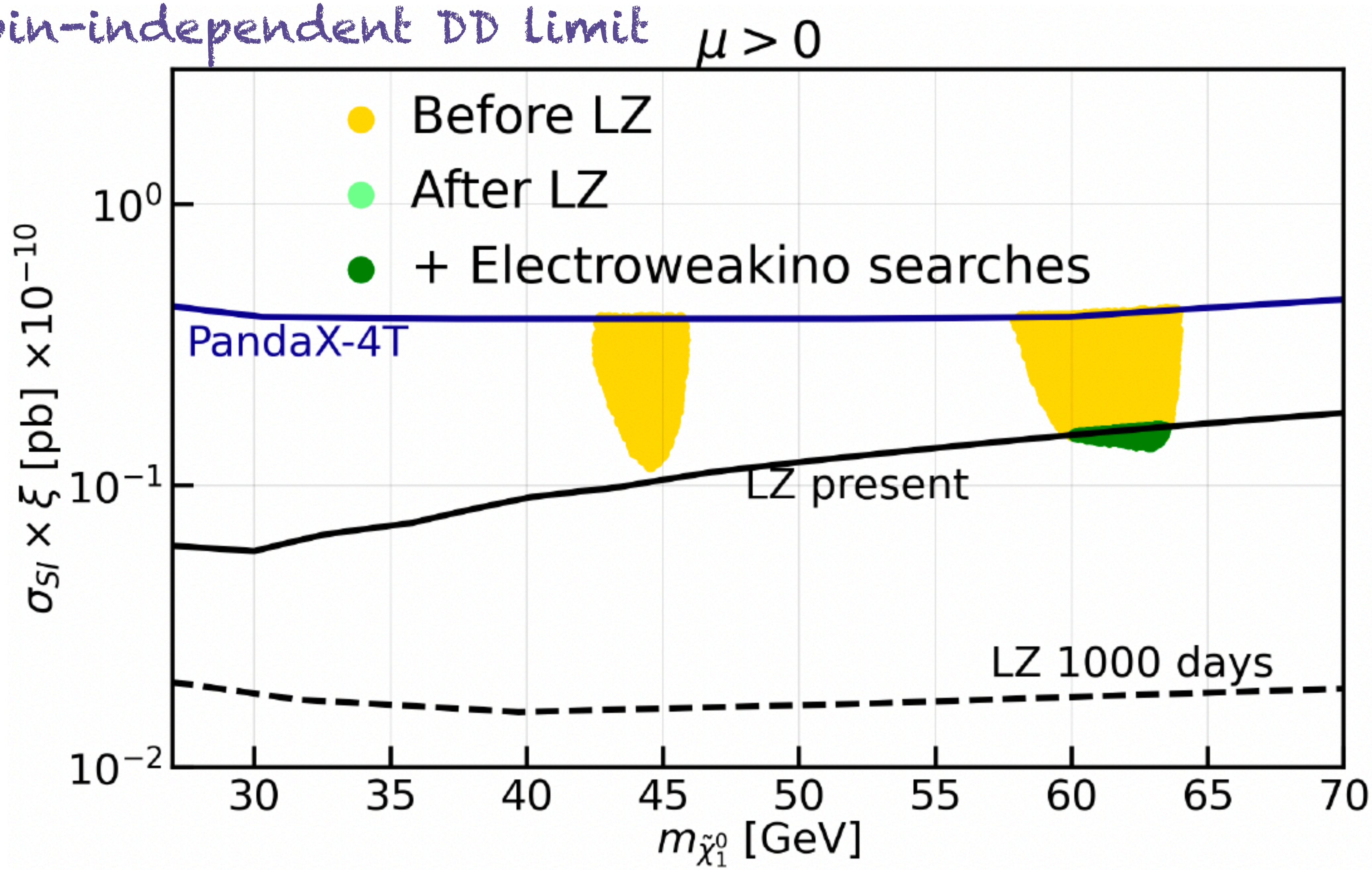


arXiv:2205.09597

Results

The Positive μ Scenario

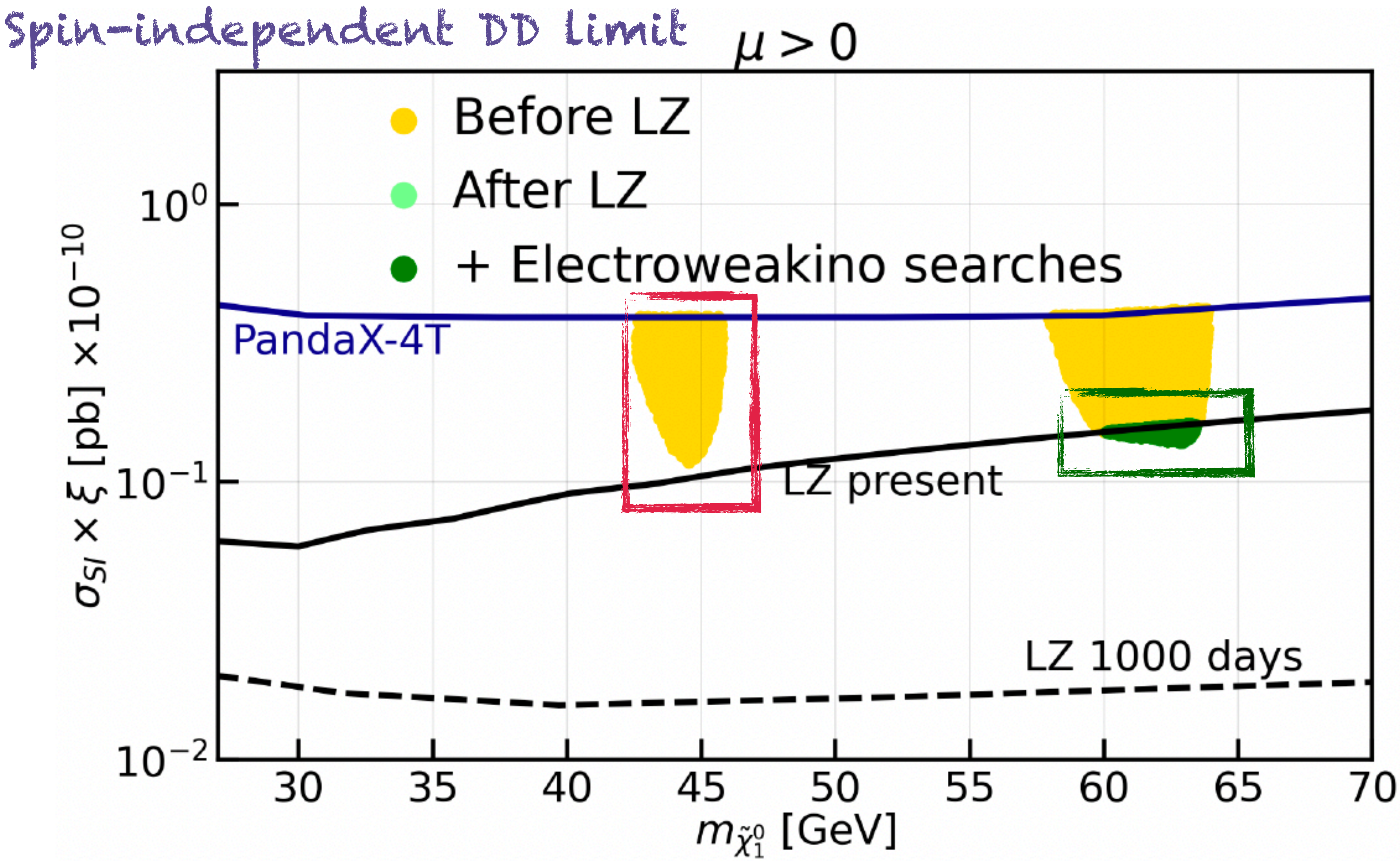
Spin-independent DD limit



DD limits restrict allowed parameter space to Z and h funnel regions since here relic density can be satisfied even with smaller coupling due to resonance enhancement

Before LZ: constraints from LEP, flavor, Higgs constraints, relic density and the DD experiments **XENON-1T**, **PICO-60** and **PandaX-4T**

The Positive μ Scenario



Z-funnel excluded

Allowed region in h-funnel

Well within the reach of the full LZ data

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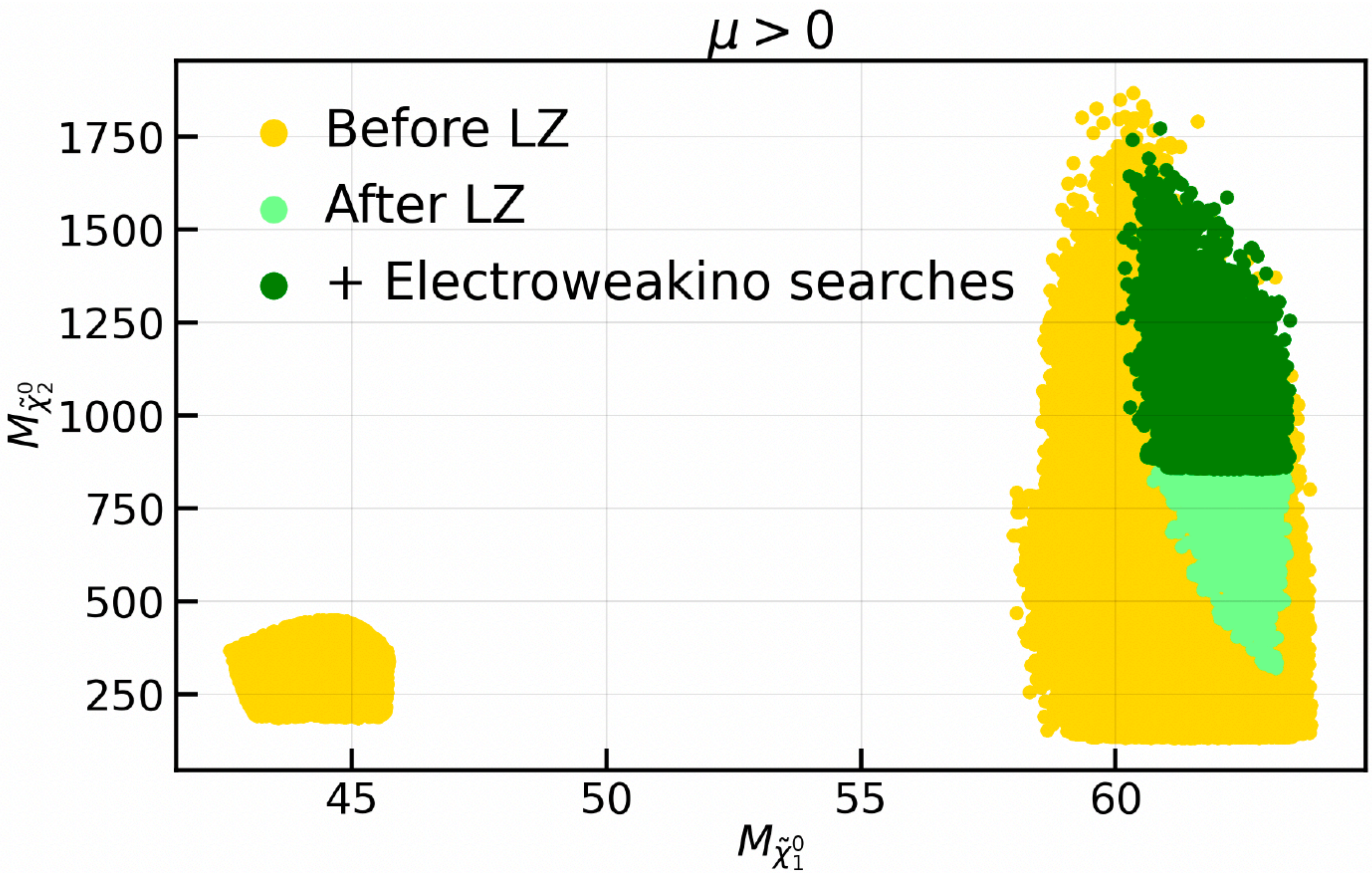

Higgsinos heavier than ~ 850 GeV allowed from electroweakino searches

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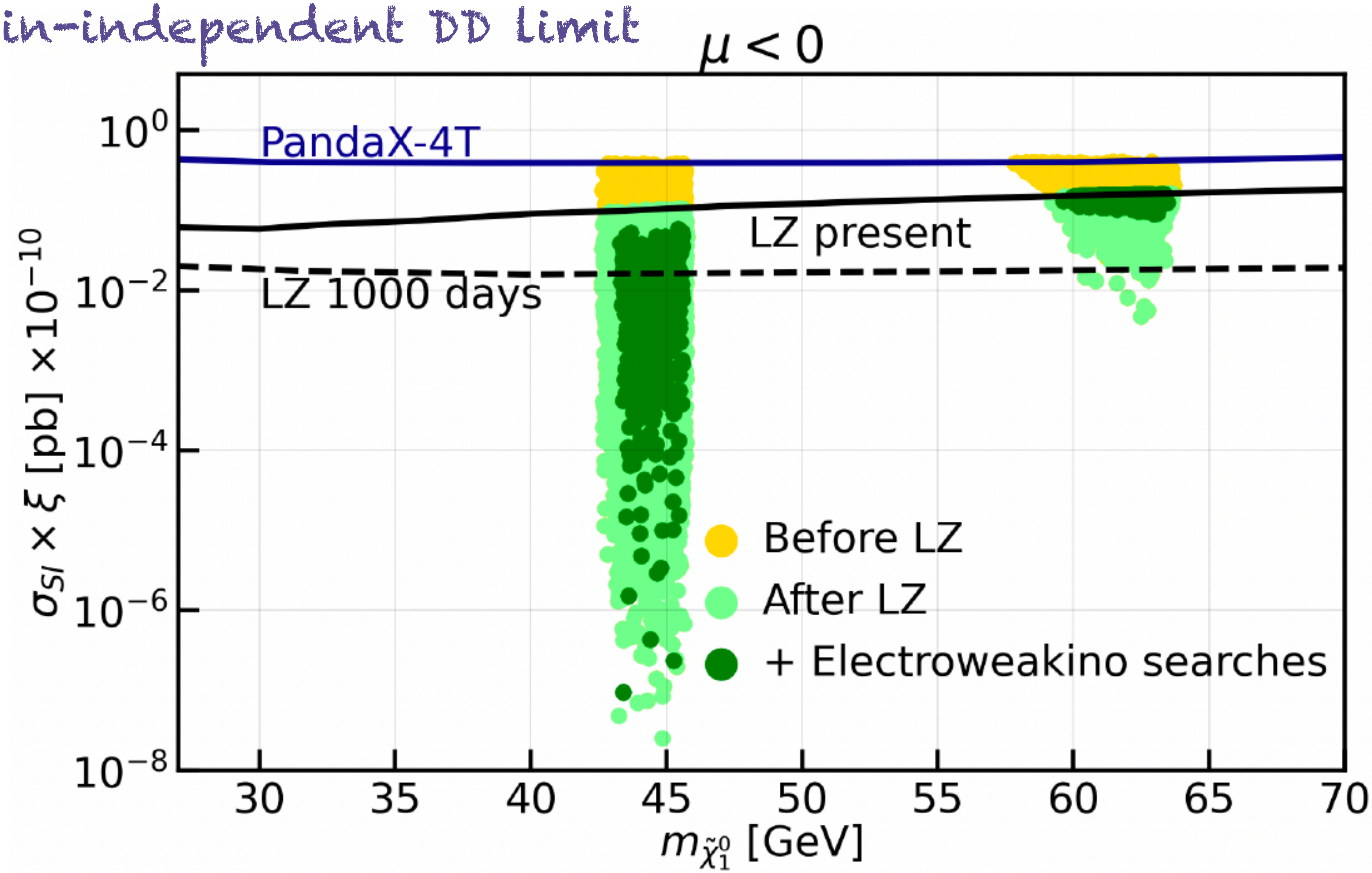
The Negative μ Scenario

Spin-independent DD Limit



Allowed regions in both Z and h funnels

h-funnel well within the reach of the full LZ data

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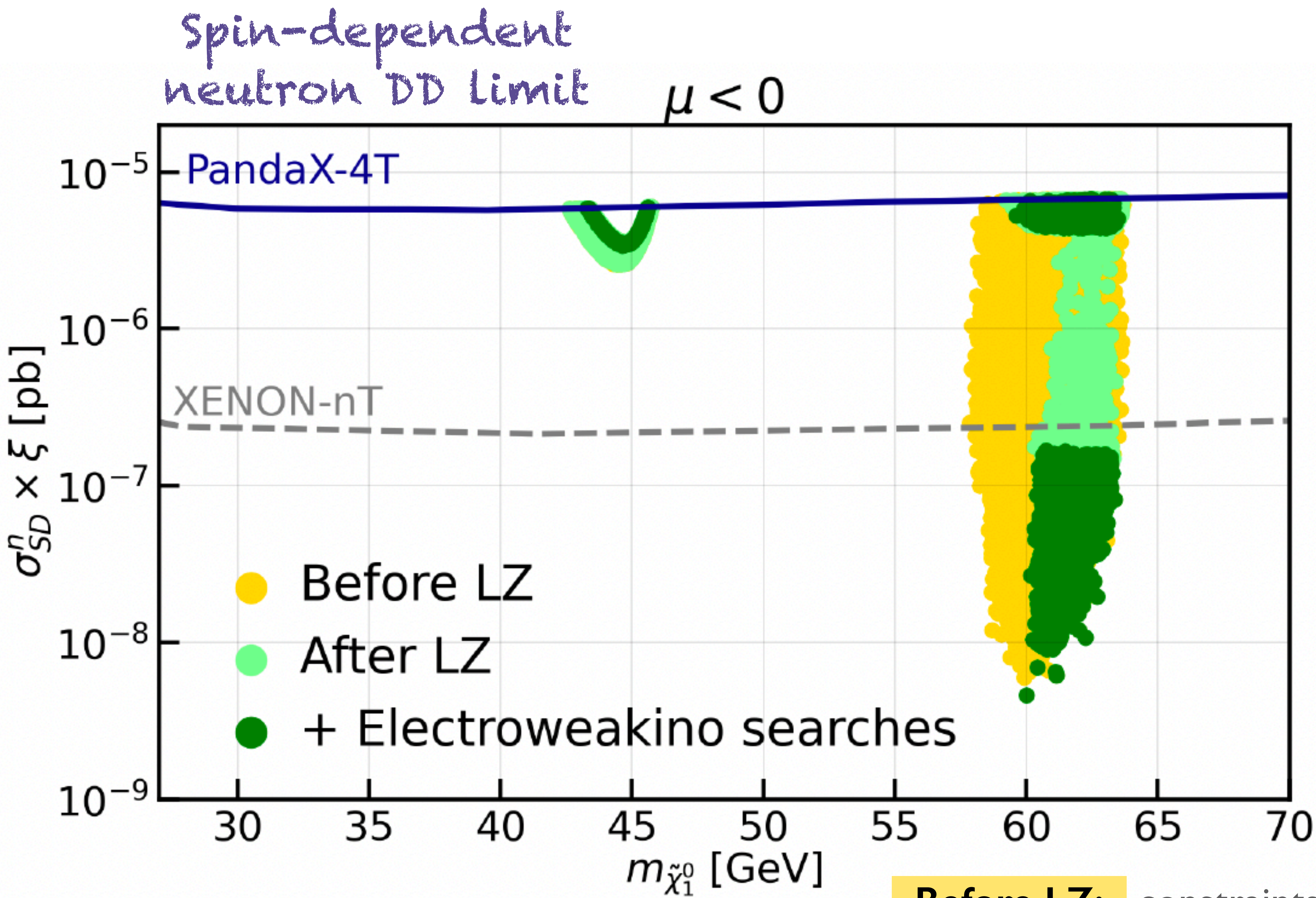
The Negative μ Scenario



Z-funnel well within the reach of XENON-nT data

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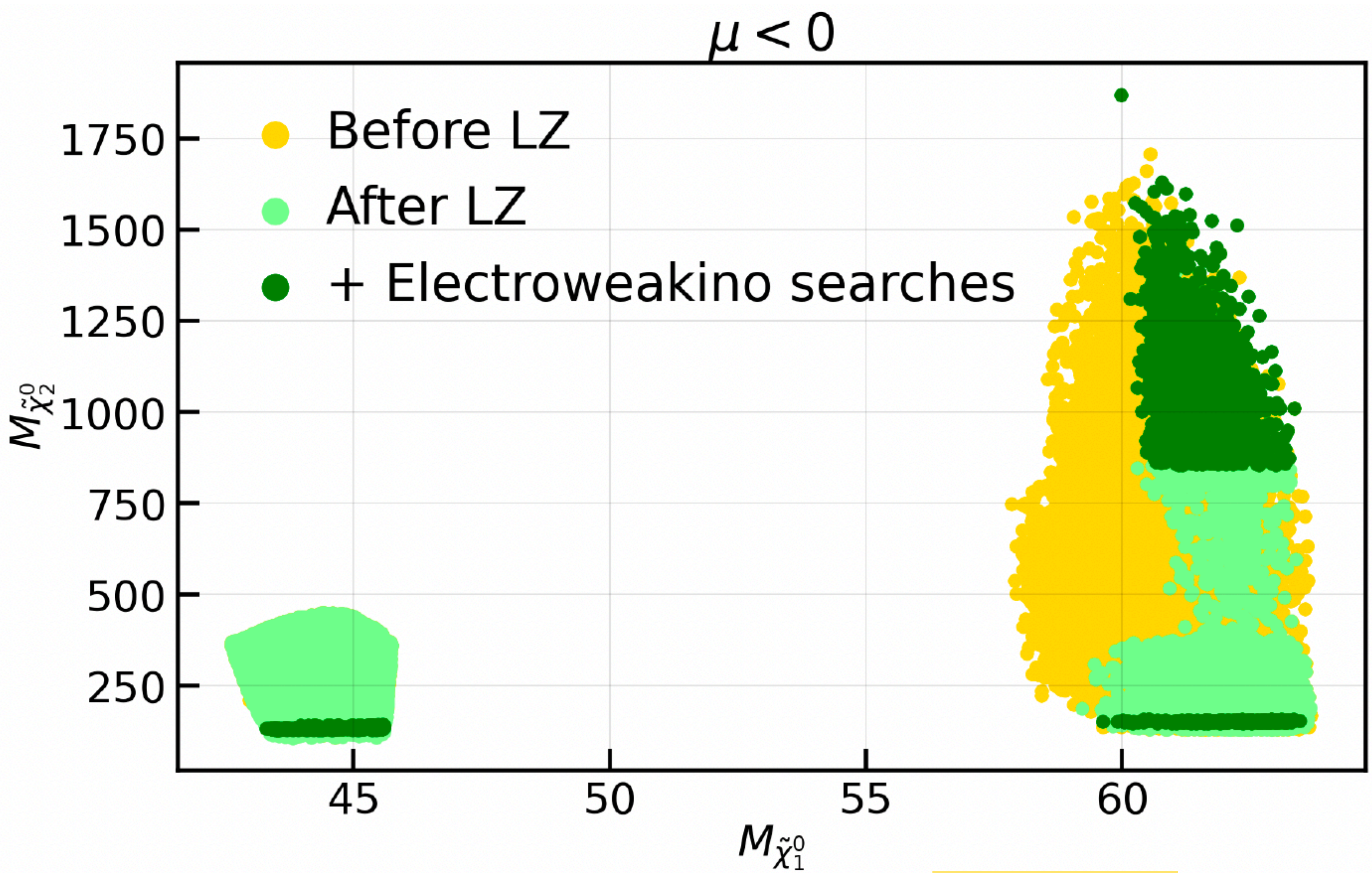
The Negative μ Scenario



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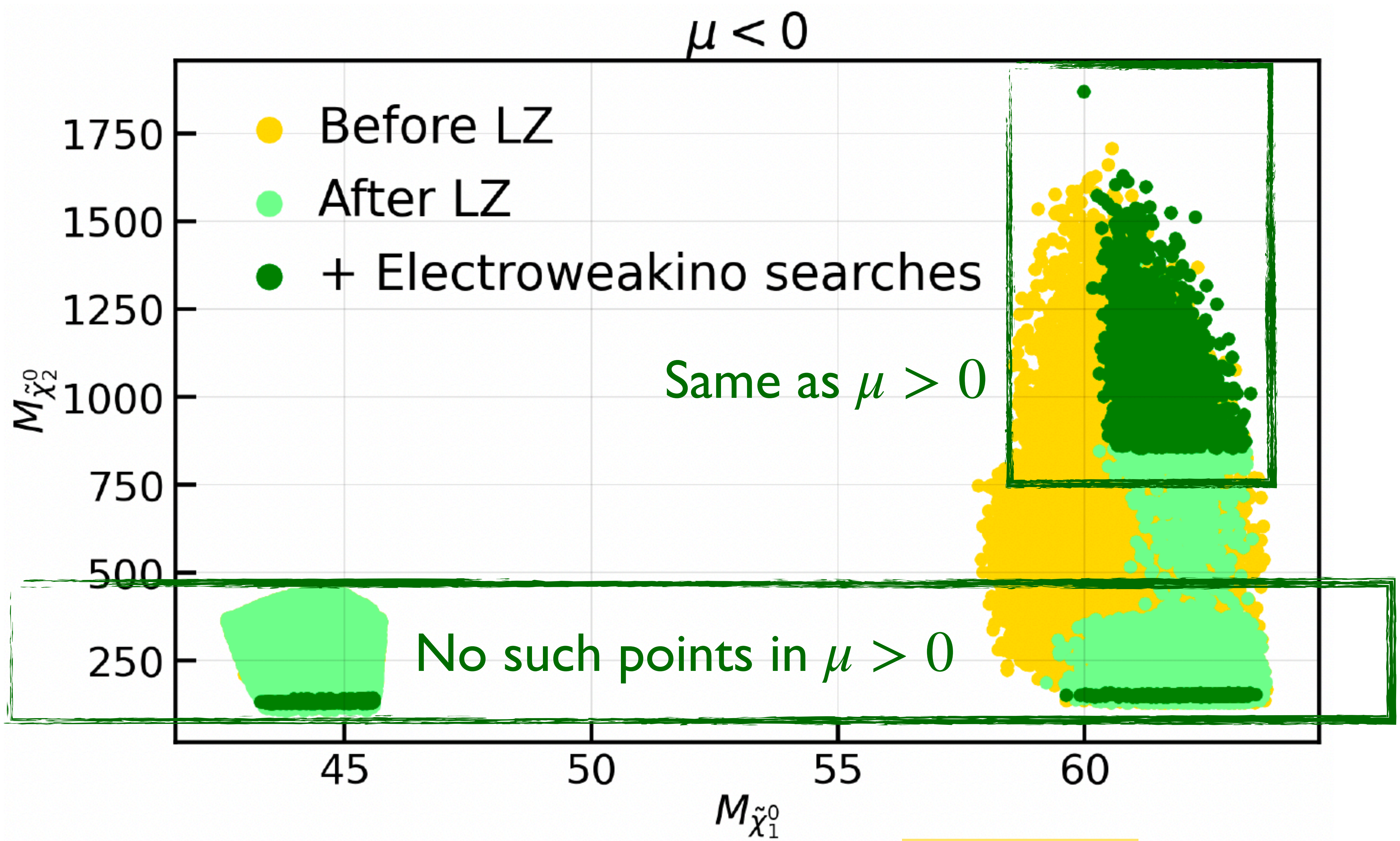


Before LZ: constraints from LEP, flavor, Higgs constraints, relic density and the DD experiments **XENON-1T**, **PICO-60** and **PandaX-4T**

Light higgsinos: impact of LZ dependent on the sign of μ

LZ limits the SI DD cross-section

Both h and H contribute to this

$\mu > 0$

These contributions constructively interfere for down type quarks

tanβ enhanced

$\mu < 0$

when $g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} < 0$

These contributions destructively interfere for down type quarks

Even for same $g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0}$ coupling, the SI DD cross-section increases for $\mu > 0$ and decreases for $\mu < 0$ for high tanβ

(scaled with the relic density)

Relic density depends on $g_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0}$ in Z-funnel and $g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0}$ in h-funnel

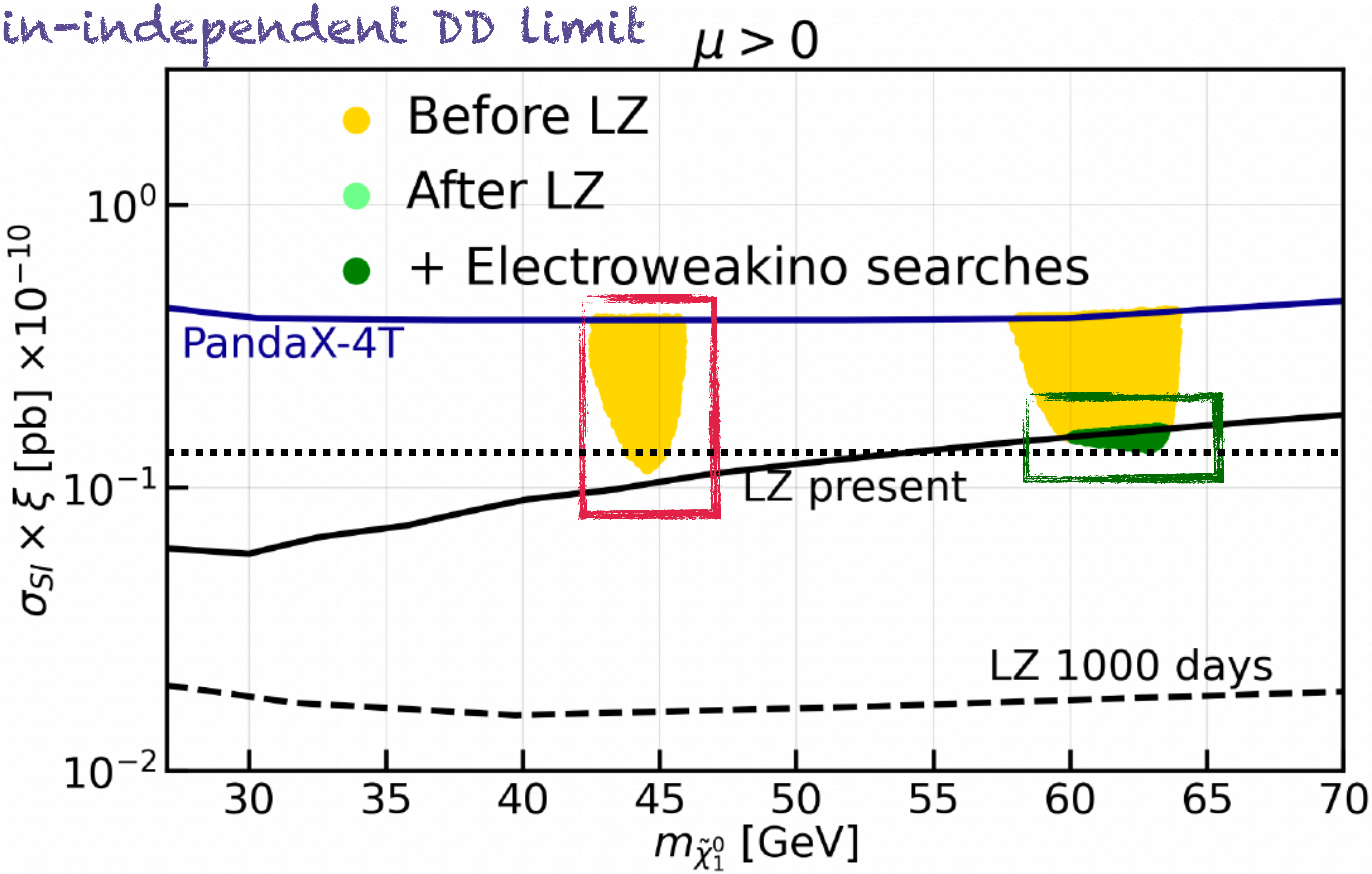
ALLOWED POINTS IN $\mu < 0$ WITH LIGHT HIGGSINOS

Can we tune the parameters to evade the constraints?

Revisit

The Positive μ Scenario

Spin-independent DD limit



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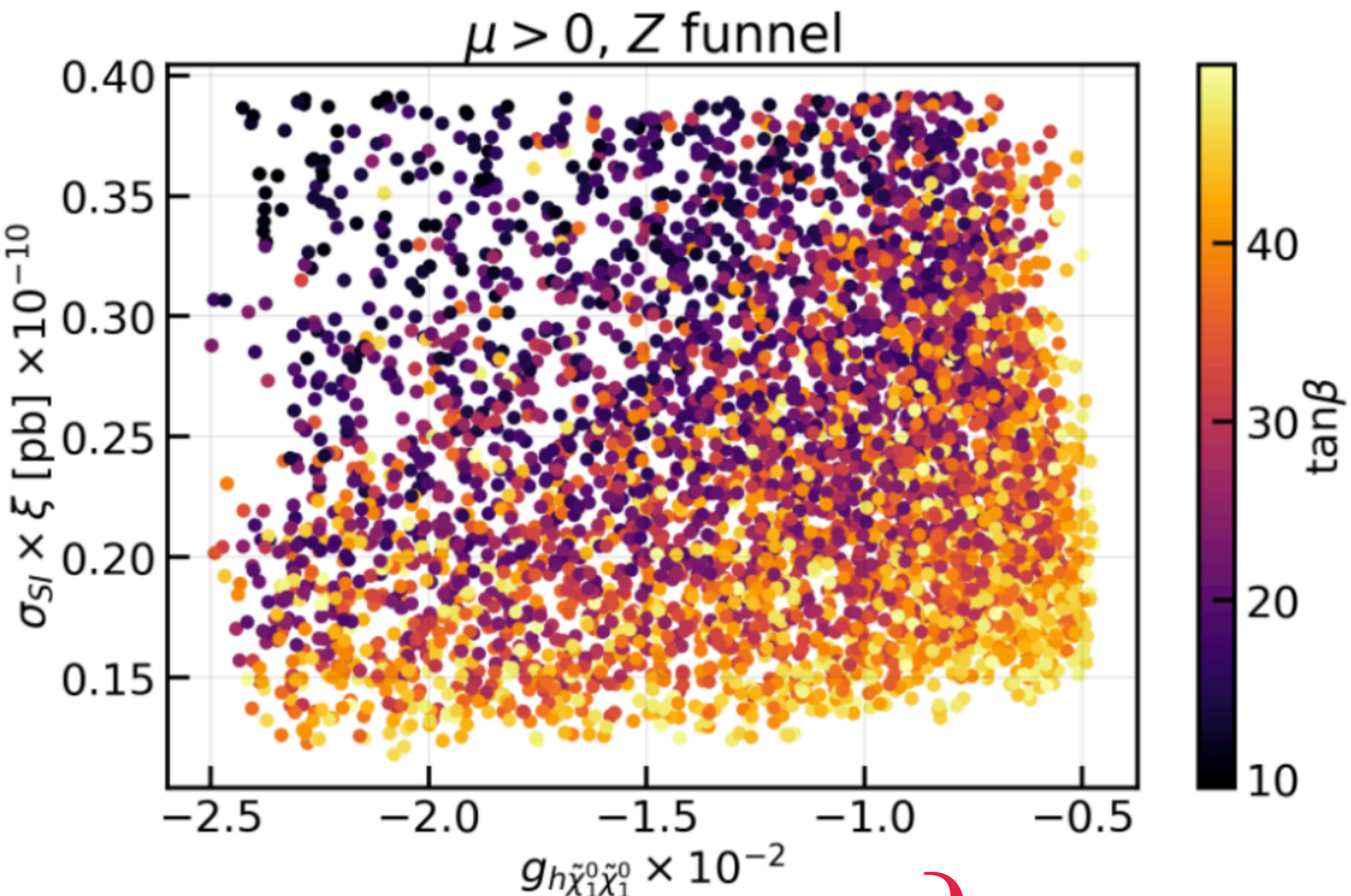
The Z-funnel for $\mu > 0$



Low $\tan\beta$: High magnitude of $g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0}$

High $\tan\beta$: Low magnitude of $g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0}$,

but added contribution from $g_{H\tilde{\chi}_1^0\tilde{\chi}_1^0}$

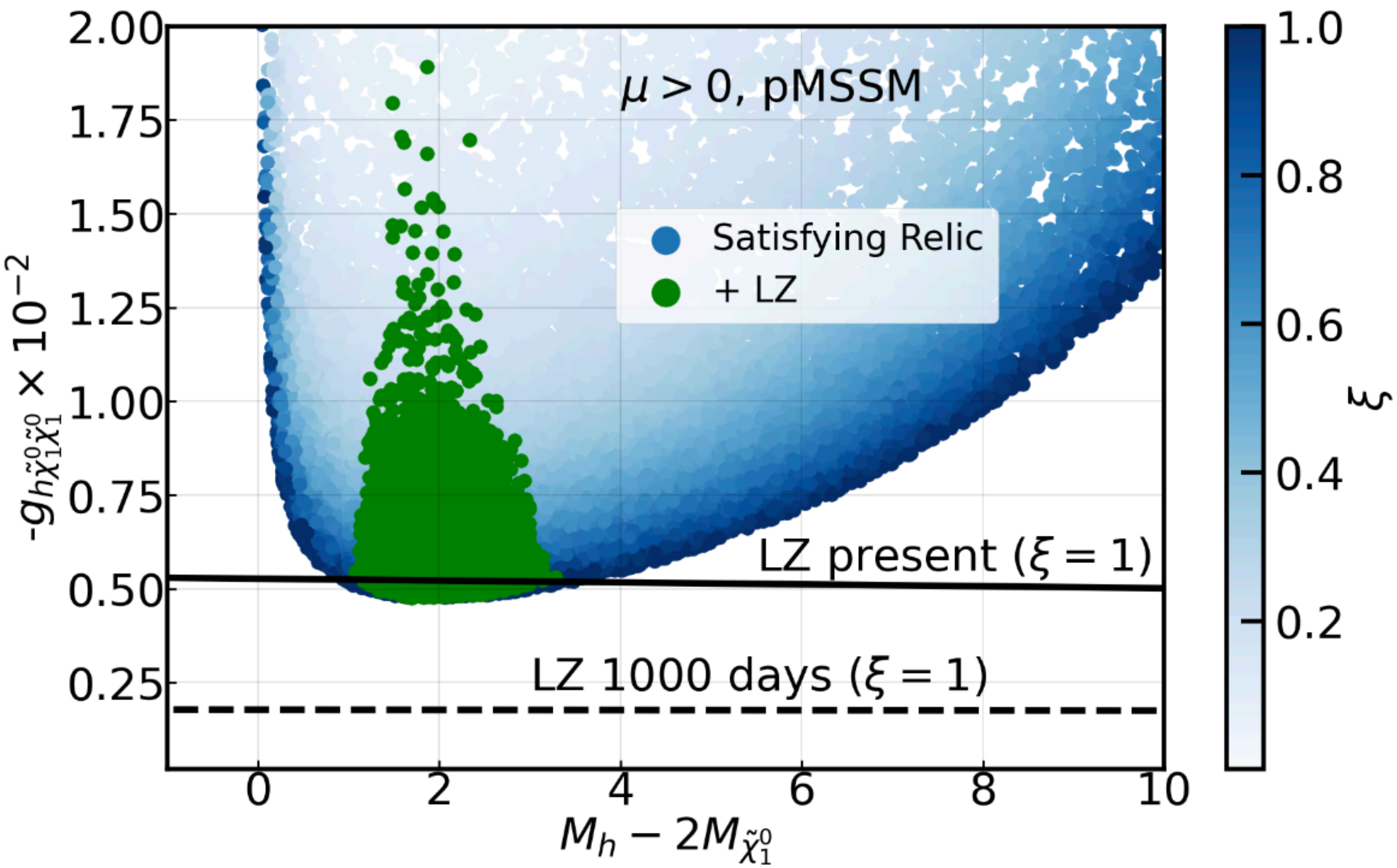
Z-FUNNEL EXCLUDED BY LZ

Taking into account 20% theoretical uncertainty in relic density - a small allowed region opens up after LZ

EXCLUDED BY ELECTROWEAKINO SEARCHES

The h-funnel for $\mu > 0$

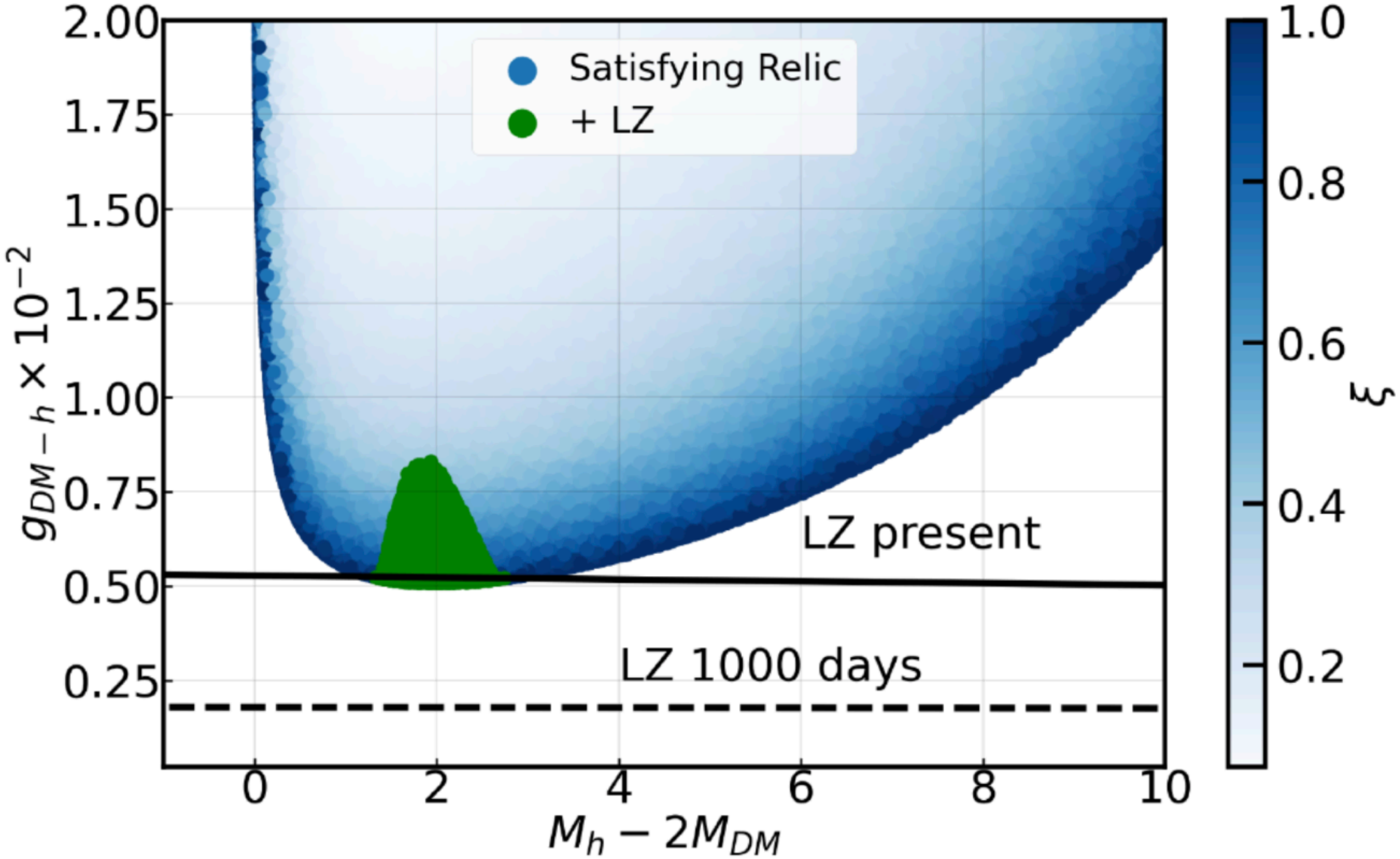
- Heavy higgsino have low values of couplings of LSP with Z and h
 - relic density condition not satisfied
- In h-funnel, extra handle of tanβ
 - relic satisfied only for low tanβ where coupling is high
- Effect of H not important



Heavy higgsinos in the h-funnel

- Heavy higgsino have low values of couplings of LSP with Z and h
  - relic density condition not satisfied
- In h-funnel, extra handle of tanβ
  - relic satisfied only for low tanβ where coupling is high
- Effect of H not important

Similar to any Majorana fermion coupled to only h



ALSO STRONGLY CONSTRAINED

Can be probed with few more days of LZ data

Light higgsinos still allowed by electroweakino searches?

Light higgsinos survive in the region where

$$M_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_3^0} - M_{\tilde{\chi}_1^0} \approx M_Z$$

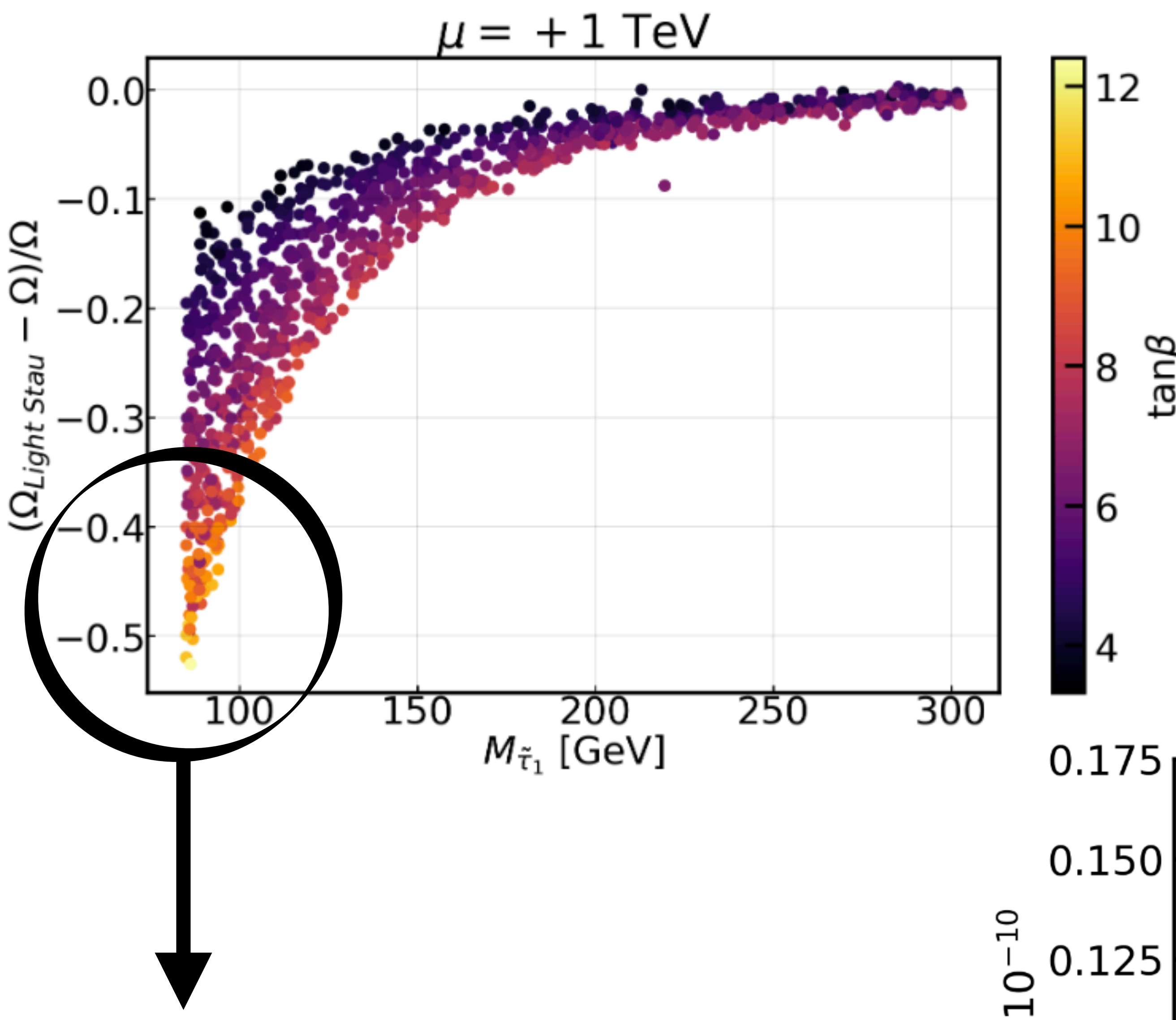
Performed an analysis with leptonic final states using XGBOOST

Signal significance of 3.6 (1.5) with 20% (50%) systematic uncertainty with 137 fb^{-1} of data at 14 TeV

Could be probed with upcoming analyses of the Run-2 data which have not yet been implemented in `SModelS` or in the **Run-3 of LHC**

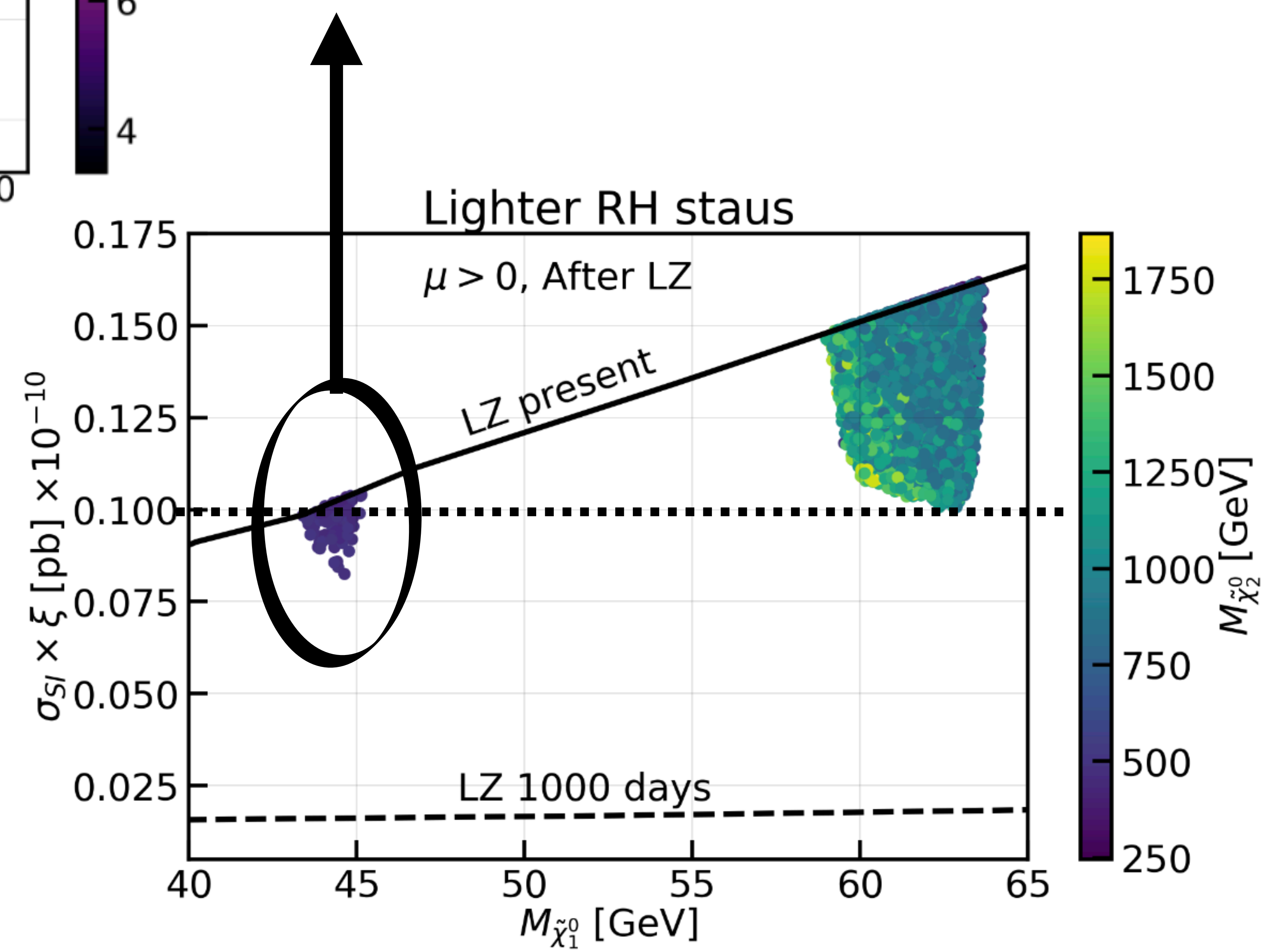
Experimental collaborations need to focus on this region of light higgsinos to provide a conclusive statement about their present status.

Caveat: Light staus



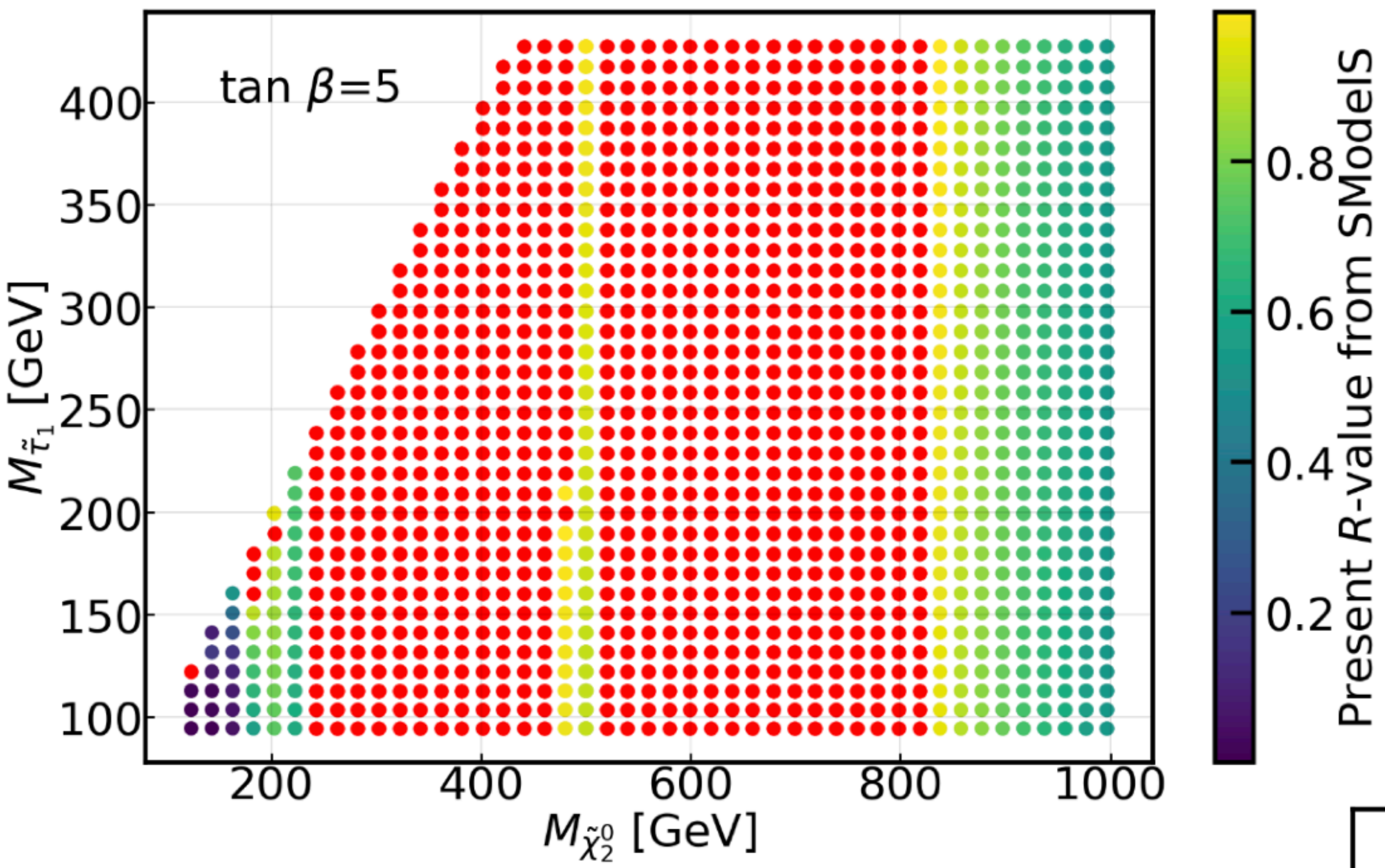
A region in the Z-funnel open up and in the h-funnel, we can go to lower DD cross-sections

- can be probed by full run of LZ



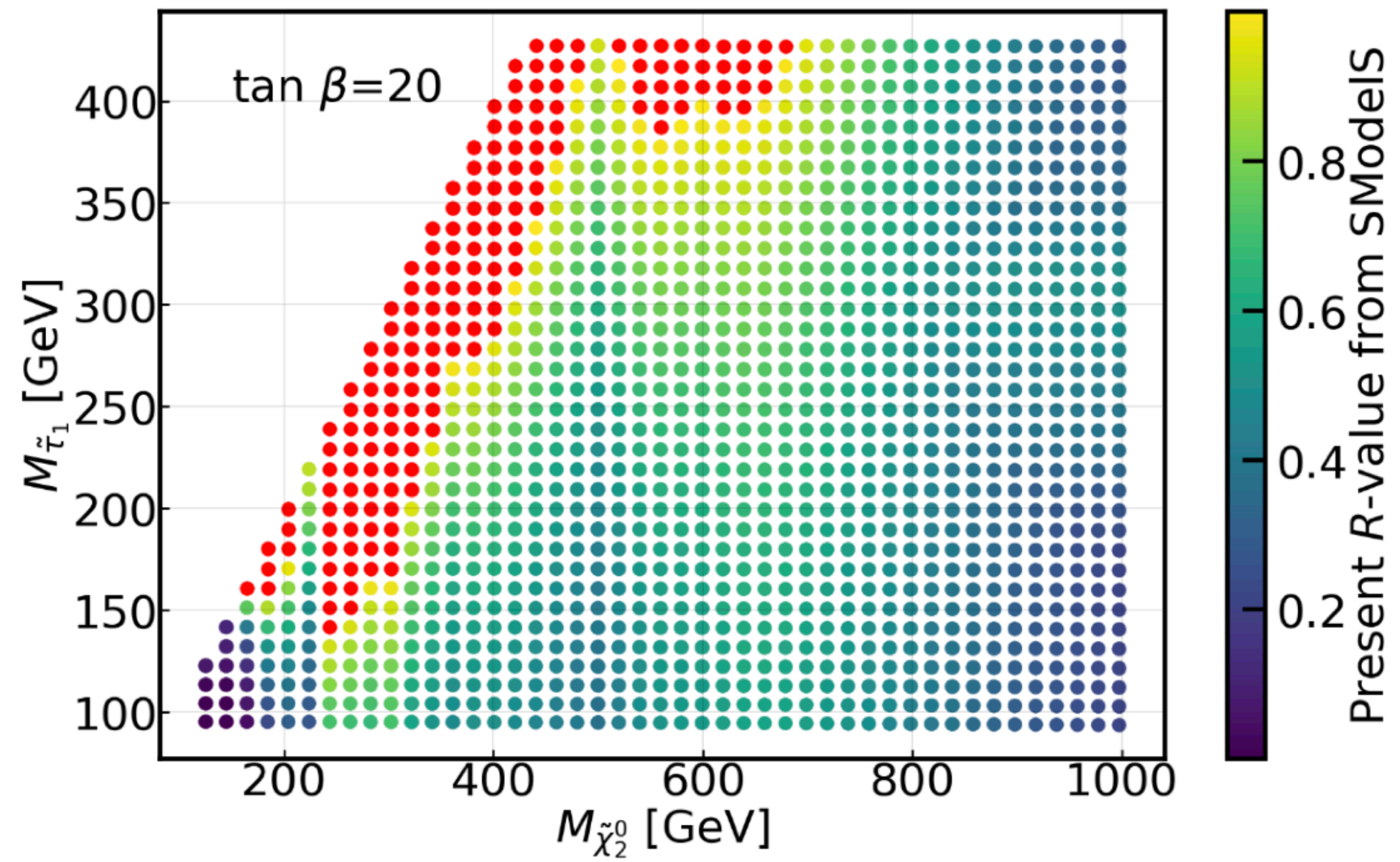
Below 100 GeV, the relic density can be reduced by 50% in the presence of a 90-95 GeV RH stau

Caveat: Light staus



Red regions: Excluded by present searches implemented in SModelS

Limits on Higgsinos weaken when their branching to staus increases



New regions of parameter space open - can be probed at LHC Run-3

Summary

The current experiments, especially the **recent results from the electroweakino searches at the LHC** and the **LZ dark matter DD experiment** have squeezed the allowed parameter space to regions which can either be

- regions of **heavy higgsinos** very close to being probed by few days of **LZ** data
- contain very low mass higgsinos which can be targeted at the **Run-3 of LHC** with dedicated analyses **to be sensitive in this narrow gap**.

In the presence of **light staus**, extra regions of parameter space open up

- due to reduced relic density
- relaxed collider constraints when higgsinos decay to stau

These regions are also within the reach of the **LZ experiment and the LHC Run-3**.

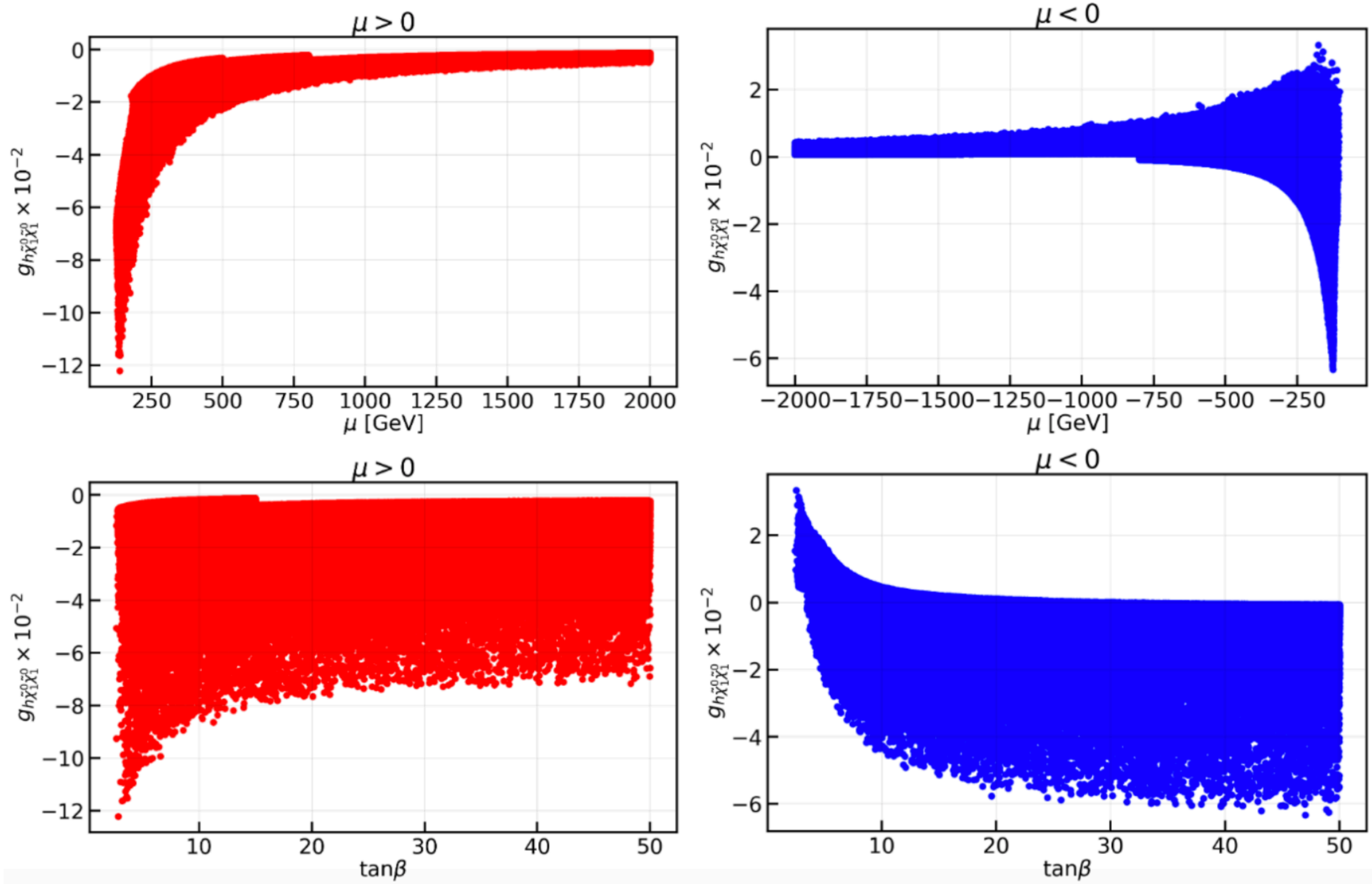
Takeaway message

How does this very conventional dark matter candidate stand against the recent experimental results?

At present, we are at a very exciting juncture where the *experiments lined up might exclude the possibility of a light neutralino thermal DM in pMSSM altogether*, or we might be *very close to start observing the first hints of new physics*.

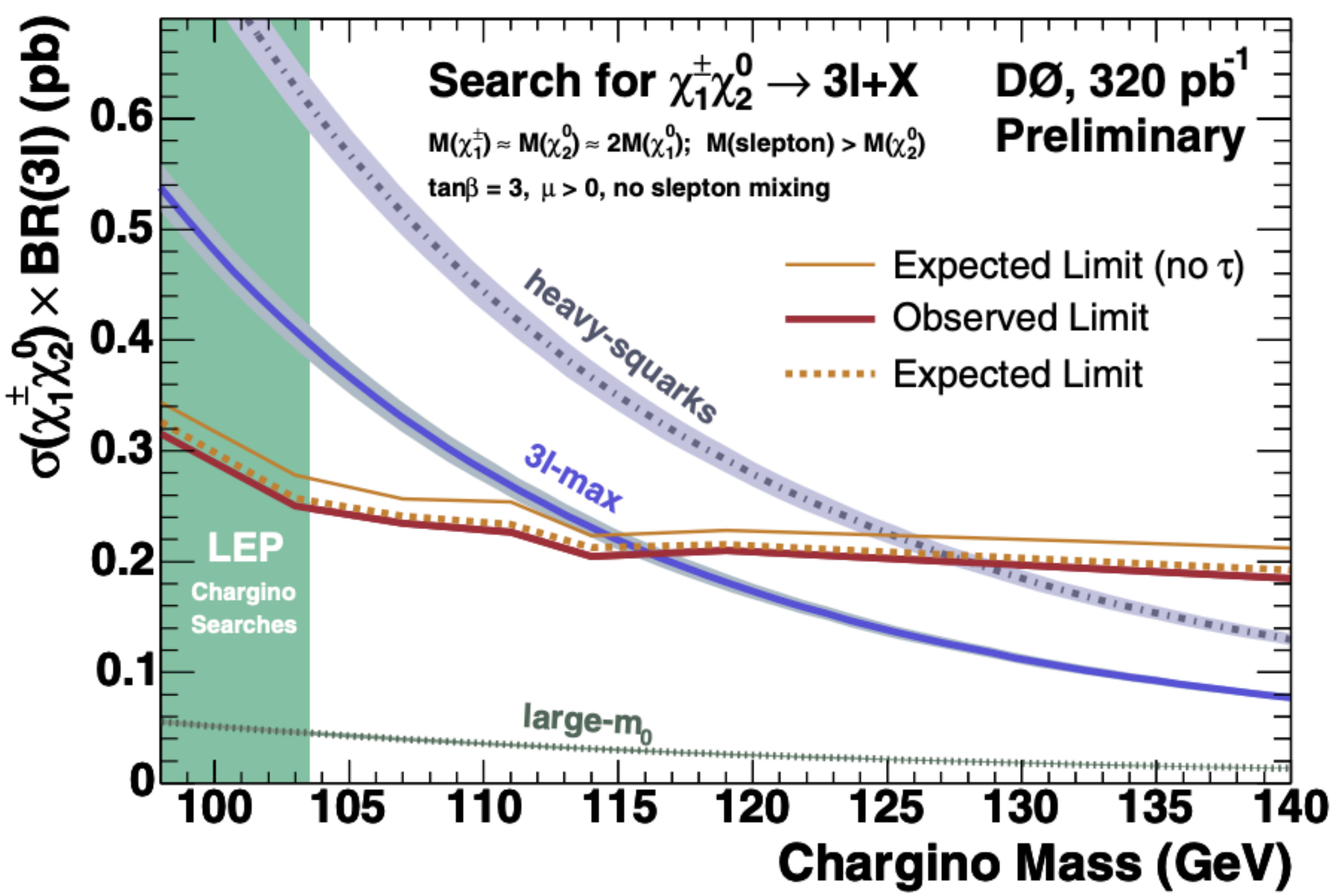
Thank you for your attention

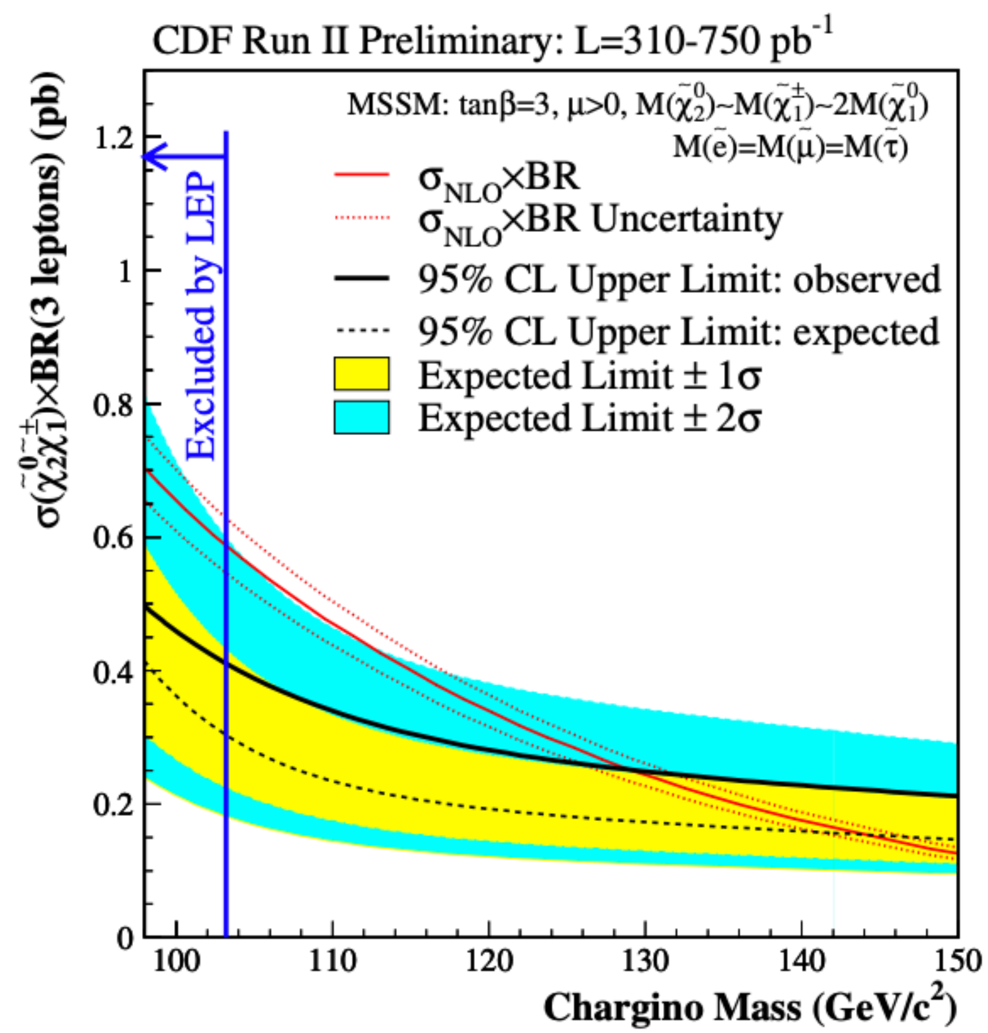
Back up slides



Benchmarks (*mass parameters in* GeV)			$m_h[\Delta^{FH}_{M_h}]$ [GeV]	$\sigma_{SI} \times \xi \times 10^{-10}$ [pb]
$\mu > 0$	h-funnel	$M_t = 173.21,\ M_1 = 62.5,\ M_2 = 2000,\ \mu = 1000,\ \tan\beta = 5,\ M_A = 3000,$ $M_{\tilde{Q}_{3L}} = 10000,\ M_{\tilde{t}_R} = 10000,\ M_{\tilde{b}_R} = 10000,\ A_t = 10000,\ M_3 = 3000$	125.38 [±0.97]	0.151
$\mu < 0$	Z-funnel	$M_t = 173.21,\ M_1 = 44,\ M_2 = 2000,\ \mu = -124,\ \tan\beta = 5,\ M_A = 3000,$ $M_{\tilde{Q}_{3L}} = 10000,\ M_{\tilde{t}_R} = 10000,\ M_{\tilde{b}_R} = 10000,\ A_t = 10000,\ M_3 = 3000$	125.88 [±0.96]	0.746×10^{-3}
	h-funnel	$M_t = 173.21,\ M_1 = 68,\ M_2 = 2000,\ \mu = -150,\ \tan\beta = 50,\ M_A = 3000,$ $M_{\tilde{Q}_{3L}} = 5000,\ M_{\tilde{t}_R} = 5000,\ M_{\tilde{b}_R} = 5000,\ A_t = -5000,\ M_3 = 3000$	125.67 [±0.63]	0.143
		$M_t = 173.21,\ M_1 =,\ M_2 = 2000,\ \mu = -1000,\ \tan\beta = 4.5,\ M_A = 3000,$ $M_{\tilde{Q}_{3L}} = 10000,\ M_{\tilde{t}_R} = 10000,\ M_{\tilde{b}_R} = 10000,\ A_t = 10000,\ M_3 = 3000$	125.15 [±0.99]	0.150

Tevatron Limit





Beyond the Standard Model physics at the Tevatron,
Mario P Giordani 2006 J. Phys.: Conf. Ser. 53 329

XGBOOST analysis

Final state: 3l+MET
No SFOS pair of leptons

Backgrounds: $lll\nu (l \equiv e, \mu, \tau), ZZ, t\bar{t}, VVV$, Wh, Zh, ggF and VBF production of h with $h \to ZZ^*$, $t\bar{t}h, t\bar{t}W$, and $t\bar{t}Z$

exactly three leptons satisfying $p_T > 25{,}25{,}20$ GeV and $|\eta| < 2.4$, a veto on b-jets with $p_T > 30$ GeV and $|\eta| < 2.5$.

- Transverse momenta (p_T) of the three leptons
- Transverse mass (M_T) and contransverse mass (M_{CT}) of each of the three leptons with the $\not{E}_T$
- Minimum and maximum values of ΔR between opposite sign lepton pairs along with their $\Delta\eta$ values
- Invariant mass of the opposite sign lepton pairs with minimum and maximum ΔR
- Missing transverse momentum
- Number of jets in the event with the p_T of the two leading jets
- Scalar sum of p_T of all the jets in the event (H_T)
- Invariant mass of the three leptons

Following are the hyperparameters of the XGBOOST model:

```
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'max_depth':7, 'alpha':5, 'eval_metric':'mlogloss', 'num_round':1000, 'early_stopping_rounds':3
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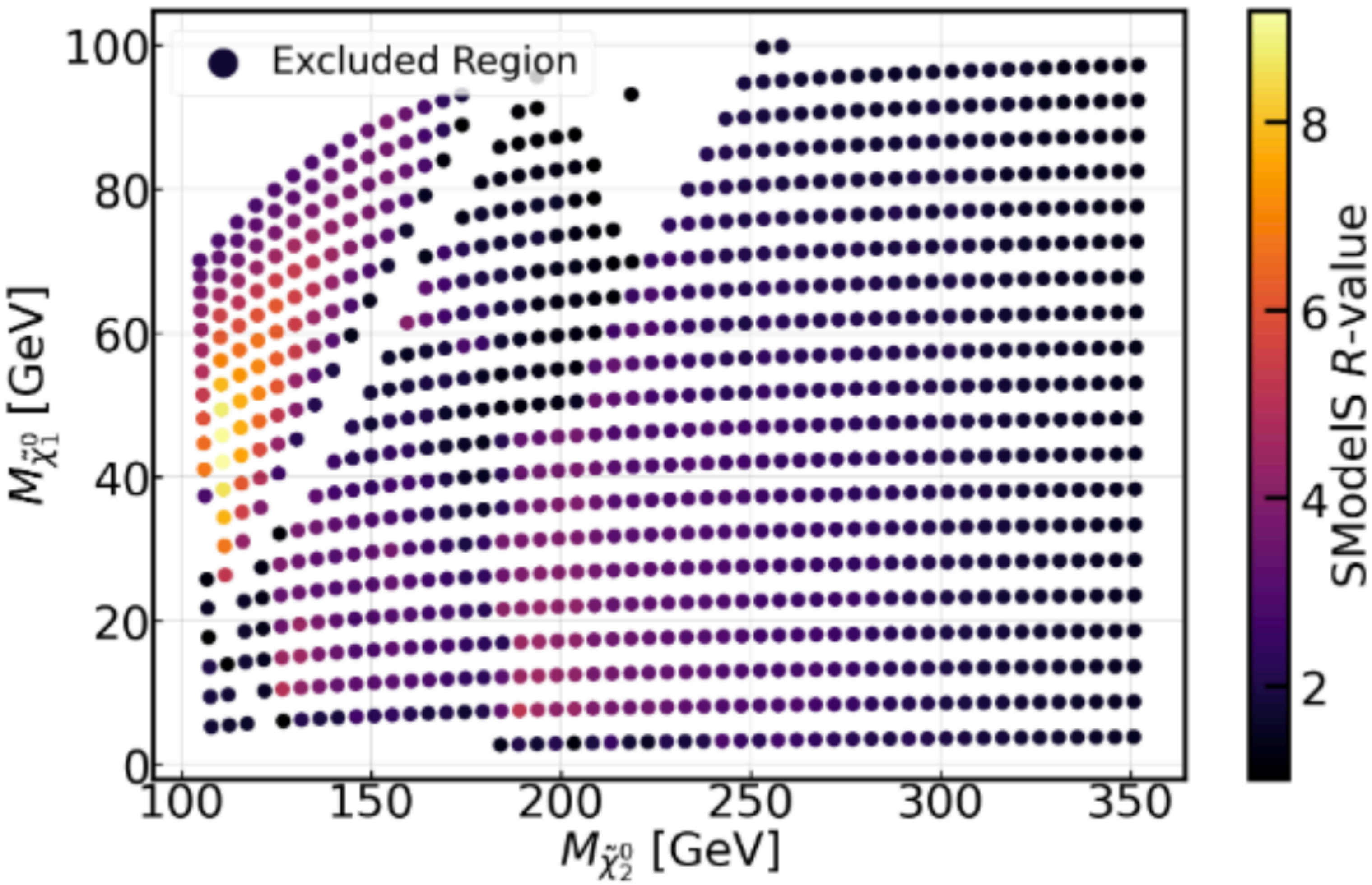
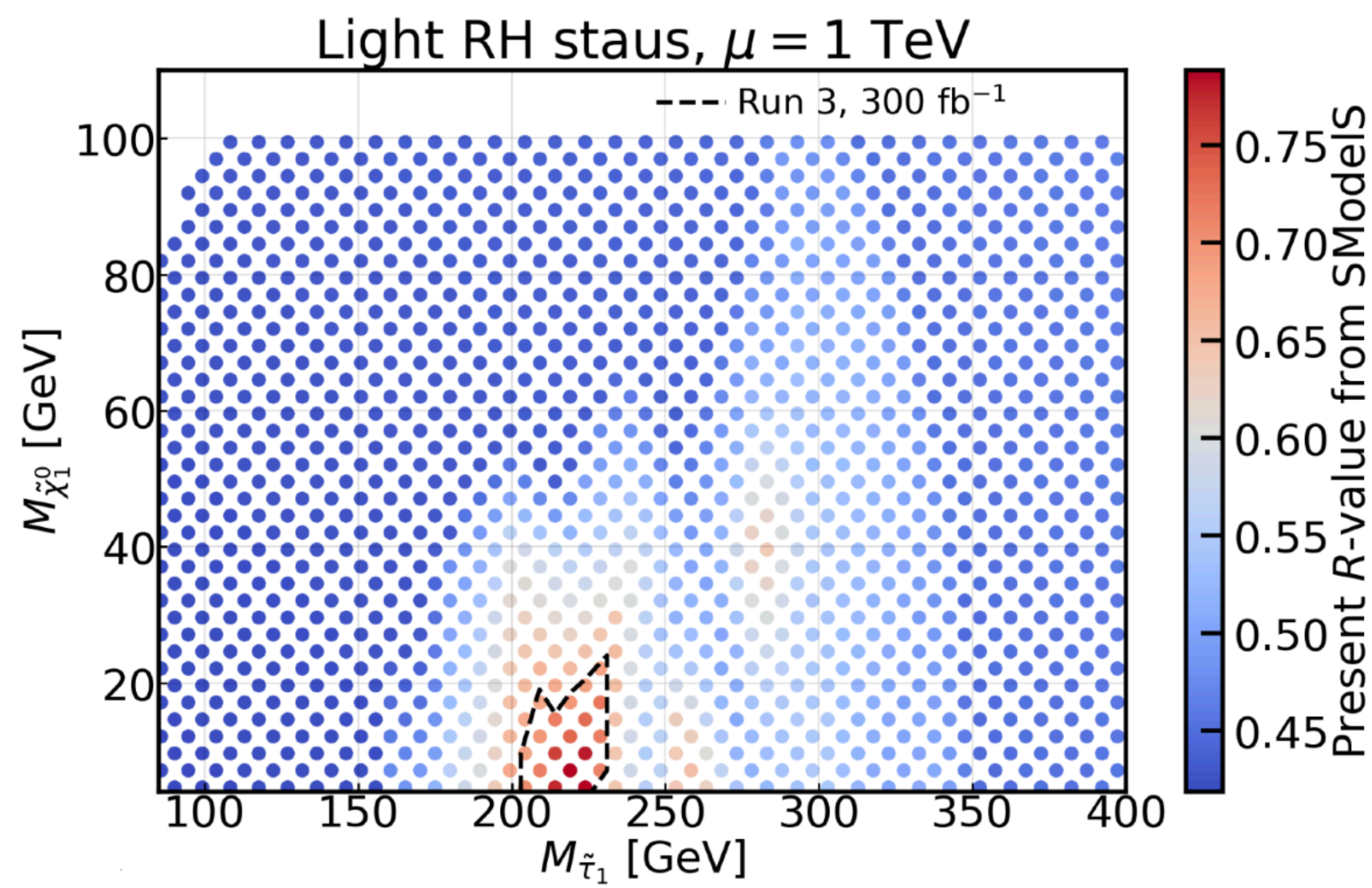


Excluded Region
$M_{\tilde{\chi}_1^0}$ [GeV]
$M_{\tilde{\chi}_2^0}$ [GeV]
SModelS R-value



Light RH staus, $\mu = 1$ TeV
Run 3, 300 fb^{-1}
$M_{\tilde{\chi}_1^0}$ [GeV]
$M_{\tilde{\tau}_1}$ [GeV]
Present R-value from SModelS