Status of the Light SUSY DM in the PMSSM

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NIKHEF - November29, 2023.

Renovated NIKHEF

- Introduction.

- Low mass ($m_{LSP} < m_{h_{SM}}/2$) DM in SUSY.

1 $\tilde{\chi}_1^0$ LSP: pMSSM

2 If at all some comments on $\tilde{\chi}_1^0$ LSP in NMSSM and $\tilde{\nu}_R$ (work by others)

Credit: I have stolen freely from a very nice set of slides made by Rhitaja Sengupta for a talk.

Many of us grew up in the period where SUSY was the 'standard BSM' and the Lightest Supersymmetric Particle (LSP) was the most attractive, Weakly Interacting Massive Particle as the candidate for the DM. .

But LHC results have put the idea of 'natural' SUSY under stress and the XENON-1T, PandaX (4T), LZ results have put the WIMP paradigm under stress.

Experimental constraints on masses of various sparticles from the LHC

These then translate into constraints on parameters of the SUSY models : most of the parameters are related to SUSY breaking!

Masses of sparticles decided by SUSY breaking parameters. Their couplings are SM couplings g_1, g_2 and g_3 as decided by SUSY. Couplings of mass eigenstates depend on both: SUSY and SUSY breaking!

Many SUSY breaking mass parameters are constrained to have very high values.

One mass that is still allowed to be 'low' is the lightest neutralino $\tilde{\chi}_1^0$

Lightest Neutralino in the MSSM

Extending SM to MSSM

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

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

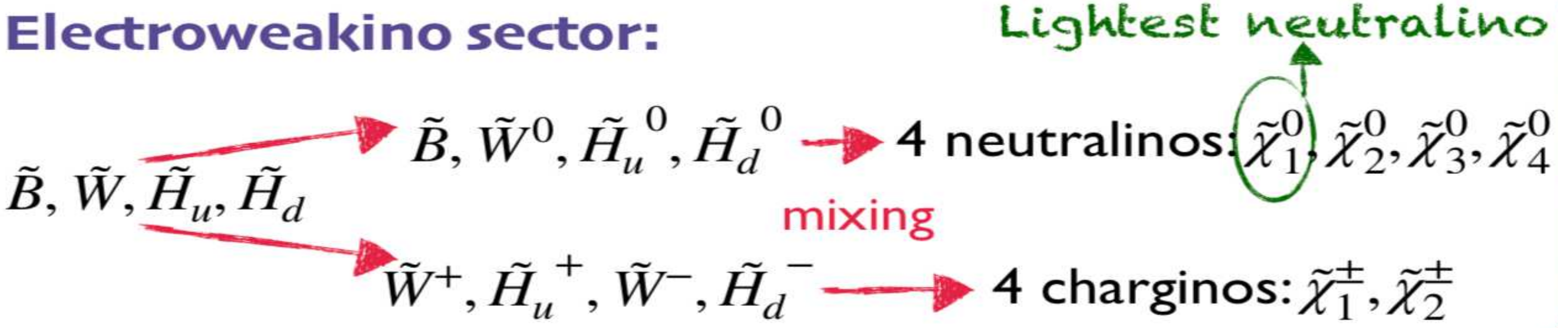
Supersymmetry (SUSY):

Weyl fermion ↔ complex scalar fermions ↔ sfermions

complex scalar ↔ Weyl fermion Higgs bosons ↔ higgsinos

gauge bosons ↔ Weyl fermion gauge bosons ↔ gauginos

Electroweakino sector:



Lightest neutralino

$\tilde{B}, \tilde{W}, \tilde{H}_u, \tilde{H}_d$

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

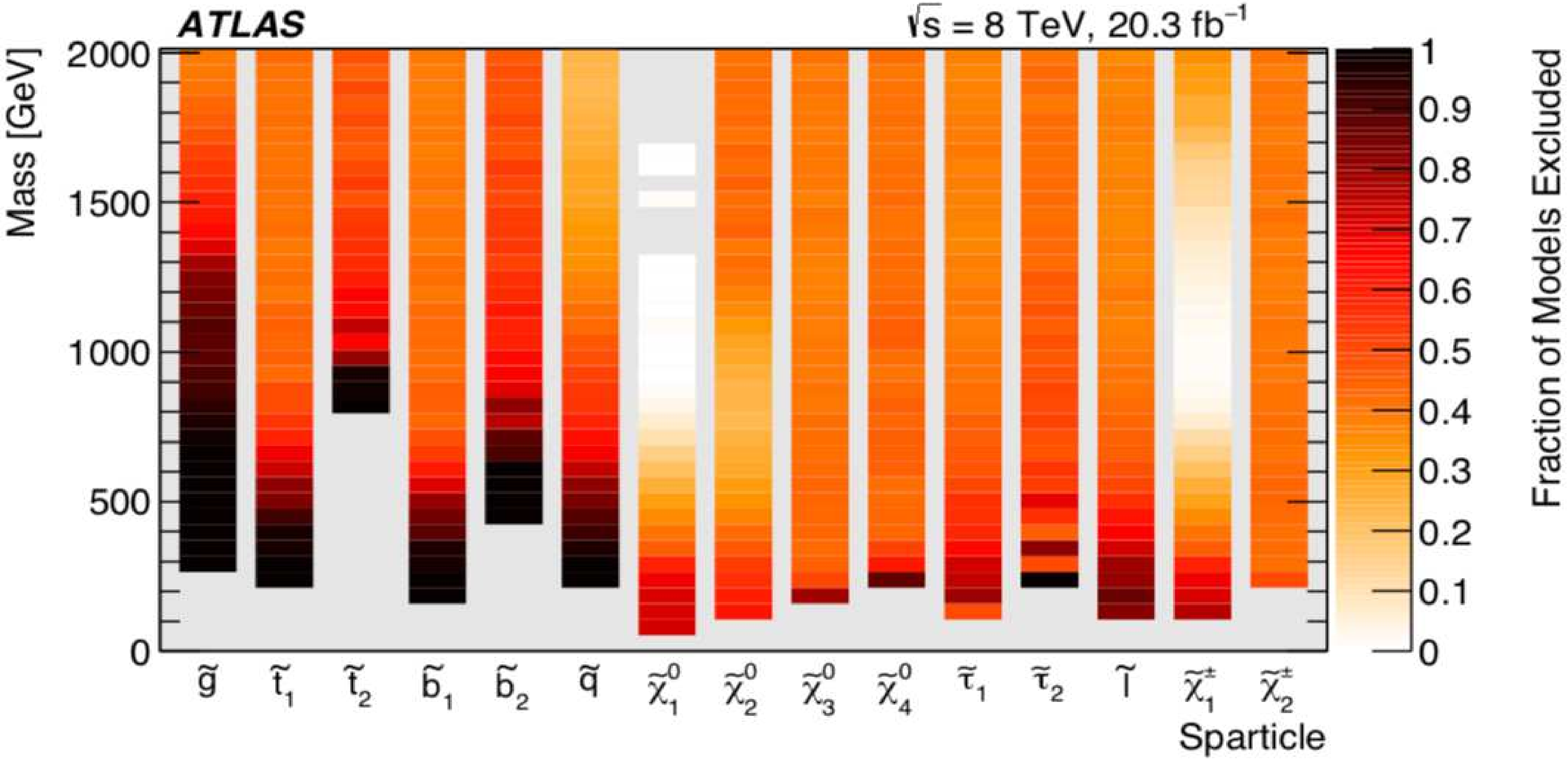
mixing

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

Among the multitude of SUSY breaking parameters only four are relevant for determining the masses and the couplings of the $\tilde{\chi}$- ElectroWeakino sector at tree level:

SUSY breaking gaugino masses M_1, M_2 and Higgs sector parameters μ and $\tan\beta$. At loop levels some of the parameters of the $t, \tilde{t}$ sector as well become relevant.

For the neutralino sector it is diagonalisation of a four by four matrix and for the chargino sector that of a two by two matrix.



SMS analyses transferred to (phenomenological minimal supersymmetric standard model) pMSSM model. A small mass $\tilde{\chi}_1^0$ still allowed in pMSSM! From the PDG

However, for the best fit points of various SUSY analyses LSP has mass a few hundred GeV! (Bagnaschi et al, arXiv: 1610.10084)

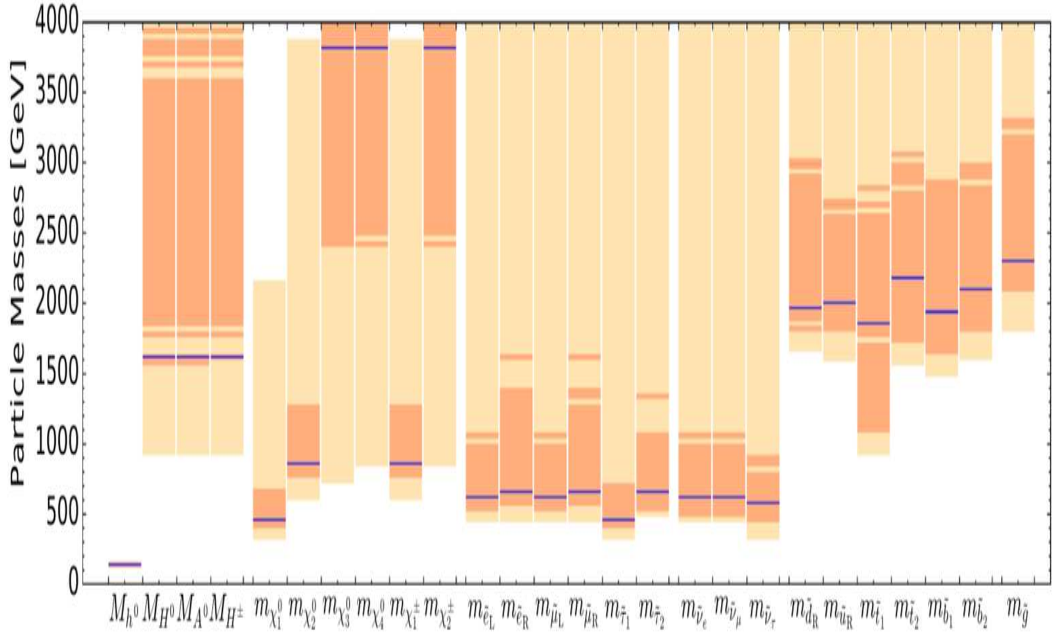
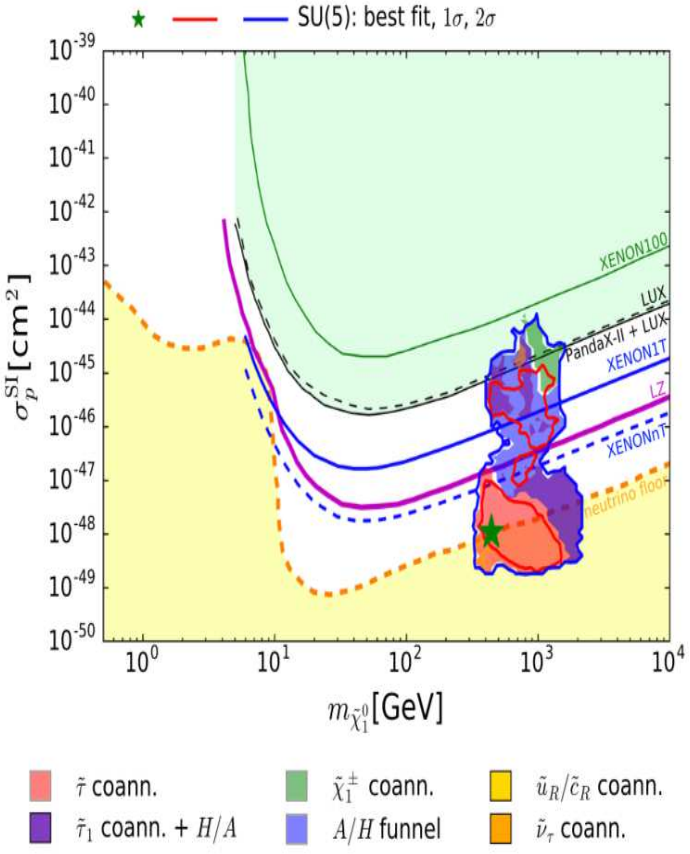


Fig. 12 The one-dimensional 68 and 95% CL ranges of masses we obtain for the current fit in the supersymmetric SU(5) model, shown in dark and light orange, respectively. The best-fit point is represented by blue lines



In general LHC constraints on the Electro Weakinos are the weakest.

Run-II data 35fb^{-1} .

Higgsino upto 390 GeV ruled out. G. Pozzo et al. Phys. Lett. B, 789:582–591, 2019. arXiv: 1807.01476 : Pure Wino upto 650 GeV ruled out (CMS data). These used W/Z's decaying into leptons Leptonic final states

Latest from analysis of hadronically decaying boosted bosons ATLAS, Phys. Rev. D, 104 (2021) 112010. with Wino mass limits going upto 1060 GeV (Higgsino upto 900 GeV), for LSP lighter than 400 (200) GeV. Need large mass difference with the LSP.

Critically evaluate the case of a light LSP (in general light EW sector). That is the subject of my talk: A light LSP ($2m_{\tilde{\chi}_1^0} < m_{h125}$)

Why does a theorist find the idea of a light $\tilde{\chi}_1^0$ attractive?

The small mass of the observed Higgs 'smells' of SUSY

But its mass close to the upper limit of 132 GeV in MSSM implies larger values of M_S!

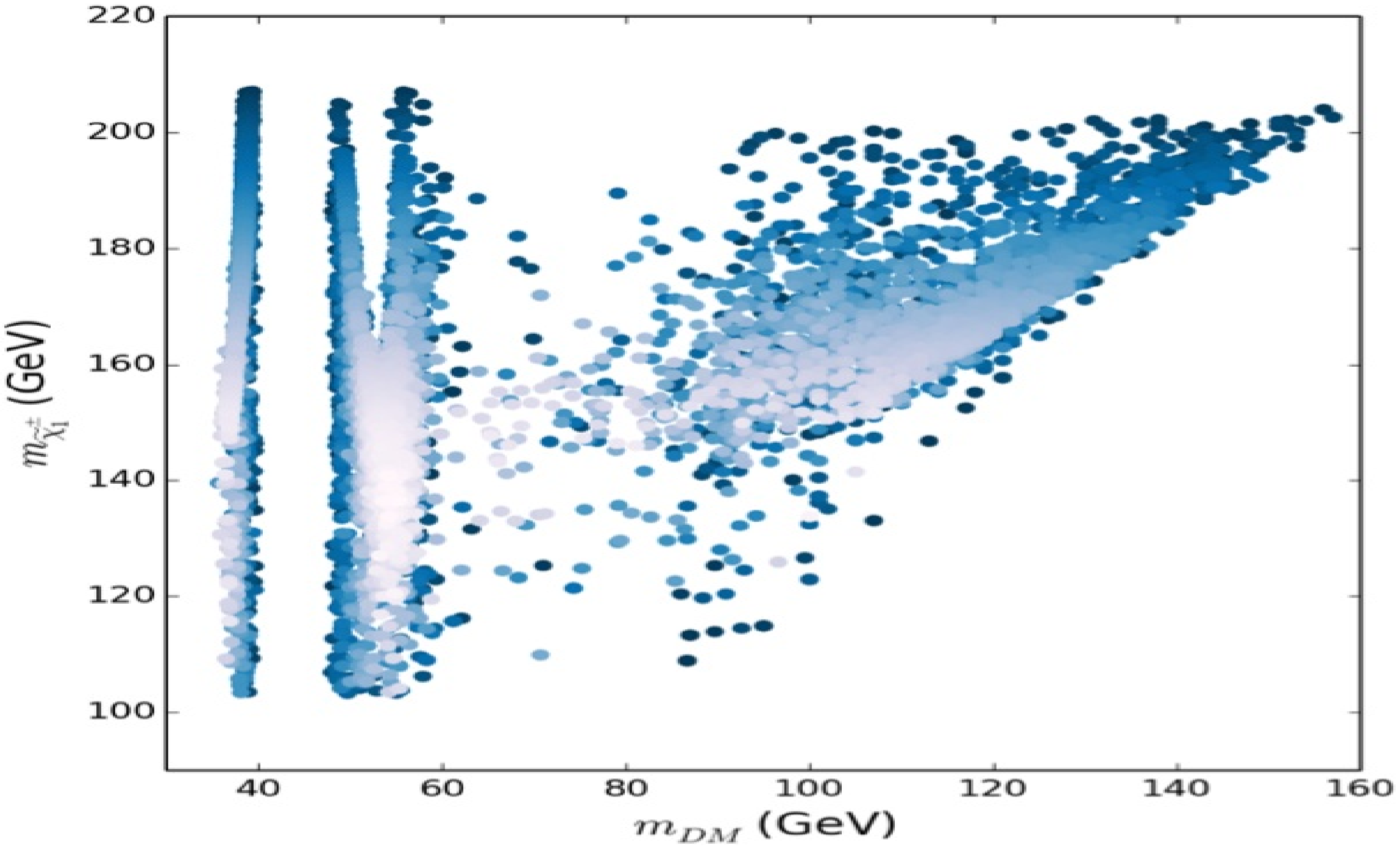
For many people this indicates 'unnaturalness' ! For example Dine: "Naturalness Under Stress"......

(On a lighter note: who are we to tell 'Nature' what is 'natural!')

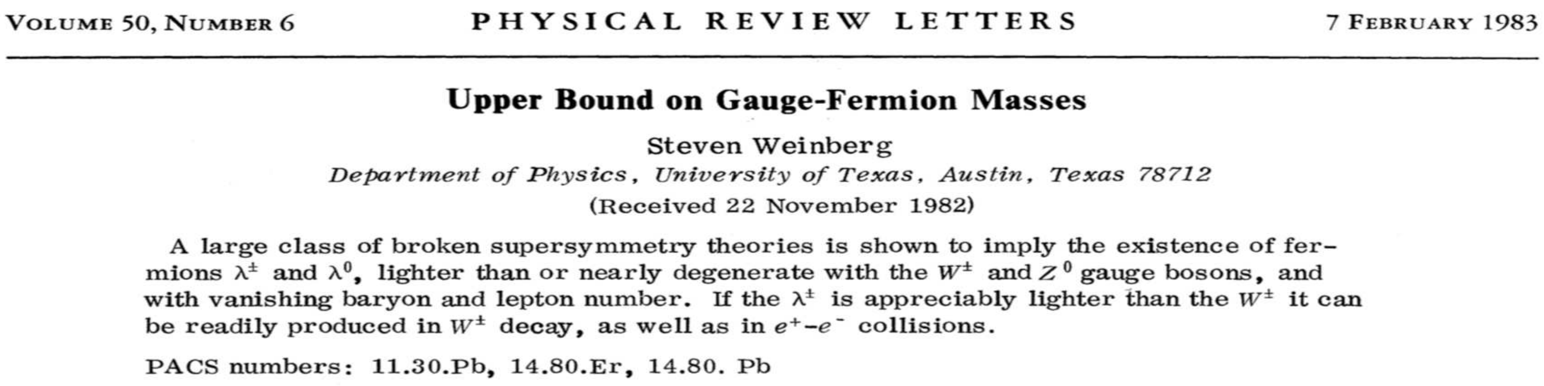
More seriously, Tata et al suggested a new measure of 'naturalness' Δ_{EW} which can be small even if the conventional measure suggested by Barbieri-Giudice (J. Ellis) Δ_{BG} is large.

1612.06333v1: M. van Beekveld, W. Beenakker, Caron, Peeters and Austri: a light LSP is 'natural' in this sense in the PMSSM. More recent JHEP 01 (2020) 147 analysis shows similar results.

1612.06333v1: M. van Beekveld, W. Beenakker, Caron, Peeters and Ruiz de Austri. light to dark, Δ varies from 4 to 10.



The Master told us long back



VOLUME 50, NUMBER 6 PHYSICAL REVIEW LETTERS 7 FEBRUARY 1983

Upper Bound on Gauge-Fermion Masses

Steven Weinberg
Department of Physics, University of Texas, Austin, Texas 78712
(Received 22 November 1982)

A large class of broken supersymmetry theories is shown to imply the existence of fermions $\lambda^{\pm}$ and λ^0, lighter than or nearly degenerate with the $W^{\pm}$ and Z^0 gauge bosons, and with vanishing baryon and lepton number. If the $\lambda^{\pm}$ is appreciably lighter than the $W^{\pm}$ it can be readily produced in $W^{\pm}$ decay, as well as in e^+-e^- collisions.

PACS numbers: 11.30.Pb, 14.80.Er, 14.80. Pb

Weinberg was the first one to point out that the Eweakinos can be lightest part of the SUSY spectrum under certain conditions.

1)SUSY breaking happened through supergravity interactions in the hidden sector (Lykken, Weinberg, Hall, PRD 27, 1983)

2) Minimal Kinetic terms for the Yang Mills Superfields.

Light DM detection rumours

Co-GenT, CRESST, CDMS-SI, DAMA/LIBRA:

C.E. Aalseth et al. Phys. Rev. Lett., 106:131301, 2011. arXiv: 1002.4703. G. Angloher et al. Eur. Phys. J. C, 72:1971, 2012. arXiv: 1109.0702. Z. Ahmed et al. Science, 327:1619–1621, 2010. arXiv: 0912.3592. R. Agnese et al. Phys. Rev. Lett., 111(25):251301, 2013. arXiv: 1304.4279.

R. Bernabei et al. Eur. Phys. J. C, 67:39–49, 2010. arXiv: 1002.1028; R. Bernabei et al. Eur. Phys. J. C, 74(3):2827, 2014. arXiv: 1403.4733.

The DD reports are ruled out by Xenon, LUX

The indirect detection (Fermi-LAT) reports are 'clouded' by astrophysical uncertainties.

L. Goodenough et al. arXiv: 0910.2998. D. Hooper et al. Phys. Lett. B, 697:412–428, 2011. arXiv: 1010.2752, D. Hooper et al. Phys. Rev. D, 84:123005, 2011. aeXiv: 1110.0006, T. Daylan et al. Phys. Dark Univ., 12:1–23, 2016.

Is there a cosmological limit on how light a CDM particle can be?

C. Boehm et al. J. Phys. G, 30:279–286, 2004. arXiv: astro-ph/0208458; C. Boehm, T.A. Ensslin, and J. Silk, J. Phys. G, 30:279–286, 2004, C. Boehm et al. JCAP, 08:041, 2013. arXiv: 1303.6270

Using PLANCK limit on N_{eff} ; effective number of ν species: masses for CDM as small as $\sim$ MeV and less than a few GeV $\tilde{\chi}_1^0$ (neutralino in SUSY) can be allowed.

LSP: Two candidates: the sneutrino $\tilde{\nu}_L$ and the neutralino $\tilde{\chi}_1^0$.

$\tilde{\nu}_L$ has full strength gauge couplings to SM matter. A light $\tilde{\nu}_L$ can not be a good DM candidate and also ruled out by Direct Detection(DD) experiments.

The weakest LHC constraints from non observation are on the mass of the $\tilde{\chi}_1^0$.

Focus on $\tilde{\chi}_1^0$.

"Status of low mass LSP in SUSY"

Eur. Phys. J. ST **229**, no.21, 3159-3185 (2020), [arXiv:2010.11674 [hep-ph]] and references therein

Question to ask:

How light can a SUSY LSP candidate be and still be a viable DM candidate?

What is meant by that?

- It should not over close the Universe.(If we assume standard cosmology and hence thermal relic) (Will make some comments about non thermal case as well in the end)

- Should be allowed the Direct/Indirect detection constraints.

Planck measurements and the anisotropies tell us

$\Omega_{DM}h^2 = 0.120 \pm 0.001$

In a model the predicted relic :

$$\Omega_{\tilde{\chi}}h^2 = \frac{m_{\tilde{\chi}}n_{\tilde{\chi}}}{\rho_c} \simeq \frac{3 \times 10^{-27}\mathrm{c}m^3 s^{-1}}{\langle \sigma_{ann} v \rangle},$$

The couplings of the DM particle which decides σ_{ann} will then decide relic density which in turn will depend on the model. $\sigma_{ann} \propto \frac{g_{\tilde{\chi}}^4}{m_{\tilde{\chi}}^2}$. Combinations of $g_{\tilde{\chi}}$ and $m_{\tilde{\chi}}$ will produce the right relic.

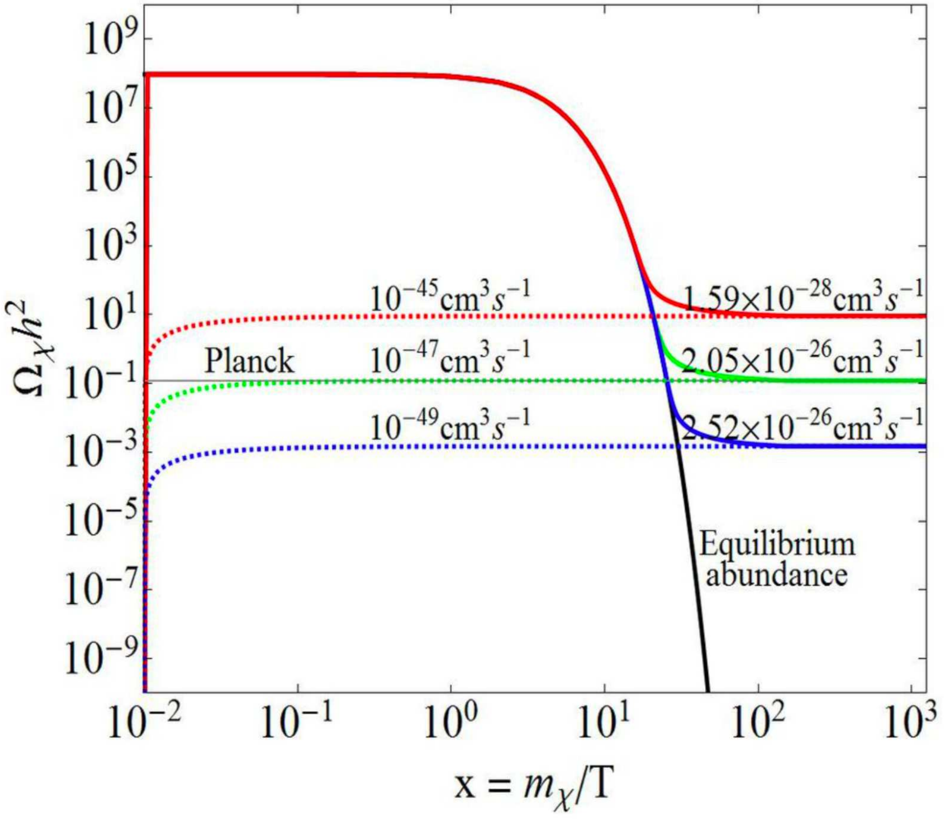
This expression above is for thermal relic, ie. the species abundance is decided by the temperature at which it falls out of thermal equilibrium, ie. freezes out.

Recall:

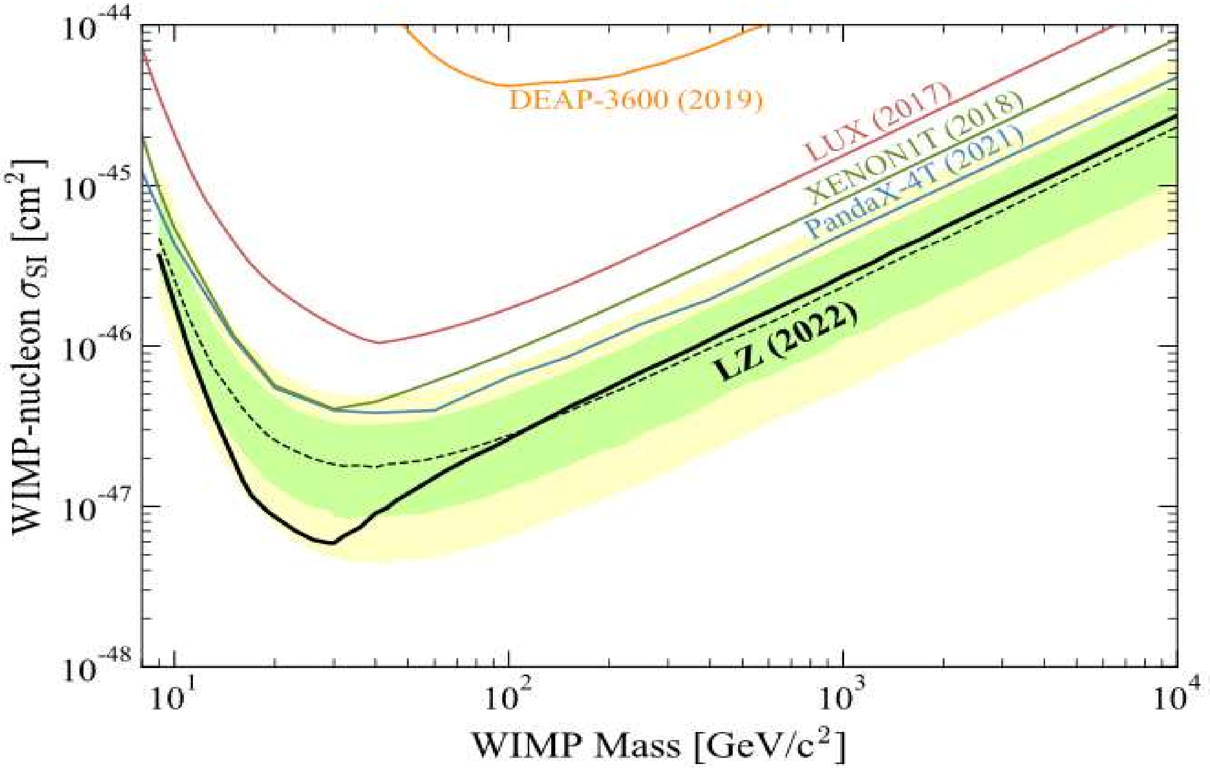
Different possibilities with freeze in and out of equilibrium decay also exist depending on mass spectrum.

With non-thermal cosmology, one could investigate model points which in principle give rise to relic higher than the observed but late time entropy injection can also make the relic consistent with observed relic.

Mainly I will talk only about usual thermal relic.



P. S. Bhupal Dev, A. Mazumdar and S. Qutub, Front. in Phys. **2** (2014), 26, arXiv:1311.5297.



This is data from only the first 60 days of exposure for LZ. It is the most stringent limit is set for spin-independent scattering at 30 GeV, excluding cross sections above$5.9 \times 10^{-48} cm^2$ at the 90% confidence level.

The relic density calculations and also the DM detection cross-sections in a model will depend on the couplings of the DM with the SM particles!

In pMSSM the $\tilde{\chi}_1^0$ is a mixture of Higgsino and Gauginos .

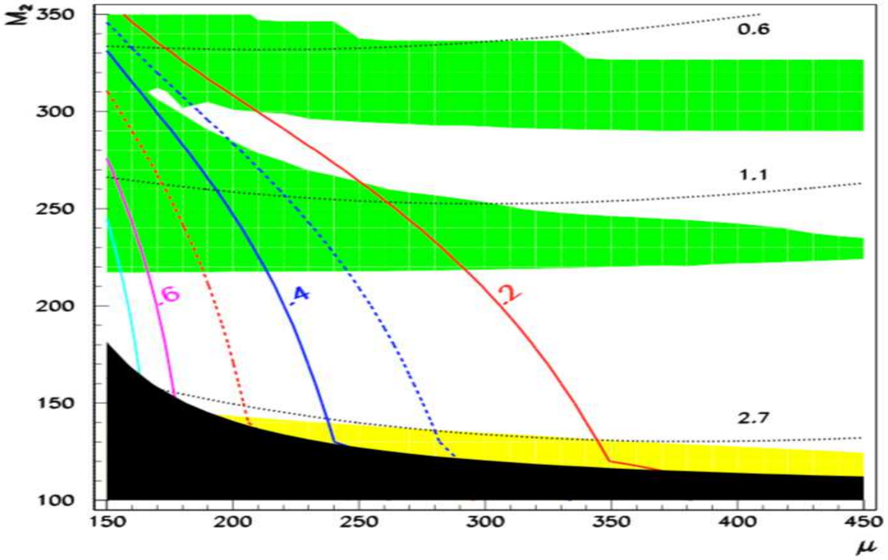
The extent of this mixing decides couplings of the $\tilde{\chi}_1^0$ with all the SM and MSSM particles.

A Wino like or Higgsino like $\tilde{\chi}_1^0$ will have to be heavy ($\sim$ TeV) to explain the observed relic due to the high cross-sections. How a model can produce a wino like LSP is a different question.

A bino-like $\tilde{\chi}_1^0$ means too high a relic density unless additional annihilation possibilities exist because of its smaller couplings!

t-channel light slepton OR a resonant annihilation via Higgs/A/Z. The Z exchange requires a nontrivial Higgsino fraction too in the neutralino! The so called 'well tempered neutralino'.

For the Higgsino-Bino well tempered relic, h_{125} **can** have appreciable branching fraction into invisible neutralino pair. In fact this was the focus of our early papers! G. Belanger, F. Boudjema, F. Donato R. M. Godbole and S. Rosier-Lees, Nucl. Phys. B **581**, 3 (2000)



Green : Relic < 0.1, White: $0.1 < \text{relic} < 0.3$, yellow : relic > 0.3

Phys. Lett. B 519 (2001) 93-102 "The MSSM invisible Higgs in the light of dark matter and g-2"

Till the DM detection experiments came in full swing the collider bounds dominated the story. In cMSSM the LEP constraint on $m_{\tilde{\chi}_1^\pm}$ and universal gaugino mass would rule out light $\tilde{\chi}_1^0$. So a light $\tilde{\chi}_1^0$ necessarily means non universal gaugino masses. Focus moved to the pMSSM

G. Belanger, F. Boudjema, F. Donato R. M. Godbole and S. Rosier-Lees, Nucl. Phys. B **581**, 3 (2000), Phys. Lett. B 519 (2001) 93-102.

Before Xenon 1T and LHC results, older relic measurements:
Lower limit of 30 GeV on the mass of the $\tilde{\chi}_1^0$.

L. Calibbi, T. Ota, Y. Takanishi, JHEP 07, 013 (2011), D.A. Vasquez, G. Belanger, C. Boehm, Phys. Rev. D 84, 095015 (2011), G. Belanger, G. D. La Rochelle, B. Dumont, R. M. Godbole,S. Kraml and S. Kulkarni, Phys. Lett. B **726** 773 (2013)

Invisible branching ratio

A light LSP can contribute to the 'invisible' decay of the Higgs.

Invisible decay of the Higgs can also be searched for at the LHC:

E.g. : R. M. Godbole, M. Guchait, K. Mazumdar, S. Moretti and D. P. Roy (2003), Phys. Lett. B **571**; D. Ghosh, R. Godbole, M. Guchait, K. Mohan and D. Sengupta, Phys. Lett. B 725, arXiv:1211.7015 [hep-ph] (2013)

Current best limit from the LHC is $\tilde{1}3\%$.ATLAS-CONF-2020-008 and $\tilde{1}4.5\%$ ATLAS: submitted to JHEP, 2202.07953

Future for looking for this 'dark' higgs is 'bright'.

LHC can reach 'invisible' BR upto 3.8%

ILC/CLIC/FCC can reach upto 0.2-0.4 %

In the current situation different possibilities to look for light $\tilde{\chi}_1^0$ in SUSY:

1)Look for Mono events or LLP. Not effective for light LSP.

2)Look for invisibly decaying Higgs.

3)Direct production of the heavier Electroweakino states ($\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ etc) and their decays. WZ mediated and WH mediated decays of heavier charginos and neutralinos.

Now we have

1)precise determination of relic,

2)strong constraints from Direct Detection

3) LEP/LHC searches for electroweakinos

4)**Measurements of Higgs X-sections and branching ratios.**

5)precision calculations of the Higgs mass.

6) measurements of the invisible width of the Higgs.

What is the situation now?

How low a mass can a viable DM candidate have in SUSY consistent with all the current exclusions? Can the future colliders probe these 'light' LSP's? Ie. can we rule out this region from collider experiments?Using phenomenology of the heavier electro weakinos.

Can models and observed relic density support a light SUSY DM particle if reported in either Direct or Indirect detection experiment? If yes what can the LHC (current,HL/LHC and HE/LHC) say about it?

Will discuss:

pMSSM : The weakest LHC constraints from non observation are on the mass of the $\tilde{\chi}_1^0$. The important parameters are μ, M_1, M_2 and $\tan\beta$. Radiative corrections bring in dependence on A_t, m_t. and even M_3. We will discuss this in the context of standard and nonstandard cosmology.

Results from

B. Bhattcharjee, R. Barman, Rhitaja Sengupta, RG Phys.Rev.Lett. 131 (2023) 1, 011802, e-Print: 2207.06238 [hep-ph]; e-print 2312.XXXXX

1) Make sure given point is allowed by a variety of current constraints: LHC constraints, LEP constraints, flavour constraints coming from B sector, Higgs sector constraints.

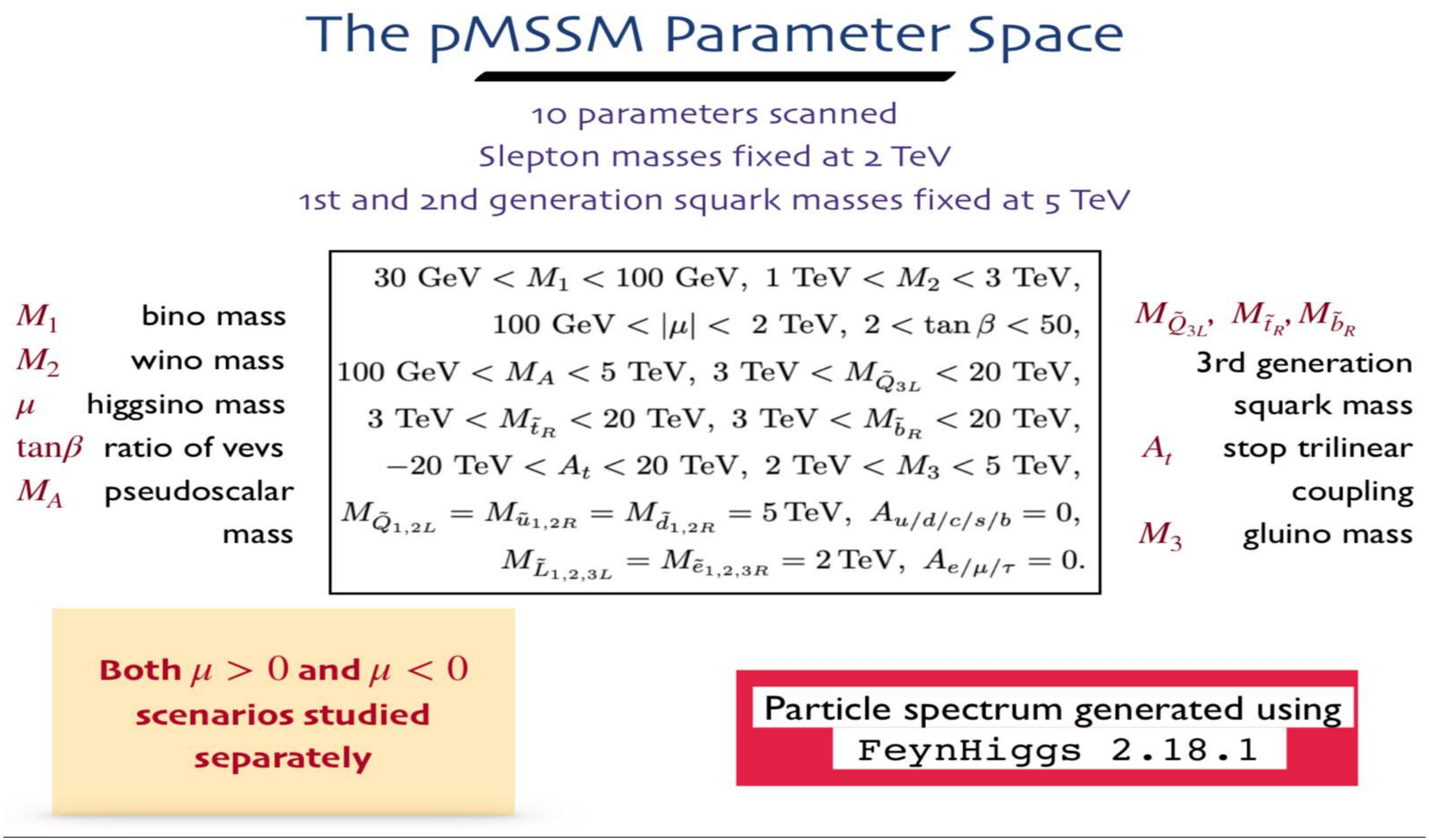
2)Calculate the invisible branching ratio for the Higgs.

3) Calculate the expected 'direct detection cross-sections.

4) Calculate the relic density for the given point.

Calculate $\xi = \Omega_{cal}h^2/\Omega_{obs}h^2 = \Omega_{cal}h^2/0.122$

$\xi \leq 1$: Thermal DM



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

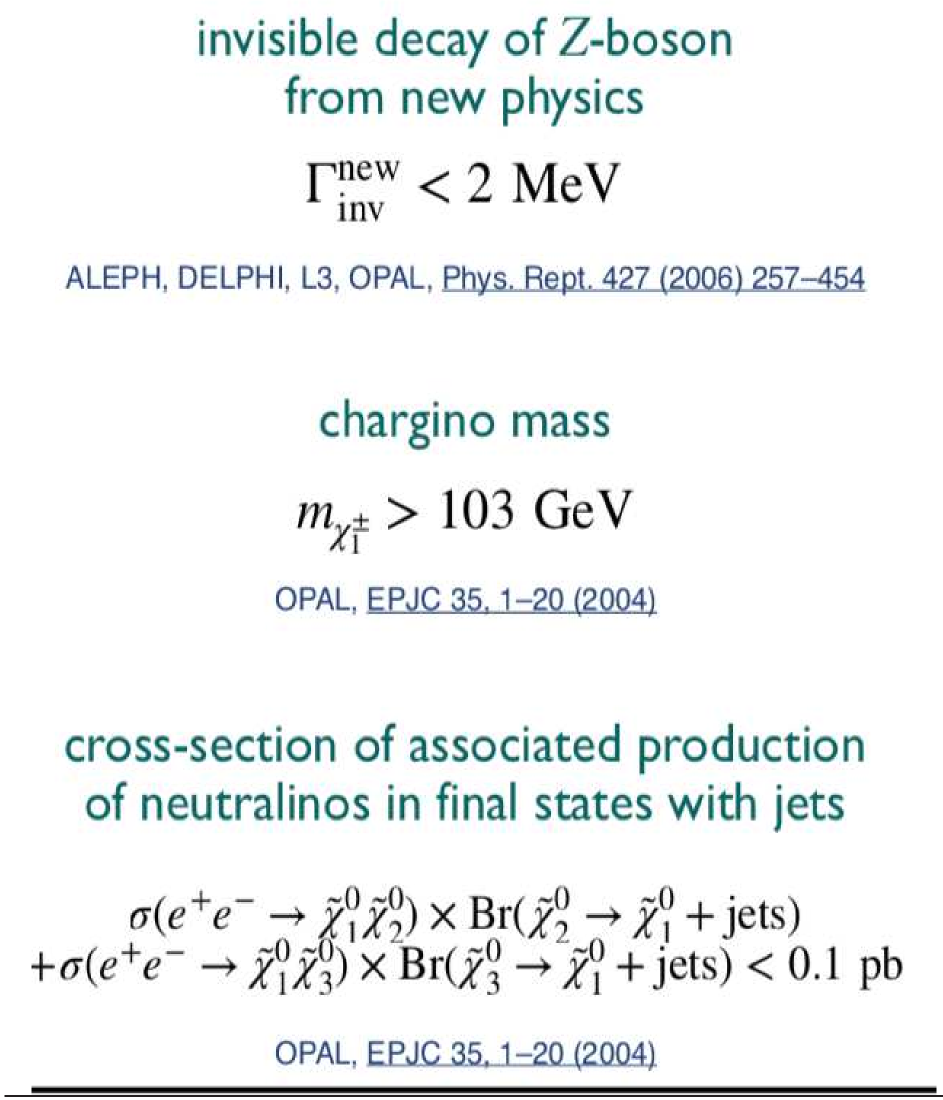
$$\boxed{\begin{aligned} 30\ \mathrm{GeV} < M_1 < 100\ \mathrm{GeV},\ 1\ \mathrm{TeV} < M_2 < 3\ \mathrm{TeV}, \\ 100\ \mathrm{GeV} < |\mu| <\ 2\ \mathrm{TeV},\ 2 < \tan\beta < 50, \\ 100\ \mathrm{GeV} < M_A < 5\ \mathrm{TeV},\ 3\ \mathrm{TeV} < M_{\tilde{Q}_{3L}} < 20\ \mathrm{TeV}, \\ 3\ \mathrm{TeV}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

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

LEP constraints.



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

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

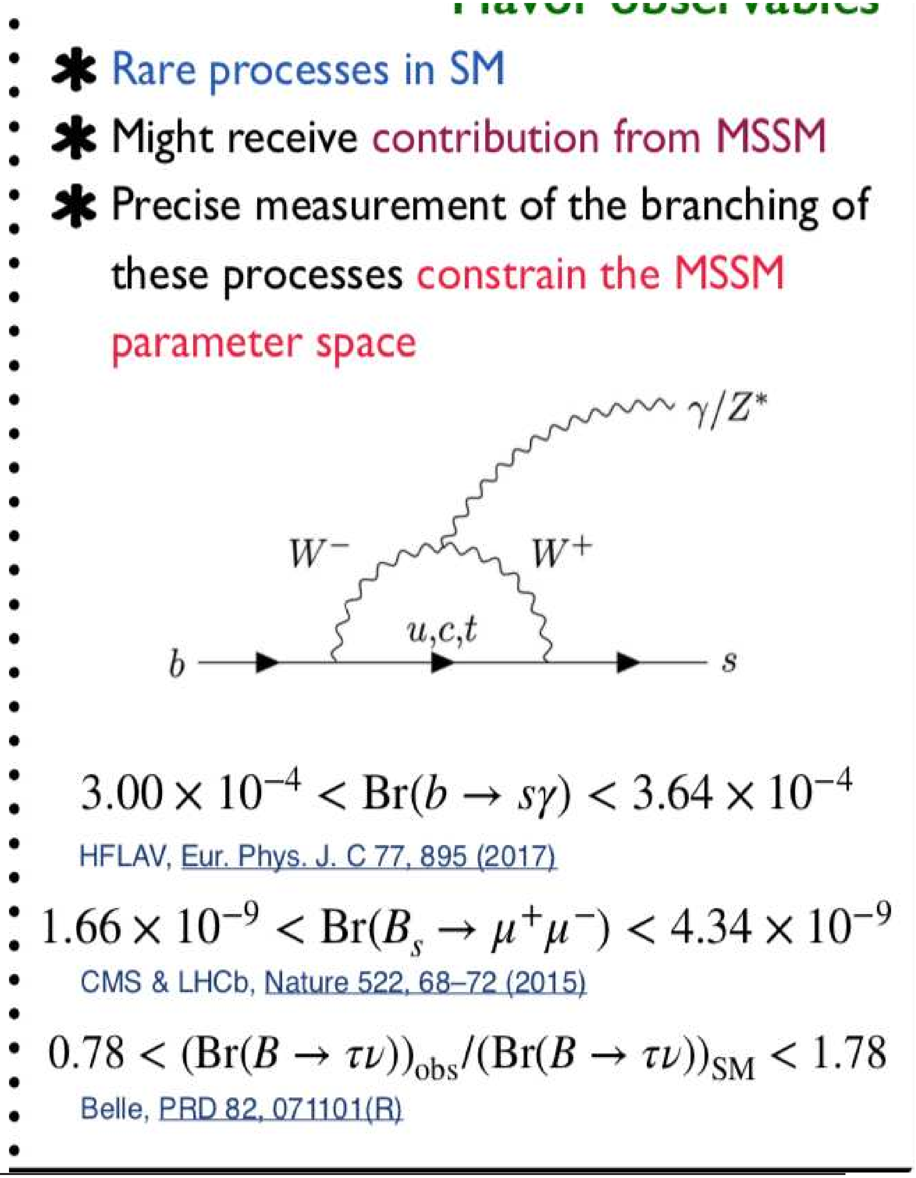
OPAL, EPJC 35, 1–20 (2004)

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)

Flavour constraints.



- 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)

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

Belle, PRD 82, 071101(R)

Current Constraints on the Parameter Space

Higgs constraints

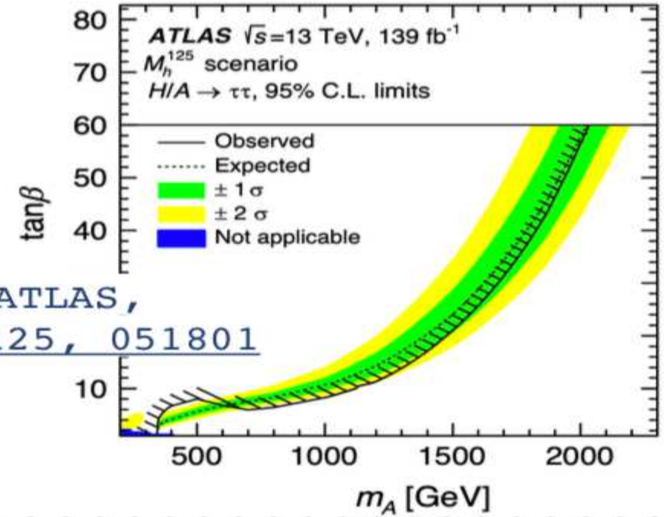
Observed Higgs mass

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

`FeynHiggs 2.18.1`

Heavy Higgs searches

`HiggsBounds 5.10.0`



ATLAS,
PRL 125, 051801

Higgs signal strength

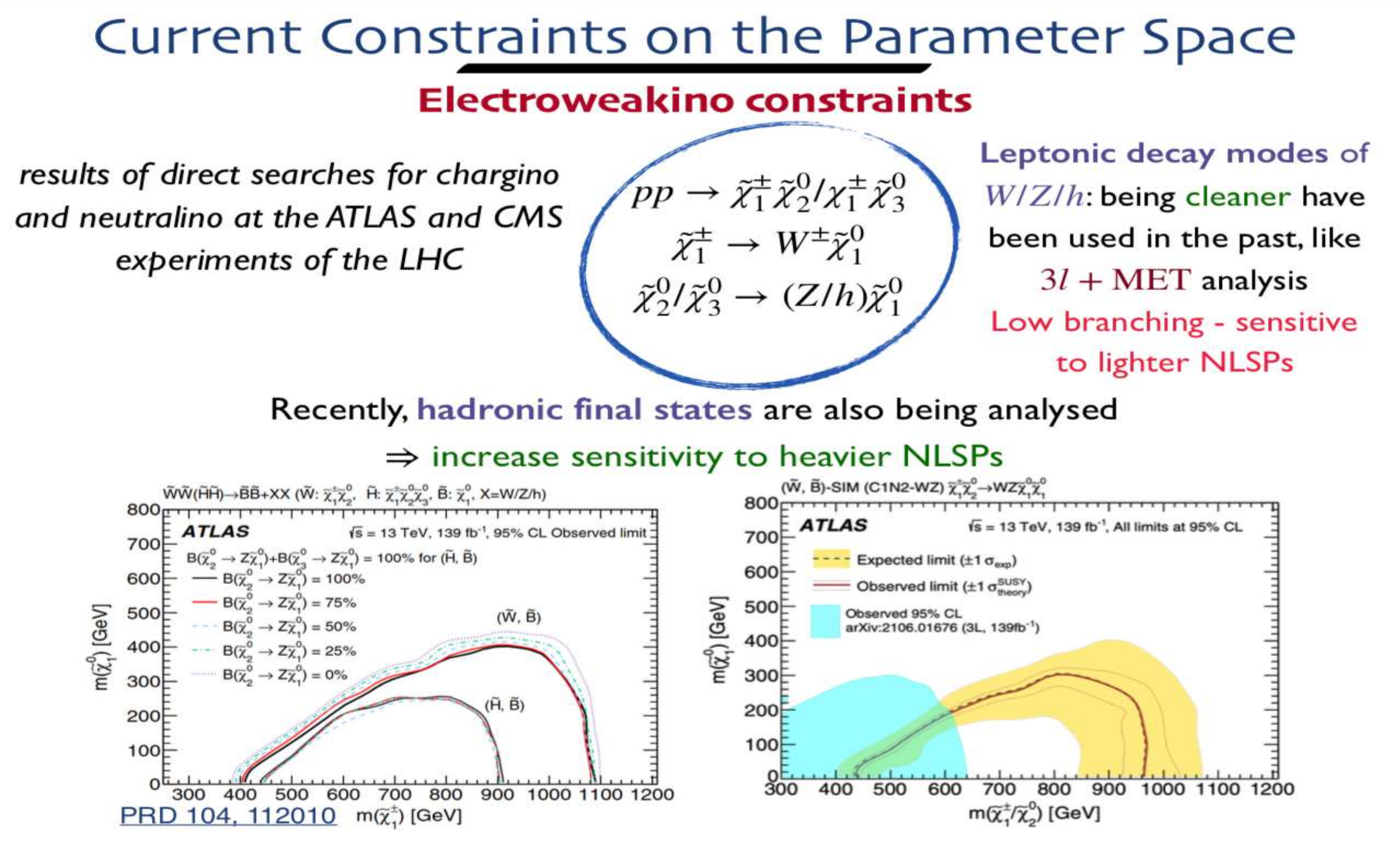
$$\mu = \frac{(\text{Production}_{\text{mode}} \times \text{Branching}_{\text{mode}})_{\text{obs}}}{(\text{Production}_{\text{mode}} \times \text{Branching}_{\text{mode}})_{\text{SM}}}$$

`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

Electroweakino constraints

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

$$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0/\chi_1^{\pm}\tilde{\chi}_3^0$$
$$\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0$$
$$\tilde{\chi}_2^0/\tilde{\chi}_3^0 \to (Z/h)\tilde{\chi}_1^0$$

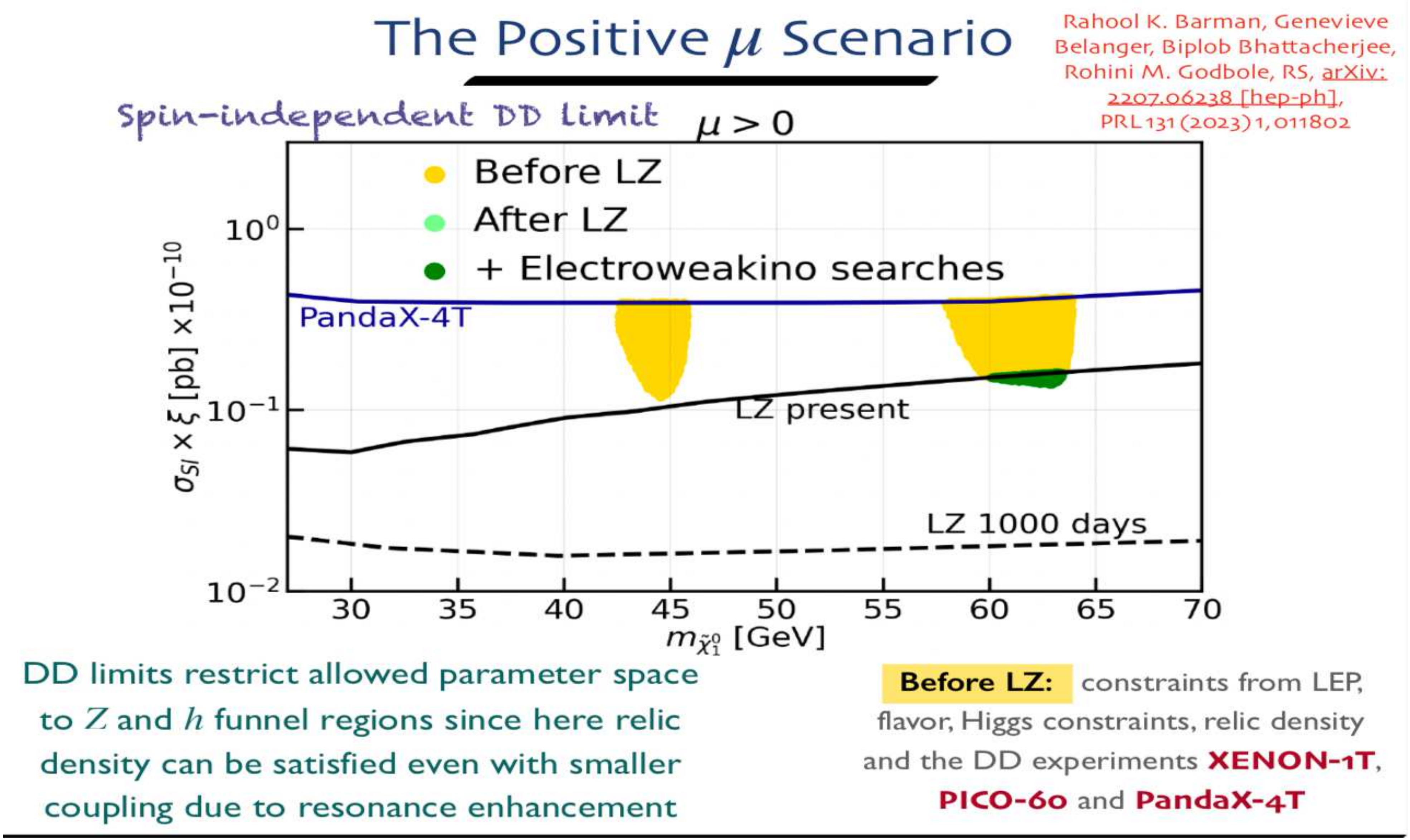
Leptonic decay modes of $W/Z/h$: being cleaner have been used in the past, like $3l + \mathrm{MET}$ analysis

Low branching - sensitive to lighter NLSPs

Recently, hadronic final states are also being analysed

⇒ increase sensitivity to heavier NLSPs

PRD 104, 112010



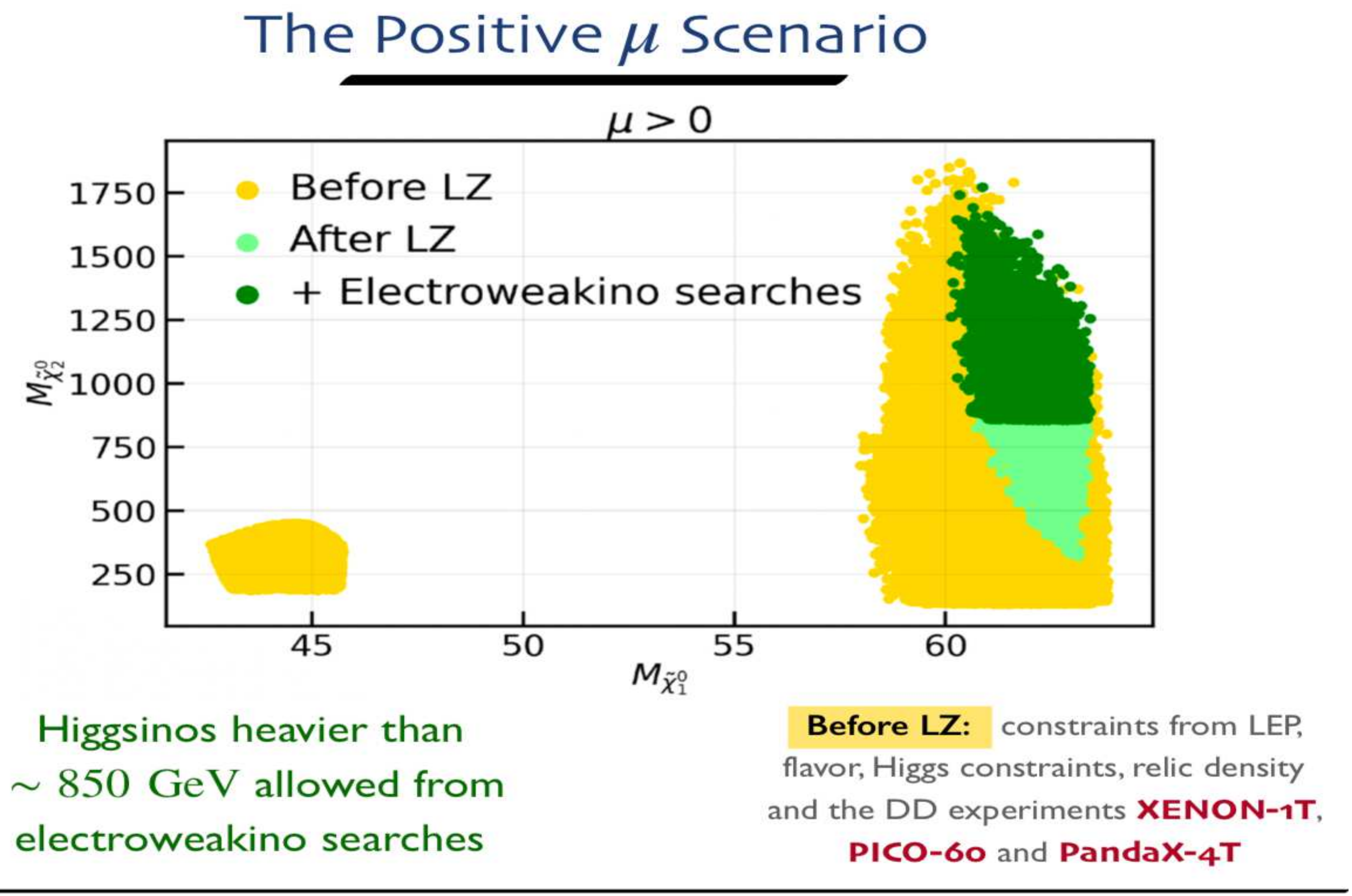
The Positive μ Scenario

Rahool K. Barman, Genevieve Belanger, Biplob Bhattacherjee, Rohini M. Godbole, RS, arXiv: 2207.06238 [hep-ph], PRL 131 (2023) 1, 011802

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**



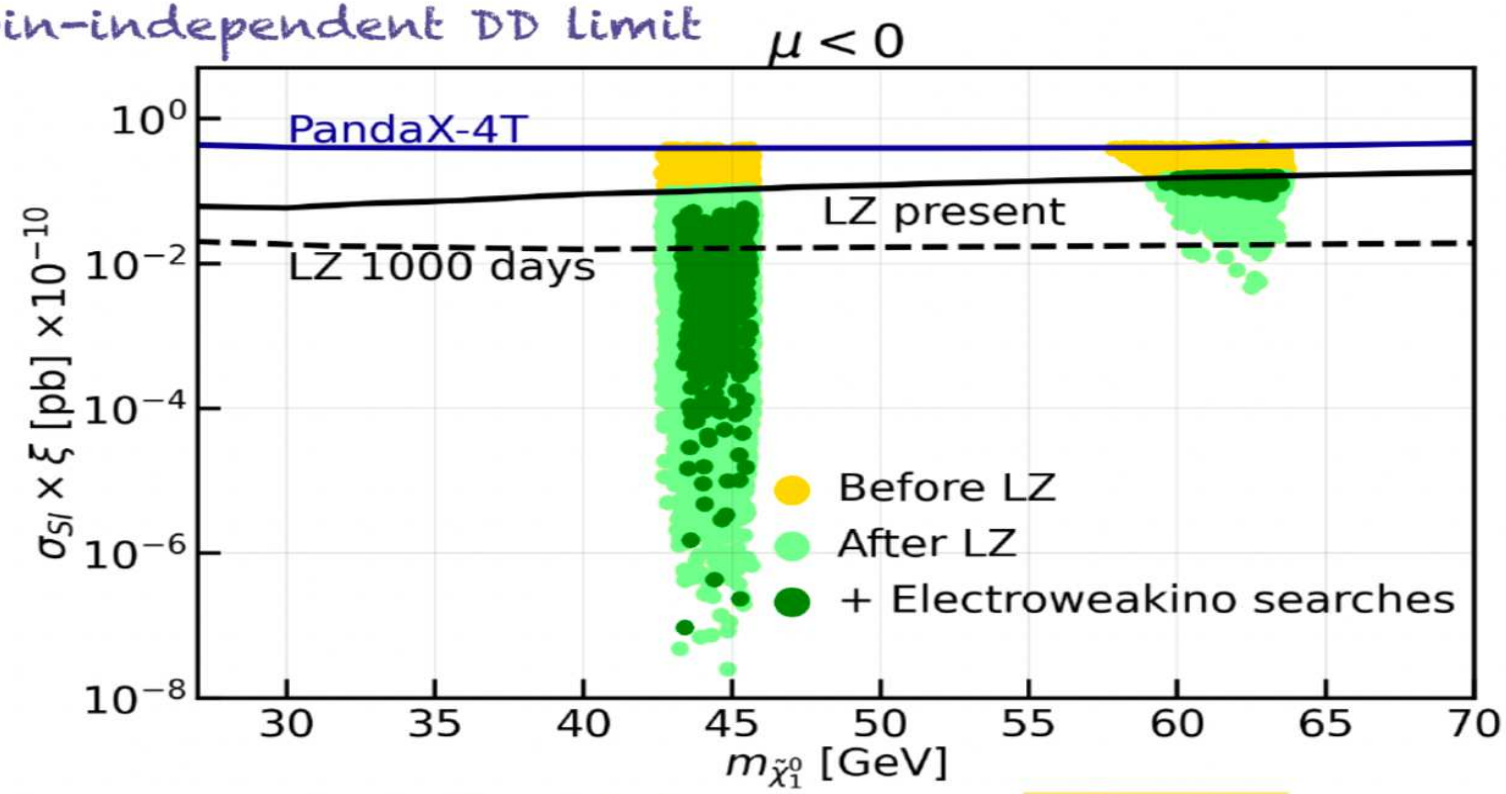
The Positive μ Scenario

Higgsinos heavier than ~ 850 GeV allowed from electroweakino searches

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

The Negative μ Scenario

Spin-independent DD limit



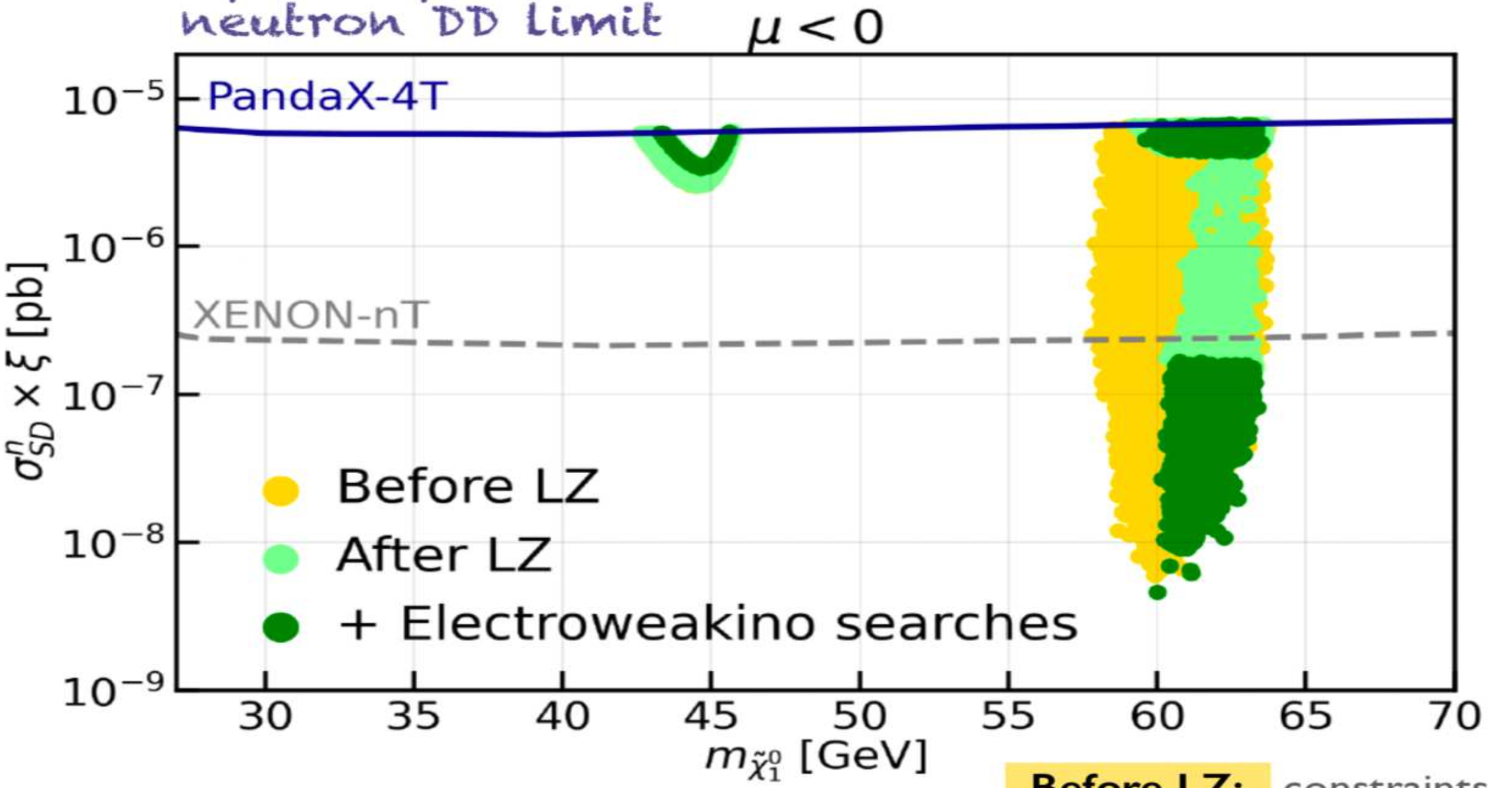
Allowed regions in both Z and h funnels

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

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

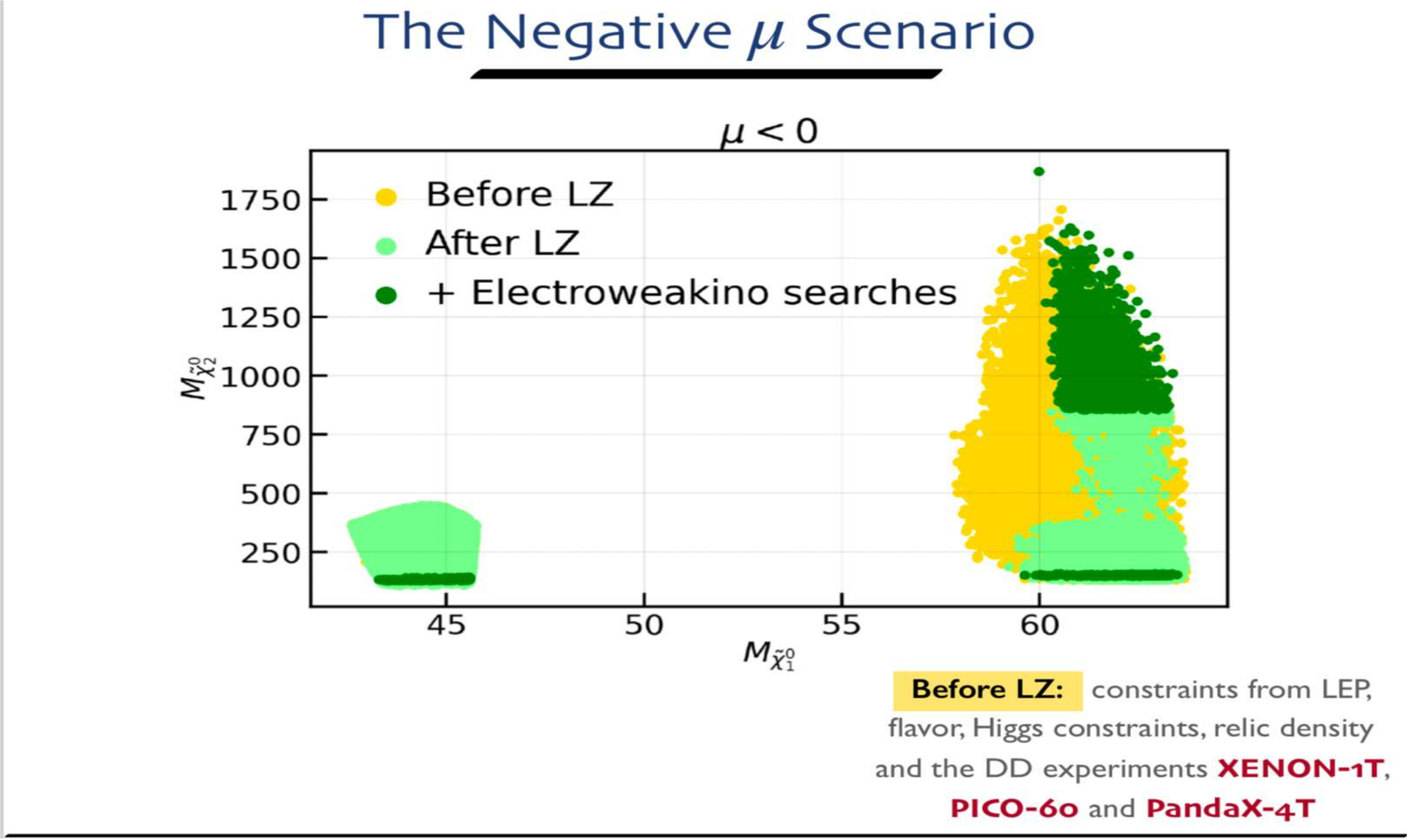
The Negative μ Scenario

Spin-dependent neutron DD limit



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

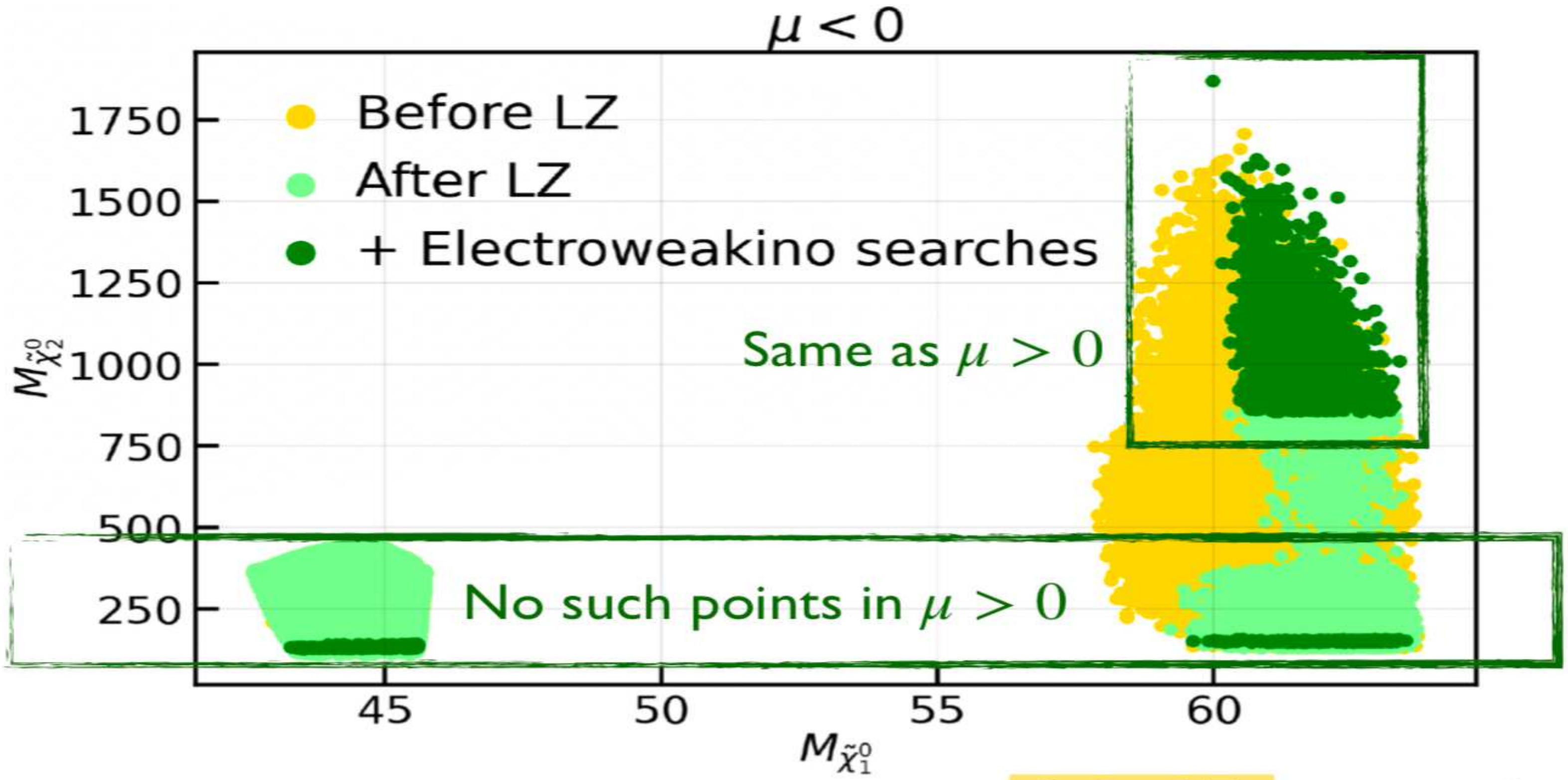
Z-funnel well within the reach of XENON-nT data



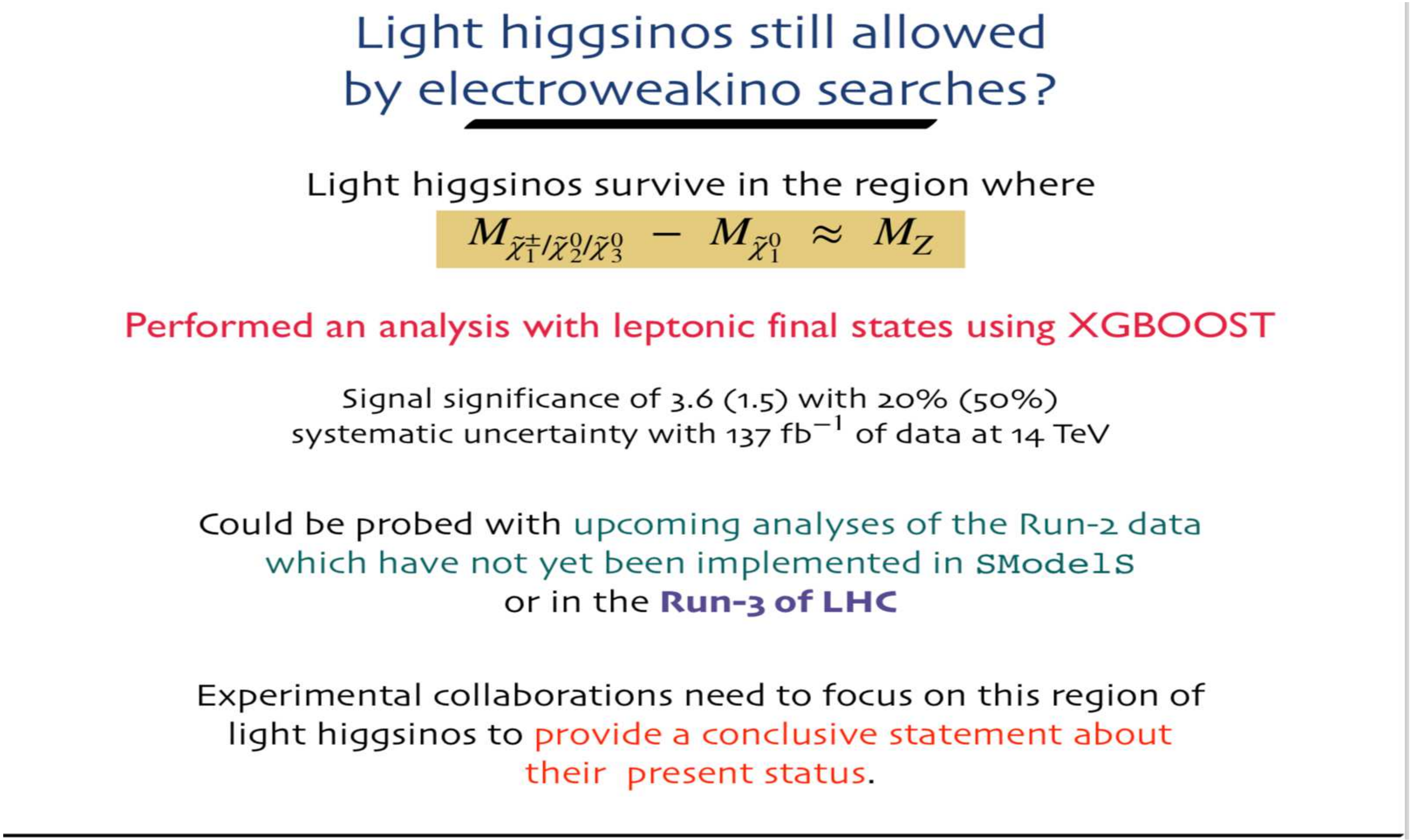
The Negative μ Scenario

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

The Negative μ Scenario



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



Light higgsinos still allowed by electroweakino searches?

Light higgsinos survive in the region where

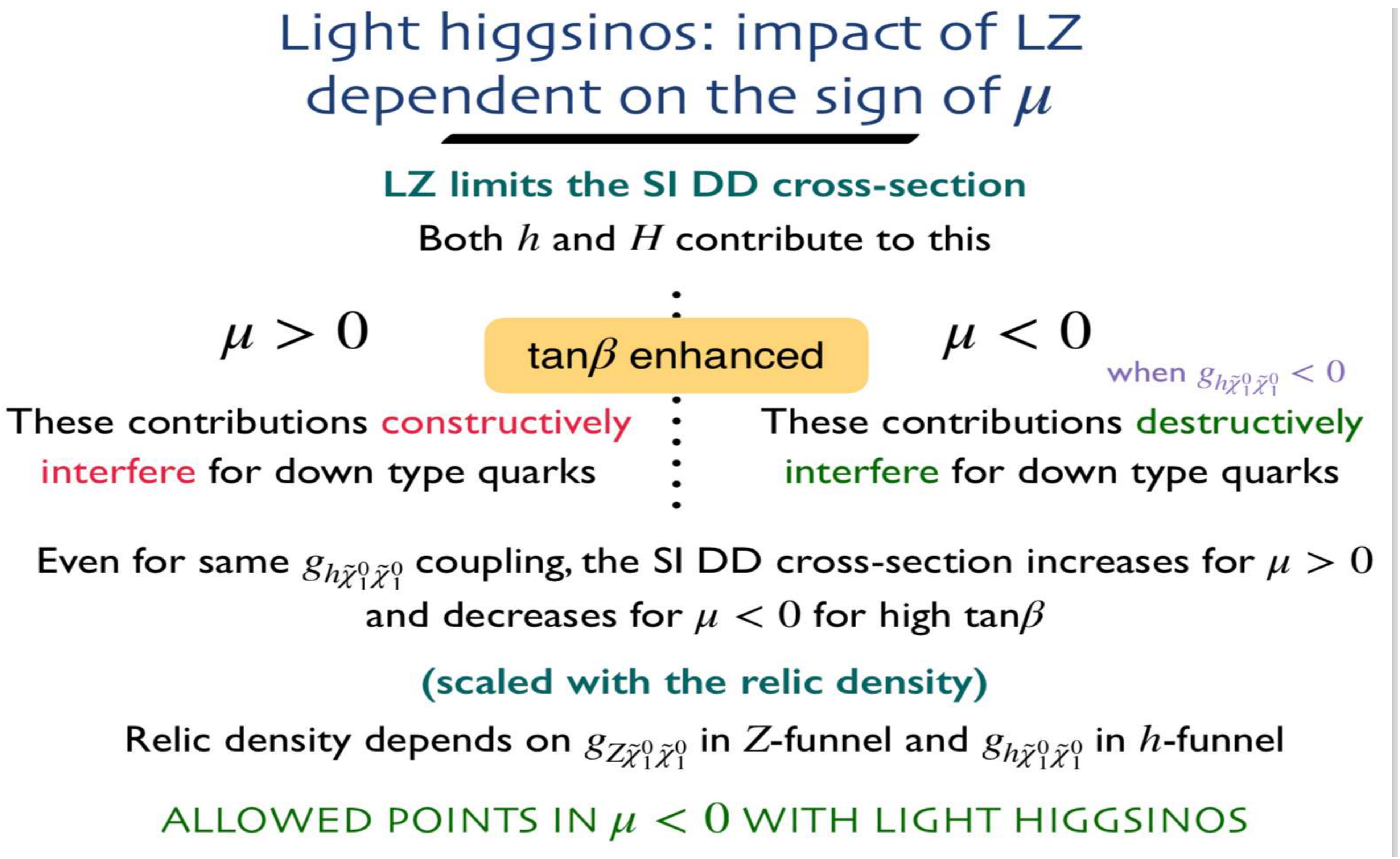
$$M_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_3^0} - M_{\tilde{\chi}_1^0} \approx M_Z$$

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.



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

$\mu > 0$

tanβ enhanced

$\mu < 0$

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

These contributions constructively interfere for down type quarks

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)

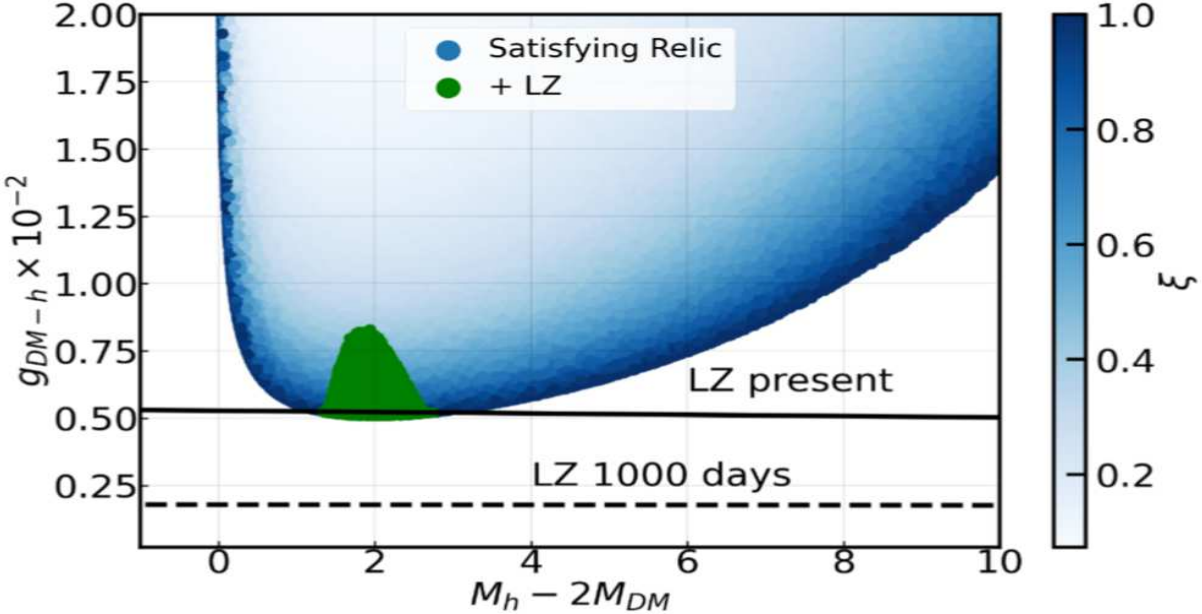
Relic density depends on $g_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0}$ in Z-funnel and $g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0}$ in h-funnel

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

Heavy higgsinos in the h-funnel

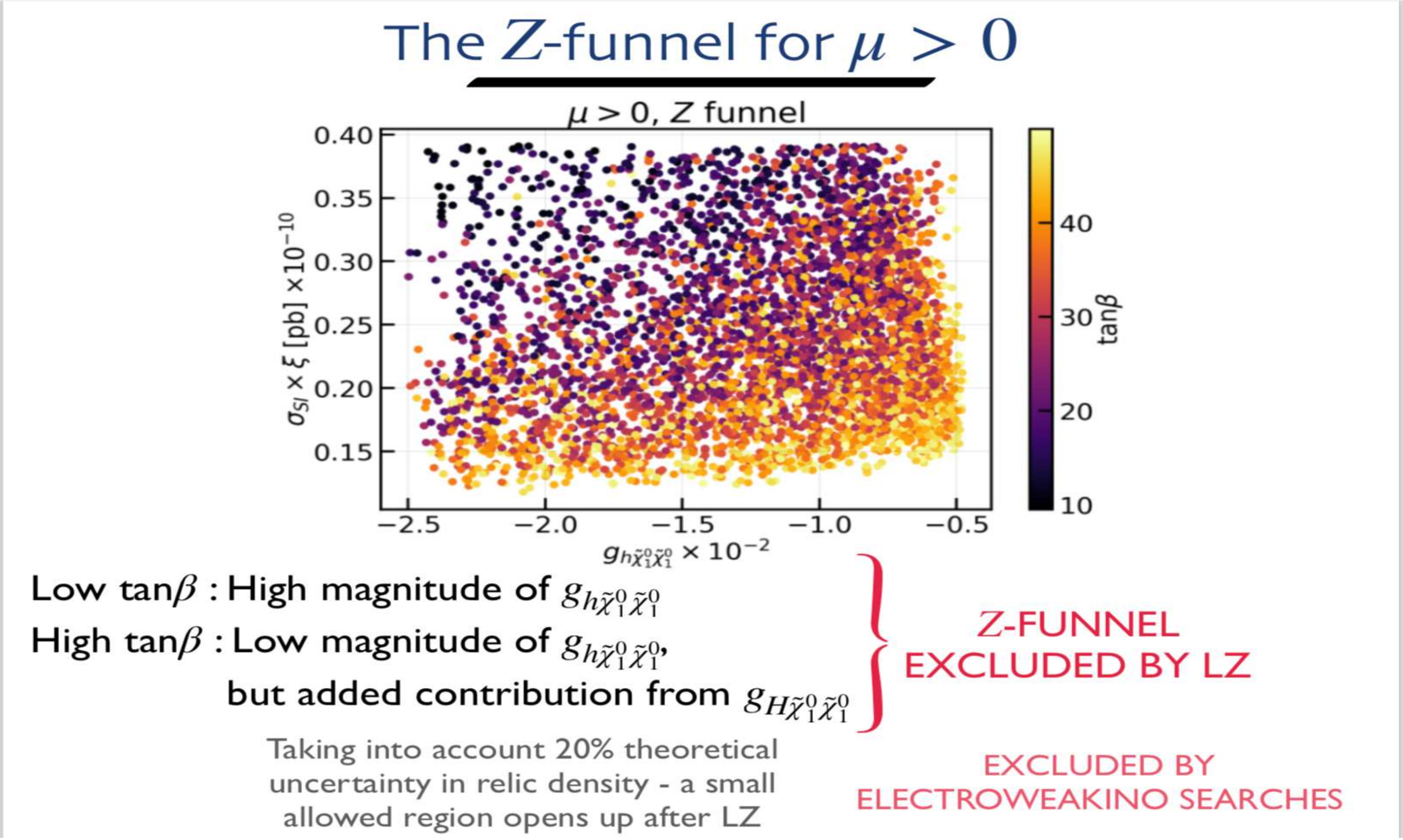
- Heavy higgsino have low values of couplings of LSP with Z and h
  - relic density condition not satisfied
- In h-funnel, extra handle of tanβ
  - relic satisfied only for low tanβ where coupling is high
- Effect of H not important

Similar to any Majorana fermion coupled to only h



ALSO STRONGLY CONSTRAINED

Can be probed with few more days of LZ data



The Z-funnel for $\mu > 0$

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

High tanβ : 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

1) What is the impact of theoretical uncertainties on the calculation of relic density.

Small additional allowed region opens up but still within the reach of future runs of LZ, Xenon-nT and LHC-run3.

2)Impact of lighter sparticles? The only one which can be light and can impact the results is a light $\tilde{\tau}$. Affects the relic results by about 25% and also the branching ratios of the Higgsinos in our XGBOOST analysis at the LHC.

The analysis of allowed regions is nontrivial. But we have just finished it. Again very small region at low masses is allowed and LHC-run3 should be able to cover it.

ii) NMSSM (Additional singlet higgs superfield) : In addition to above additional parameters related to this extra field. Additional light (pseudo)scalars. $\kappa, \lambda, A_\kappa, A_\lambda$.

iii) PMSSM + $\tilde{\nu}_R$

iv) NMSSM + $\tilde{\nu}_R$

For NMSSM it is a mixture of higgsinos and gauginos as well as a singlino. The scalars are also doublet-singlet mixtures.

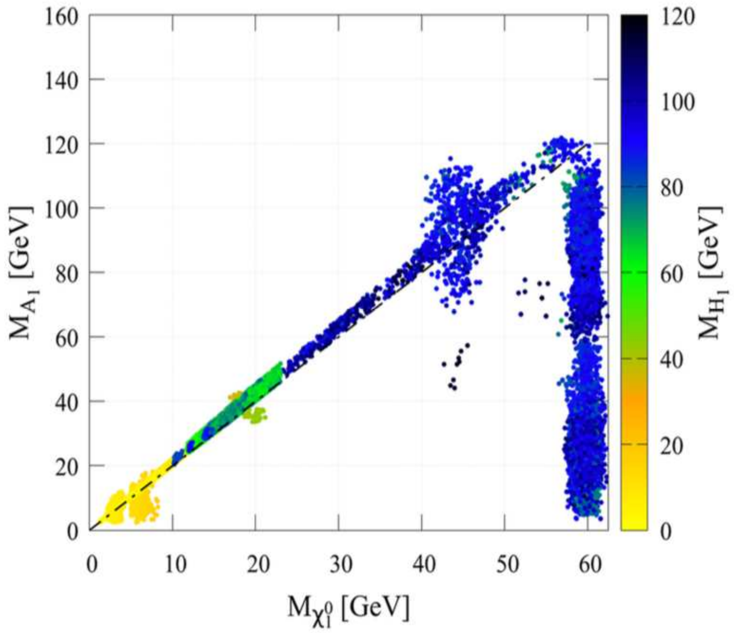
The extent of this mixing decides couplings of the $\tilde{\chi}_1^0$ with all the SM and NMSSM particles.

For case of $\tilde{\nu}_R$ LSP additional Yukawa couplings may come into play.

NMSSM superpotential extended from MSSM by adding terms $\lambda\widehat{S}\widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$

Now the neutralino mass matrix is five dimensional. There is one more neutral fermion : the singlino. The LSP is a superposition of all the five.

Has one more pseudoscalar and scalar in addition to the MSSM Higgses. Thus in principle two 'lighter states A_1, H_1 become available for resonant annihilation. Thus additional annihilation channels become possible.



h_2 identified with the observed SM -like Higgs. Possibility of a light singlet dominated h_1, a_1 lighter than 122 GeV.

$\tilde{\chi}_1^0$ Singlino or Bino dominated. Annihilations through a_1, h_1 provide the right relic No co-annihilations for our choice . Only resonance annihilations.

Along the line $2M_{\tilde{\chi}_1^0} = m_{a_1}$. Away from this it is the h_1 which provides efficient annihilation.

So in NMSSM a light LSP is easily accommodated.

Question: Light A_1, H_1 obtained with low values of κ, λ. Is that natural?

Our LSP is mostly singlino. Difficulty to search for a mixed, light LSP region.

Plan to do first a simplified model analysis and then perhaps go back to NMSSM again to understand it.

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.

1) regions of heavy higgsinos very close to being probed by few days of LZ data

OR

2) very low mass higgsinos (and low mass right handed stau) which can be targeted at the Run-3 of LHC with dedicated analyses to be sensitive in this narrow gap.

How much further up can we extend the limit of 62.5 GeV on the mass of the LSP in pMSSM?

In NMSSM a light LSP is allowed. Only thermal scenario studied. Direct detection, LHC searches and invisible branching ratio of the Higgs all offer probes of the scenario.(The analysis needs to be redone with LZ limits!)

pMSSM extended with a $\tilde{\nu}_R$: a light $\tilde{\nu}_R$ still possible. Characteristic signals. (Detailed recent analyses are not available)

We can see that this WIMP paradigm for a light LSP in pMSSM and NMSSM can be tested at the HL/HE LHC, ILC/CEPC and DD experiments.

Based on:

1)R. K. Barman, G. Belanger, B. Bhattacherjee, R. Godbole, G. Mendiratta and D. Sengupta, Phys. Rev. D 95 (2017) no.9, 095018; 1703.03838;

2)R. K. Barman, G. ,Belanger, B. Bhattacherjee, R. Godbole, D. Sengupta and X. Tata,2006.07854, Phys. Rev. D 103, (2021) 015029;

3)R, K. Barman, G. Bélanger, R. Godbole, 'Low mass LSP in SUSY' , Review :Eur.Phys.J.ST 229 (2020) 21, 3159-3185,

4)B. Banerjee, R, K. Barman, G. Bélanger, R. Godbole, **R. Sengupta** Phys.Rev.Lett. 131 (2023) 1, 011802 ; e-print: 2312.XXXXX.

These papers focus on $2m_{\tilde{\chi}_1^0} \leq m_h(125)$.

An analytic continuation of sorts of work which I had started around 2000/2001.

G. Belanger, F. Boudjema, F. Donato R. M. Godbole and S. Rosier-Lees, Nucl. Phys. B **581**, 3 (2000) [hep-ph/0002039]

G. Belanger, F. Boudjema, A. Cottrant, R. M. Godbole and A. Semenov, Phys. Lett. B **519**, 93 (2001) [hep-ph/0106275]

D. Albornoz Vasquez, G. Belanger, R. M. Godbole and A. Pukhov, Phys. Rev. D **85** (2012) 115013,[arXiv:1112.2200 [hep-ph]].

G. Belanger, G. D. La Rochelle, B. Dumont, R. M. Godbole, S. Kraml and S. Kulkarni, Phys. Lett. B **726** 773 (2013) [arXiv:1308.3735 [hep-ph]]