Constraining Resonant Dark Matter

with combined LHC electroweakino searches

Yang Zhang

School of Physics and Astronomy, Monash University

Based on arXiv:1807.01476

In collaboration with Giancarlo Pozzo

MONASH University

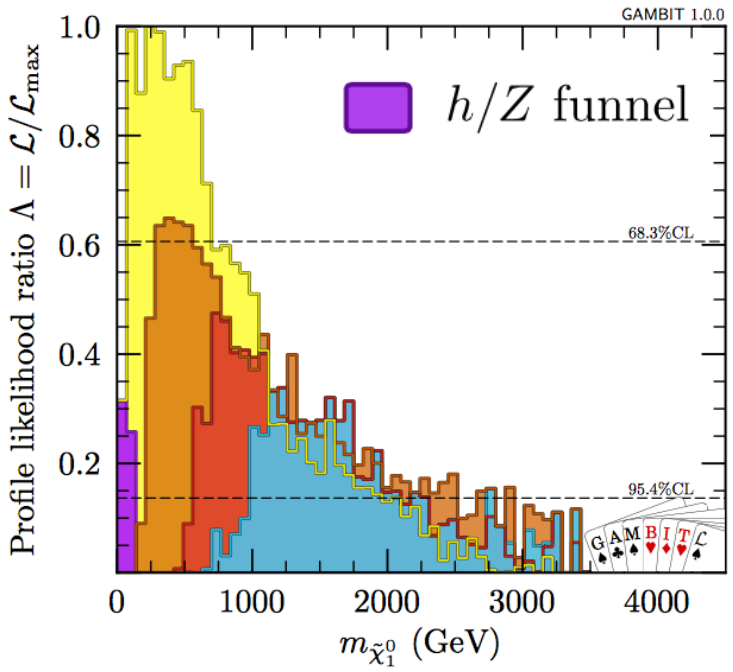
CONTENTS

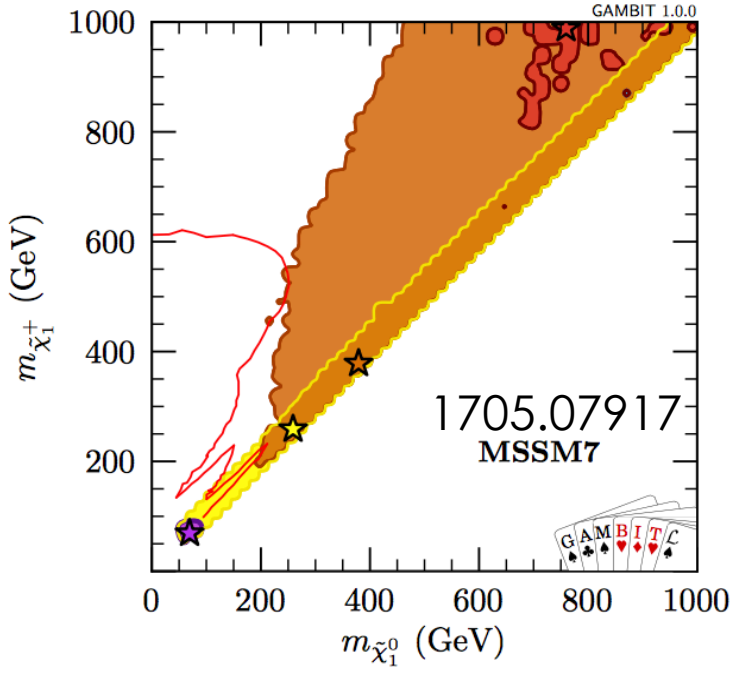
01 Introduction

The motivation of studying the Z/h-resonant DM

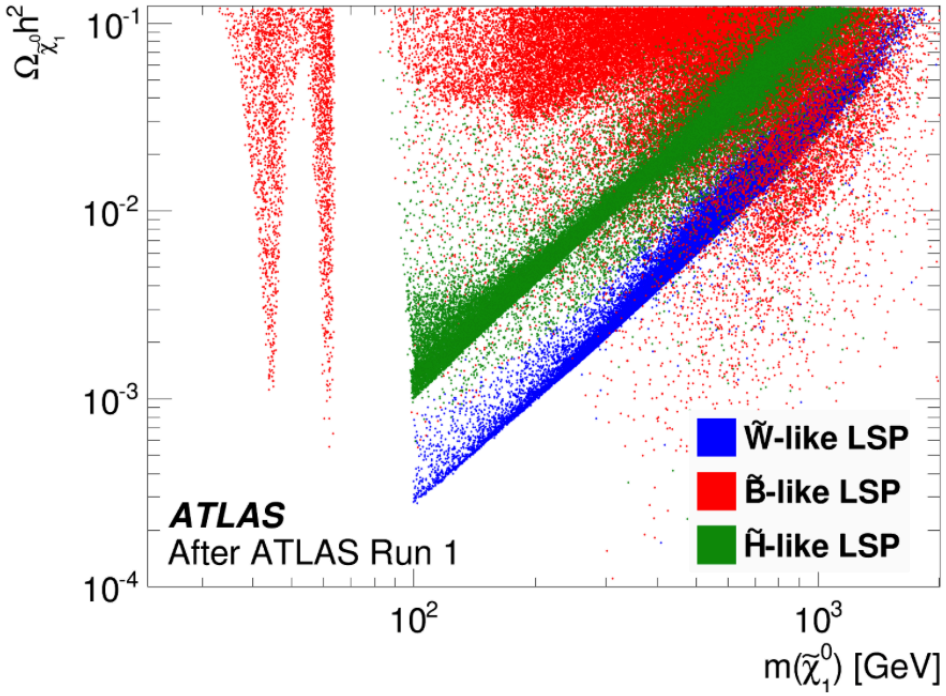
01 Introduction

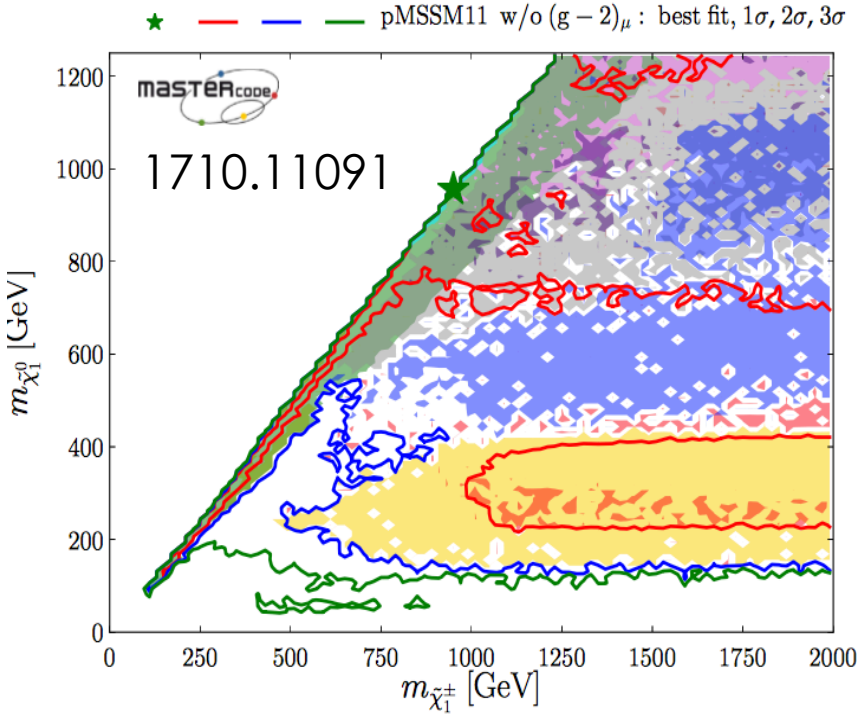
Global fit of the MSSM:

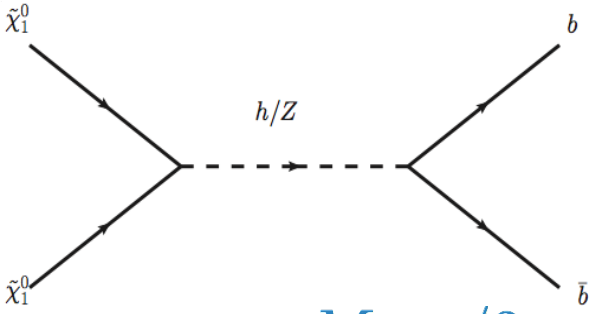




1508.06608



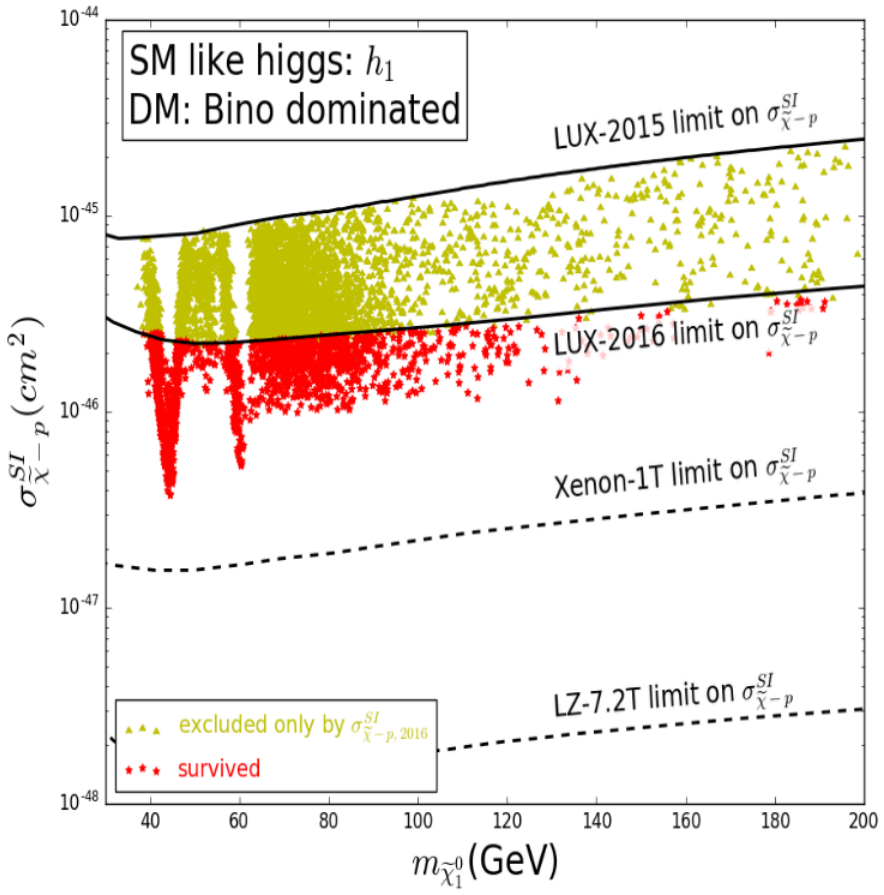


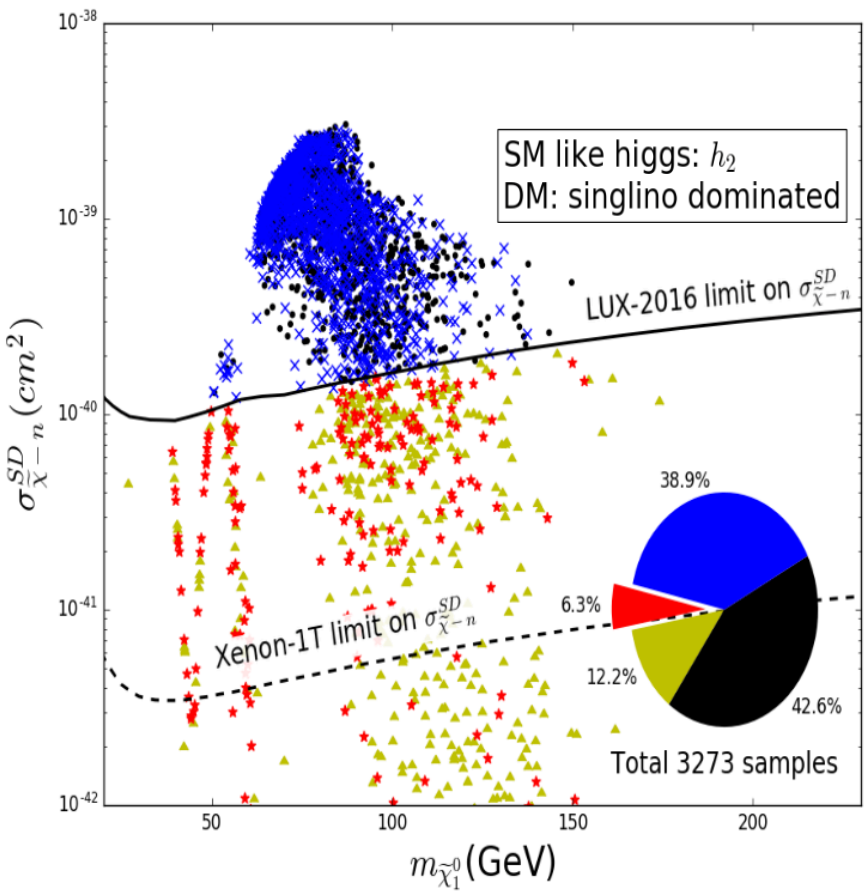


$$m_{\tilde{\chi}_1^0} \simeq M_{Z/h}/2$$

01 Introduction

The Z/h resonant Dark Matter in natural MSSM/NMSSM

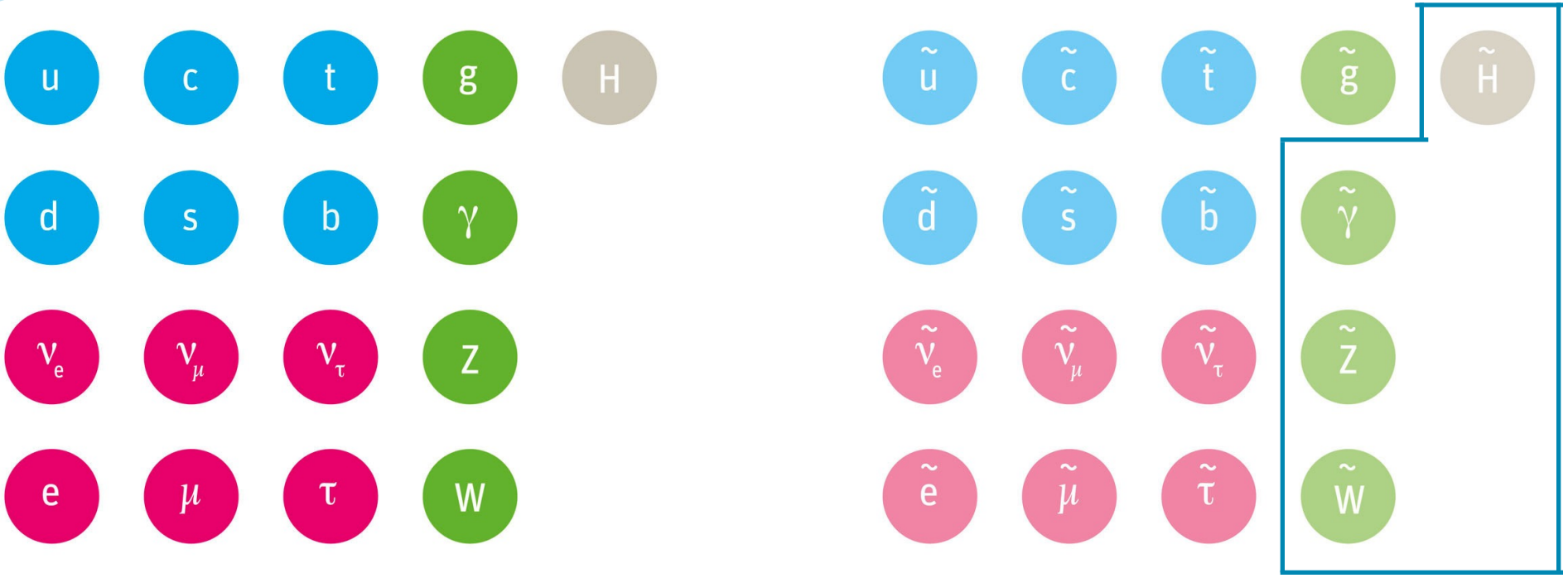




02 The Z/h-resonant DM

Parameter space & constraints

02 The Z/h-resonant DM



In the gauge-eigenstate basis $\psi^0 = (\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0)$,

$$\mathcal{L}_{\text{neutralino mass}} = -\frac{1}{2}(\psi^0)^T \mathbf{M}_{\widetilde{N}} \psi^0 + \text{c.c.},$$

$$\mathbf{M}_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$

In the gauge-eigenstate basis $\psi^\pm = (\widetilde{W}^+, \widetilde{H}_u^+, \widetilde{W}^-, \widetilde{H}_d^-)$,

$$\mathcal{L}_{\text{chargino mass}} = -\frac{1}{2}(\psi^\pm)^T \mathbf{M}_{\widetilde{C}} \psi^\pm + \text{c.c.}$$

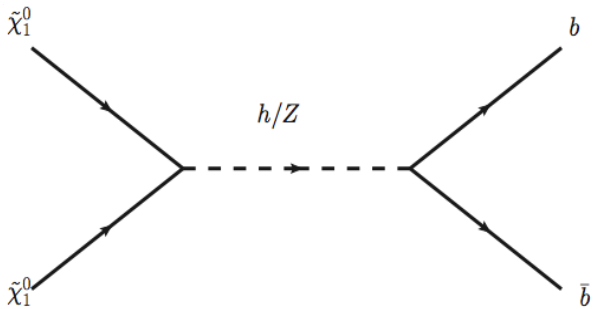
$$\mathbf{M}_{\widetilde{C}} = \begin{pmatrix} \mathbf{0} & \mathbf{X}^T \\ \mathbf{X} & \mathbf{0} \end{pmatrix}$$

$$\mathbf{X} = \begin{pmatrix} M_2 & g v_u \\ g v_d & \mu \end{pmatrix} = \begin{pmatrix} M_2 & \sqrt{2} s_\beta\, m_W \\ \sqrt{2} c_\beta\, m_W & \mu \end{pmatrix}$$

02 The Z/h-resonant DM

$$\sigma(\tilde{\chi}_1^0\tilde{\chi}_1^0 \xrightarrow{h_1} XX') \propto \left|\frac{C_{h_1\tilde{\chi}_1^0\tilde{\chi}_1^0}C_{h_1XX'}}{s-m_{h_1}^2+i\Gamma_{h_1}m_{h_1}}\right|^2 f_s(s, m_{\tilde{\chi}_1^0}^2, m_X^2, m_{x'^2})$$

$$\sigma(\tilde{\chi}_1^0\tilde{\chi}_1^0 \xrightarrow{Z} XX') \propto \left|\frac{C_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0}C_{ZXX'}}{s-m_z^2+i\Gamma_Z m_z}\right|^2 g_s(s, m_{\tilde{\chi}_1^0}^2, m_X^2, m_{X'}^2, M_Z^2)$$



$$\mathcal{L}_{\tilde{\chi}^0} = \frac{e}{s_W} h\bar{\tilde{\chi}}_1^0(N_{12} - N_{11}\tan\theta_W)(\sin\alpha N_{13} + \cos\alpha N_{14})\tilde{\chi}_1^0$$
$$+\frac{e}{s_W c_W} Z_\mu \bar{\tilde{\chi}}_i^0 \gamma^\mu \left[\frac{P_L}{2}(N_{14}^2 - N_{13}^2) + \frac{P_R}{2}(N_{14}^2 - N_{13}^2)\right]\tilde{\chi}_j^0.$$

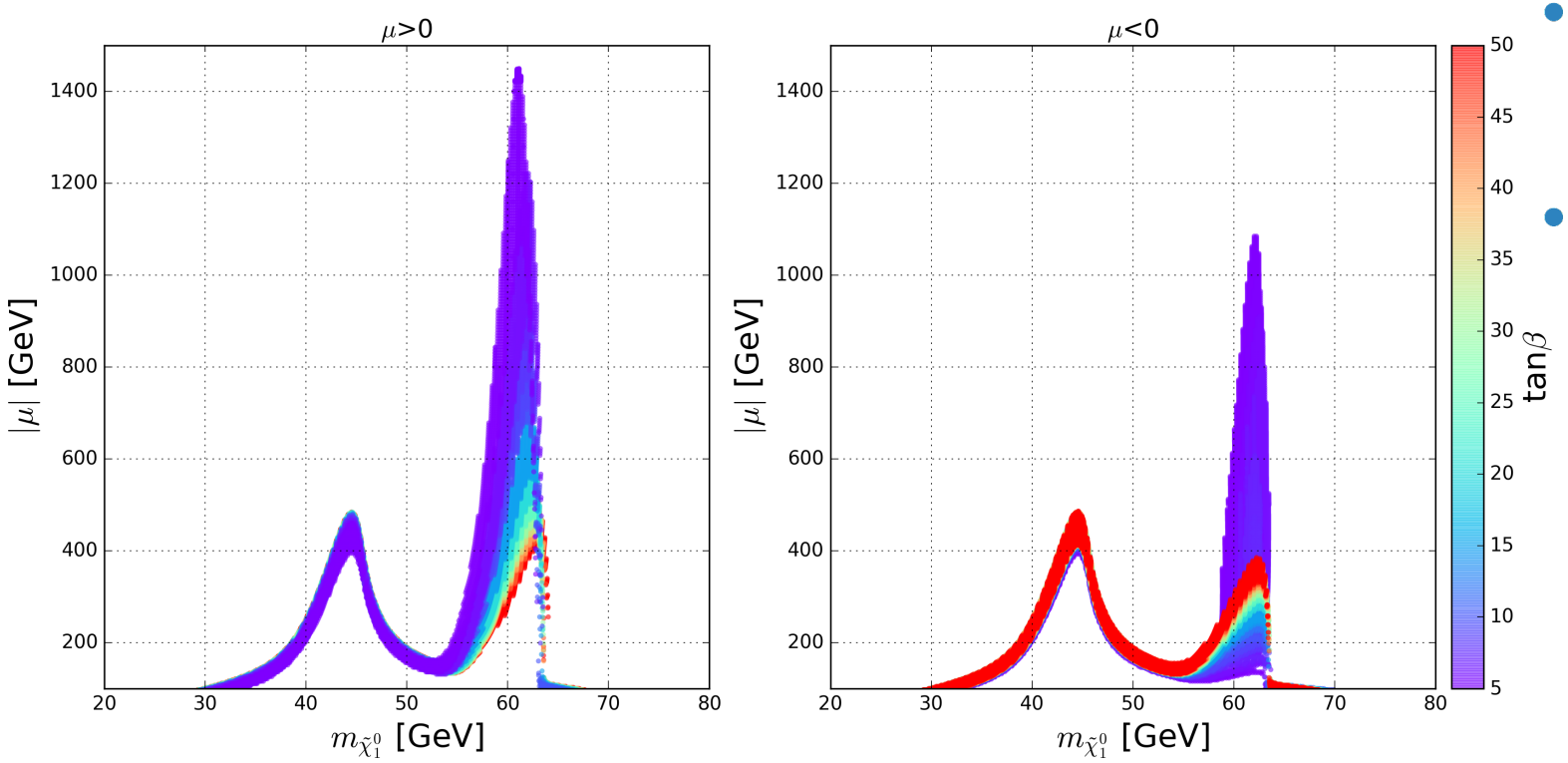
In the limit $M_1 < 100\,\mathrm{GeV} < |\mu| \ll M_2$:

$$N_{13} = \frac{M_Z s_W}{\mu}\left(s_\beta + c_\beta\frac{M_1}{\mu}\right), \qquad N_{14} = -\frac{M_Z s_W}{\mu}\left(c_\beta + s_\beta\frac{M_1}{\mu}\right)$$

$$C_Z = \frac{eM_Z^2}{\mu^2}\cos(2\beta)\left(1 + \frac{M_1^2}{\mu^2}\right), \qquad C_h = \frac{eM_Z}{\mu}\left(\sin 2\beta + \frac{M_1}{\mu}\right)$$

02 The Z/h-resonant DM

$$C_Z = \frac{eM_Z^2}{\mu^2}\cos(2\beta)\left(1+\frac{M_1^2}{\mu^2}\right), \qquad C_h = \frac{eM_Z}{\mu}\left(\sin 2\beta + \frac{M_1}{\mu}\right)$$



$$0.0959 < \Omega h^2 < 0.1439$$

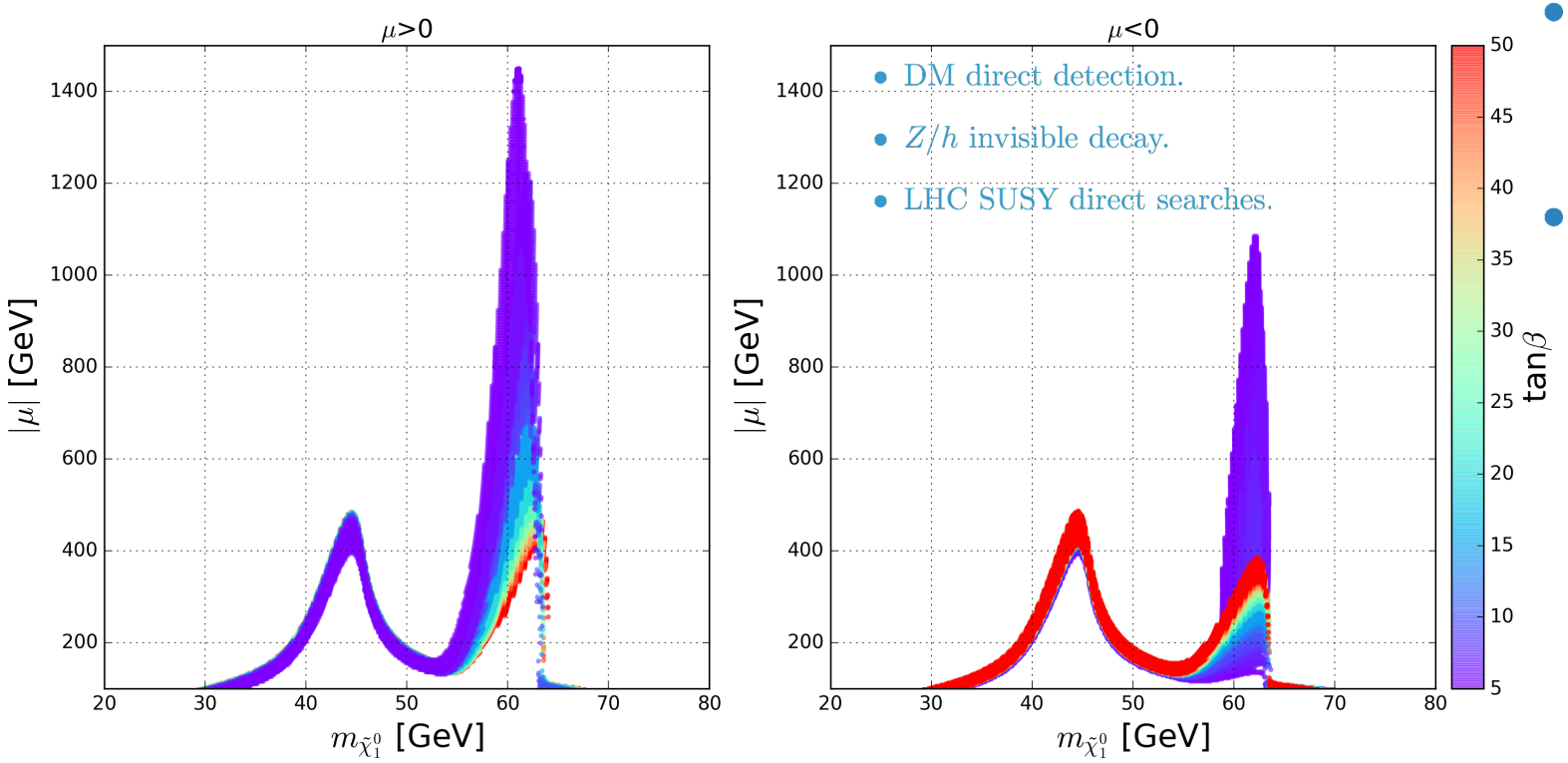
- Resonances effect.
- The Z resonance is independent of the sign of M_1/μ and it mildly depends on $\tan\beta$.
- The Higgs resonances:
  - for $\mu > 0$,the Higgsino mass has to increase from 400 GeV to 1.4 TeV with $\tan\beta$ decreasing from 50 to 5;
  - for $\mu < 0$, μ decreases from 380 GeV to 130 GeV with $\tan\beta$ decreasing from 50 to 7.

$$\sin 2\beta + M_1/\mu = 0$$

μ increases to 1.1 TeV for $\tan\beta = 5$.

02 The Z/h-resonant DM

$$C_Z = \frac{eM_Z^2}{\mu^2}\cos(2\beta)\left(1+\frac{M_1^2}{\mu^2}\right), \qquad C_h = \frac{eM_Z}{\mu}\left(\sin 2\beta + \frac{M_1}{\mu}\right)$$



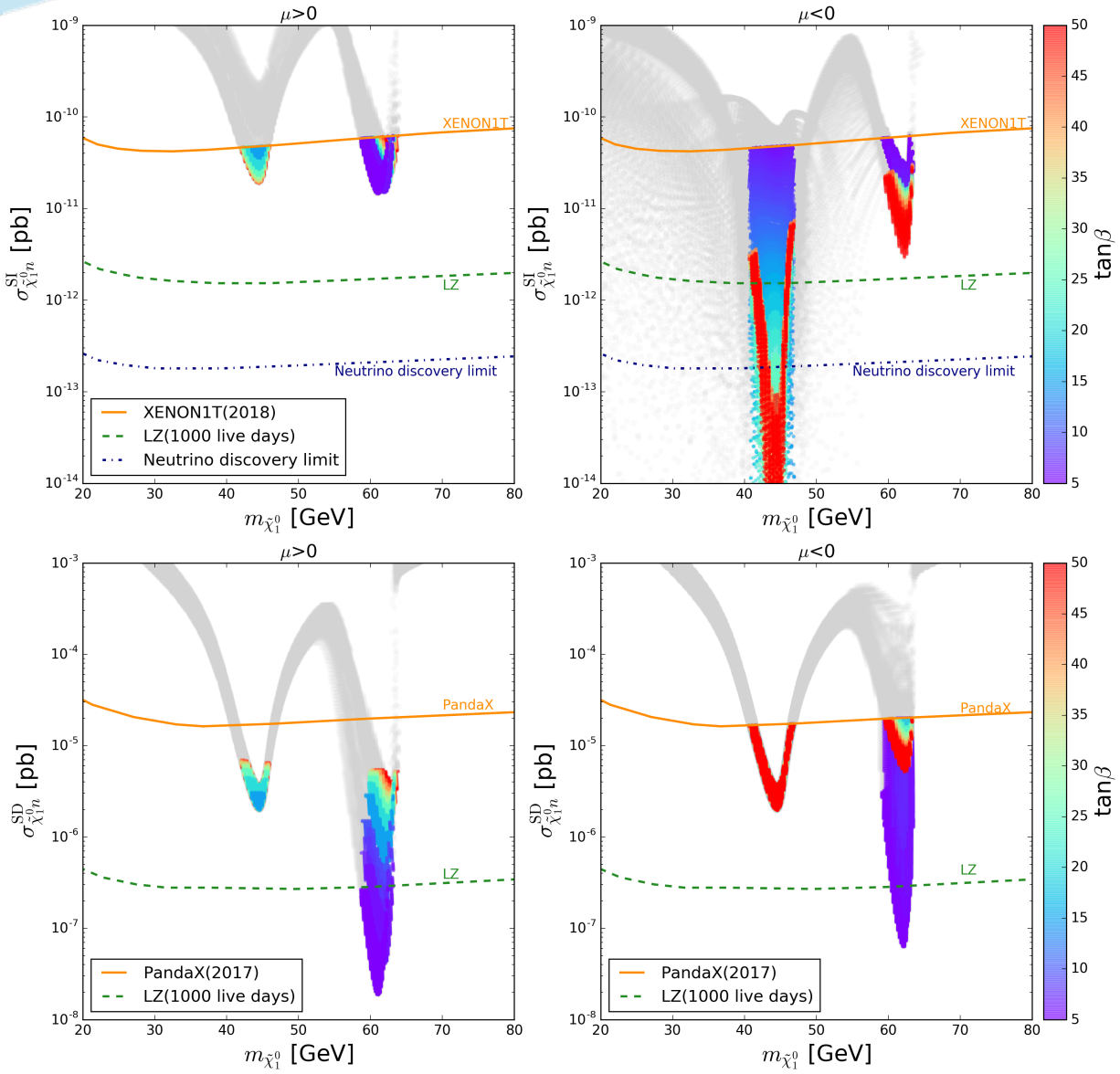
$$0.0959 < \Omega h^2 < 0.1439$$

- Resonances effect.
- The Z resonance is independent of the sign of M_1/μ and it mildly depends on $\tan\beta$.
- The Higgs resonances:
  - for $\mu > 0$,the Higgsino mass has to increase from 400 GeV to 1.4 TeV with $\tan\beta$ decreasing from 50 to 5;
  - for $\mu < 0$, μ decreases from 380 GeV to 130 GeV with $\tan\beta$ decreasing from 50 to 7.

$$\sin 2\beta + M_1/\mu = 0$$

μ increases to 1.1 TeV for $\tan\beta = 5$.

02 The Z/h-resonant DM



$$\sigma^{\rm SI}_{\tilde{\chi}^0_1 n} \simeq \frac{4\mu_r^2}{\pi}\Big[\sum_{i=1}^{2}\frac{C_{h_i\tilde{\chi}^0_1\tilde{\chi}^0_1}C_{h_i NN}}{2M^2_{h_i}}\Big]^2$$

$$\sigma^{\rm SD}_{\tilde{\chi}^0_1 n} \simeq C^2_{Z\tilde{\chi}^0_1\tilde{\chi}^0_1}\times 3.1\times 10^{-4}\ \text{pb}$$

- Large part of the Z/h funnel region has been excluded by the current DM direct detection experimental constraints.
- For $\mu > 0$ the $\sigma^{\rm SI}_{\tilde{\chi}^0_1 n}$ cross section decreases when $\tan\beta$ increases and will be detectable at LZ.
- For $\mu < 0$, due to the blind spot at

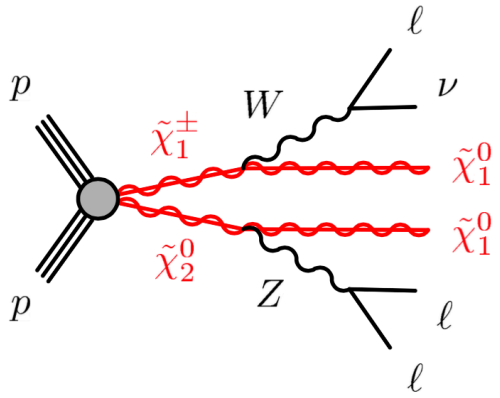
$$\sin 2\beta = M_1/\mu,$$

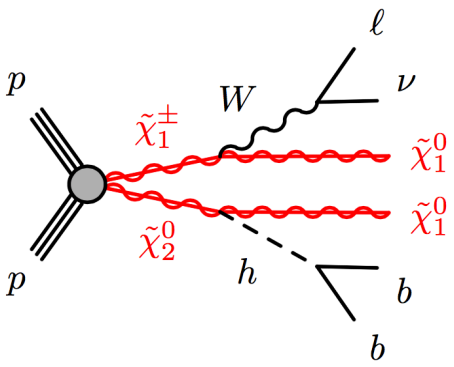
it is impossible to test Z-resonance DM for

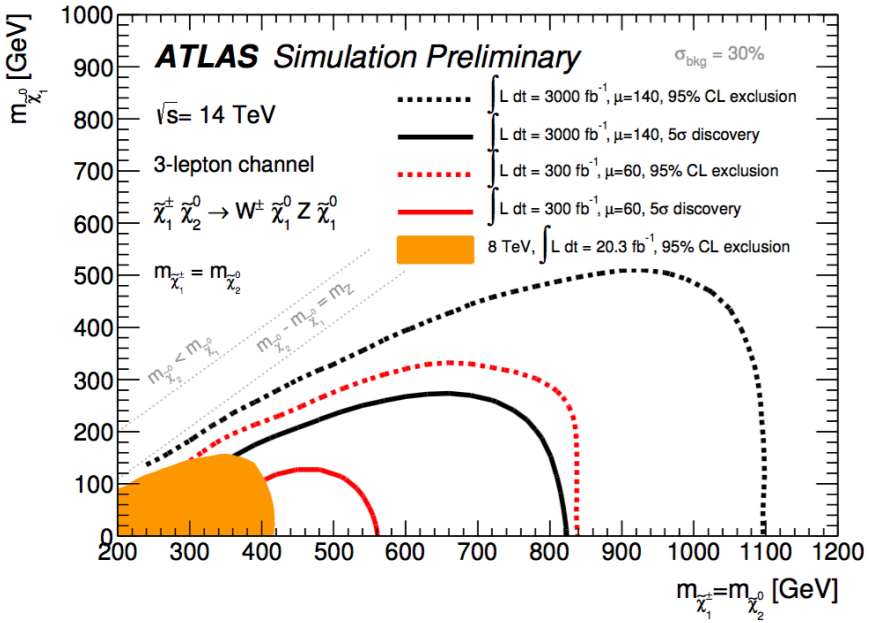
$$\tan\beta = \tan[\arcsin(45/450)/2] \simeq 20.$$

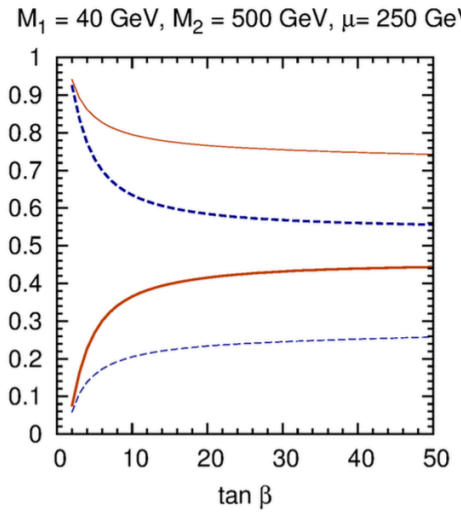
- The Z-resonant DM will be detected at LZ by SI DM-nucleon scattering.

02 The Z/h-resonant DM

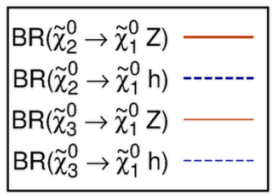


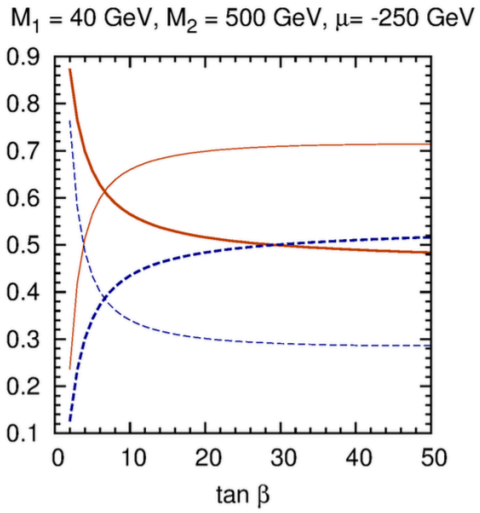


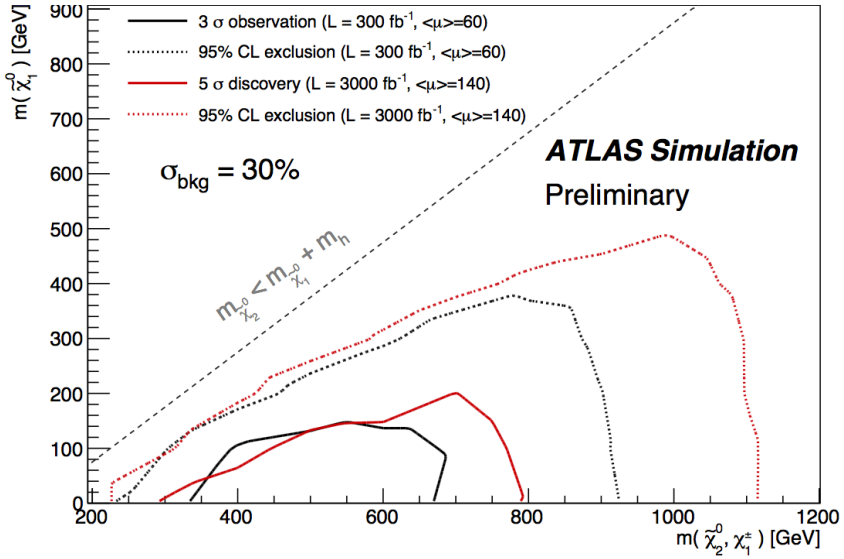




arXiv:1410.5730





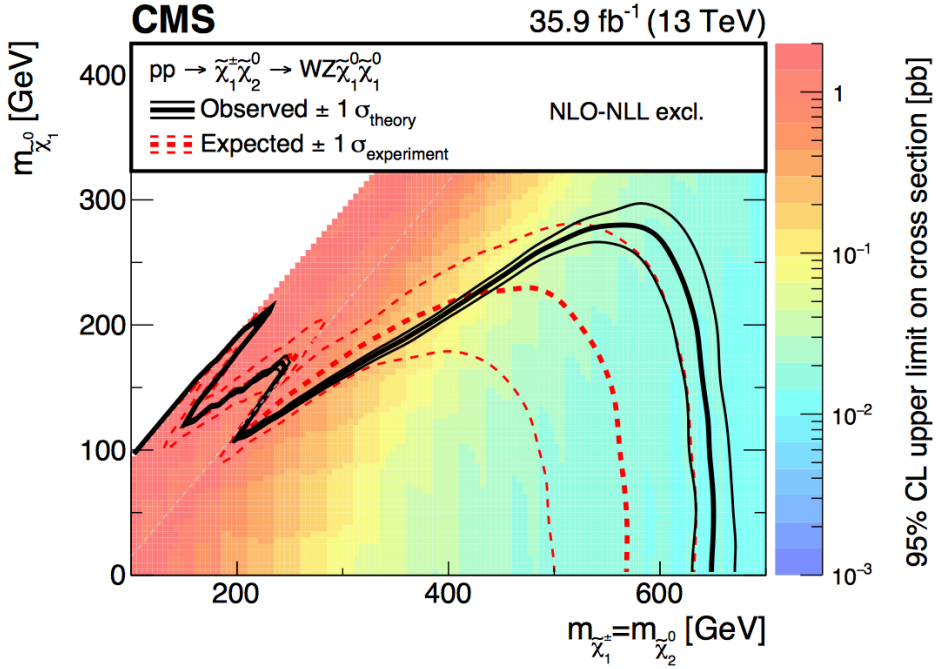


$$\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z) + \mathrm{BR}(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 Z) \simeq 108\%$$
$$\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h) + \mathrm{BR}(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 h) \simeq 92\%$$

02 The Z/h-resonant DM

arXiv: 1801.03957, CMS-SUS-17-004

Search	Signal topology WZ	WH	ZZ	ZH	HH
1ℓ 2b		✓			
4b					✓
2ℓ on-Z	✓		✓	✓	
2ℓ soft	✓				
$\geq 3\ell$	✓	✓	✓	✓	✓
$H(\gamma\gamma)$		✓		✓	✓

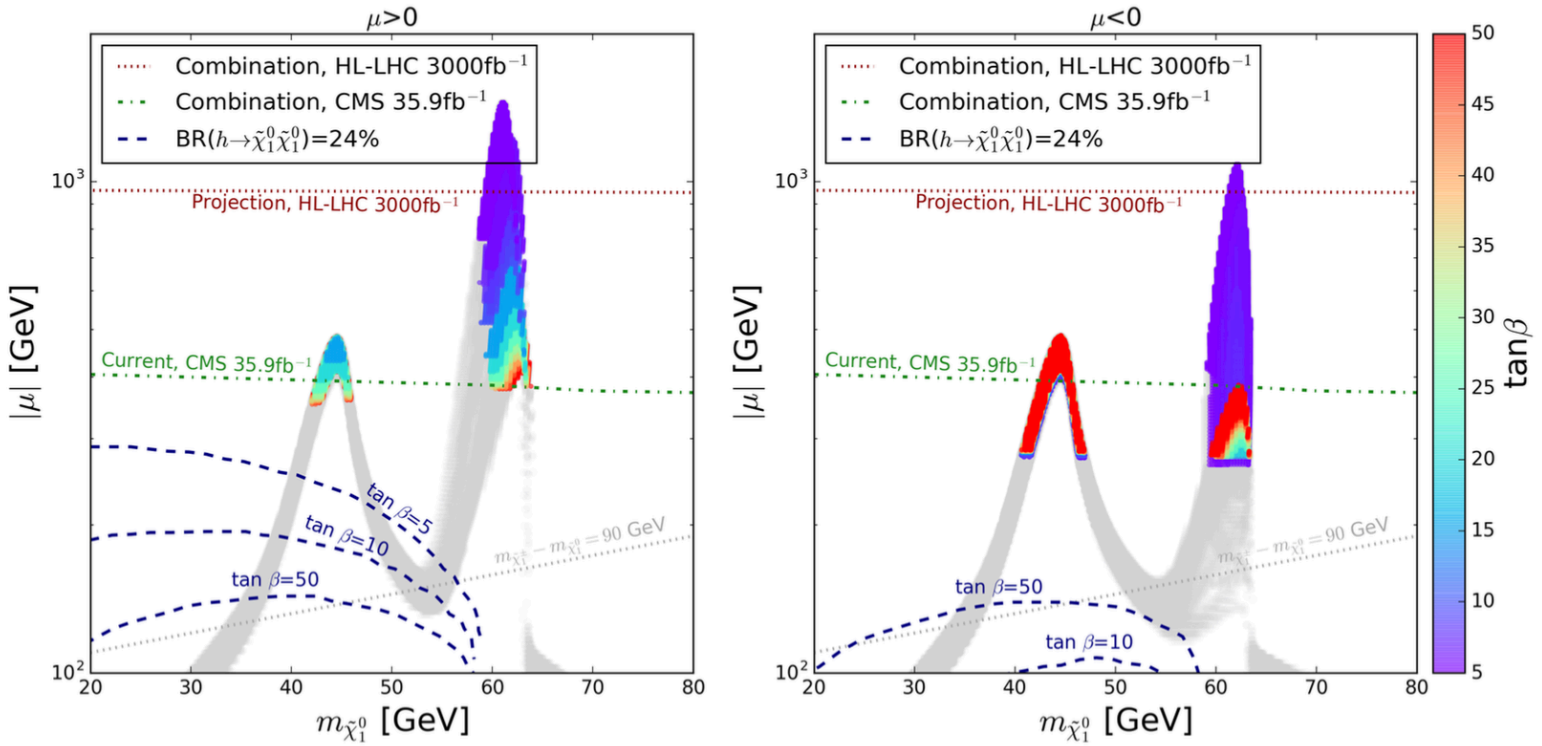


Combine them together though the $\mathtt{CL}_s$ method with

$$\mathcal{L}(\mu) = \prod_i^{N_{\rm ch}} \int d\mu' \int db_i' \frac{(\mu' s_i + b_j')^{n_i} e^{-(\mu' s_i + b_j')}}{n_i!} \times e^{\frac{-(\mu'-\mu)^2}{2\sigma_\mu^2}} \times e^{\frac{-(b_i'-b_i)^2}{2\sigma_{b_i}^2}},$$

where $\mu = 1$ (0) corresponds the signal hypothesis (the background only hypothesis).

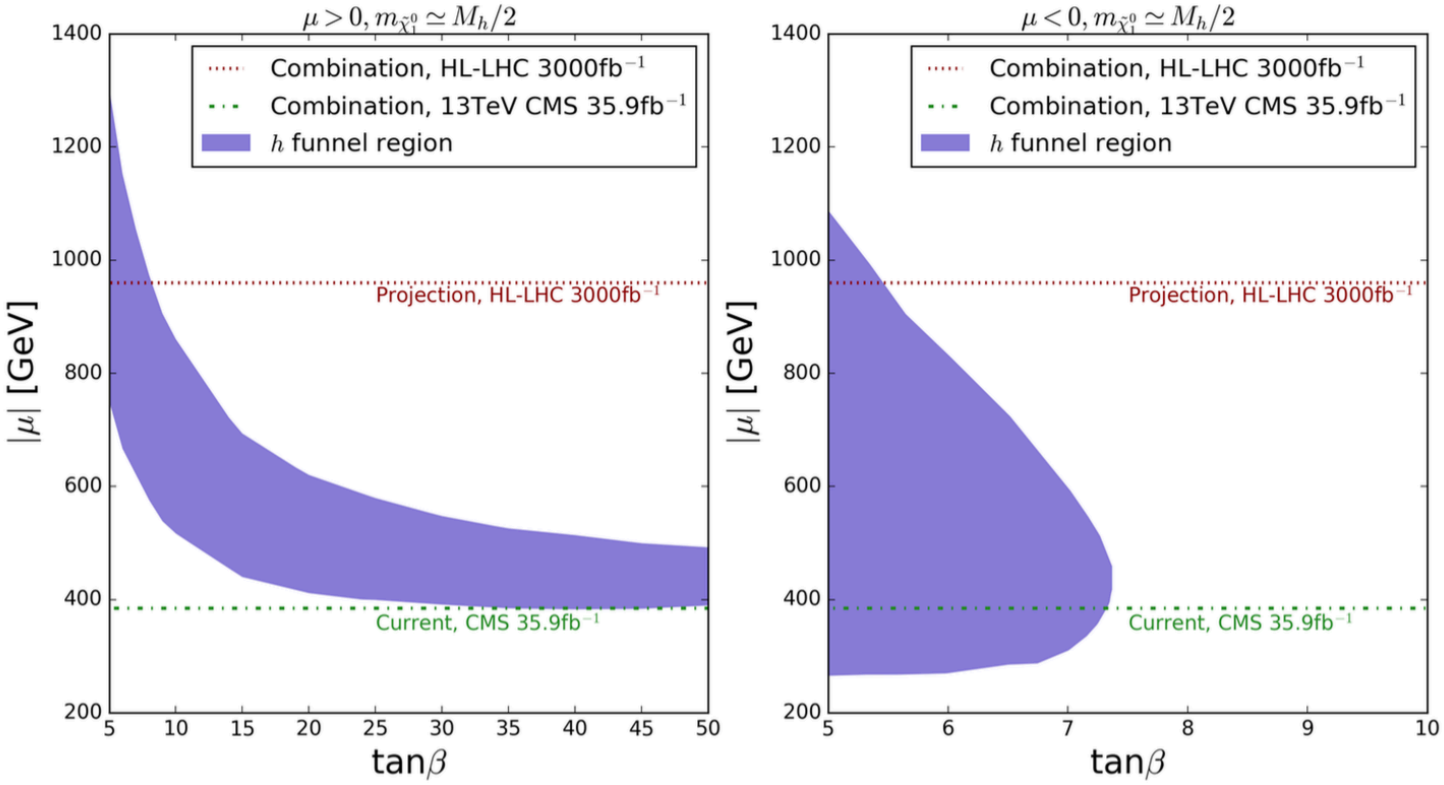
02 The Z/h-resonant DM



- The limits barely depend on $\tan\beta$ and the sign of μ, and slightly decrease with increasing $m_{\tilde{\chi}_1^\pm}$.
- The bound on the Higgsino mass parameter is about 390 GeV, which is about 100 GeV stricter than the bound obtained from individual analyses

- The Z funnel region is on the verge of complete exclusion.
- In the case of $\mu < 0$, the h funnel region can only survive with $\tan\beta < 7.4$, while the h funnel region of $\mu > 0$ is the main surviving region.

02 The Z/h-resonant DM



- We employ two electroweakino analyses at the HL-LHC proposed by ATLAS: the "3ℓ" search and the "$1\ell 2b$" search.
- The combined result pushes the bound on μ to 960 GeV, which is 150 GeV stricter than the result of each individual analysis.

- The parameter space of h funnel region will be restricted to a very small region: $\tan\beta < 8$ for $\mu > 0$ and $\tan\beta < 5.5$ for $\mu < 0$.
- Such small $\tan\beta$, however, is highly disfavoured by experimental constraints, such as the SM-like Higgs data and the muon anomalous magnetic moment.

03 Impacts on MSSM/NMSSM

The surviving parameter spaces of MSSM-8 and natural NMSSM

03 Impacts on MSSM-8

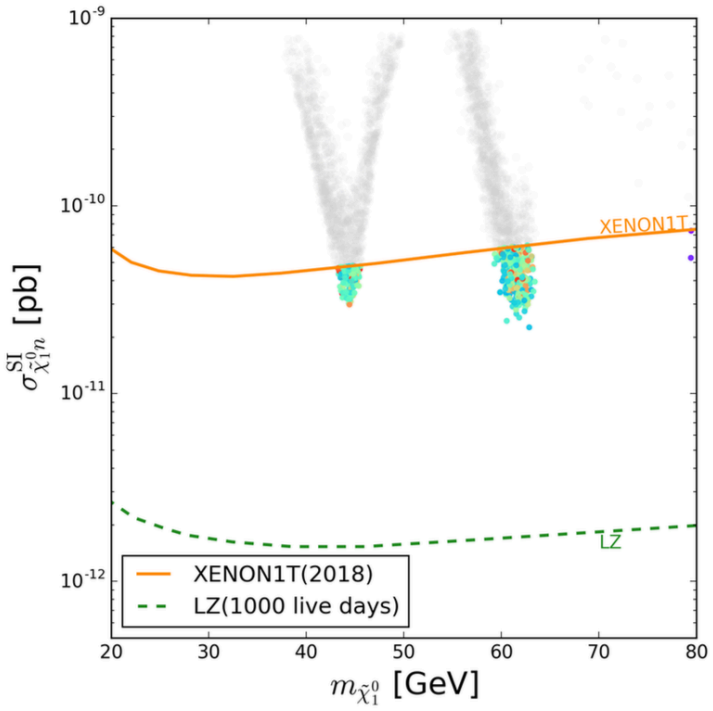
To examine the Z/h funnel region in a wider model scope and with more experimental constraint, we scan the following parameter space:

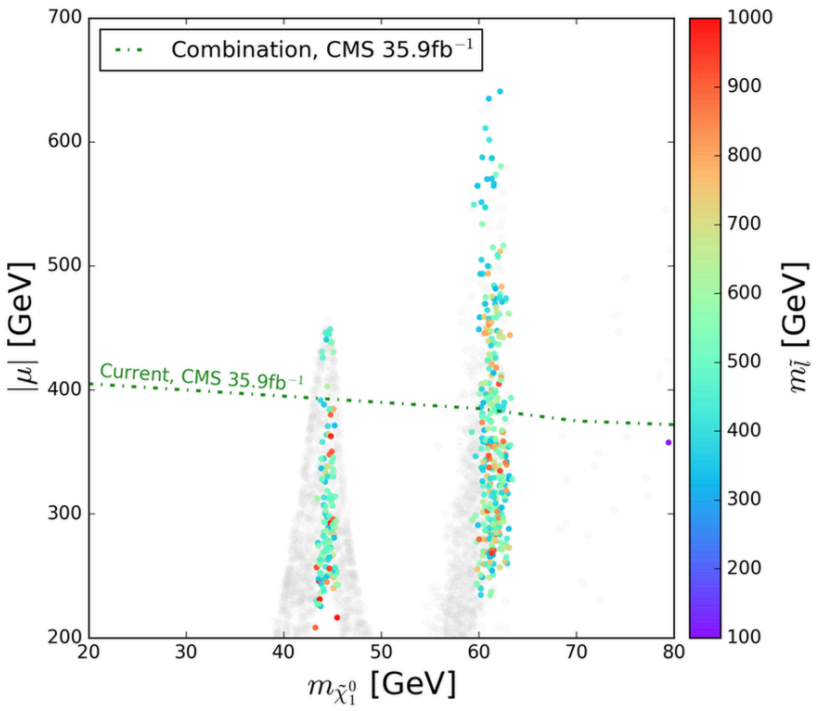
$$2 < \tan\beta < 60, \qquad 10\ \text{GeV} < M_1 < 100\ \text{GeV}, \qquad 100\ \text{GeV} < M_2 < 1000\ \text{GeV},$$
$$100\ \text{GeV} < \mu < 1500\ \text{GeV}, \qquad 50\ \text{GeV} < M_A < 2\ \text{TeV},$$
$$|A_t = A_b| < 5\ \text{TeV}, \qquad 200\ \text{GeV} < m_{Q_3}, \qquad m_{U_3} = m_{D_3} < 2\ \text{TeV},$$
$$100\ \text{GeV} < m_{L_{1,2,3}} = m_{E_{1,2,3}} = A_{E1,2,3} < 2\ \text{TeV}.$$

The mass of the gluino and the first two generation squarks are fixed to 2 TeV.
Additional constraints:

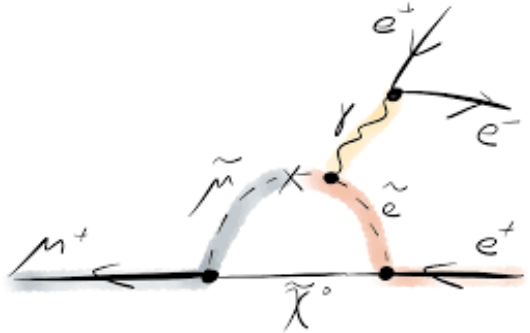
- B-physics constraints, such as the precise measurements of $B \to X_s\gamma$, $B_s \to \mu^+\mu^-$, $B_d \to X_s\mu^+\mu^-$ and the mass differences ΔM_d and ΔM_s;
- the muon anomalous magnetic moment (a_μ), the measured value of which deviates from the SM prediction (a_μ^{SM});
- constraints on the Higgs sector included in the packages `HiggsBounds` and `HiggsSignal`.

03 Impacts on MSSM-8





$$\Omega h^2 < 0.1439$$



- The Z/h funnel regions are tightly restricted by the DM direct detection constraints
- The combination of electroweakino searches further excludes regions where the ratio of the neutralino relic density over the observed DM density is smaller than 58% (19%) for the Z (h) funnel region.
- The constraint on a_μ, which requires $\tan\beta > 9$, reduces the height of the h funnel region.
- The surviving samples require either a light slepton or a light chargino.

03 Impacts on natural NMSSM

$$W_{\rm NMSSM} = W_F + \lambda \hat{H}_u \cdot \hat{H}_d \hat{S} + \frac{1}{3}\kappa \hat{S}^3$$

$$\mu_{\rm eff} = \lambda < \hat{S} >$$

$$\begin{aligned} V &= |\lambda S|^2(|H_u|^2 + |H_d|^2) + |\lambda H_u H_d + \kappa S^2|^2 \\ &+ \frac{1}{8}\bar{g}(|H_u|^2 - |H_d|^2)^2 + \frac{1}{2}g^2|H_u^\dagger H_d|^2 \\ &+ \tilde{m}_u^2|H_u|^2 + \tilde{m}_d^2|H_u|^2 + \tilde{m}_S^2|S|^2 + (\lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + h.c.) \end{aligned}$$

1 extra CP-even Higgs
1 extra CP-odd Higgs

$$\psi = (-i\widetilde{B}, -i\widetilde{W}^3, \widetilde{H}_d, \widetilde{H}_u, \widetilde{S})$$

1 extra Neutralino

$$0 < \lambda < 0.75, \quad 0 < \kappa < 0.75, \quad 2 < \tan\beta < 60, \quad 100\ \text{GeV} \le m_{\tilde{l}} \le 1\ \text{TeV},$$

$$100\ \text{GeV} \le \mu \le 1\ \text{TeV}, \quad 50\ \text{GeV} \le M_A \le 2\ \text{TeV}, \quad |A_\kappa| \le 2\ \text{TeV},$$

$$100\ \text{GeV} \le M_{Q_3}, M_{U_3} \le 2\ \text{TeV}, \quad |A_t| \le \min(3\sqrt{M_{Q_3}^2 + M_{U_3}^2}, 5\ \text{TeV}),$$

$$20\ \text{GeV} \le M_1 \le 500\ \text{GeV}, \quad 100\ \text{GeV} \le M_2 \le 1\ \text{TeV}.$$

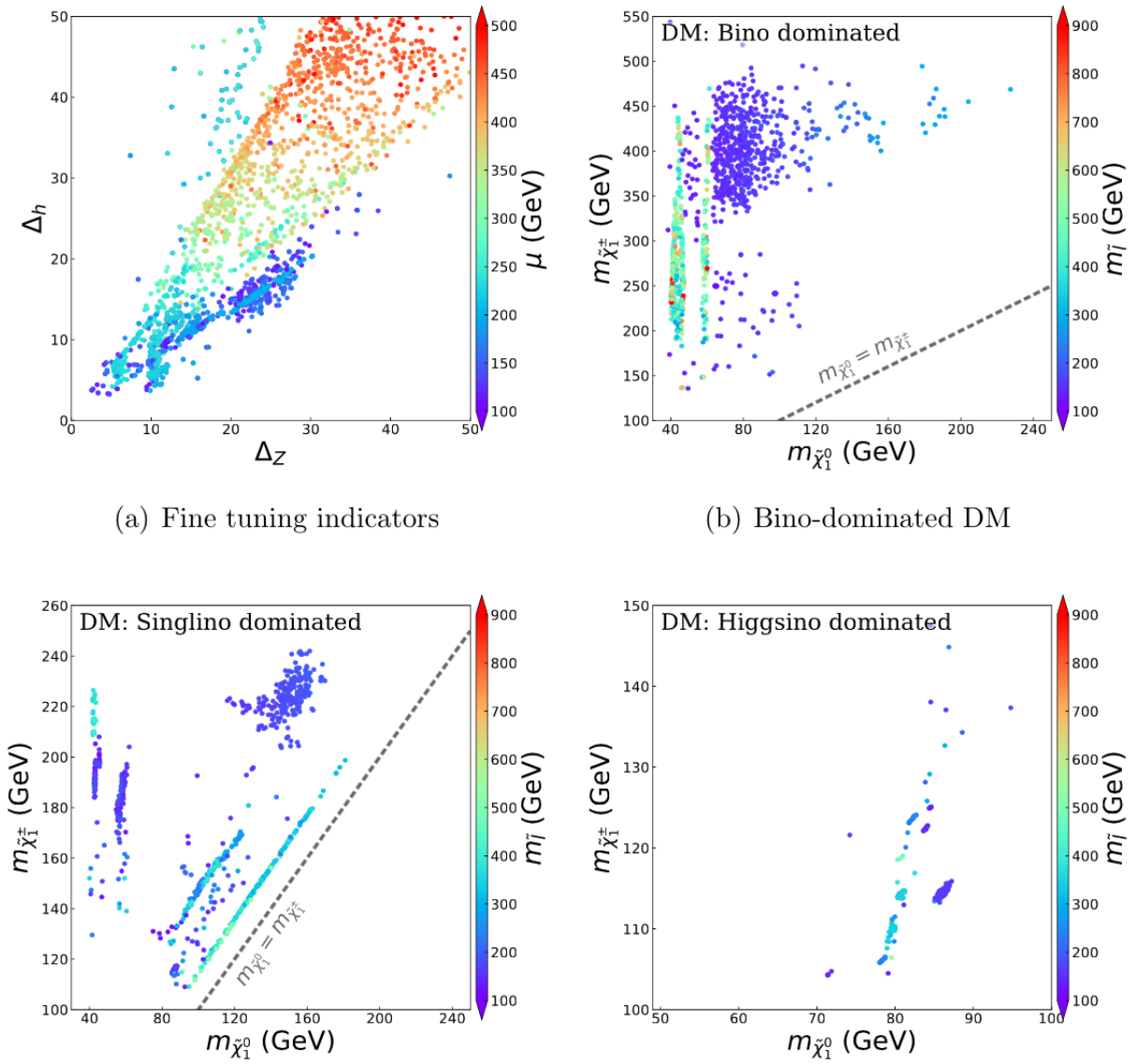
Similar constraints to MSSM

$$0.0959 < \Omega h^2 < 0.1439$$

$$\Delta_Z < 50\ \&\ \Delta_h < 50$$

03 Impacts on natural NMSSM

arXiv:1808.xxxxx
Junjie Cao, Liangliang Shang, Yuanfang Yue, Yang Zhang, Pengxuan Zhu



(a) Fine tuning indicators (b) Bino-dominated DM

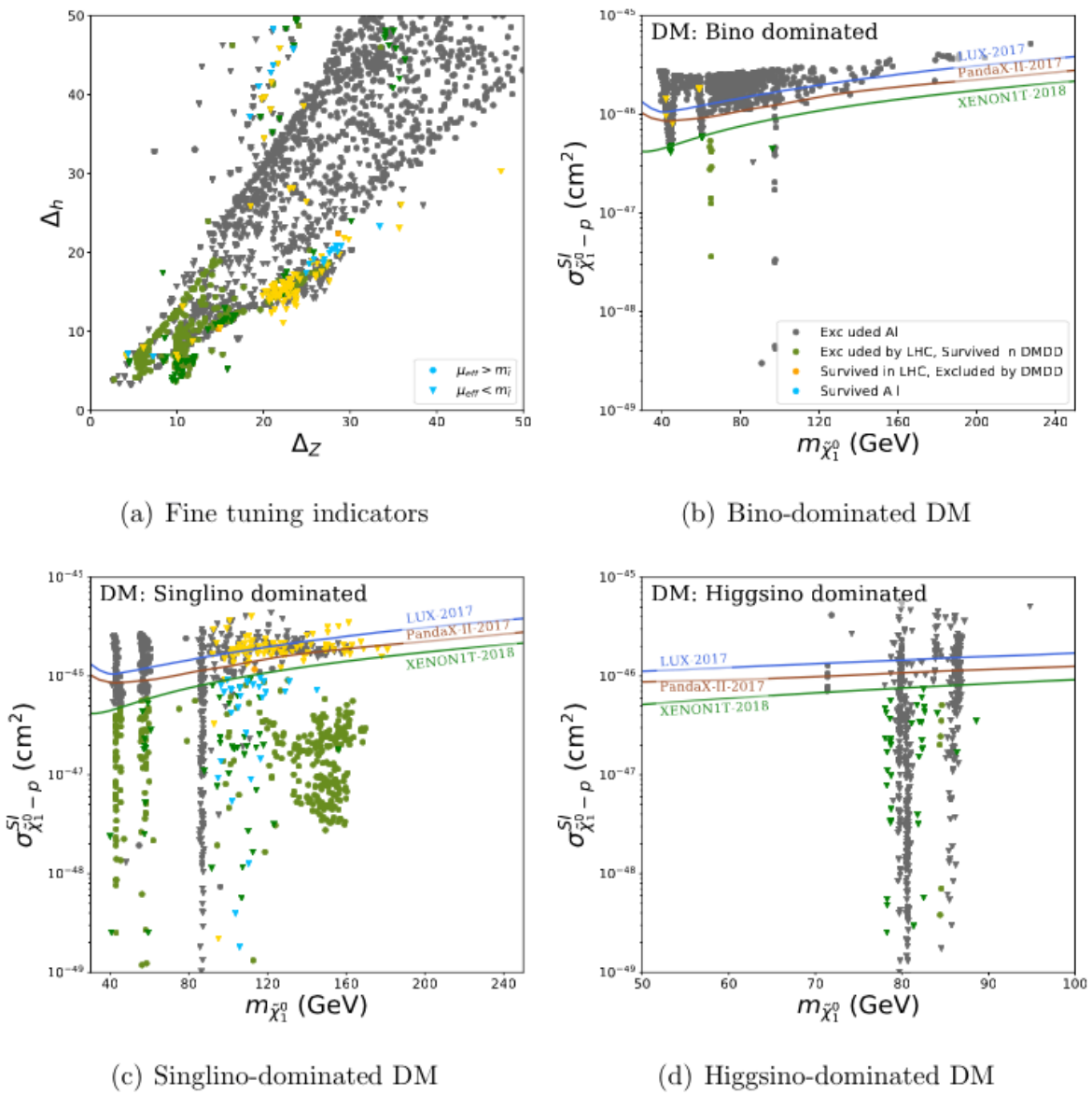
(c) Singlino-dominated DM (d) Higgsino-dominated DM

The $\triangle_Z$ and $\triangle_h$ can be as low as about 1.7, and $\triangle_h \leq 50$ requires $\mu < 547$ GeV.
The samples can be classified into three types:

- Bino-dominated DM scenario.
  - $m_{\tilde{\chi}_1^0} \simeq m_{Z/h_1}$,
  - $m_{\tilde{\chi}_1^0} \simeq (m_{h_1} + m_{h_2})/2 \simeq 90$ GeV
  - $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{l}}$.
- Singlino-dominated DM scenario.
  - All above mechanisms,
  - $m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_1^0}$.
- Higgsino-dominated DM scenario. The $\tilde{H}_u^0$, $\tilde{S}$ and $\tilde{H}_d^0$ components of DM are comparable in magnitude with the largest one coming from the $\tilde{H}_u^0$.

03 Impacts on natural NMSSM

arXiv:1808.xxxxx
Junjie Cao, Liangliang Shang, Yuanfang Yue, Yang Zhang, Pengxuan Zhu



(a) Fine tuning indicators

(b) Bino-dominated DM

(c) Singlino-dominated DM

(d) Higgsino-dominated DM

- ~~Bino-dominated DM scenario.~~
- Singlino-dominated DM scenario.
  - ~~$m_{\tilde{\chi}^0_1} \simeq m_{Z/h_1}$,~~
  - ~~$m_{\tilde{\chi}^0_1} \simeq (m_{h_1} + m_{h_2})/2 \simeq 90$ GeV~~
  - ~~$m_{\tilde{\chi}^0_1} \simeq m_{\tilde{l}}$.~~
  - $m_{\tilde{\chi}^\pm_1} \simeq m_{\tilde{\chi}^0_1}$.
- ~~Higgsino-dominated DM scenario.~~

The survived region:

- $m_{\tilde{\chi}^0_1} \simeq m_{\tilde{\chi}^\pm_1} \in [90, 150]$ GeV.
- $m_{\tilde{l}} \in [155, 560]$ GeV.
- $\Delta_h \in [7, 50]$ and $\Delta_Z \in [4, 33]$

04 Conclusions

Simplified Model

The Z funnel region is on the brink of exclusion, the h funnel for $\mu < 0$ only survives if $\tan\beta < 7.4$, and the h funnel for $\mu > 0$ is the main surviving region.
Future DM direct detection experiments can explore the whole region, while the HL-LHC can exclude $\tan\beta > 8$ for $\mu > 0$ and $\tan\beta > 5.5$ for $\mu < 0$.

MSSM-8 / natural NMSSM

After applying the muon anomalous magnetic moment constraint only a tiny part of the Z/h funnel region survives which will soon be probed by ongoing experiments.

In the near future

The Z/h funnel region will not satisfy the following constraints simultaneously:
(1) DM relic density (including low bound), (2) DM direct detection, (3) muon g-2
(4) LHC searches for eletroweakinos, (5) LHC searches for sleptons

THANK YOU!

Constraining Resonant Dark Matterwith combined LHC electroweakino searches

Yang Zhang

School of Physics and Astronomy, Monash University

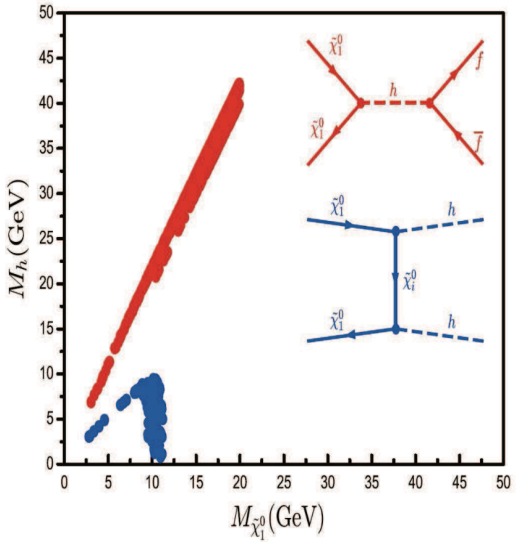
Based on arXiv:1807.01476

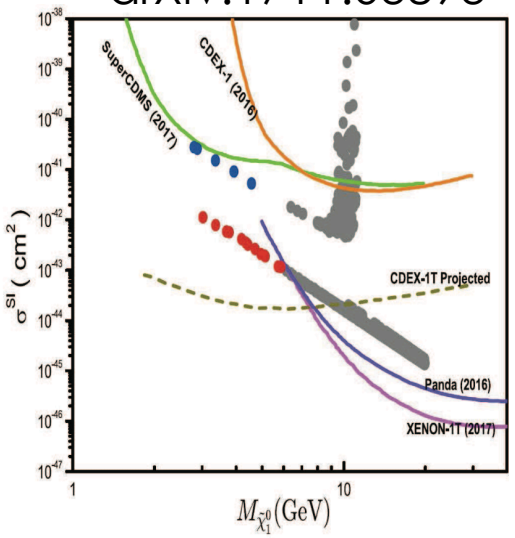
In collaboration with Giancarlo Pozzo

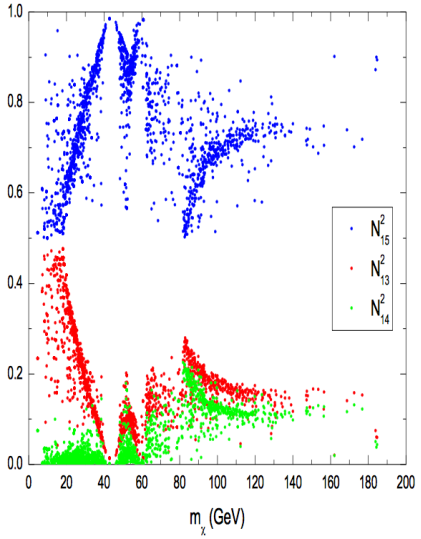
MONASH University

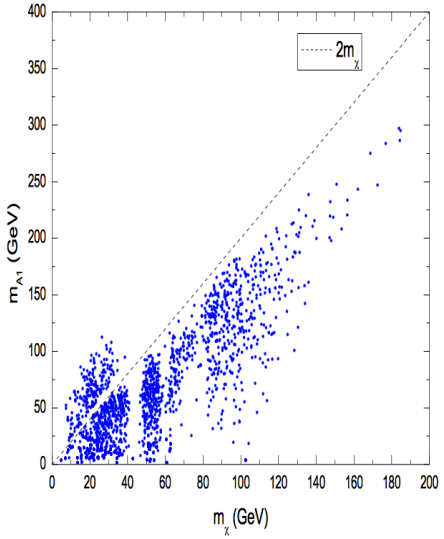
05 Backup

arXiv:1711.03893

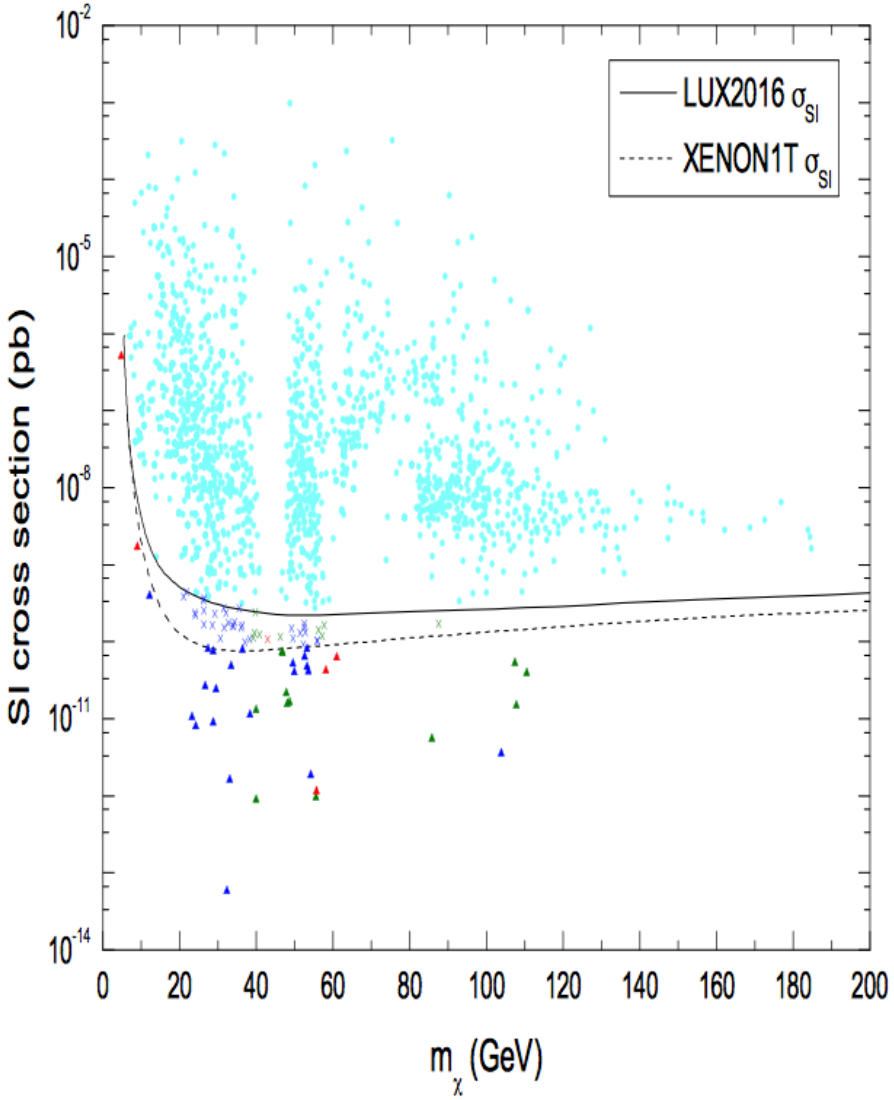








arXiv:1703.00343



05 Backup

	BP1	BP2	BP3	BP4
$\tan\beta$	30	10	30	30
M_1 (GeV)	50	50	50	80
μ (GeV)	390	390	-390	390
$m_{\tilde{\chi}_1^0}$ (GeV)	49.5	46.4	48.6	78.0
$m_{\tilde{\chi}_2^0}$ (GeV)	401	402	402	402
$m_{\tilde{\chi}_3^0}$ (GeV)	403	403	403	403
$m_{\tilde{\chi}_1^\pm}$ (GeV)	400	399	400	399
$\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z)$	45%	39%	39%	33%
$\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h)$	55%	61%	61%	67%
$\mathrm{BR}(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 Z)$	63%	68%	69%	75%
$\mathrm{BR}(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 h)$	37%	32%	31%	35%
$\sigma_{\tilde{\chi}_{2,3}^0 \tilde{\chi}_1^\pm}$ (fb)	59.45	59.48	59.48	59.46
CL_s^{3l}	0.238 ± 0.007	0.240 ± 0.007	0.251 ± 0.007	0.265 ± 0.007
CL_s^{2l}	0.266 ± 0.018	0.246 ± 0.018	0.238 ± 0.017	0.231 ± 0.016
CL_s^{1l2b}	0.549 ± 0.009	0.552 ± 0.009	0.563 ± 0.009	0.553 ± 0.009
$\mathrm{CL}_s^{\mathrm{combine}}$	0.049 ± 0.005	0.051 ± 0.006	0.052 ± 0.005	0.054 ± 0.006

05 Backup

	$\tilde{\chi}_1^\pm\tilde{\chi}_1^0$(250,1)		$\tilde{\chi}_1^\pm\tilde{\chi}_1^0$(350,100)		$\tilde{\chi}_1^\pm\tilde{\chi}_1^0$(500,1)		$\tilde{\chi}_1^\pm\tilde{\chi}_1^0$(500,125)	
	CMS	CM	CMS	CM	CMS	CM	CMS	CM
All events	4901.0	4901.0	1309.1	1309.1	290.2	290.2	290.3	290.3
≤ 1 good lepton, $E_T^{\rm miss} > 50$ GeV	1035.1	1296.3	328.1	359.0	89.0	94.3	86.9	95.9
2nd lepton veto	1011.4	1157.6	321.2	319.8	87.3	85.0	85.3	87.1
Isolated track veto	994.3	-	316.6	-	85.8	-	84.1	-
Tau veto	989.6	1126.2	315.3	306.8	85.5	81.5	83.9	83.5
=2 jets	542.3	673.9	162.9	193.5	42.3	57.4	41.1	58.9
=2 b-tags	242.6	215.6	74.9	65.0	19.7	20.5	19.5	19.7
$90 < M_{b\bar{b}} < 150$ GeV	214.4	177.9	65.6	50.9	17.5	16.6	17.6	15.4
$M_{CT} > 170$ GeV	67.2	66.2	26.7	23.9	11.9	11.2	10.9	9.9
$E_T^{\rm miss} > 125$ GeV	54.8	50.0	22.9	19.4	10.9	10.1	9.9	8.9
$M_T > 150$ GeV	17.6	13.7	10.7	8.5	7.1	6.2	6.5	5.6
SR($E_T^{\rm miss} < 200$ GeV)	7.6	6.4	2.7	2.7	0.9	1.0	1.0	0.9
SR($E_T^{\rm miss} > 200$ GeV)	10.0	7.4	8.0	5.8	6.3	5.2	5.5	4.7
CL_s	<0.05	0.006	≃0.05	0.038	$\gtrsim 0.05$	0.086	>0.05	0.129

Table 4. Validations for cut-flows of the "$1\ell 2b$" search [58] for various signal model points. The "CM" stands CheckMATE. The "-" means that the corresponding cut is not applied. The yields in "All events" of "CM" are normalized to "All events" of "CMS".

05 Backup

In the limit of $|\mu| \ll |M_1|, |M_2|$, the elements of the rotation matrix N roughly satisfy:

$$N_{i3} : N_{i4} : N_{i5} \simeq \lambda(v_d\mu - v_u m_{\tilde{\chi}_1^0}) : \lambda(v_u\mu - v_d m_{\tilde{\chi}_1^0}) : (m^2_{\tilde{\chi}_1^0} - \mu^2).$$

In the limit of $|\mu| \ll |M_1|, |M_2|$,

$$N_{11} : N_{13} : N_{14} \simeq (m^2_{\tilde{\chi}_1^0} - \mu^2) : -\frac{g_1}{\sqrt{2}}(v_u\mu + v_d m_{\tilde{\chi}_1^0}) : \frac{g_1}{\sqrt{2}}(v_d\mu + v_u m_{\tilde{\chi}_1^0}).$$

When we discuss the naturalness of the NMSSM, we consider two fine tuning quantities defined by [54]

$$\Delta_Z = \max_i \left|\frac{\partial \log m_Z^2}{\partial \log p_i}\right|, \quad \Delta_h = \max_i \left|\frac{\partial \log m_h^2}{\partial \log p_i}\right|, \tag{2.7}$$

where h represents the SM-like Higgs boson, p_i denotes SUSY parameters at the weak scale, and it includes the parameters listed in Eq.(2.5) and top quark Yukawa coupling Y_t with the latter used to estimate the sensitivity to stop masses. Obviously, Δ_Z (Δ_h) measures

[2] As was pointed out in [54], if the NMSSM is considered as the low energy realization of an (unknown) overarching ultimate theory, Δ_Z and Δ_h can be thought of as providing a lower bound on electroweak fine-tuning. Any parameter point with a low Δ_Z and Δ_h implies that the ultimate theory may be low fine-tuned at high energy scale. By contrast, if the point correspond to large Δ_Z and Δ_h, the underlying theory must be fine-tuned.

$$\Delta_{EW} < \Delta_{BG} \lesssim \Delta_{HS}$$

The model-independent $\Delta_{\rm EW}$ measures how naturally a model can generate the measured value of m_Z (m_h) in terms of weak scale parameters alone.