Roadmap of Dark Matter models for Run 3

CERN

Is the light neutralino thermal dark matter in the pMSSM ruled out?

based on PRL 131 (2023) 1, 011802 and arXiv:2402.07991

with Rahool K. Barman, Geneviève Bélanger, Biplob Bhattacherjee, and Rohini Godbole

Rhitaja Sengupta

bctp

UNIVERSITÄT BONN

14.05.2024

Why MSSM DM?

SUSY is a well established and well motivated BSM theory

Provides solutions to many drawbacks of the SM, along with a DM candidate in RPC SUSY

Discovery of the light Higgs boson (~125 GeV) complies with SUSY

The lightest neutralino in RPC MSSM is a well motivated candidate for thermal DM

$$M_{\tilde{\chi}_1^0} \lesssim \frac{M_h}{2}$$

Annihilations to SM particles only via the Z and the light Higgs boson

Contributes to the invisible decay of the Higgs boson

Why MSSM DM?

Has been in limelight for a long time

$\Downarrow$

Has been under test at multiple experiments

No hints yet

A relatively smaller allowed parameter space

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

Are there any gaps which can be focal points for Run-3 of LHC?

The lightest neutralino DM in pMSSM

* **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

The lightest neutralino DM in pMSSM

✱ 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*

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

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

N_{1i} : ith component in $\tilde{\chi}_1^0$, where $i = \tilde{B}, \tilde{W}^0, \tilde{H}_u^{\ 0}, \tilde{H}_d^{\ 0}$

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

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

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

M_1 bino mass

M_2 wino mass

μ higgsino mass

$\tan\beta$ ratio of vevs

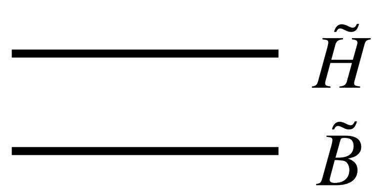
M_A pseudoscalar mass

$M_{\tilde{Q}_{3L}}$, $M_{\tilde{t}_R}$, $M_{\tilde{b}_R}$ 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`

Present constraints

- Searches at LEP
- Flavor constraints
- Higgs constraints
- Dark Matter constraints
- Electroweakino searches

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- Searches at LEP
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invisible decay of Z-boson from new physics

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

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

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

OPAL, EPJC 35, 1–20 (2004)

Present constraints

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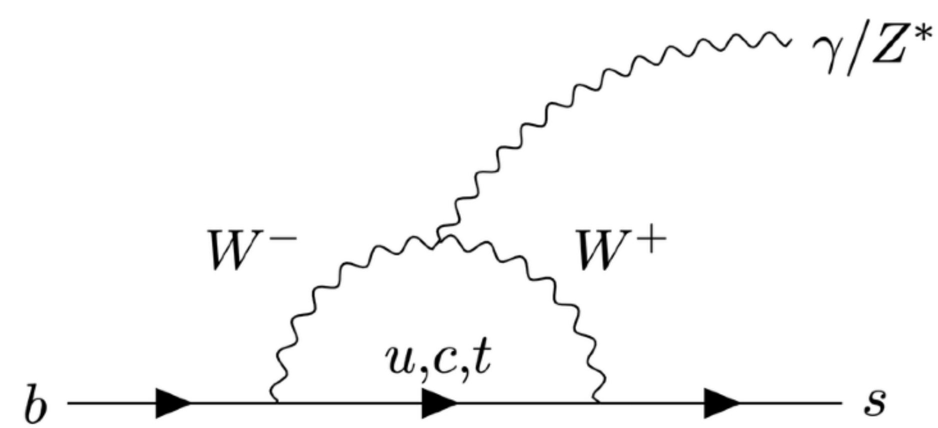
* Rare processes in SM
* Might receive contribution from MSSM
* Precise measurement of the branching of these processes constrain the MSSM parameter space



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

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

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

CMS & LHCb, Nature 522, 68–72 (2015)

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

Belle, PRD 82, 071101(R)

Present constraints

Searches at LEP

Flavor constraints

Higgs constraints

Dark Matter constraints

Electroweakino searches

observed Higgs boson mass

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

`FeynHiggs 2.18.1`

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

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

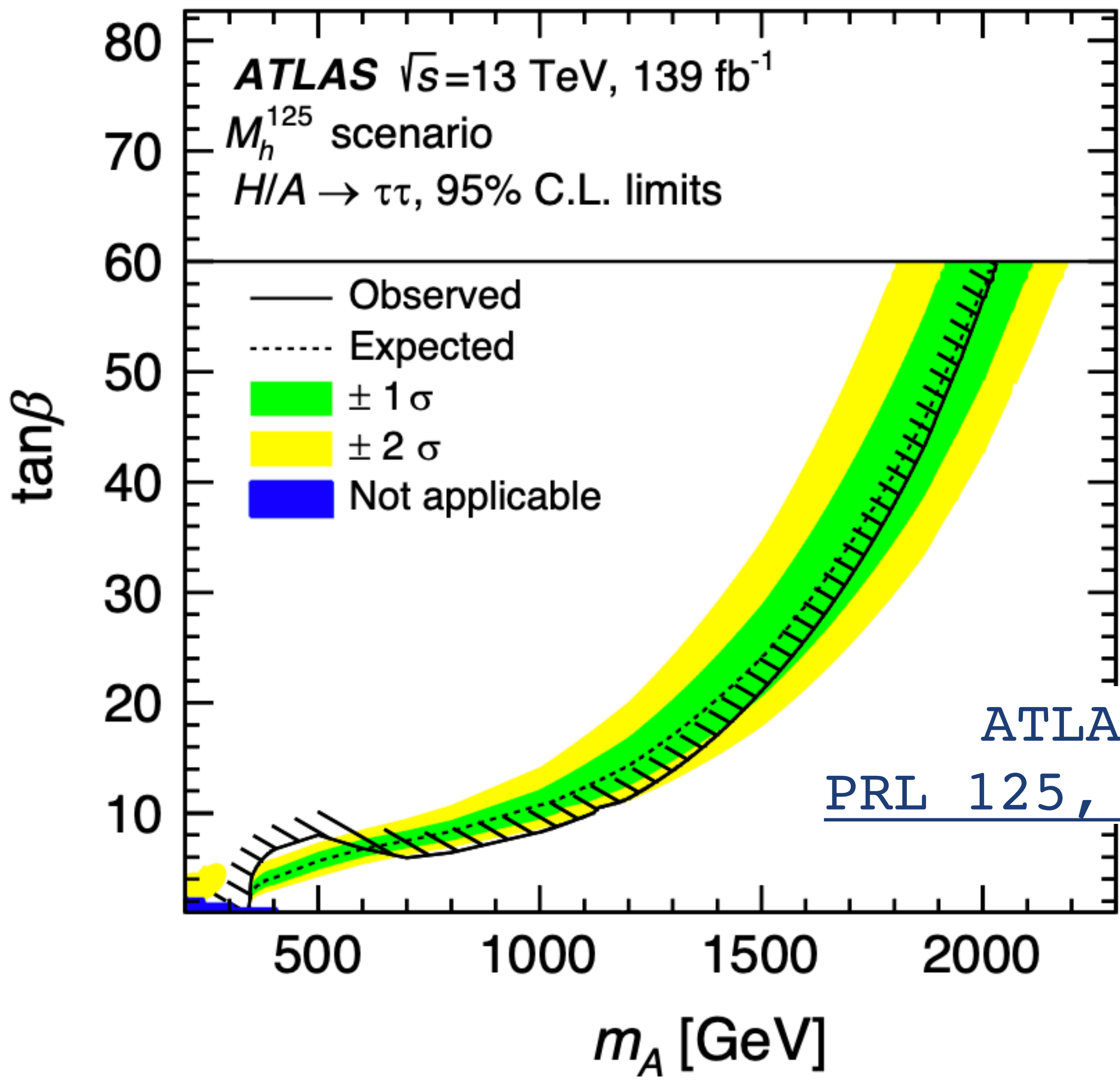
ATLAS, ATLAS-CONF-2020-052

Present constraints

- Searches at LEP
- Flavor constraints
- **Higgs constraints**
- Dark Matter constraints
- Electroweakino searches

Heavy Higgs searches

`HiggsBounds 5.10.0`



ATLAS, [PRL 125, 051801]

Present constraints

- Searches at LEP
- Flavor constraints
- Higgs constraints
- **Dark Matter constraints**
- Electroweakino searches

Relic density

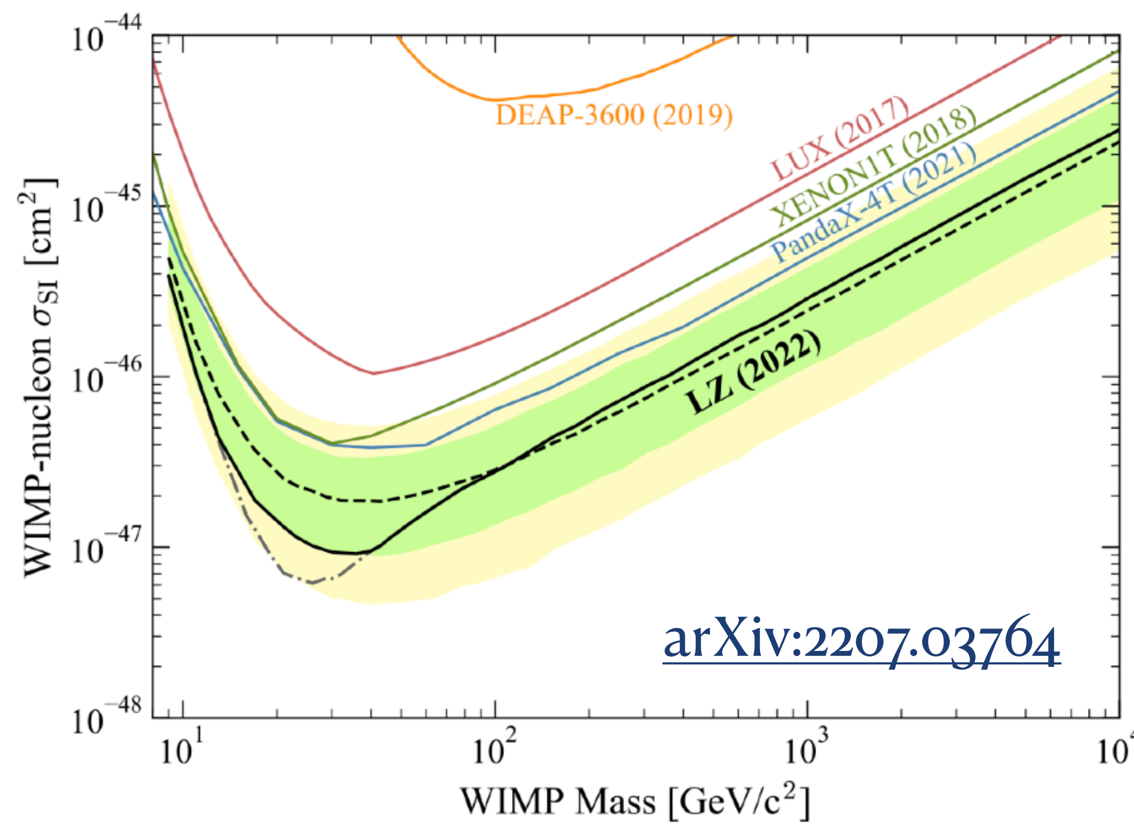
Observed relic density of Dark Matter:

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

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

If underabundant, multi-component DM

Direct DM detection



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

Present constraints

- Searches at LEP
- Flavor constraints
- Higgs constraints
- Dark Matter constraints
- **Electroweakino searches**

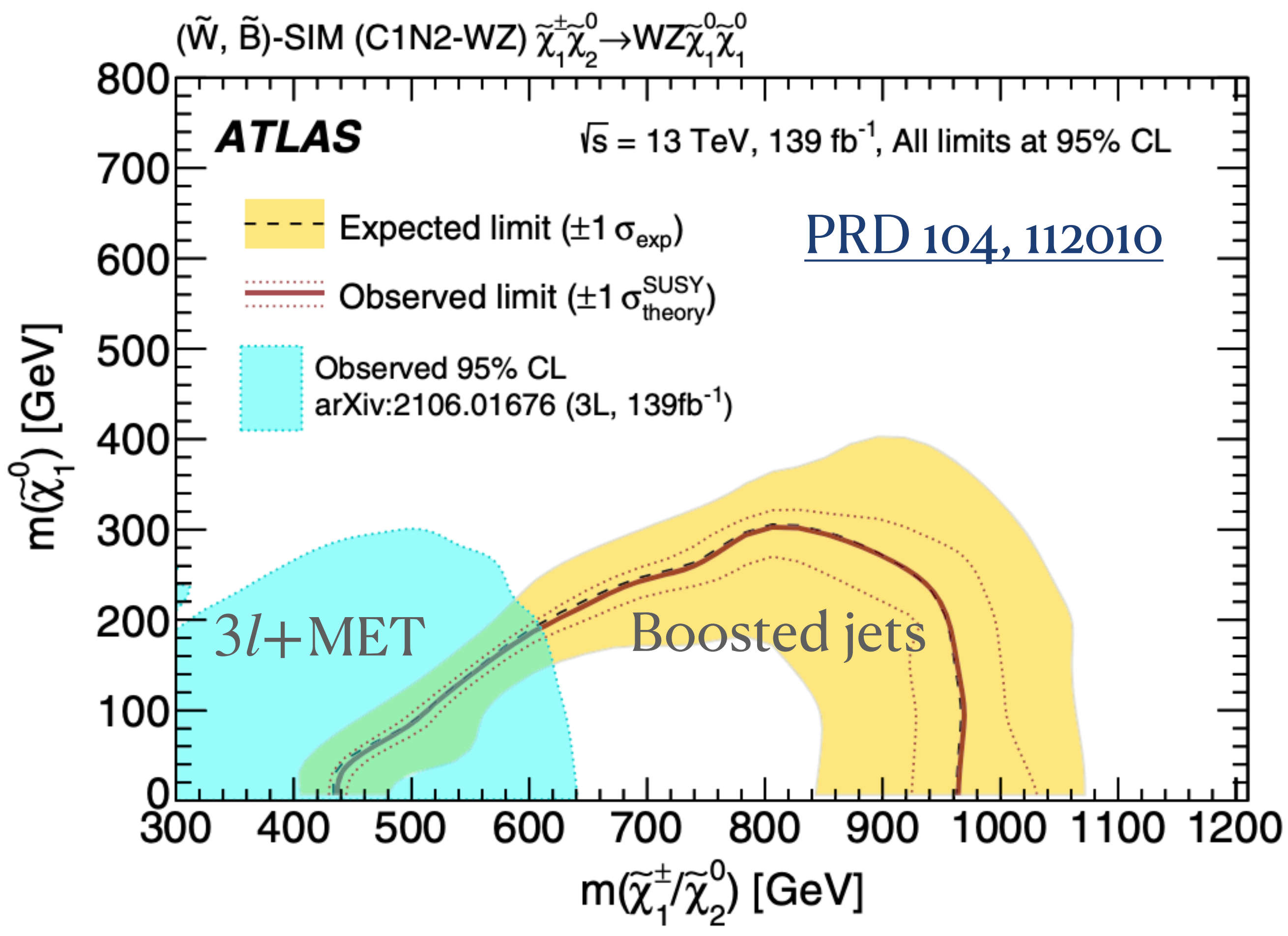
results of direct searches for chargino and neutralino at the ATLAS and CMS experiments of the LHC

SModelS 2.2.1

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

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

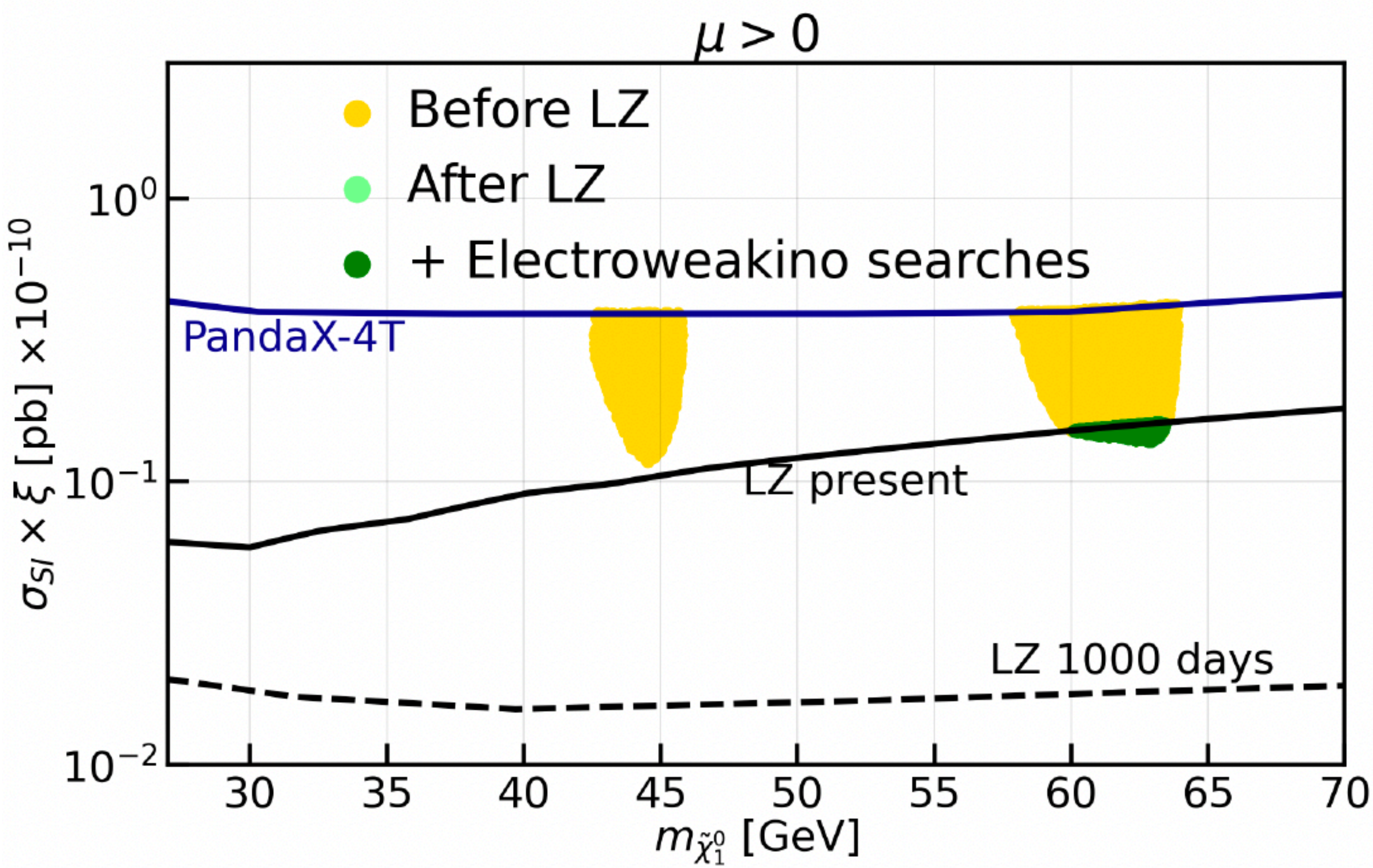
$$\tilde{\chi}_2^0 / \tilde{\chi}_3^0 \to (Z/h) \tilde{\chi}_1^0$$



Current status

- Positive μ

Spin-independent DD limit

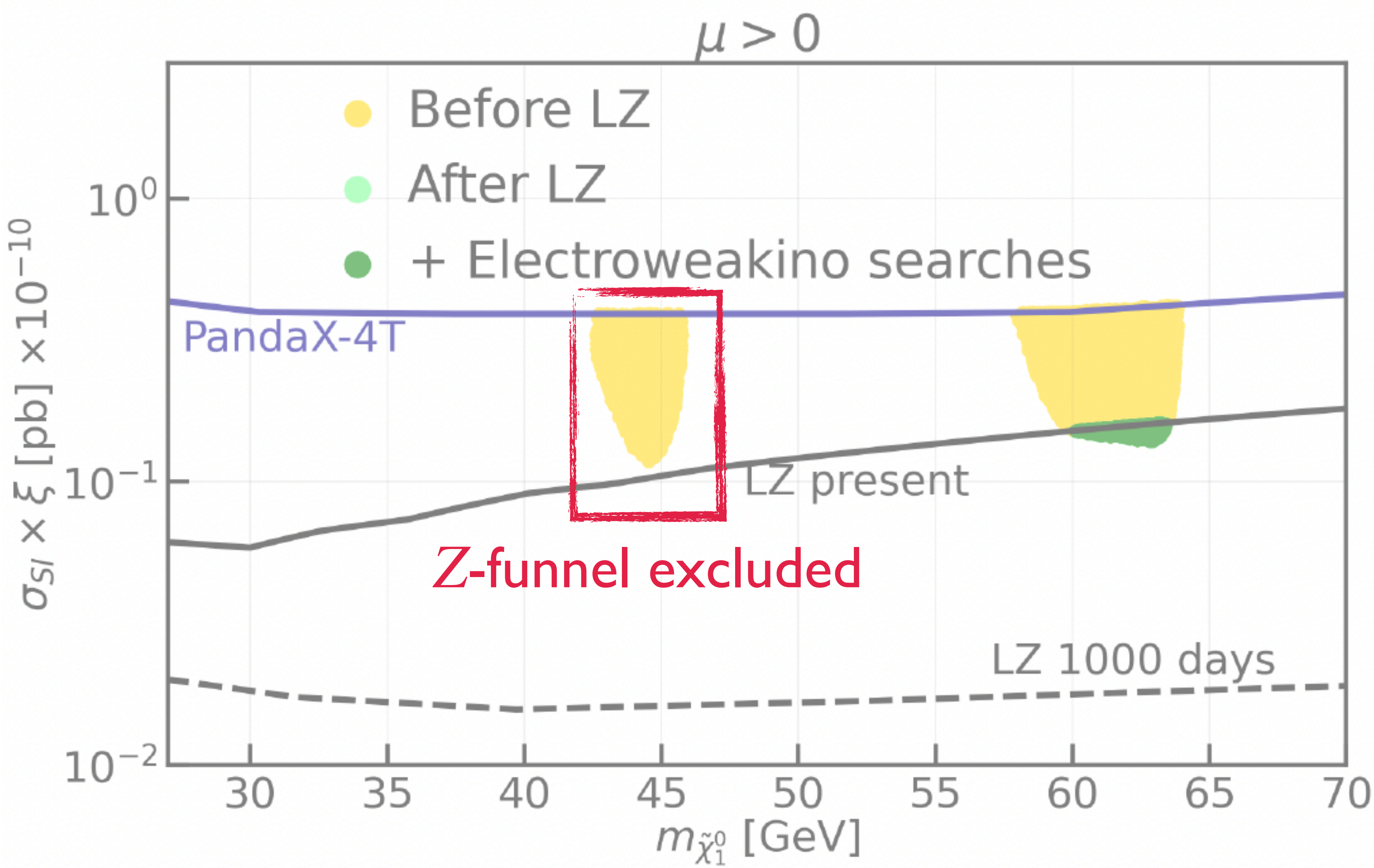


Before LZ: constraints from LEP, flavor, Higgs constraints, relic density and the DD experiments **XENON-1T**, **PICO-60** and **PandaX-4T**

Current status

- **Positive μ**

Spin-independent DD limit



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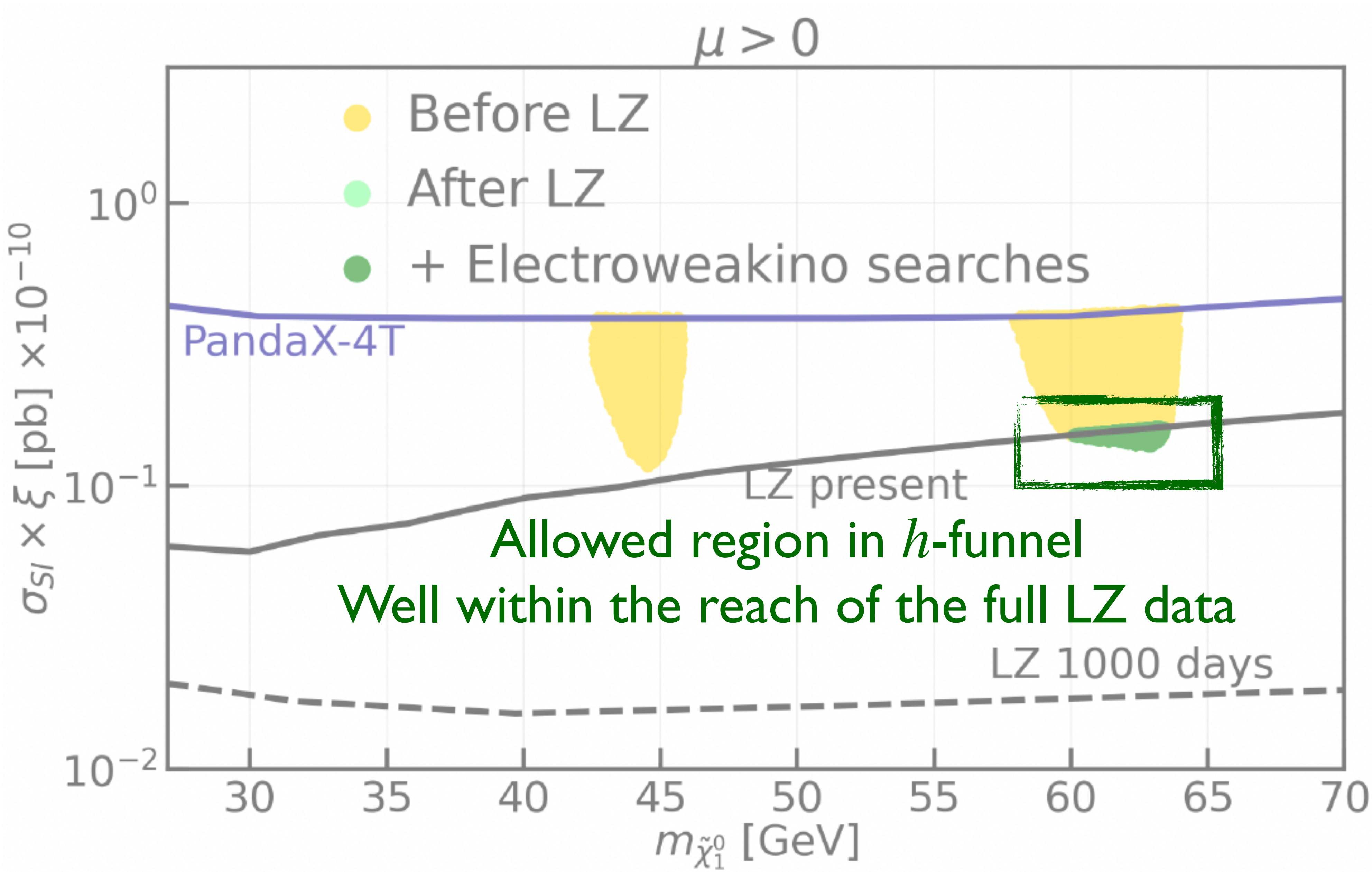

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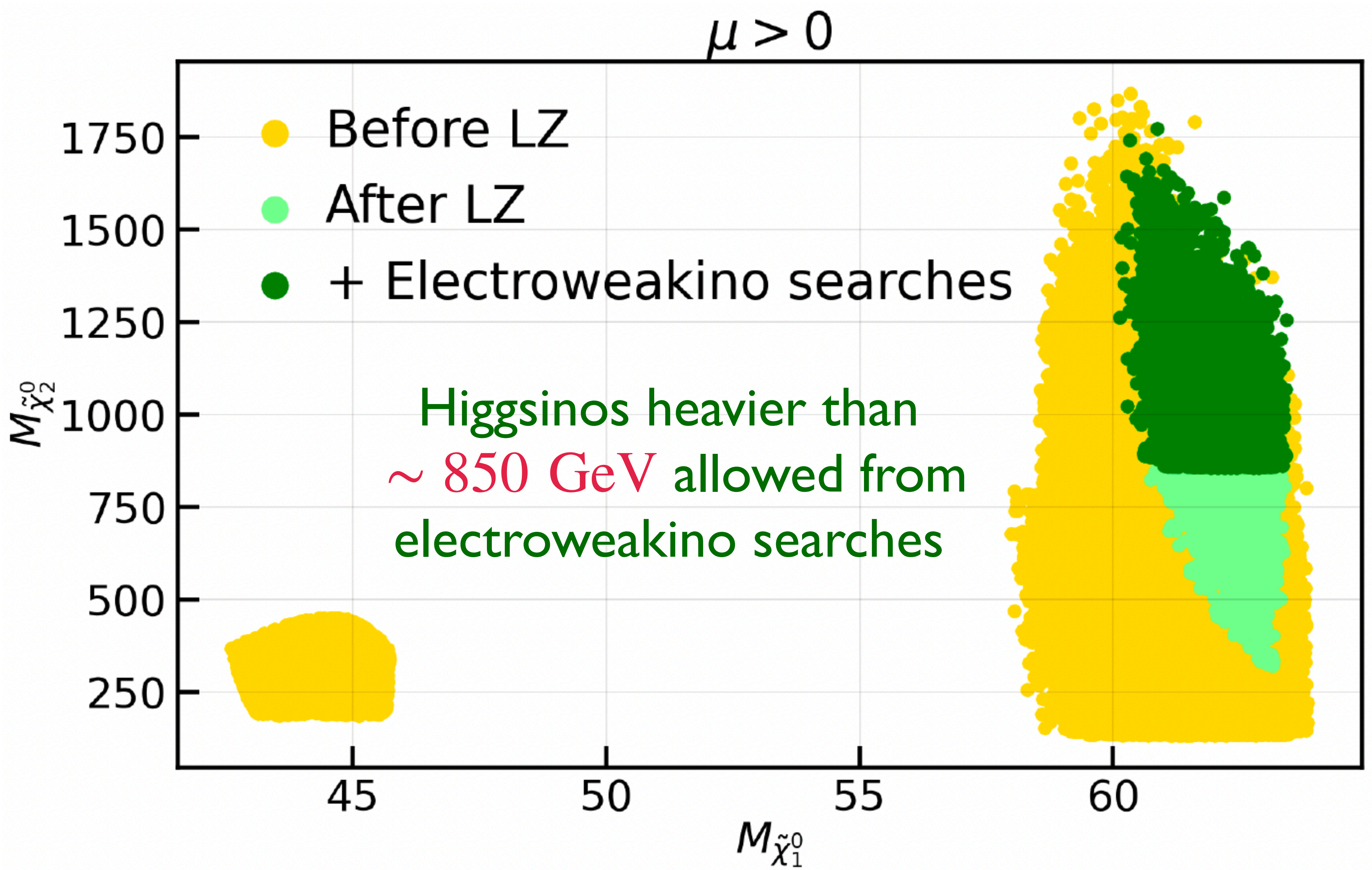


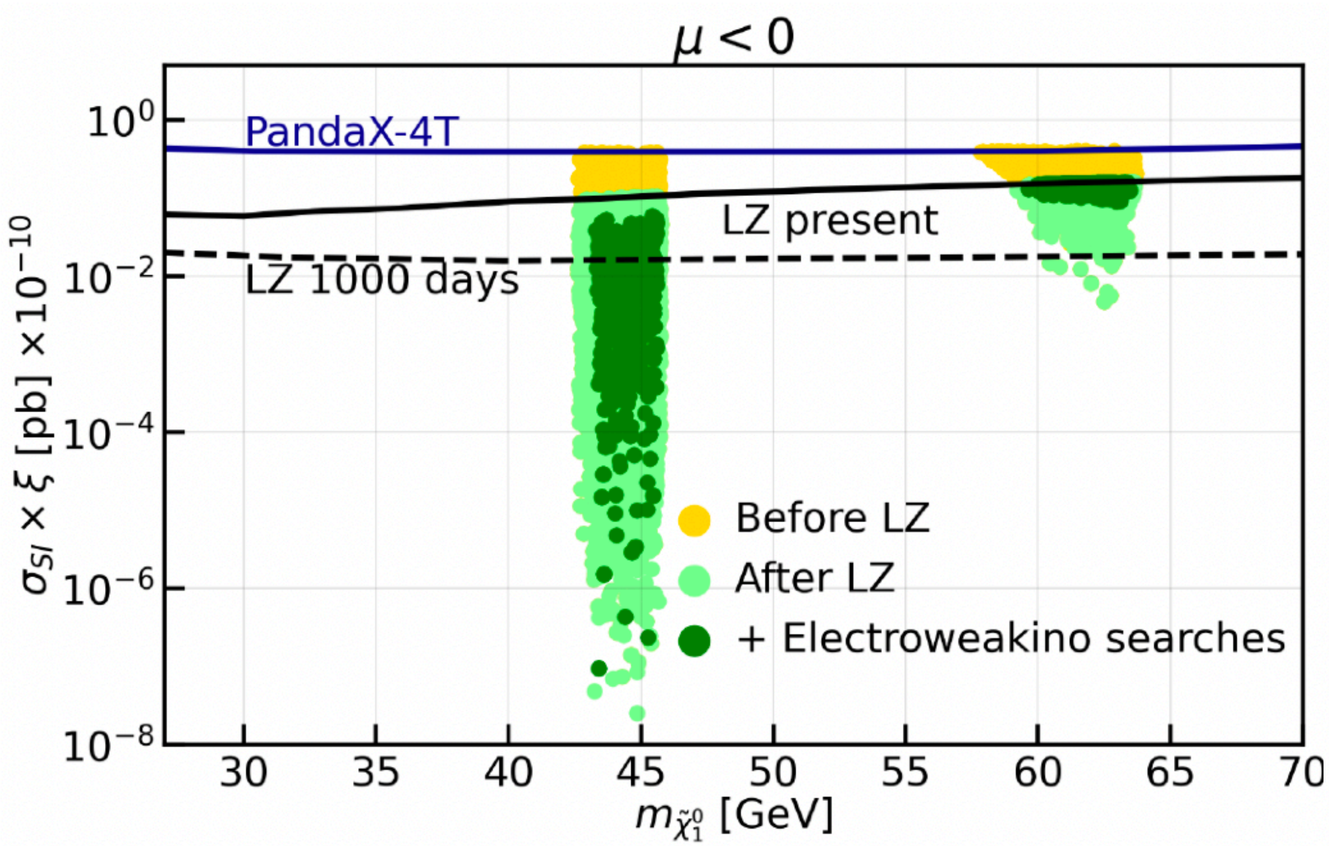
Before LZ: constraints from LEP, flavor, Higgs constraints, relic density and the DD experiments **XENON-1T**, **PICO-60** and **PandaX-4T**

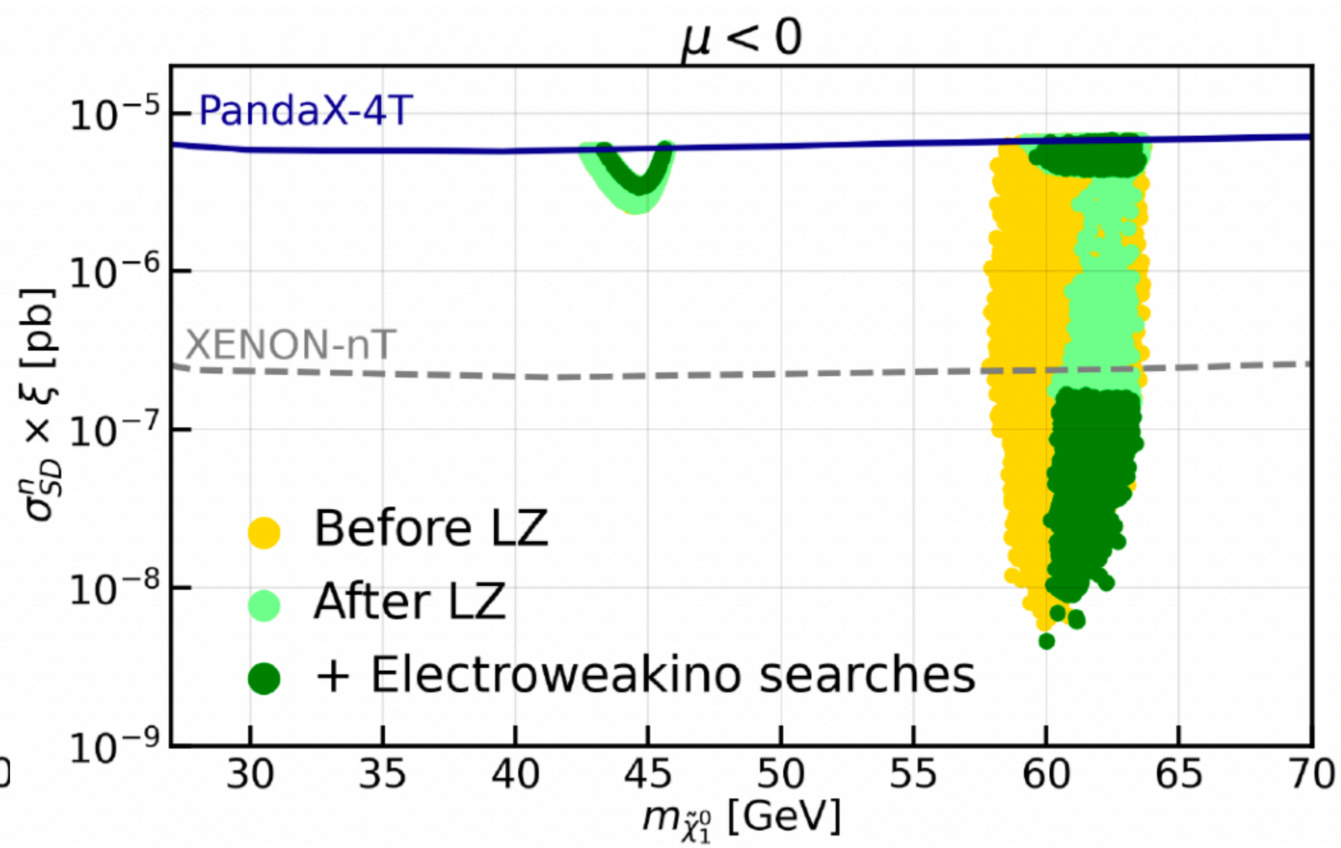
Current status

Negative μ

Spin-independent DD limit

Spin-dependent neutron DD limit





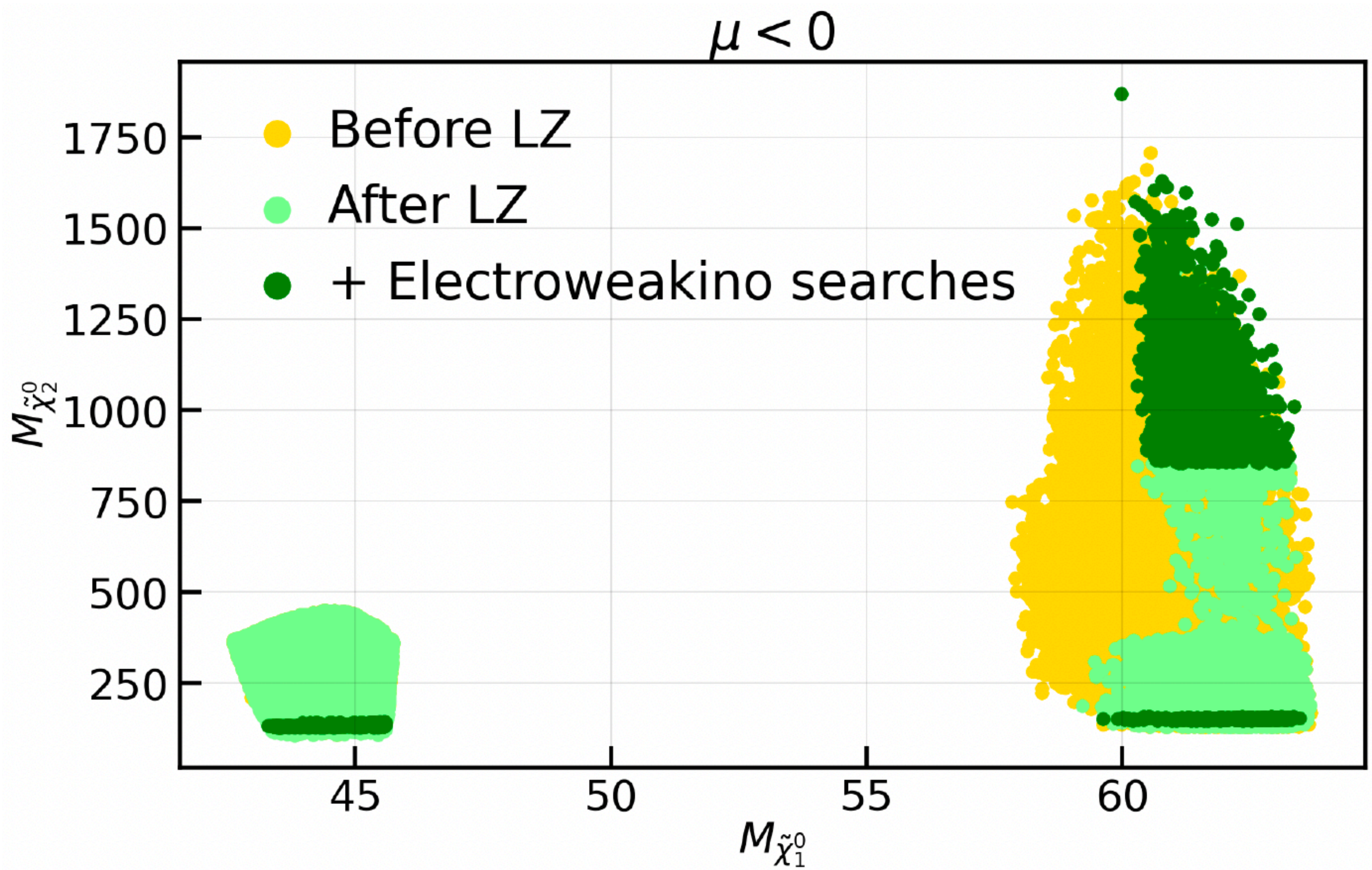
h-funnel within the reach of the full LZ data

Z-funnel within the reach of Xenon-nT

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

Current status

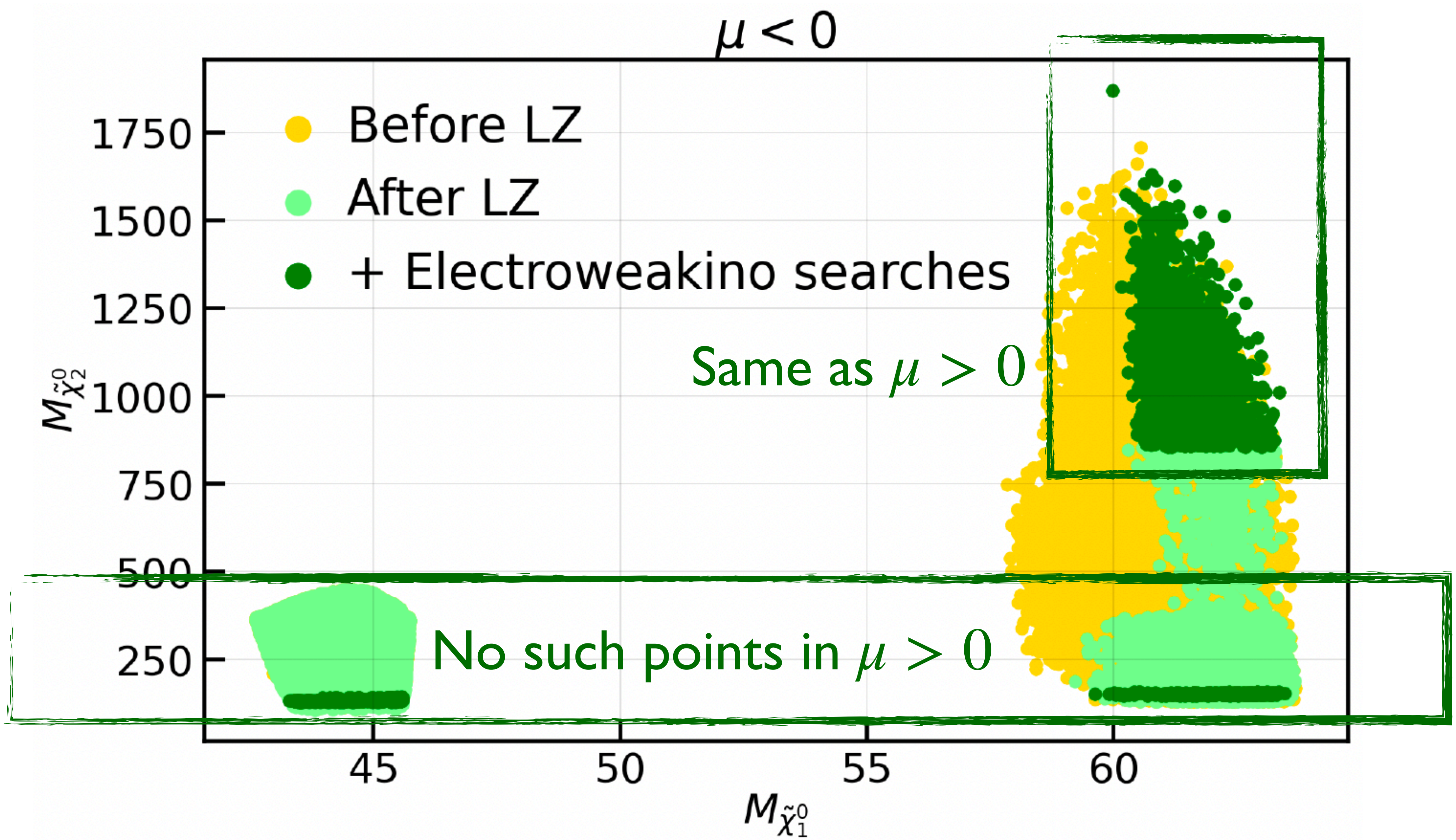
- Negative μ



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

Current status

- Negative μ



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

Impact of LZ dependent on the sign of μ

LZ limits the SI DD cross-section

Both h and H contribute to this

tanβ enhanced

$\mu > 0$

These contributions constructively interfere for down type quarks

$\mu < 0$

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

A few words on the parameter space scan...

Random scan over the parameter space

↓

Tune M_1 such that $M_{\tilde{\chi}_1^0}$ is within $\frac{M_Z}{2} \pm 5$ GeV and $\frac{M_h}{2} \pm 3$ GeV

Scanned over 3×10^8 parameter space points

Dedicated scans:

(A) high values of $|\mu|$ (≳ 800 GeV) with low tan β (≲ 10) in the h funnel of both positive and negative μ,

(B) low values of $|\mu|$ (≲ 200 GeV) in both the Z and h funnels of negative μ

Roadmap of light neutralino DM for Run-3

- Heavy higgsinos
- Light higgsinos
- Light staus
- Hints for non-standard cosmology

Roadmap of light neutralino DM for Run-3

Heavy higgsinos

Light higgsinos

Light staus

Hints for non-standard cosmology

Heavy higgsinos

			Benchmarks (*mass parameters in* GeV)	$M_h[\Delta^{FH}_{M_h}]$ [GeV]	$\sigma_{SI} \times \xi \times 10^{-10}$ [pb]
$\mu > 0$	h-funnel	BP1	$M_t = 173.21,\ M_1 = 62.5,\ M_2 = 2000,\ \mu = 1000,\ \tan\beta = 5,\ M_A = 3000,$ $M_{\tilde{Q}_{3L}} = 10000,\ M_{\tilde{t}_R} = 10000,\ M_{\tilde{b}_R} = 10000,\ A_t = 10000,\ M_3 = 3000$	125.38 [±0.97]	0.151
$\mu < 0$	Z-funnel	BP2	$M_t = 173.21,\ M_1 = 44,\ M_2 = 2000,\ \mu = -124,\ \tan\beta = 5,\ M_A = 3000,$ $M_{\tilde{Q}_{3L}} = 10000,\ M_{\tilde{t}_R} = 10000,\ M_{\tilde{b}_R} = 10000,\ A_t = 10000,\ M_3 = 3000$	125.88 [±0.96]	7.46×10^{-4}
	h-funnel	BP3	$M_t = 173.21,\ M_1 = 68,\ M_2 = 2000,\ \mu = -150,\ \tan\beta = 50,\ M_A = 3000,$ $M_{\tilde{Q}_{3L}} = 5000,\ M_{\tilde{t}_R} = 5000,\ M_{\tilde{b}_R} = 5000,\ A_t = -5000,\ M_3 = 3000$	125.67 [±0.63]	0.143
		BP4	$M_t = 173.21,\ M_1 =,\ M_2 = 2000,\ \mu = -1000,\ \tan\beta = 4.5,\ M_A = 3000,$ $M_{\tilde{Q}_{3L}} = 10000,\ M_{\tilde{t}_R} = 10000,\ M_{\tilde{b}_R} = 10000,\ A_t = 10000,\ M_3 = 3000$	125.15 [±0.99]	0.150

- Hadronic decay channels of the W and Z bosons more sensitive than the leptonic ones
- The current ATLAS result for the hadronic final state excludes higgsinos below 850 GeV
- Assuming that the upper limit on the cross-section improves by a factor of $\sqrt{\mathscr{L}}$ with increasing luminosity $\mathscr{L}$,
  - Run-3 will be able to probe higgsinos up to a mass of 900-925 GeV
  - HL-LHC will further increase the sensitivity to ~ 1100 GeV

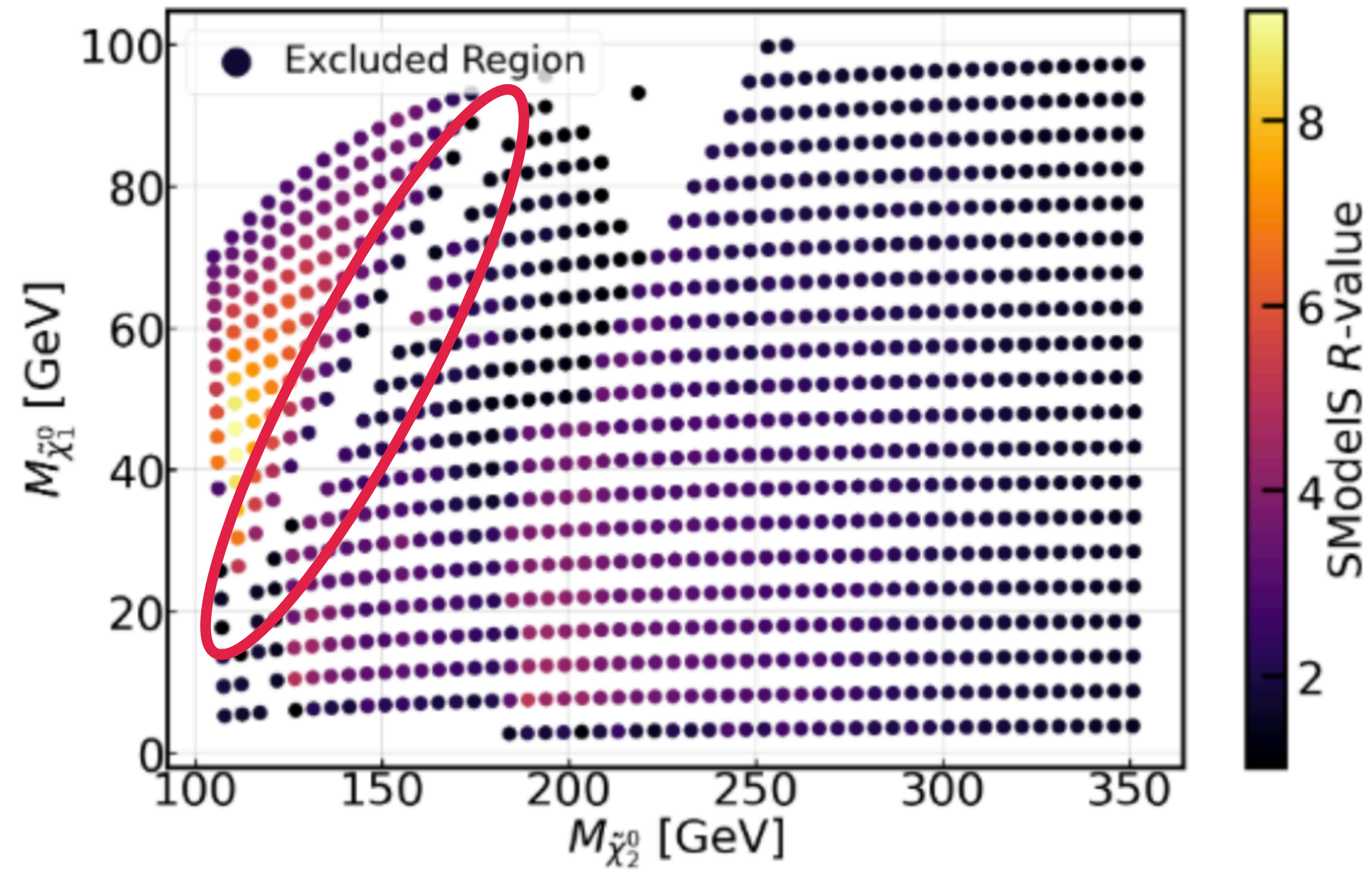
Roadmap of light neutralino DM for Run-3

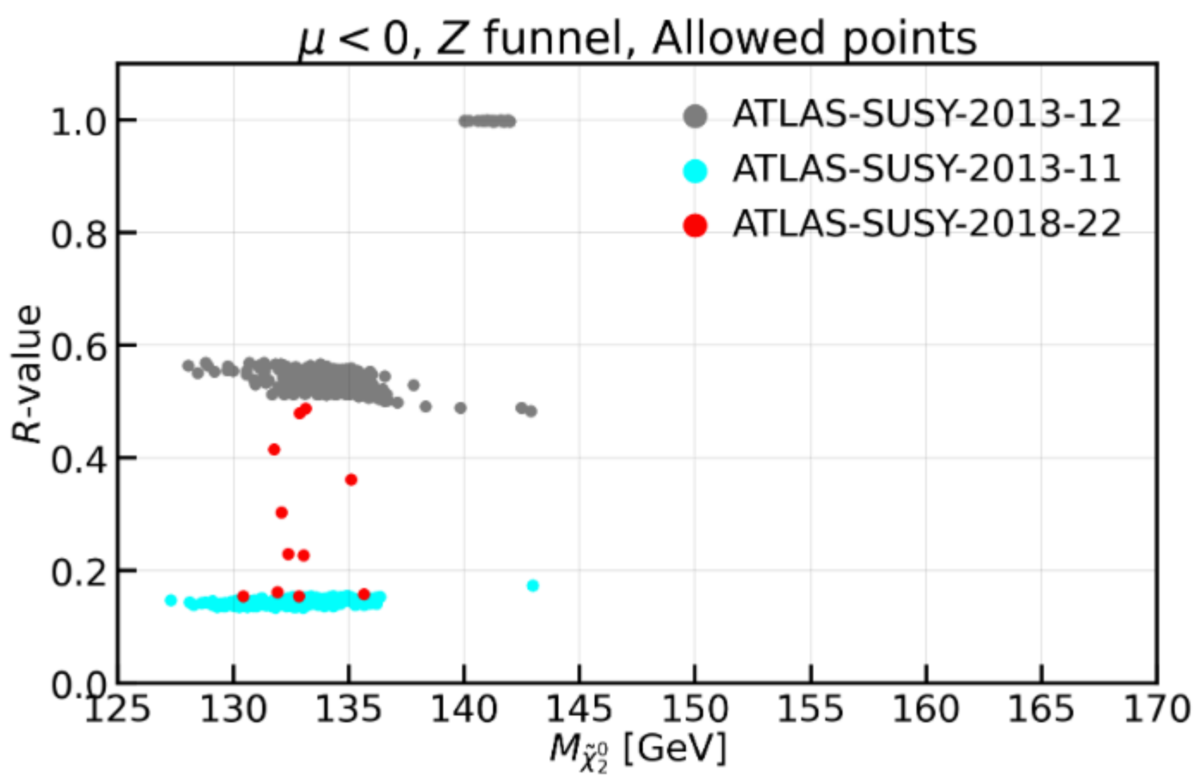
Light higgsinos

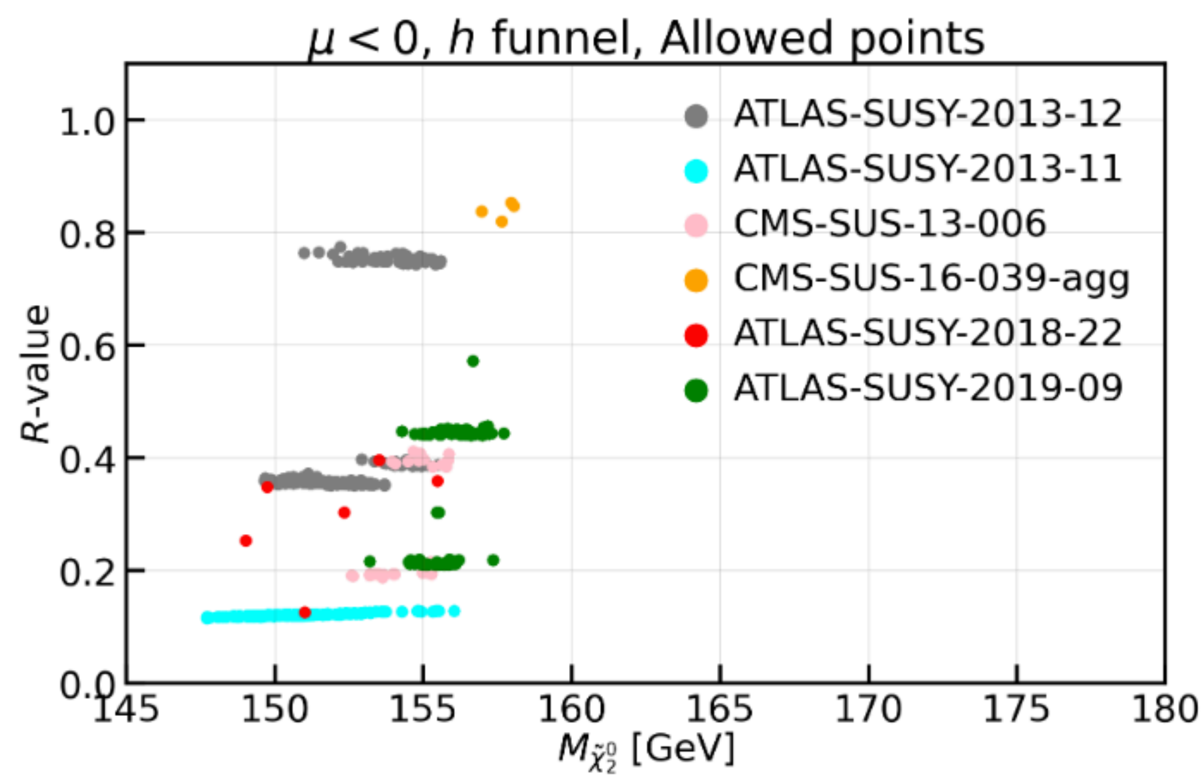
Light higgsinos still allowed by electroweakino searches?

Light higgsinos survive in the region where

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







Light higgsinos

Benchmarks (*mass parameters in* GeV)				$M_h[\Delta^{FH}_{M_h}]$ [GeV]	$\sigma_{SI} \times \xi \times 10^{-10}$ [pb]
$\mu > 0$	h-funnel	BP1	$M_t = 173.21,\ M_1 = 62.5,\ M_2 = 2000,\ \mu = 1000,\ \tan\beta = 5,\ M_A = 3000,$ $M_{\tilde{Q}_{3L}} = 10000,\ M_{\tilde{t}_R} = 10000,\ M_{\tilde{b}_R} = 10000,\ A_t = 10000,\ M_3 = 3000$	125.38 [$\pm$0.97]	0.151
	Z-funnel	BP2	$M_t = 173.21,\ M_1 = 44,\ M_2 = 2000,\ \mu = -124,\ \tan\beta = 5,\ M_A = 3000,$ $M_{\tilde{Q}_{3L}} = 10000,\ M_{\tilde{t}_R} = 10000,\ M_{\tilde{b}_R} = 10000,\ A_t = 10000,\ M_3 = 3000$	125.88 [$\pm$0.96]	7.46×10^{-4}
$\mu < 0$	h-funnel	BP3	$M_t = 173.21,\ M_1 = 68,\ M_2 = 2000,\ \mu = -150,\ \tan\beta = 50,\ M_A = 3000,$ $M_{\tilde{Q}_{3L}} = 5000,\ M_{\tilde{t}_R} = 5000,\ M_{\tilde{b}_R} = 5000,\ A_t = -5000,\ M_3 = 3000$	125.67 [$\pm$0.63]	0.143
	h-funnel	BP4	$M_t = 173.21,\ M_1 = ,\ M_2 = 2000,\ \mu = -1000,\ \tan\beta = 4.5,\ M_A = 3000,$ $M_{\tilde{Q}_{3L}} = 10000,\ M_{\tilde{t}_R} = 10000,\ M_{\tilde{b}_R} = 10000,\ A_t = 10000,\ M_3 = 3000$	125.15 [$\pm$0.99]	0.150

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 $|\eta| < 2.5$.

Background	Cross section [pb]	Generated using	Total generated
$lll\nu$	0.4684×1.2	MadGraph 2.7.3	9.98×10^6
WZ, leptonic, $2j$ matched	1.253×1.2	MadGraph 2.7.3	4.97×10^6
ZZ, leptonic, $2j$ matched	0.1186×1.2	MadGraph 2.7.3	1.25×10^6
$t\bar{t}$, leptonic	55.36×1.74	MadGraph 2.7.3	6×10^7
VVV, inclusive	0.2678×1.2	MadGraph 2.7.3	2.5×10^6
Wh, inclusive	1.504 [104]	Pythia 8.306	5×10^6
Zh, inclusive	0.883 [104]	Pythia 8.306	5×10^6
ggF $h \to ZZ$, leptonic	0.0137	Pythia 8.306	5×10^6
VBF $h \to ZZ$, leptonic	0.00115	Pythia 8.306	5×10^6
$t\bar{t}h$, inclusive	0.6113 [104]	Pythia 8.306	5×10^6
$t\bar{t}W$, leptonic	0.01387×1.22	MadGraph 2.7.3	2.5×10^6
$t\bar{t}Z$, leptonic	0.00644×1.23	MadGraph 2.7.3	2.5×10^6

XGBOOST analysis

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

Veto
$|M_{ll} - M_Z| < 10$ GeV

BP2
off-shell Z boson

- 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 $\not{E}_{\mathrm{T}}$
- 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:

`‘objective’:‘multi:softprob’, ‘colsample_bytree’:0.3, ‘learning_rate’:0.1, ‘num_class’:12, ‘max_depth’:7, ‘alpha’:5, ‘eval_metric’:‘mlogloss’, ‘num_round’:1000, ‘early_stopping_rounds’:3`

XGBOOST analysis

Final state: 3l+MET
SFOS pair of lepton

$|M_{ll} - M_Z| < 10$ GeV

BP3
on-shell Z boson

- Transverse momenta (p_T) of the three leptons
- Transverse mass (M_T) and contransverse mass (M_{CT}) of the lepton, which is not part of the SFOS pair of leptons, with the $\not{E}_T$
- ΔR and $\Delta\eta$ between the SFOS lepton pair
- $\Delta\phi$ and $\Delta\eta$ between the SFOS lepton pair system and the unpaired lepton
- $\Delta\phi$ between the SFOS lepton pair system and $\not{E}_T$
- $\Delta\phi$ between the unpaired lepton and $\not{E}_T$
- 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)

Following are the hyperparameters of the XGBOOST model:

`'objective':'multi:softprob', 'colsample_bytree':0.3, 'learning_rate':0.1, 'num_class':12, 'max_depth':7, 'alpha':5, 'eval_metric':'mlogloss', 'num_round':1000, 'early_stopping_rounds':3`

Light higgsinos - our analysis

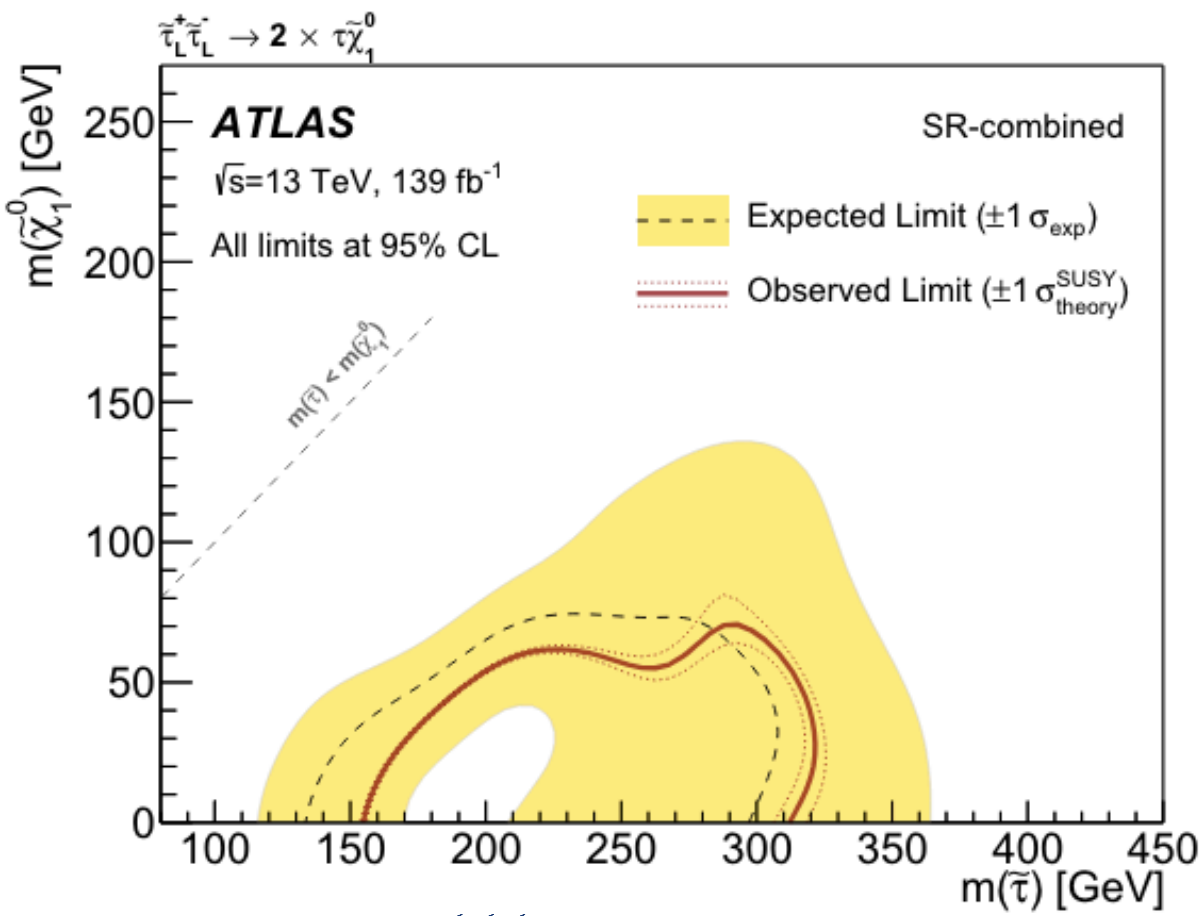
Number of events for $\mathcal{L} = 137\,\text{fb}^{-1}$		BP2	BP3
Backgrounds	$lll\nu$	205.6	–
	WZ, leptonic, $2j$ matched	–	46.7
	ZZ, leptonic, $2j$ matched	14.7	5.8
	$t\bar{t}$, leptonic	677.6	21.8
	VVV, inclusive	13.0	2.3
	Wh, inclusive	46.5	1.4
	Zh, inclusive	7.4	1.4
	ggF $h \to ZZ$, leptonic	2.2	0.002
	VBF $h \to ZZ$, leptonic	0.2	6.0×10^{-4}
	$t\bar{t}h$, inclusive	8.2	0.3
	$t\bar{t}W$, leptonic	9.2	0.5
	$t\bar{t}Z$, leptonic	2.5	1.0
	Total	987.1	81.2
Signal		763.4	112.1
Significance with 20% systematic uncertainty		3.1	4.5
Significance with 50% systematic uncertainty		1.3	1.98

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**

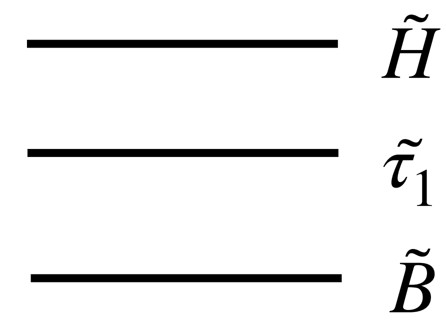
Experimental collaborations need to focus on this region of light higgsinos to provide a conclusive statement about their present status.

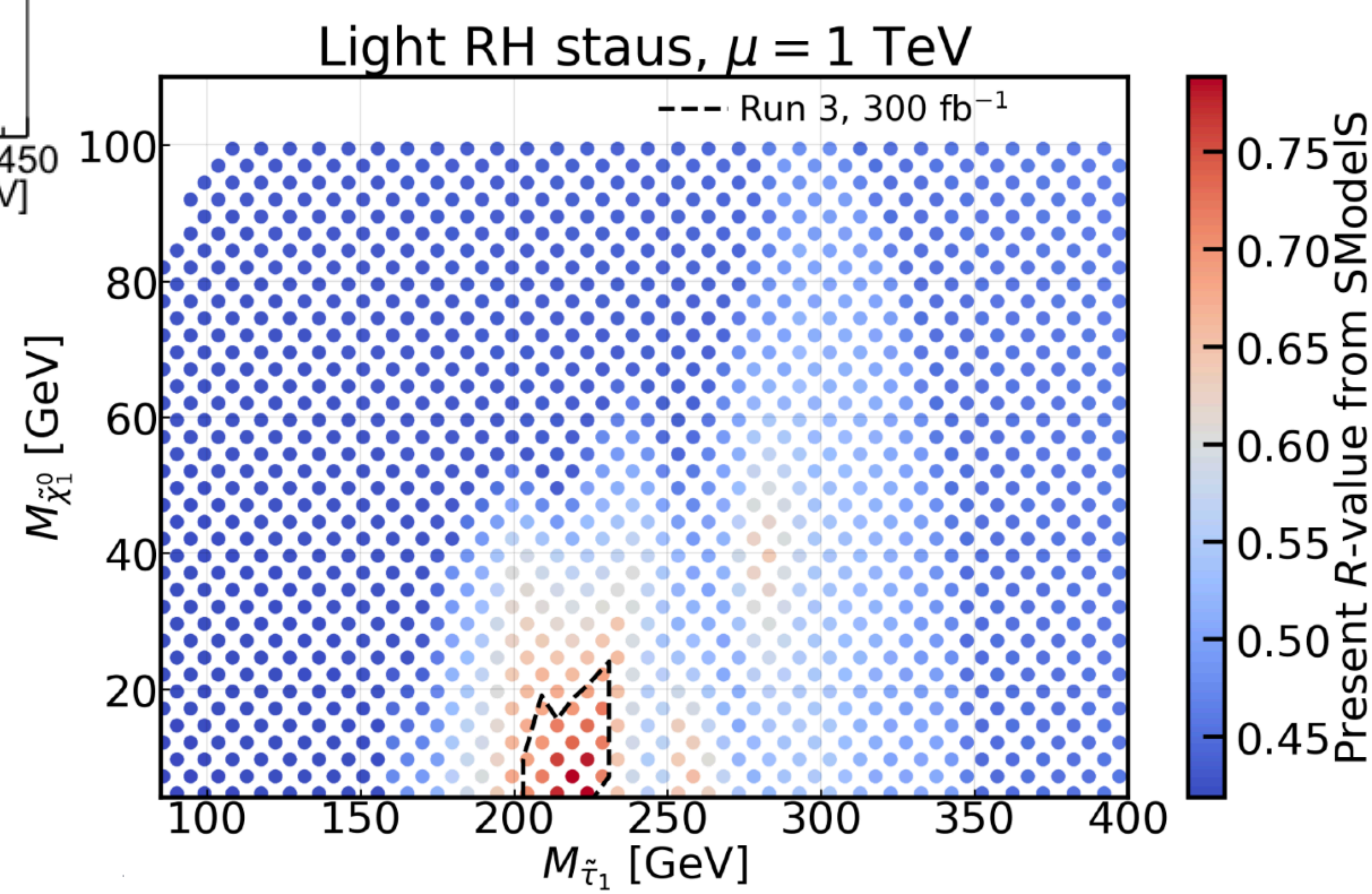
Roadmap of light neutralino DM for Run-3

Light staus

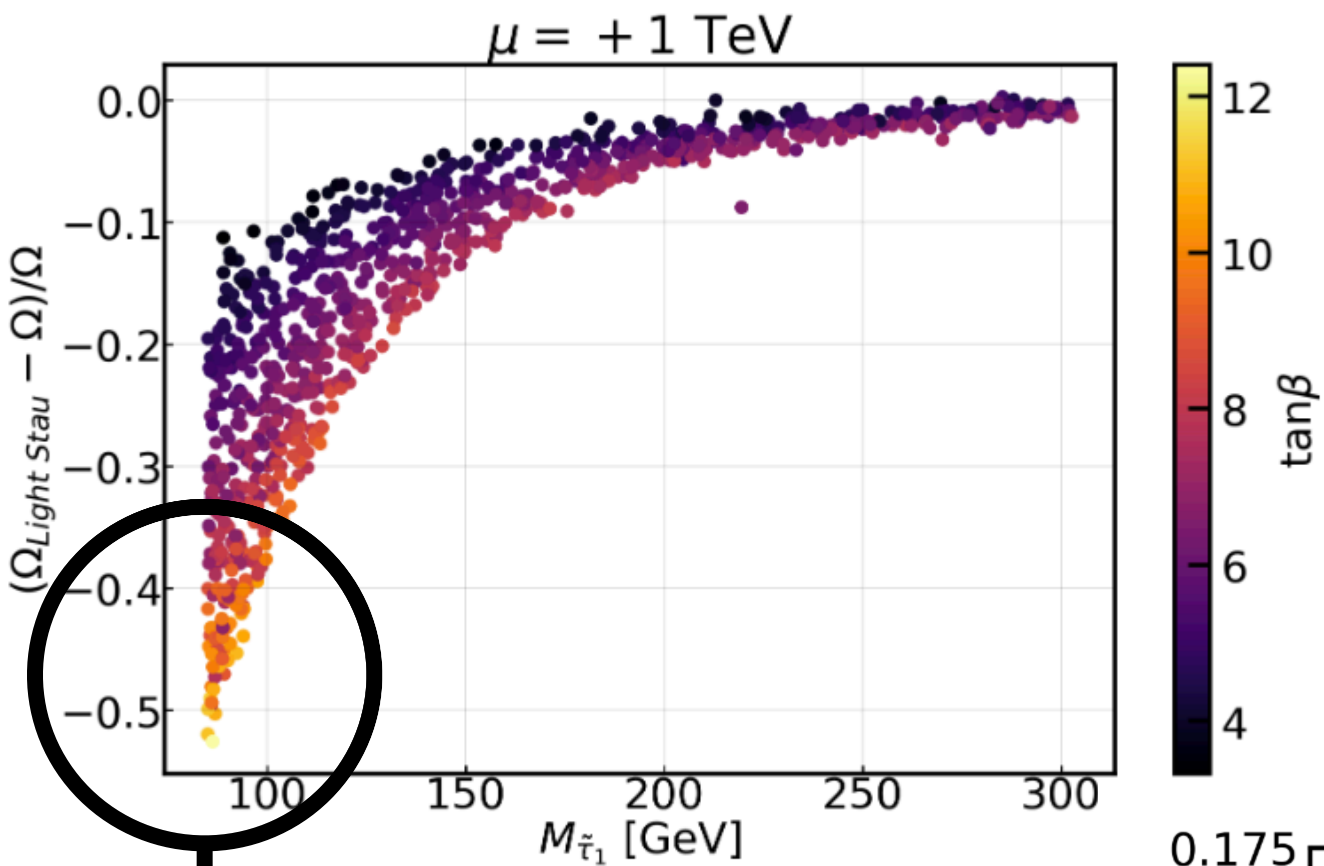


arXiv:1911.06660



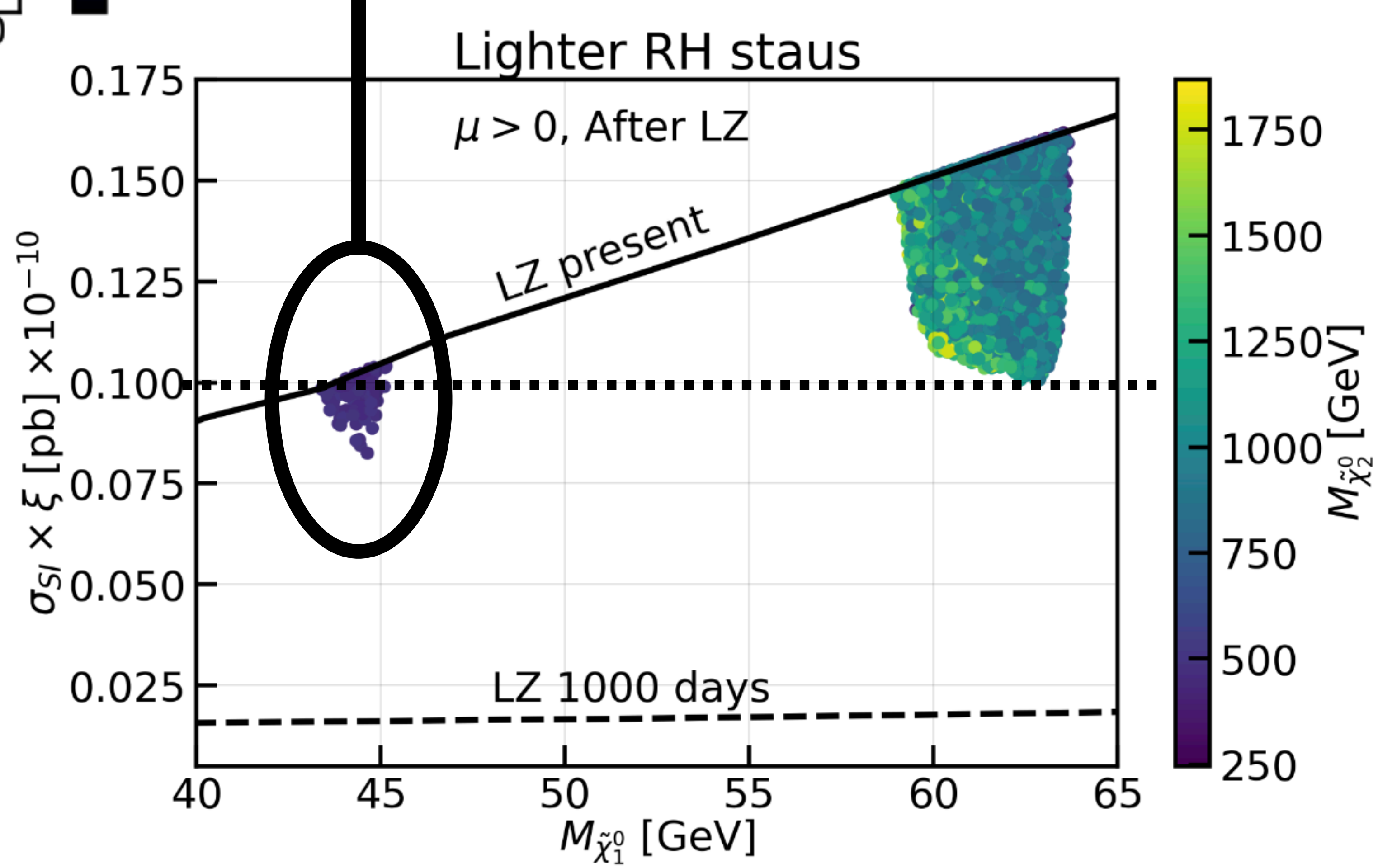


Impact on relic density



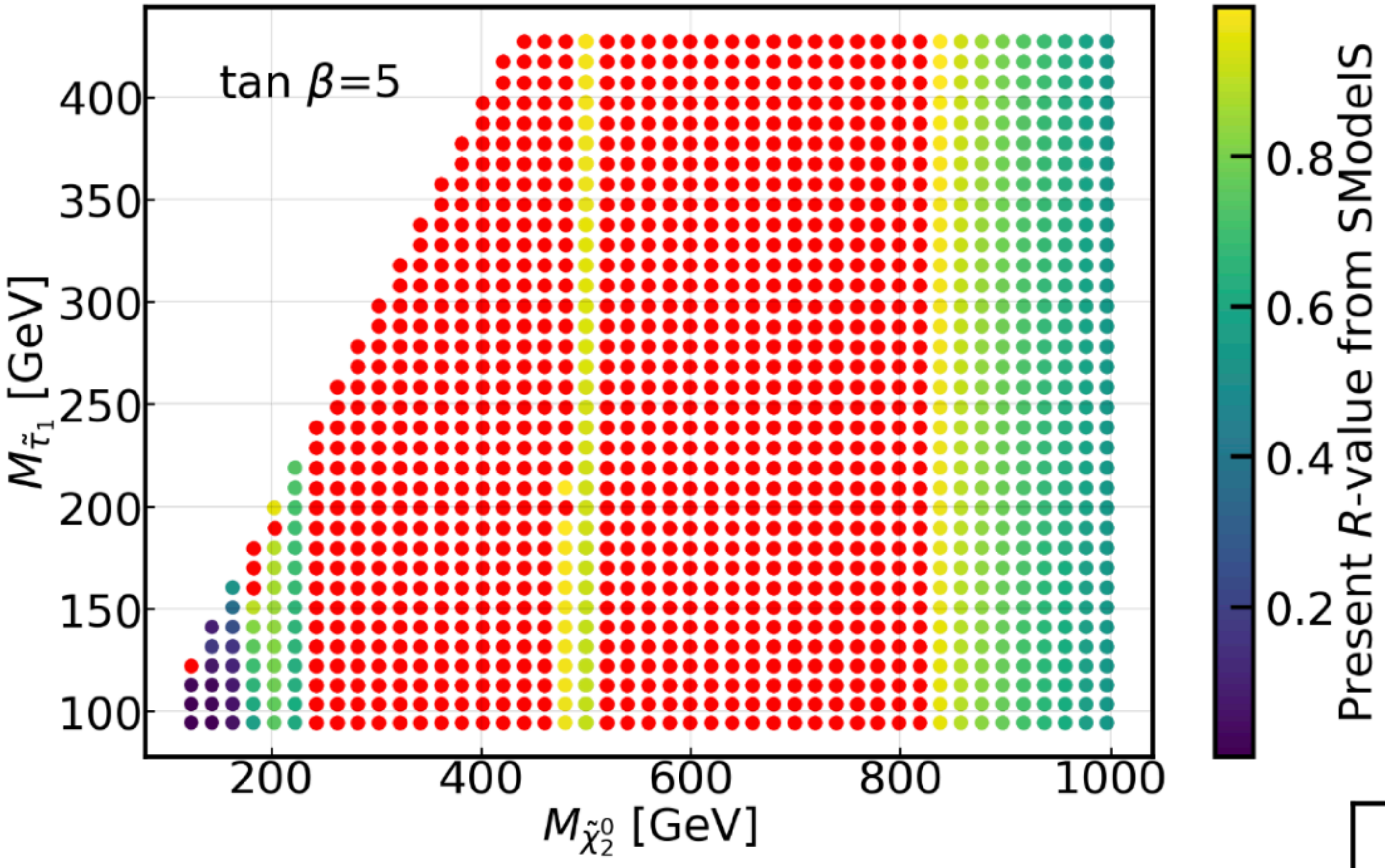
A region in the Z-funnel open up and in the h-funnel, we can go to lower DD cross-sections

- 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

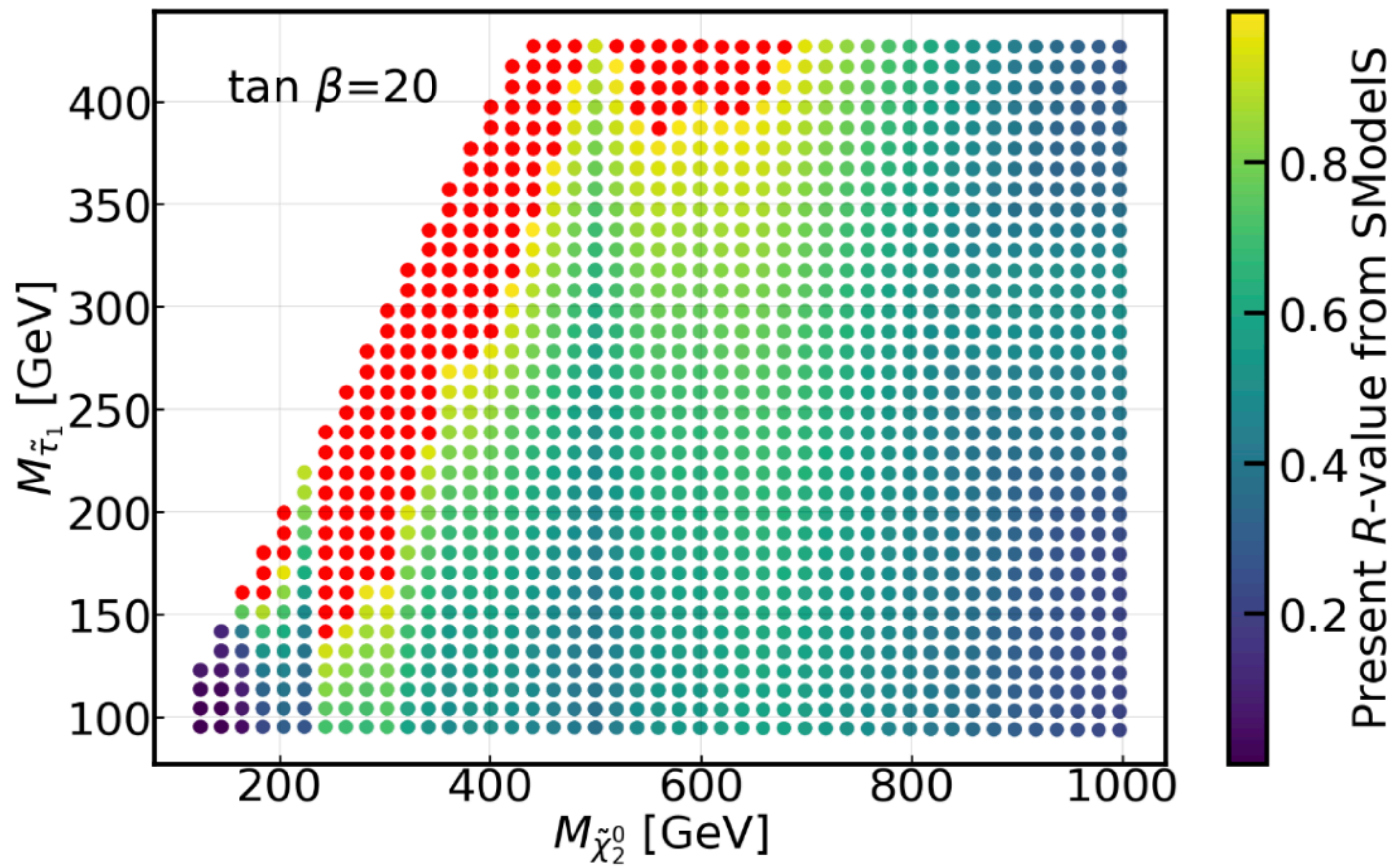
Impact on electroweakino search results at LHC



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



Stau benchmarks for Run-3

Benchmarks with light staus (*mass parameters in* GeV)				$M_h[\Delta^{FH}_{M_h}]$ [GeV]	$\sigma_{SI} \times \xi \times 10^{-10}$ [pb]
$\mu < 0$	Z-funnel	BP5	$M_t = 173.21,\ M_1 = 44,\ M_2 = 2000,\ \mu = -124,\ \tan\beta = 5,\ M_A = 3000,$ $M_{\tilde{Q}_{3L}} = M_{\tilde{t}_R} = M_{\tilde{b}_R} = A_t = 10000,\ M_3 = 3000,\ M_{\tilde{e}_{3R}} = 85$	125.86[±0.96]	7.45×10^{-4}
	h-funnel	BP6	$M_t = 173.21,\ M_1 = 68,\ M_2 = 2000,\ \mu = -150,\ \tan\beta = 50,\ M_A = 3000,$ $M_{\tilde{Q}_{3L}} = M_{\tilde{t}_R} = M_{\tilde{b}_R} = 5000,\ A_t = -5000,\ M_3 = 3000,\ M_{\tilde{e}_{3R}} = 85$	125.65[±0.63]	0.137
$\mu > 0$	Z-funnel	BP7	$M_t = 173.21,\ M_1 = 44,\ M_2 = 2000,\ \mu = 500,\ \tan\beta = 50,\ M_A = 6000,$ $M_{\tilde{Q}_{3L}} = M_{\tilde{t}_R} = M_{\tilde{b}_R} = 4500,\ A_t = 4000,\ M_3 = 5000,\ M_{\tilde{e}_{3R}} = 85$	125.11[±0.99]	0.095
	h-funnel	BP8	$M_t = 173.21,\ M_1 = 62,\ M_2 = 2000,\ \mu = 500,\ \tan\beta = 20,\ M_A = 6000,$ $M_{\tilde{Q}_{3L}} = M_{\tilde{t}_R} = M_{\tilde{b}_R} = 4500,\ A_t = 4000,\ M_3 = 5000,\ M_{\tilde{e}_{3R}} = 150$	124.77[±0.97]	0.152

τ-enriched final states

We perform a similar analysis like the $3l$+MET, including the hadronic decays of the tau leptons

BP5 and BP6: can be probed with our analysis at the Run-3 using 300 fb^{-1} of data, with a signal significance ≳ **2σ**, despite a large systematic uncertainty of **50%**.

BP7: if the uncertainty can be brought down to **5%**, we can achieve more than **3σ** significance

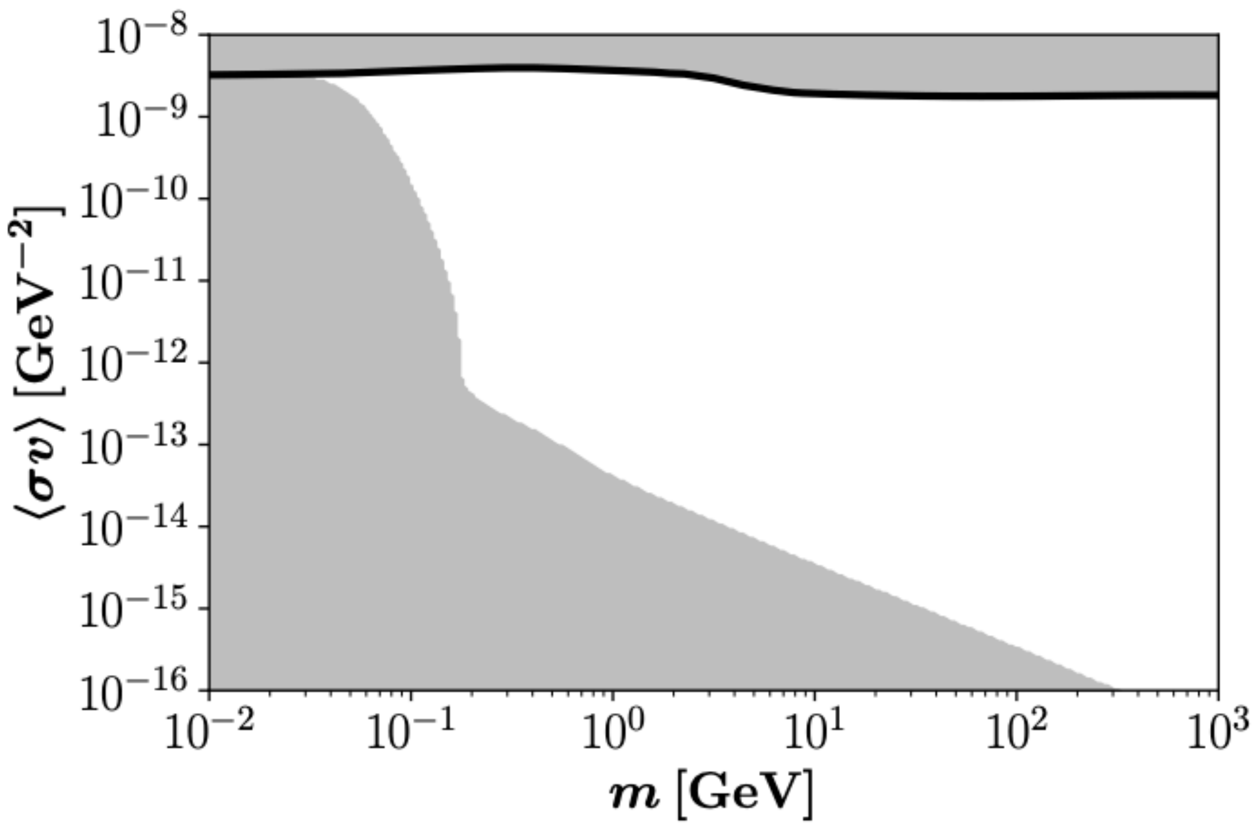
BP8: we require the uncertainty to be around **2%** to have **3σ** significance.

Roadmap of light neutralino DM for Run-3

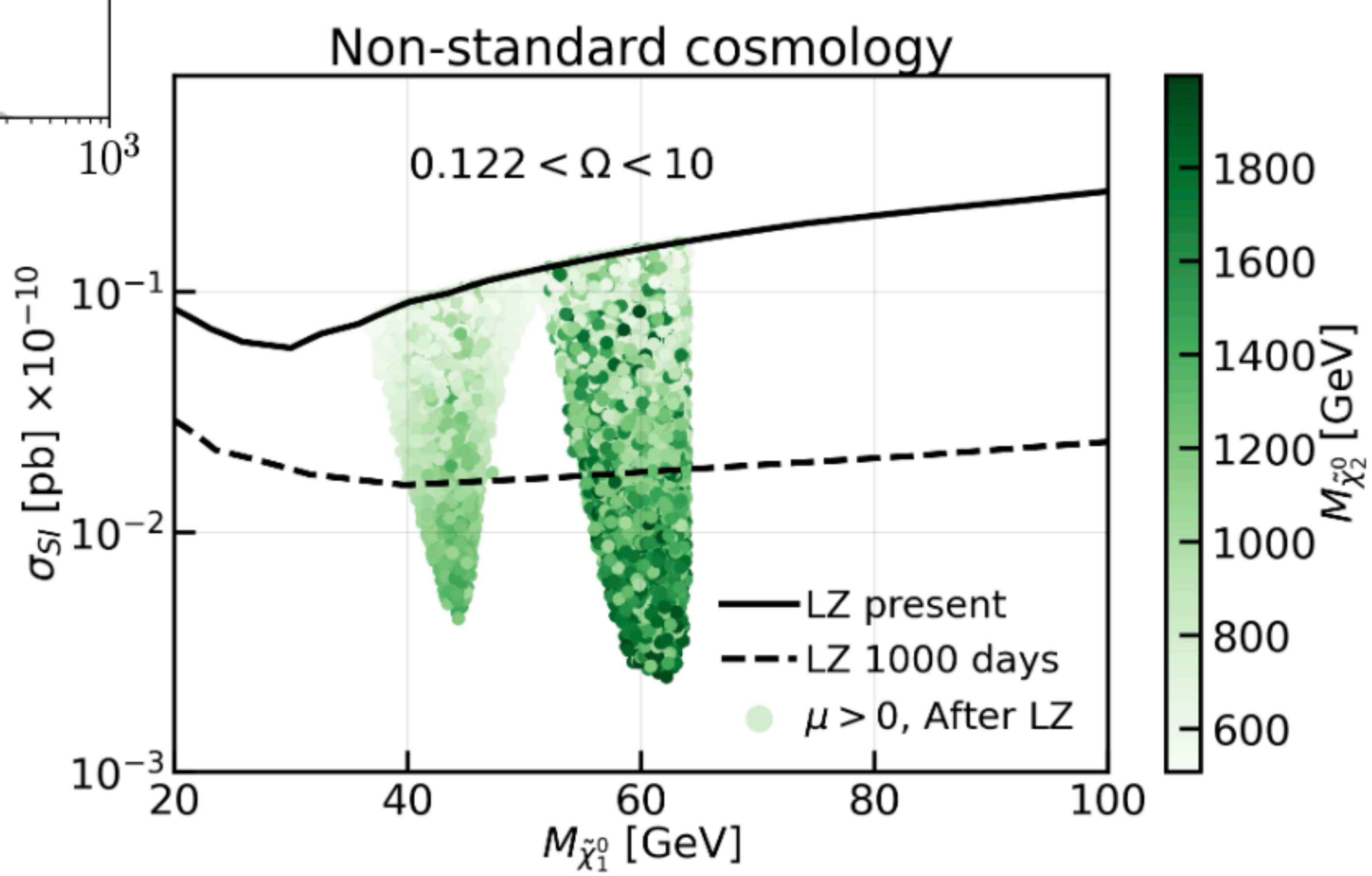
Hints for non-standard cosmology

Late injection of entropy in the Universe

$$Y = \frac{n}{s}$$



Reconstructing Non-standard Cosmologies with Dark Matter
P. Arias, N. Bernal, Alan Herrera, Carlos Maldonado
arXiv:1906.04183



Parameter space extends beyond the LZ projected bound

Heavier Higgsinos (>500 GeV) possible even in the Z funnel

Hints for non-standard cosmology

Can we tell if its standard or non-standard cosmology?

Z-funnel: Observation of higgsinos heavier than 500 GeV in the collider

h-funnel: Observation of higgsinos having TeV masses in the collider even with large $\tan\beta$

along with a DM signal from DD experiments

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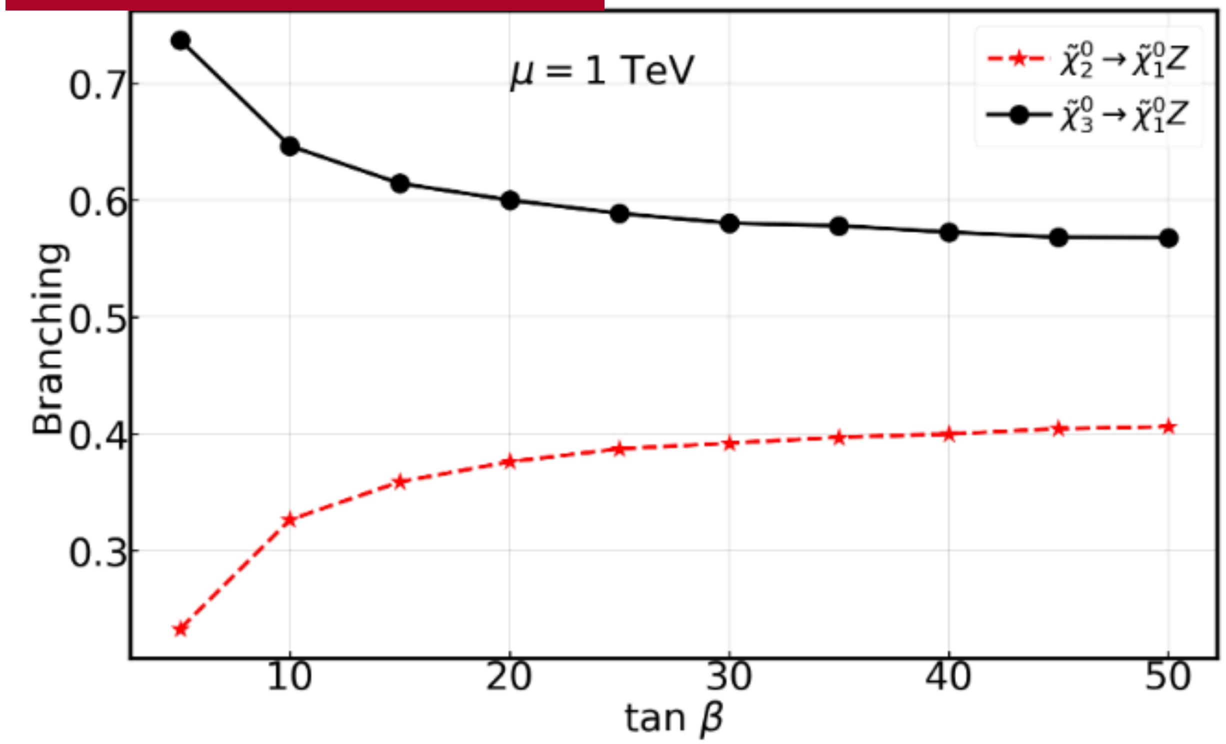
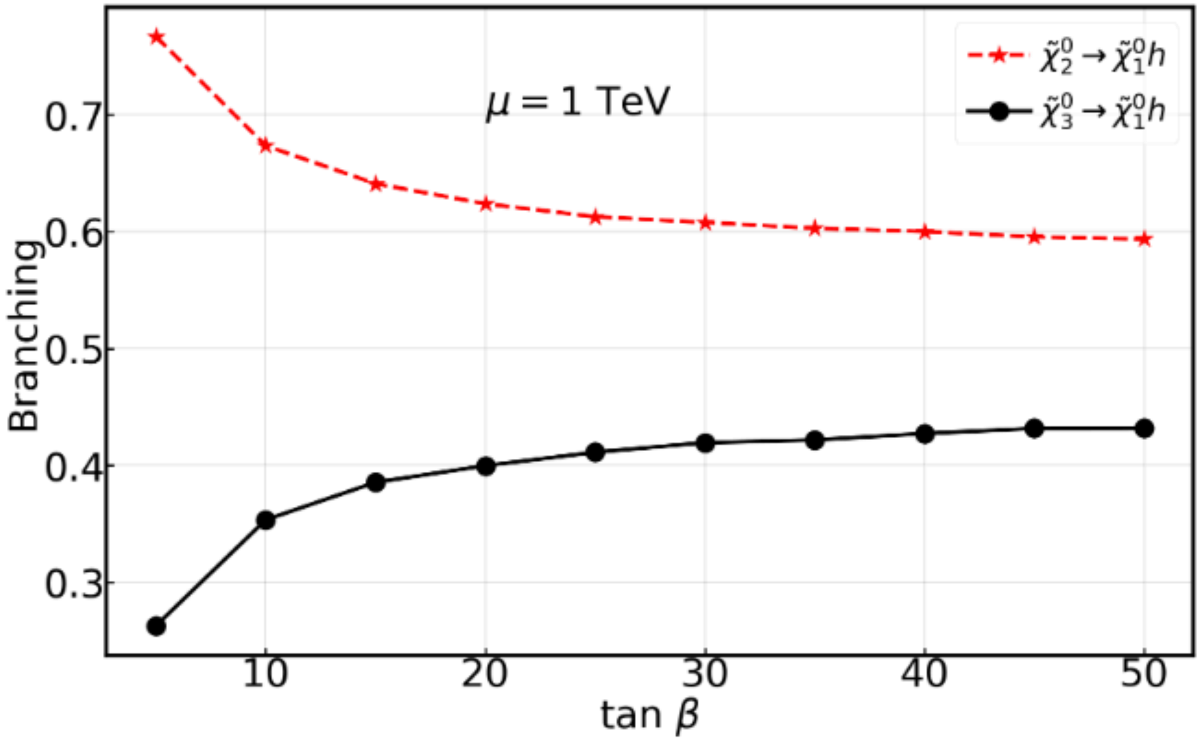
Dependence of branching ratio with $\tan\beta$

Without light staus





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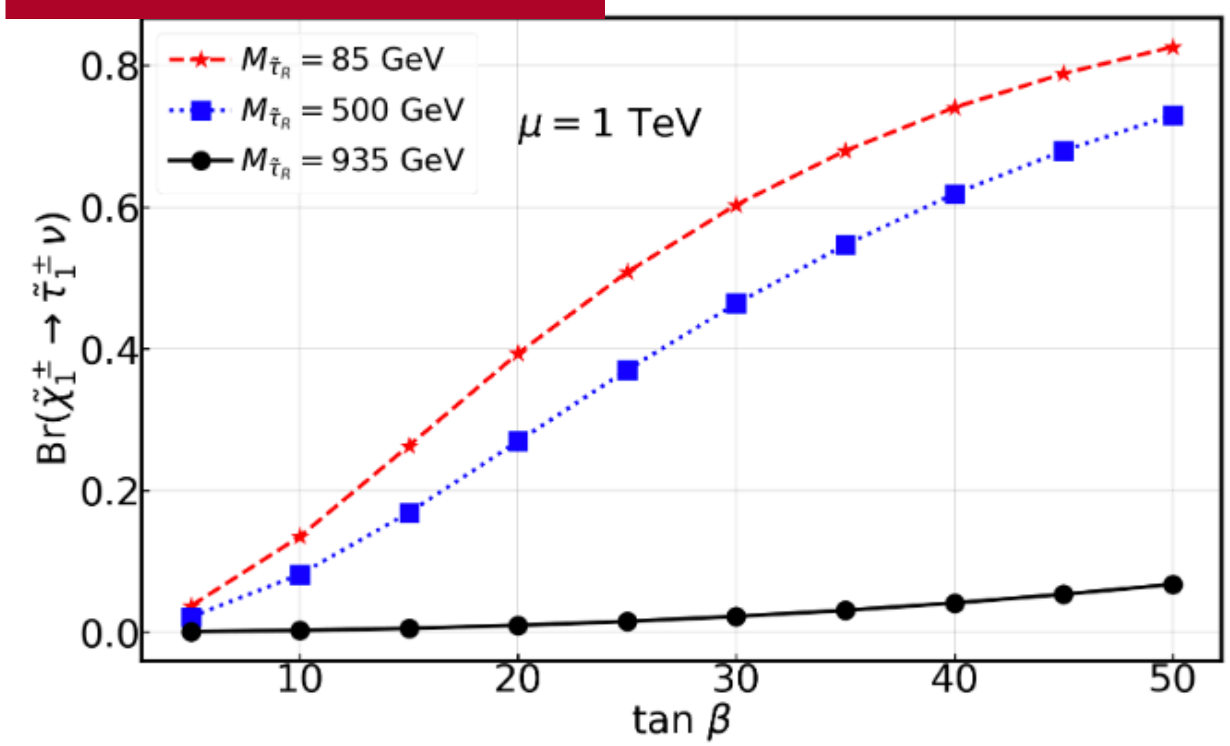

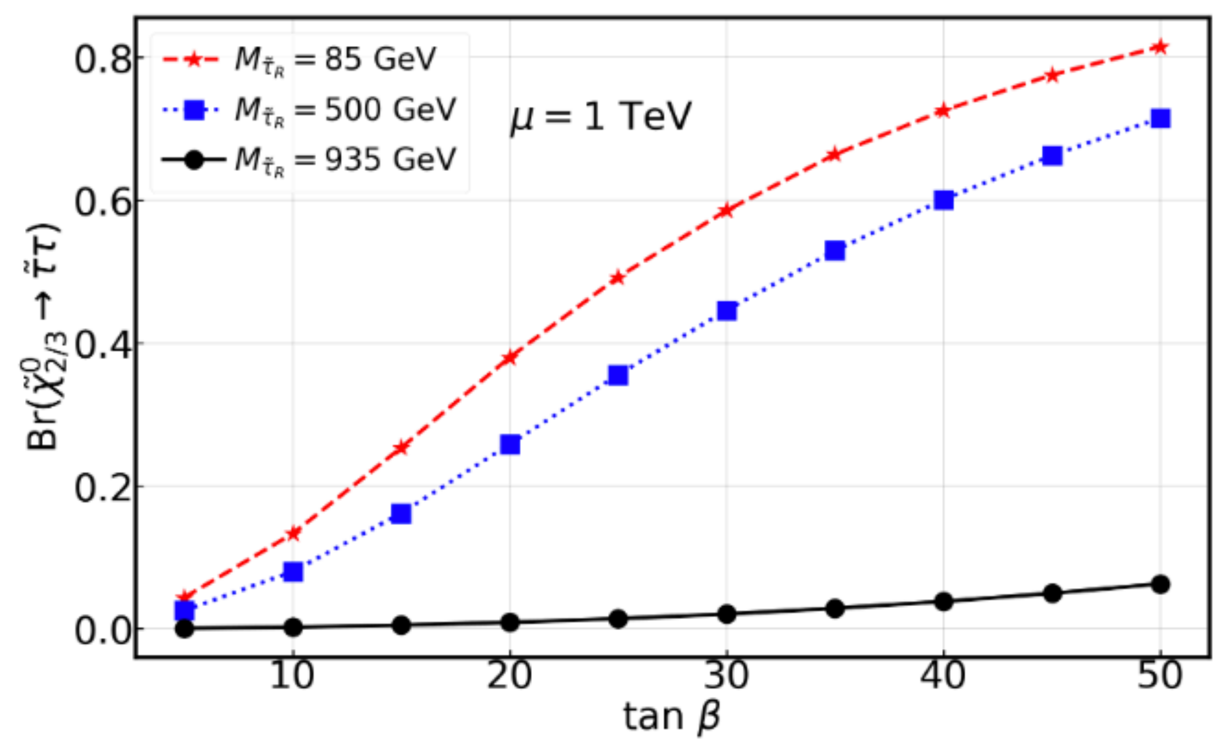

Summary

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**.

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- relaxed collider constraints when higgsinos decay to stau

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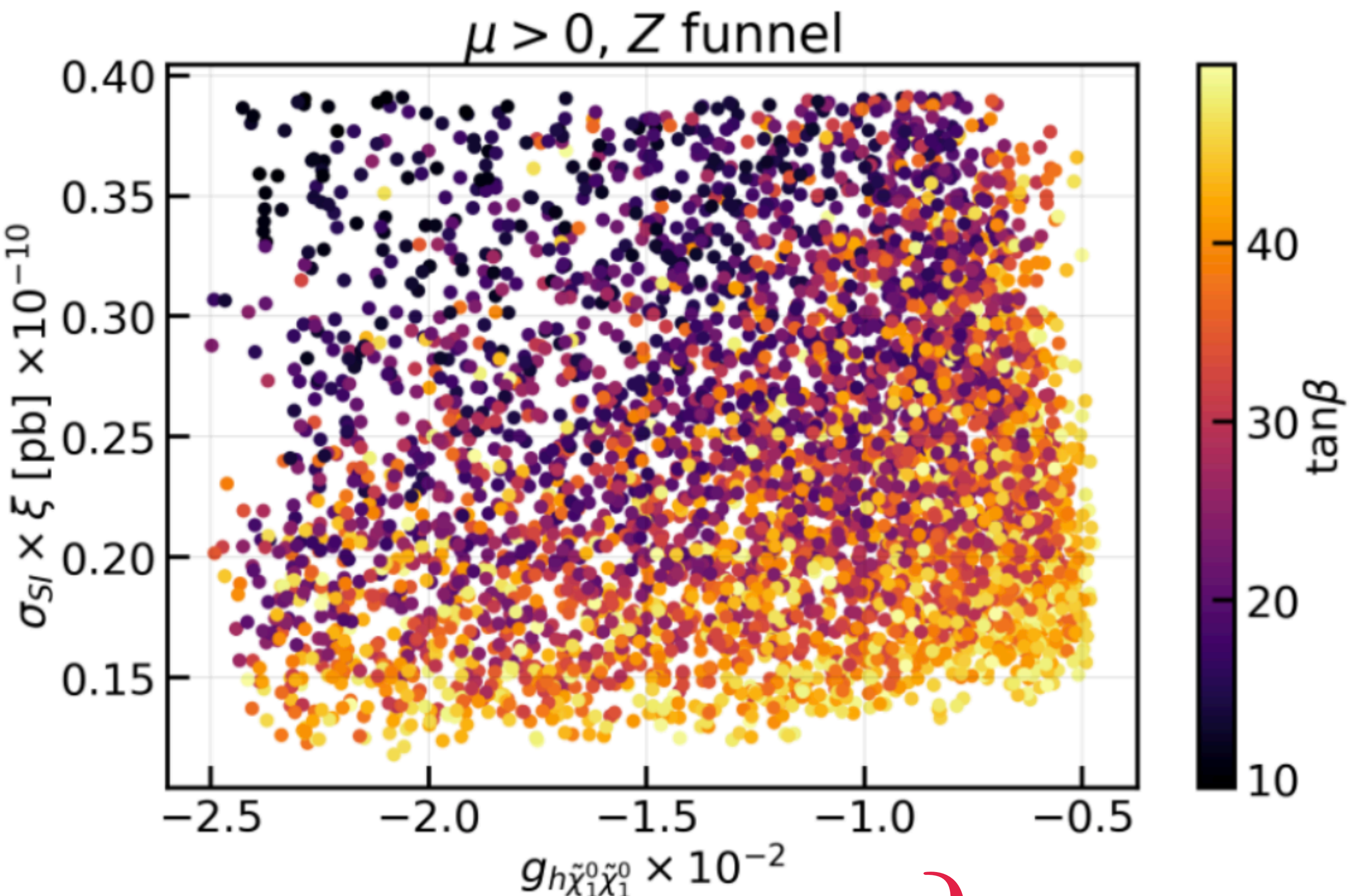
Non-standard cosmology can allow parameter regions which are not possible in the standard cosmology :

can we discriminate between the two from signals in collider and DM experiments?

Back up slides

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

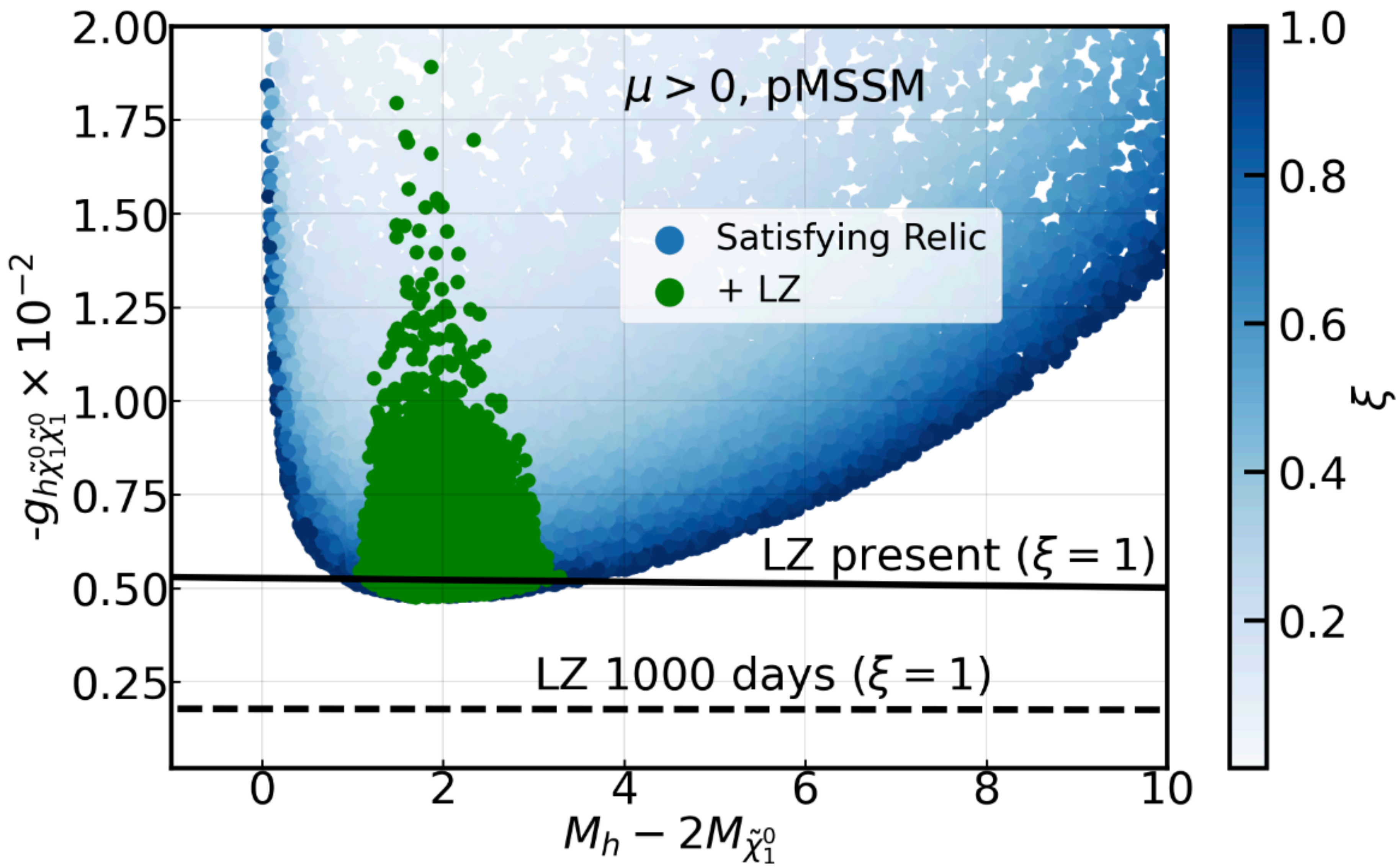
Z-FUNNEL EXCLUDED BY LZ

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

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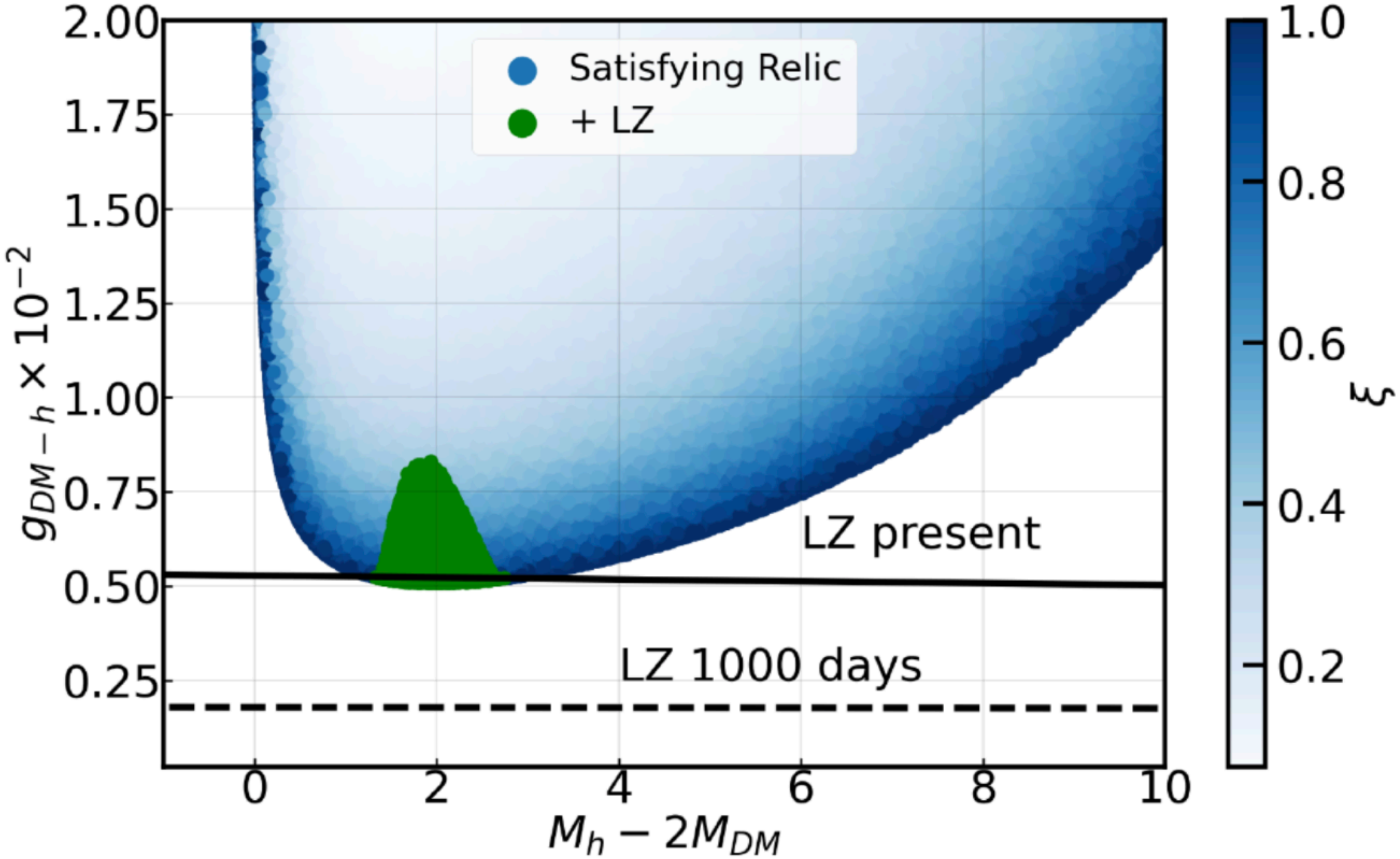
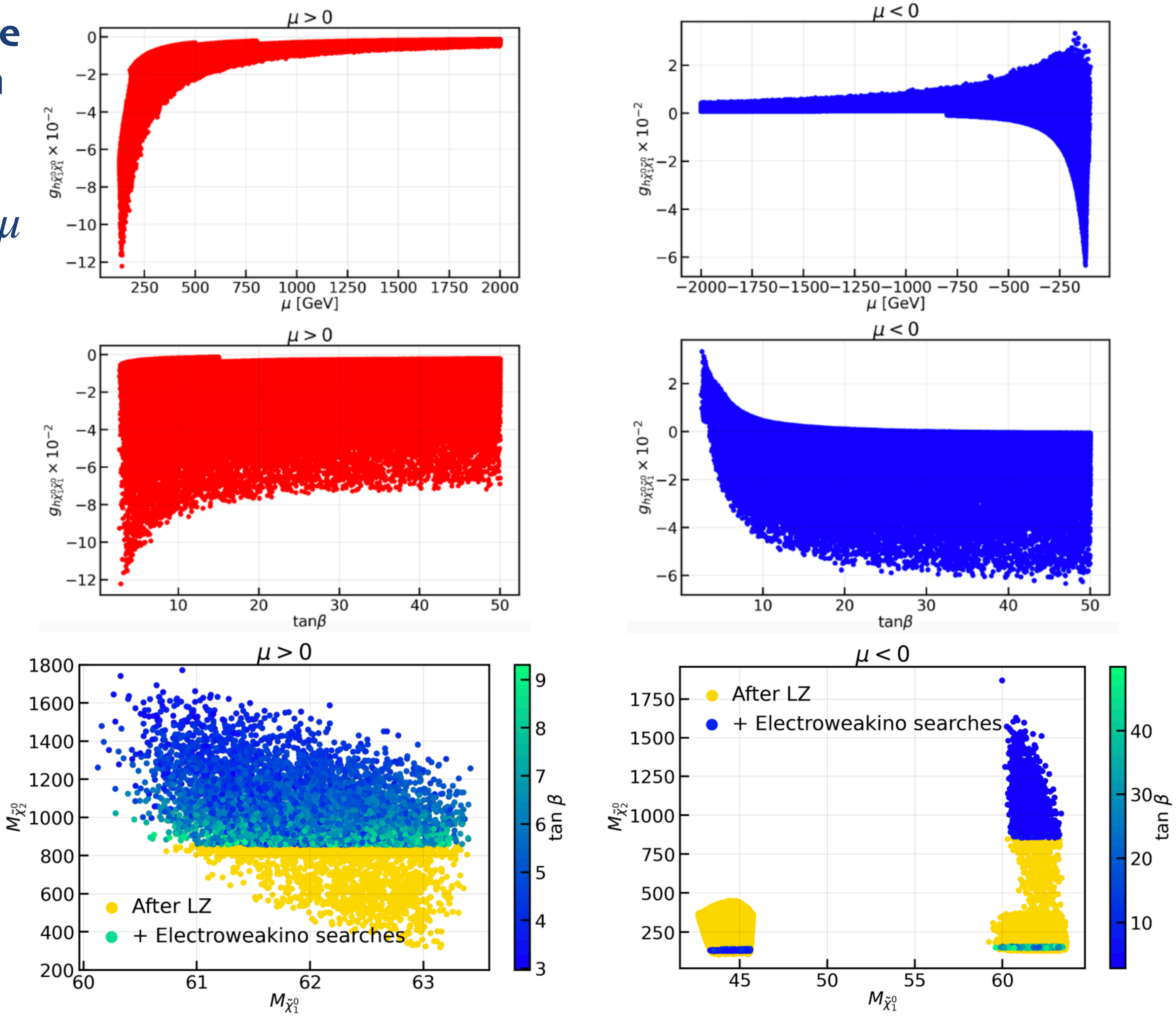
Similar to any Majorana fermion coupled to only h



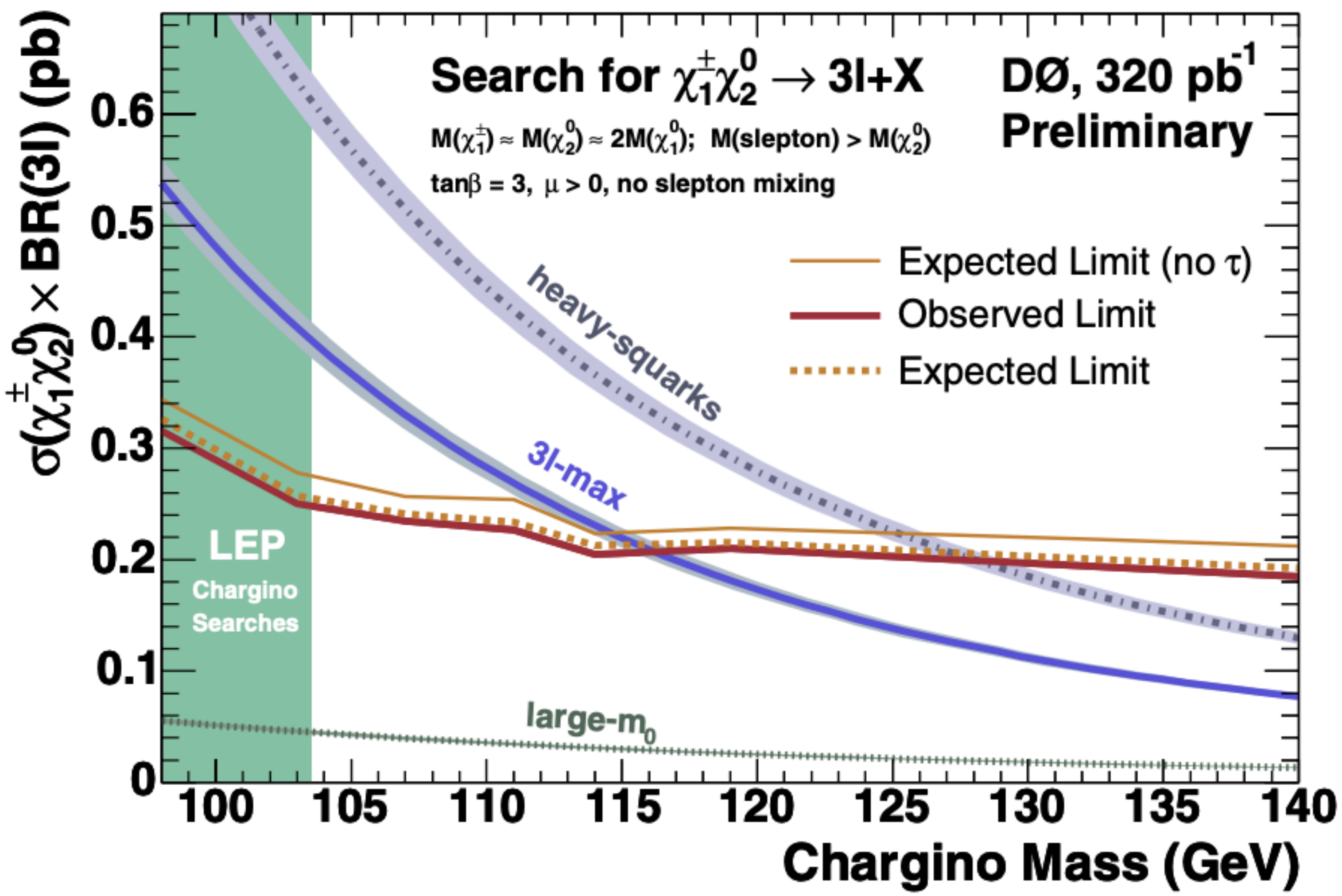
ALSO STRONGLY CONSTRAINED

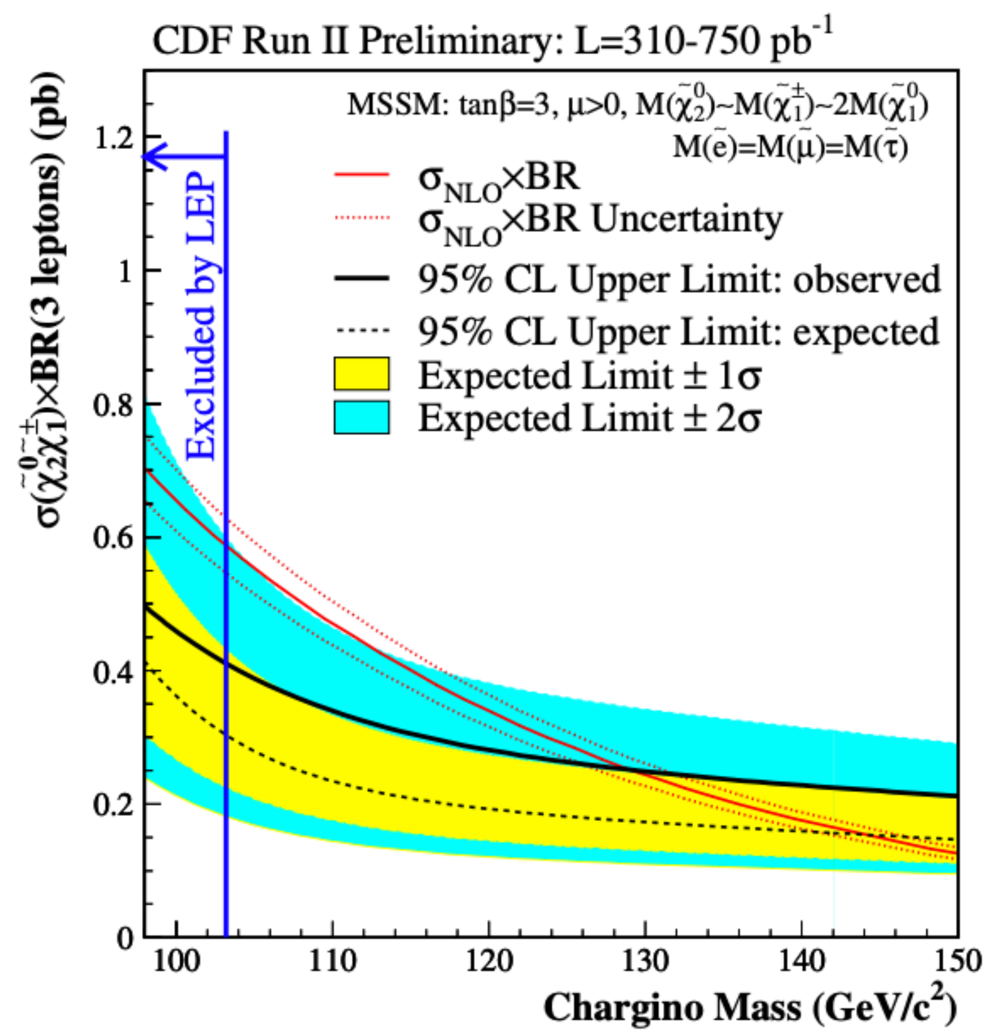
Can be probed with few more days of LZ data

Difference between positive and negative μ



Tevatron Limit





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