Towards co-annihilation benchmark scenarios:

Neutralino DM with Dirac (instead of Majorana) **gaugino masses**

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based on ongoing work with
Mark Goodsell, Humberto Reyes-Gonzalez, Sophie L. Williamson

!! references incomplete, results preliminary !!

Snowmass 2021, EF10 DM@Colliders topical meeting June 4, 2020

MOTIVATION

- Most studies of SUSY are based on the MSSM —or simple extensions thereof— where gauginos acquire Majorana soft masses

- Introducing instead (or in addition) Dirac masses for gauginos leads to quite distinct phenomenological features *

- Consequences for limits on gluinos and squarks studied recently

  Heikinheimo, Kellerstein, Sanz, 1111.4322; Kribs, Martin, 1203.4821 & 1308.3468 (Snowmass whitepaper);
  Goodsell, SK, Reyes-Gonzalez, Williamson, 1812.09293; Diessner, Kalinowski, Kotlarski, Stöckinger, 1907.11641

- But also significant impact on EW-ino, including neutralino DM, phenomenology

  Hsieh, 0708.3970; Choi, Drees, Freitas, Zerwas, 0808.2410;
  Belanger, Benakli, Goodsell, Moura, Pukhov, 0905.1043;
  ……..

*) moreover, this is theoretically well motivated, e.g., simplest models of global SUSY breaking preserve R-symmetry

DIRAC GAUGINO MASSES

- To introduce Dirac masses for gauginos, one has to **add a Weyl fermion in the adjoint representation** of each gauge group

  → new singlet $\mathbf{S}$, triplet $\mathbf{T}$ and octet $\mathbf{O}$ chiral superfields

$$\mathcal{L} \sim \int d^2\theta \Big[\sqrt{2}\, m_{DY} \theta^\alpha \mathbf{W}_{1\alpha} \mathbf{S} + 2\sqrt{2}\, m_{D2} \theta^\alpha \mathrm{tr}\left(\mathbf{W}_{2\alpha} \mathbf{T}\right) + 2\sqrt{2}\, m_{D3} \theta^\alpha \mathrm{tr}\left(\mathbf{W}_{3\alpha} \mathbf{O}\right) \Big] + \mathrm{h.c.}$$

- Concrete realisations differ in the choice of additional fields added to the MSSM, and the treatment of the R-symmetry.

- Generically two classes of models, depending on whether the R-symmetry is conserved (e.g. MRSSM) or violated (e.g. MDGSSM).

neutralinos are Dirac fermions

neutralinos are pseudo-Dirac (Majorana) fermions

MINIMAL DIRAC GAUGINO MODEL

MDGSSM

- Minimal extension of the MSSM allowing for Dirac gaugino masses
  (add one adjoint chiral superfield for each gauge group, and nothing else)

Chiral and gauge multiplet fields of the MSSM

Superfield	Scalars	Fermions	Vectors	$(SU(3), SU(2), U(1)_Y)$	R
$\mathbf{H_u}$	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$		$(\mathbf{1}, \mathbf{2}, 1/2)$	R_H
$\mathbf{H_d}$	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$		$(\mathbf{1}, \mathbf{2}, \text{-}1/2)$	$2 - R_H$
$\mathbf{W}_{\mathbf{3},\alpha}$		λ_3	G_μ	$(\mathbf{8}, \mathbf{1}, 0)$	1
$\mathbf{W}_{\mathbf{2},\alpha}$		$\tilde{W}^0, \tilde{W}^\pm$	$W_\mu^\pm, W_\mu^0$	$(\mathbf{1}, \mathbf{3}, 0)$	1
$\mathbf{W}_{\mathbf{Y},\alpha}$		$\tilde{B}$	B_μ	$(\mathbf{1}, \mathbf{1}, 0)$	1

Additional chiral and gauge multiplet fields in the case of Dirac gauginos

Superfield	Scalars, $R = 0$	Fermions, $R = -1$	$(SU(3), SU(2), U(1)_Y)$
$\mathbf{O}$	$O^a = \frac{1}{\sqrt{2}}(O_1^a + iO_2^a)$	χ_O^a	$(\mathbf{8},\mathbf{1},0)$
$\mathbf{T}$	$T^0 = \frac{1}{\sqrt{2}}(T_P^0 + iT_M^0), T^\pm$	$\tilde{W}'^0, \tilde{W}'^\pm$	$(\mathbf{1},\mathbf{3},0)$
$\mathbf{S}$	$S = \frac{1}{\sqrt{2}}(S_R + iS_I)$	$\tilde{B}'^0$	$(\mathbf{1},\mathbf{1},0)$

- Explicit R-symmetry breaking in the Higgs sector from B_μ term

MINIMAL DIRAC GAUGINO MODEL

MDGSSM

$$W = W_{\mathrm{MSSM}} + \lambda_S \mathbf{S}\,\mathbf{H_u}\cdot\mathbf{H_d} + 2\lambda_T\,\mathbf{H_d}\cdot\mathbf{T}\mathbf{H_u}$$

$$\mathcal{M}_N = \begin{pmatrix} 0 & m_{DY} & 0 & 0 & -\frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W s_\beta & -\frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W c_\beta \\ m_{DY} & 0 & 0 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & 0 & 0 & m_{D2} & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W s_\beta & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W c_\beta \\ 0 & 0 & m_{D2} & 0 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -\frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W s_\beta & -m_Z s_W c_\beta & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W s_\beta & m_Z c_W c_\beta & 0 & -\mu \\ -\frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W c_\beta & m_Z s_W s_\beta & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W c_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

neutralino mass matrix

$$\mathcal{M}_C = \begin{pmatrix} 0 & m_{D2} & \frac{2\lambda_T}{g_2} m_W c_\beta \\ m_{D2} & 0 & \sqrt{2} m_W s_\beta \\ -\frac{2\lambda_T}{g_2} m_W s_\beta & \sqrt{2} m_W c_\beta & \mu \end{pmatrix}$$

chargino mass matrix

6 neutralinos and 3 charginos — instead of 4 and 2 in the MSSM

MINIMAL DIRAC GAUGINO MODEL

MDGSSM

$$W = W_{\mathrm{MSSM}} + \lambda_S \mathbf{S}\,\mathbf{H_u}\cdot\mathbf{H_d} + 2\lambda_T\,\mathbf{H_d}\cdot\mathbf{T}\mathbf{H_u}$$

induce small pair-wise mass splittings

$$\mathcal{M}_N = \begin{pmatrix} 0 & m_{DY} & 0 & 0 & -\frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W s_\beta & \frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W c_\beta \\ m_{DY} & 0 & 0 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & 0 & 0 & m_{D2} & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W s_\beta & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W c_\beta \\ 0 & 0 & m_{D2} & 0 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -\frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W s_\beta & -m_Z s_W c_\beta & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W s_\beta & m_Z c_W c_\beta & 0 & -\mu \\ -\frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W c_\beta & m_Z s_W s_\beta & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W c_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

neutralino mass matrix

$$\mathcal{M}_C = \begin{pmatrix} 0 & m_{D2} & \frac{2\lambda_T}{g_2} m_W c_\beta \\ m_{D2} & 0 & \sqrt{2} m_W s_\beta \\ -\frac{2\lambda_T}{g_2} m_W s_\beta & \sqrt{2} m_W c_\beta & \mu \end{pmatrix}$$

chargino mass matrix

6 neutralinos and 3 charginos — instead of 4 and 2 in the MSSM

MINIMAL DIRAC GAUGINO MODEL

MDGSSM

- Extended EW-ino spectrum: 6 neutralinos, 3 charginos

- Neutralinos are pseudo-Dirac Majorana fermions → pairs with small mass splittings between the bino or wino and its adjoint

- E.g. for $m_{DY} \ll m_{D2}, \mu$: pair of bino/U(1) adjoint (co)LSP with

$$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \simeq \left| 2 \frac{M_Z^2 s_W^2}{\mu} \frac{(2\lambda_S^2 - g_Y^2)}{g_Y^2} c_\beta s_\beta \right|$$

- Opens new possibilities for co-annihilation scenarios

Belanger, Benakli, Goodsell, Moura, Pukhov, 0905.1043

PARAMETER SCAN

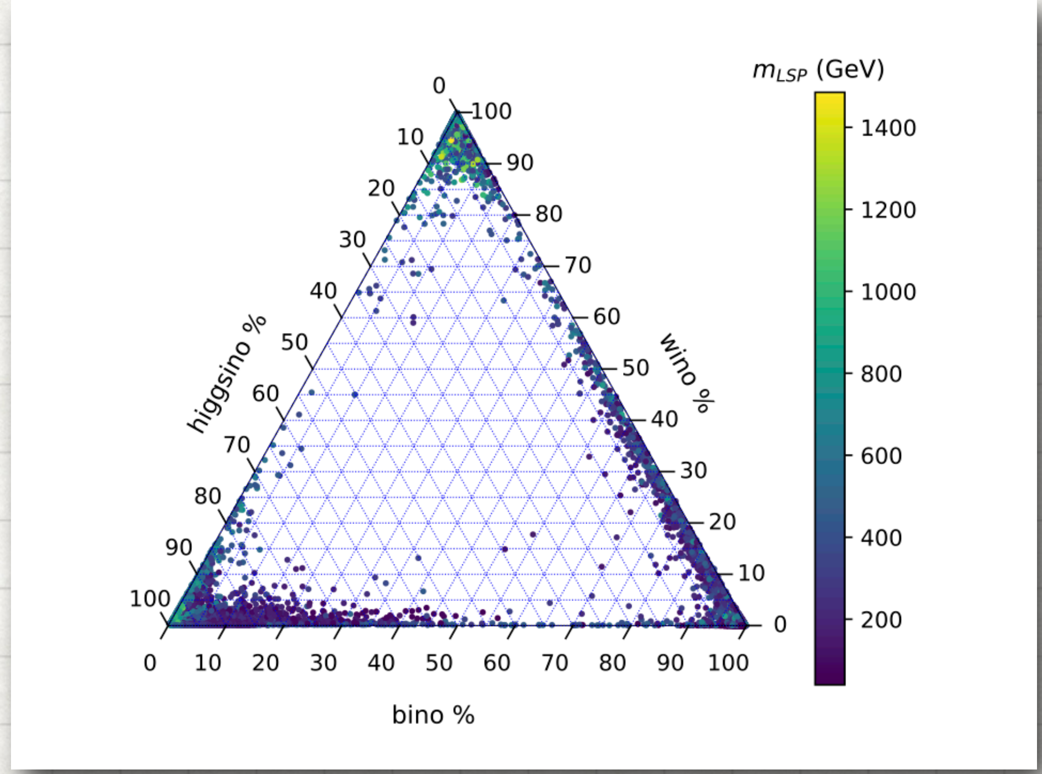
- MCMC scan of EW-ino parameter space

$$0 < m_{DY},\, m_{D2},\, \mu < 2\ \mathrm{TeV}; \quad 1.7 < \tan\beta < 60; \quad -3 < \lambda_S,\, \lambda_T < 3$$

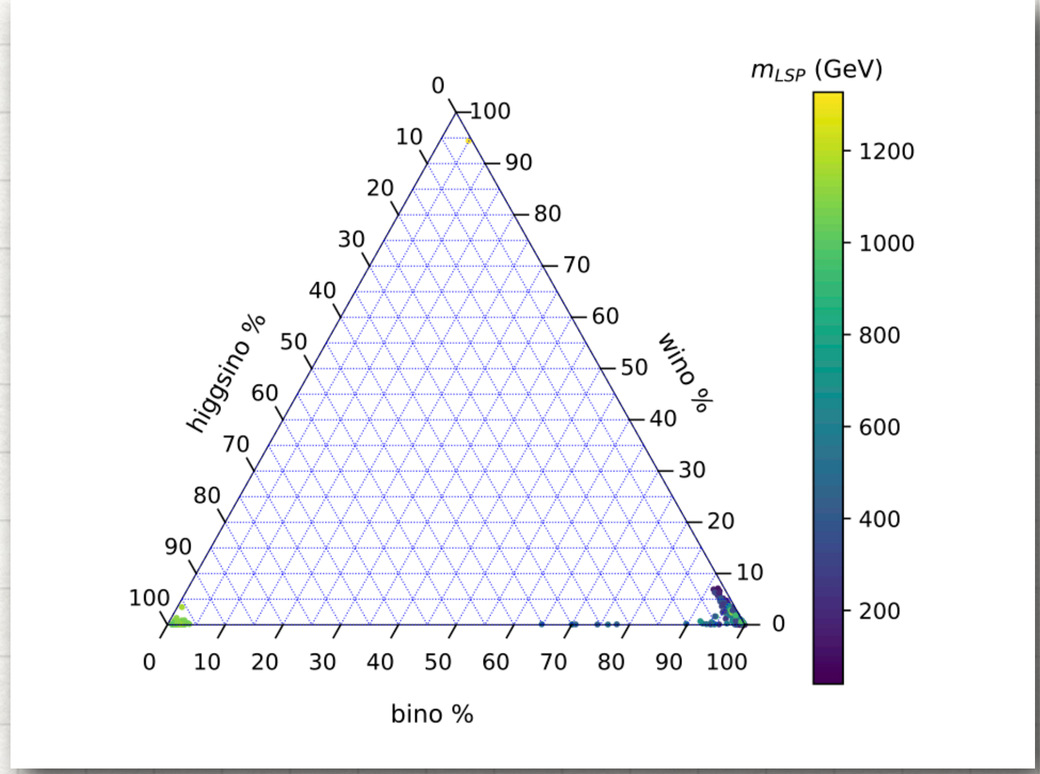
rest of the spectrum (gluinos, squarks, sleptons, add. Higgses) assumed to be heavy

- Constraints from relic density, direct DM detection (esp. Xenon100), LEP, Δ**ρ**, LHC Higgs measurements (incl. H→inv.), etc.

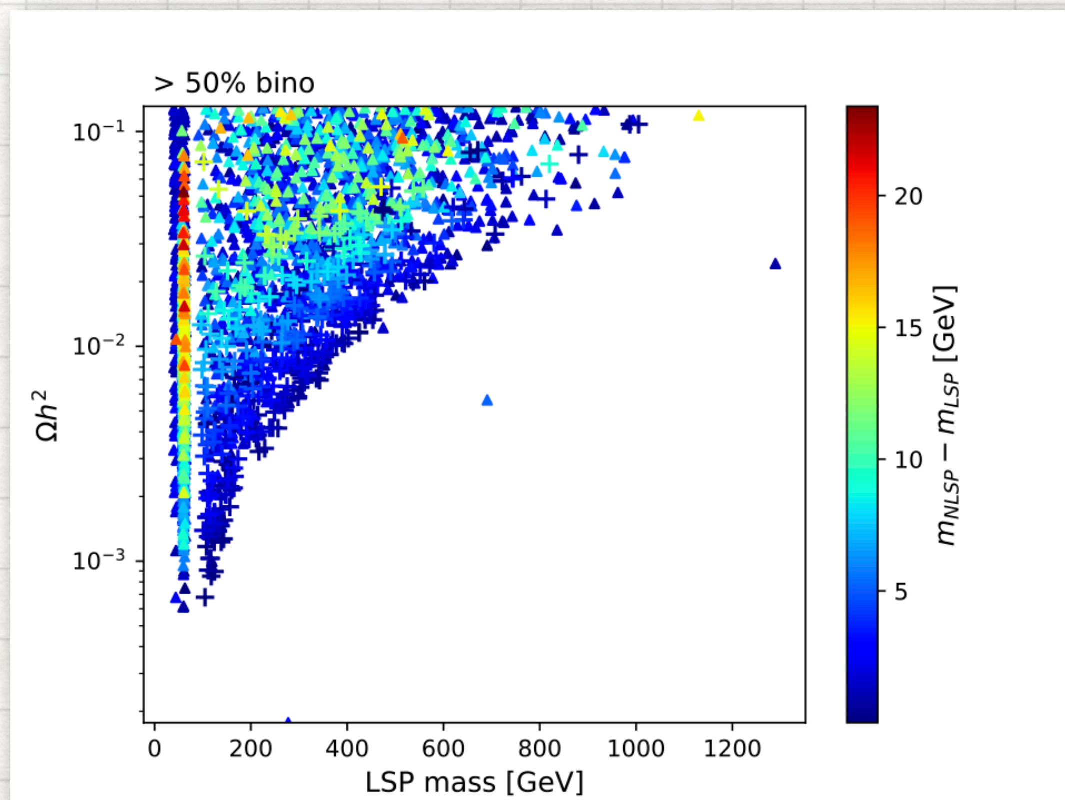
$\Omega h^2 < 0.132$

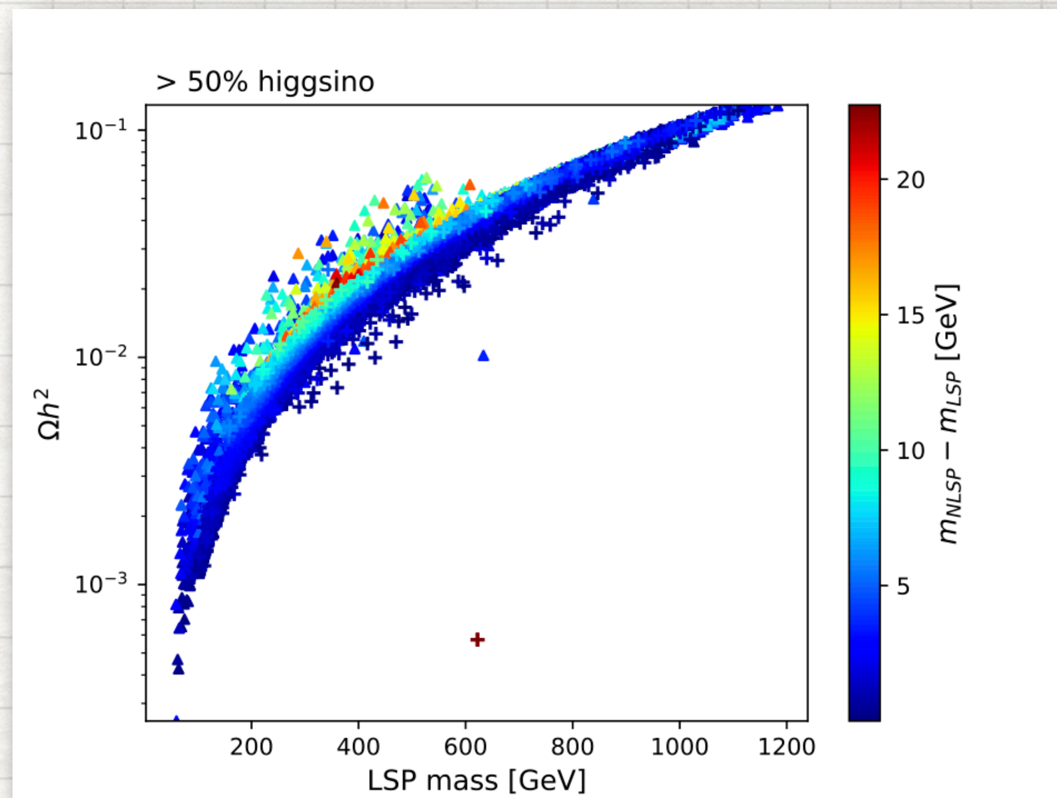


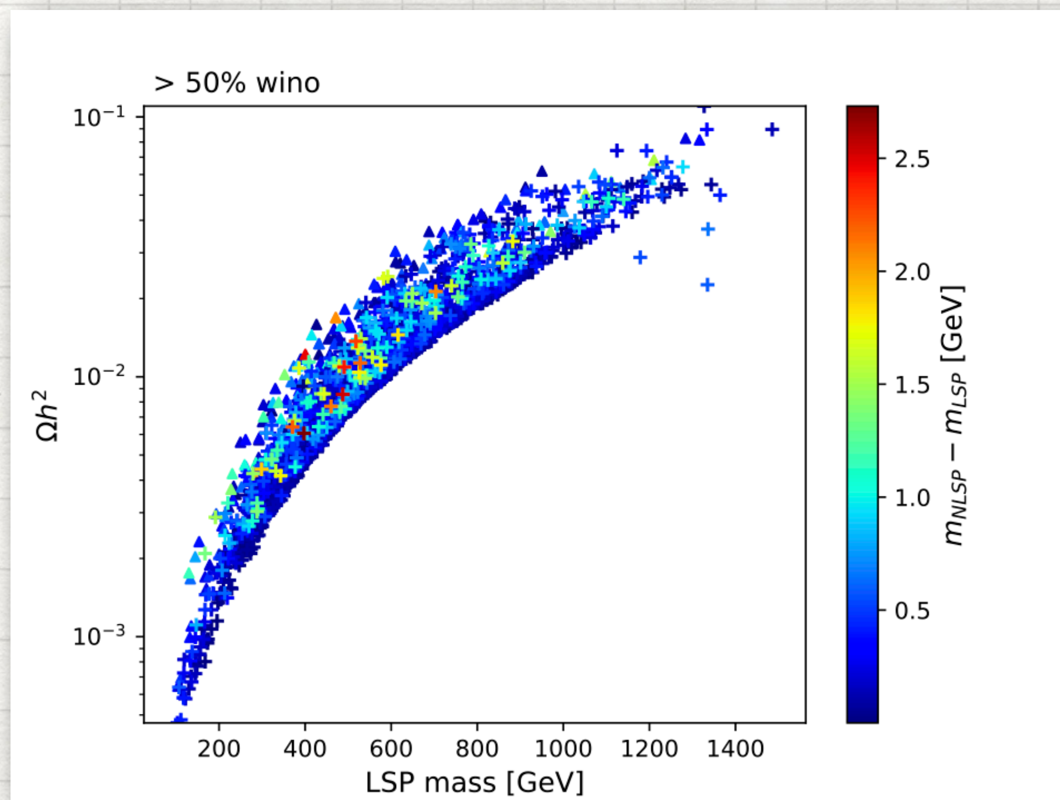
$\Omega h^2 = \Omega h^2_{\mathrm{Planck}} \pm 10\% = [0.108,\, 0.132]$



NEUTRALINO DM IN THE MDGSSM

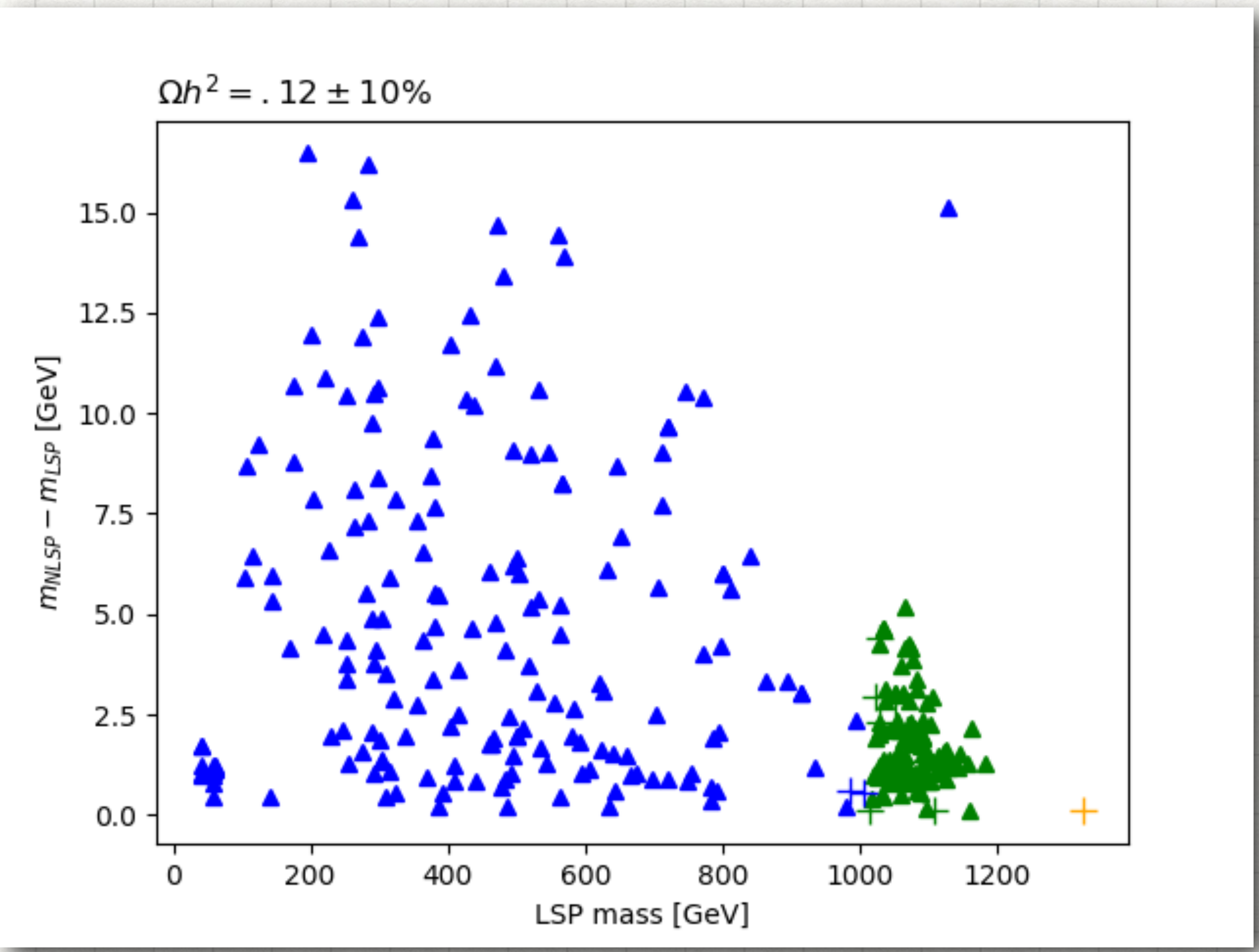






triangles: neutral NLSP
crosses: charged NLSP

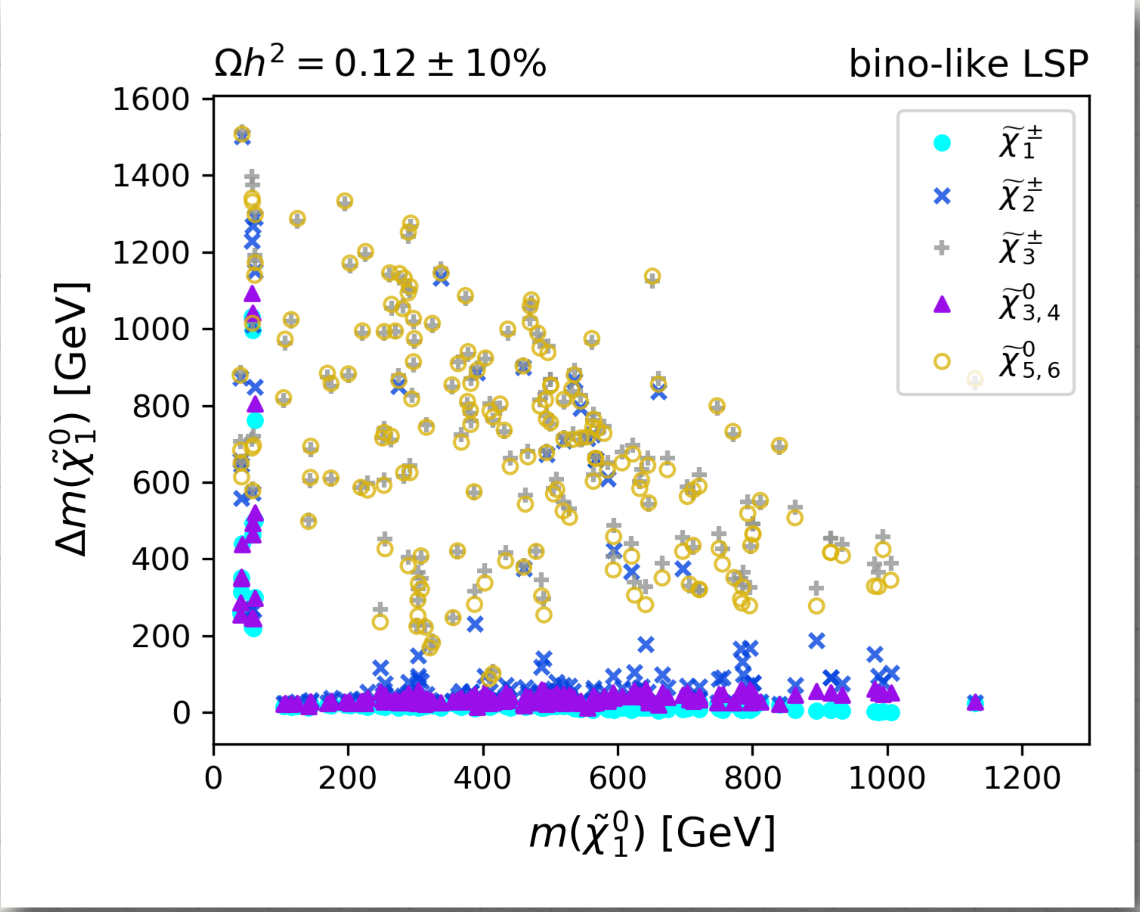
NEUTRALINO DM IN THE MDGSSM

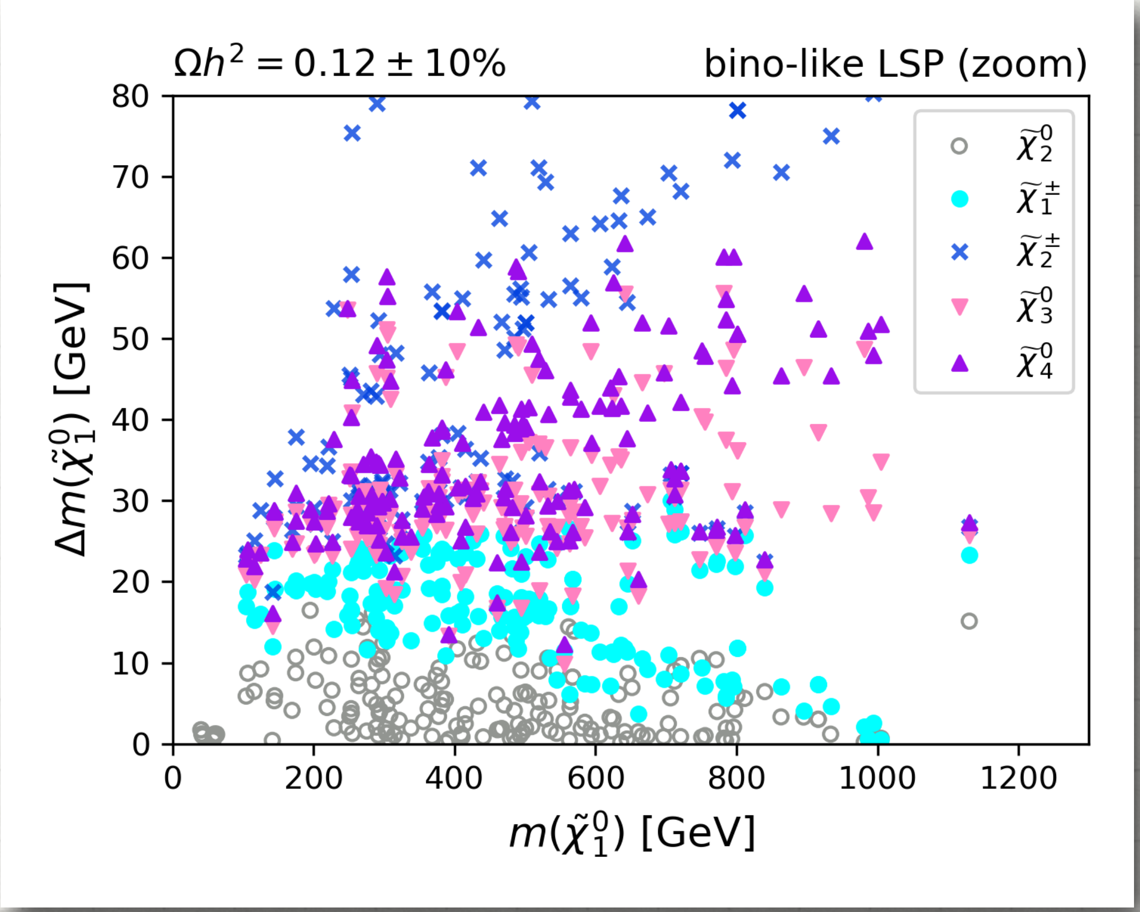


blue: bino, green: higgsino, gold: wino DM

triangles: neutral, crosses: charged NLSP

MASS SPLITTINGS IN BINO DM SCENARIOS

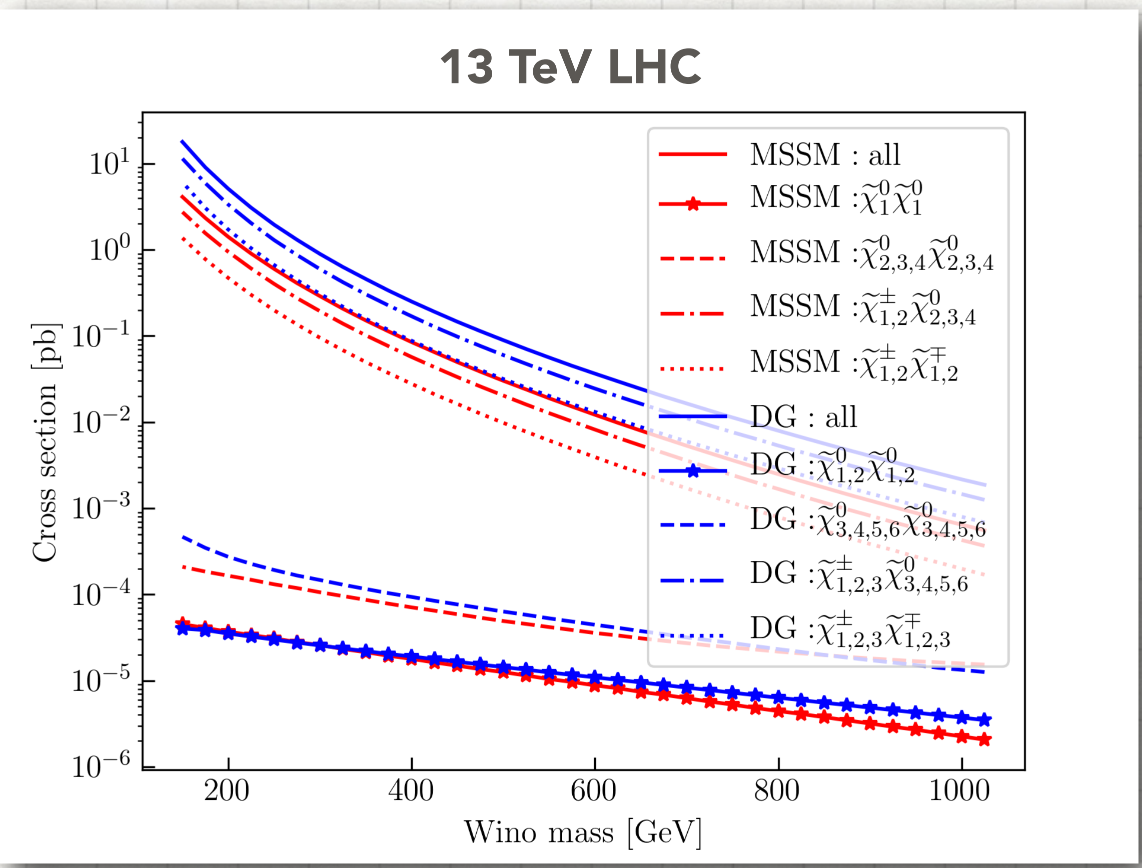




Goodsell, SK, Reyes-Gonzalez, Williamson, in progress

COLLIDER SIGNALS

- DM motivates sub-TeV bino-wino or bino-higgsino scenarios compressed within 10s of GeV
- More n.d.o.f. → larger production cross sections than in MSSM (roughly a factor 3-4)
- Extended EW-ino spectrum → potentially richer signals



μ=1400 GeV, tan β=10

DG: $m_{D2} = 1.2\times m_{DY}$; MSSM: $M_2 = 1.2\times M_1$

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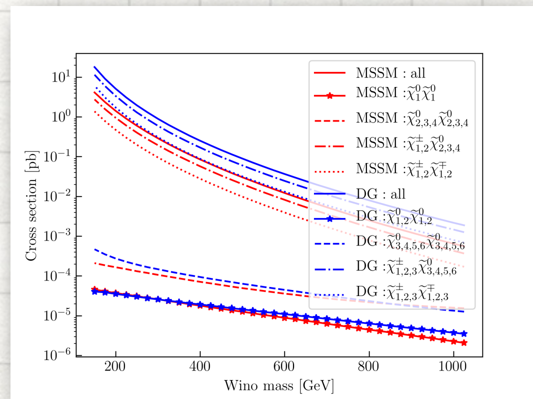

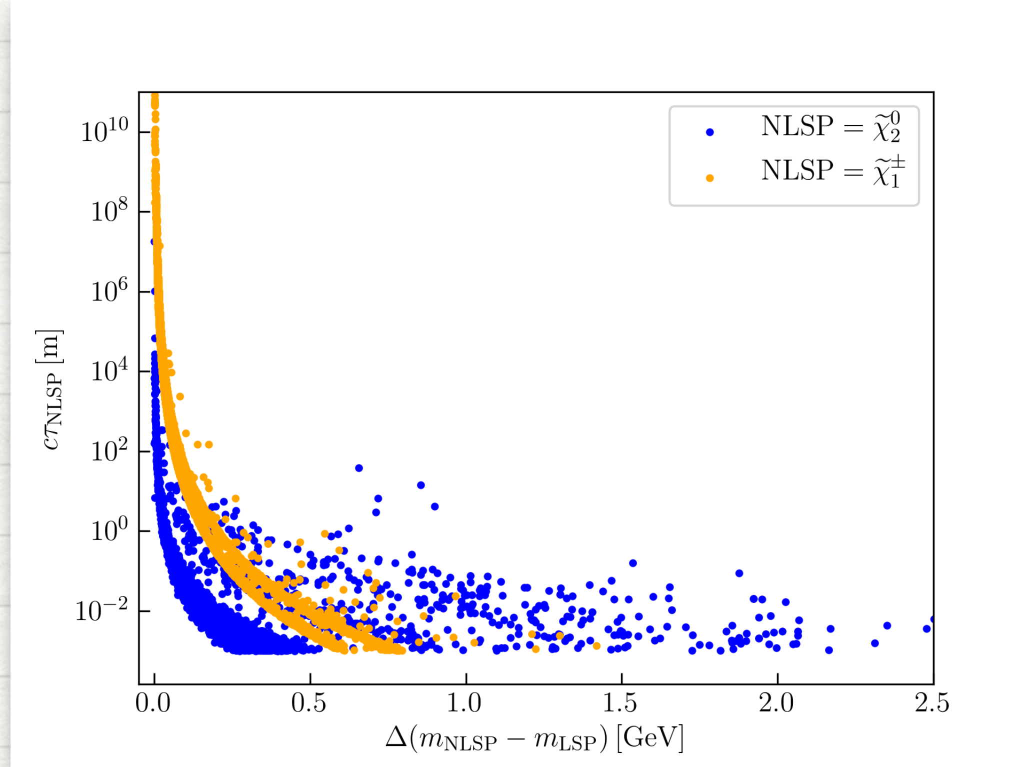

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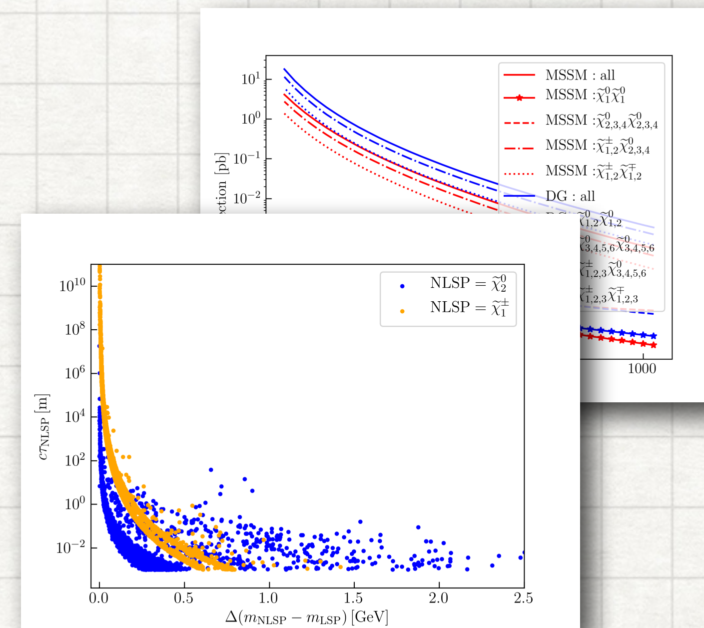
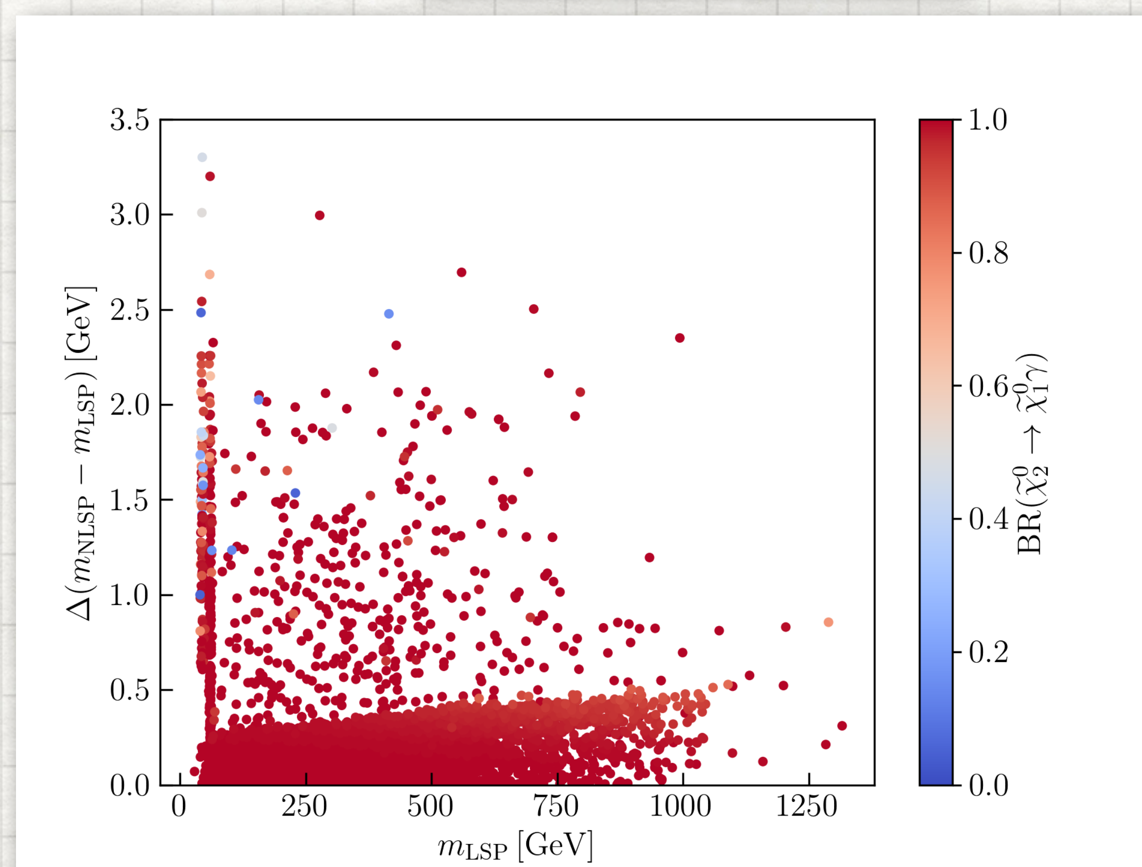
- Small mass splittings often lead to long-lived particles (neutral and/or charged)
- 2nd neutralino dominantly decays into LSP+(soft) photon
  might future exp. see this?





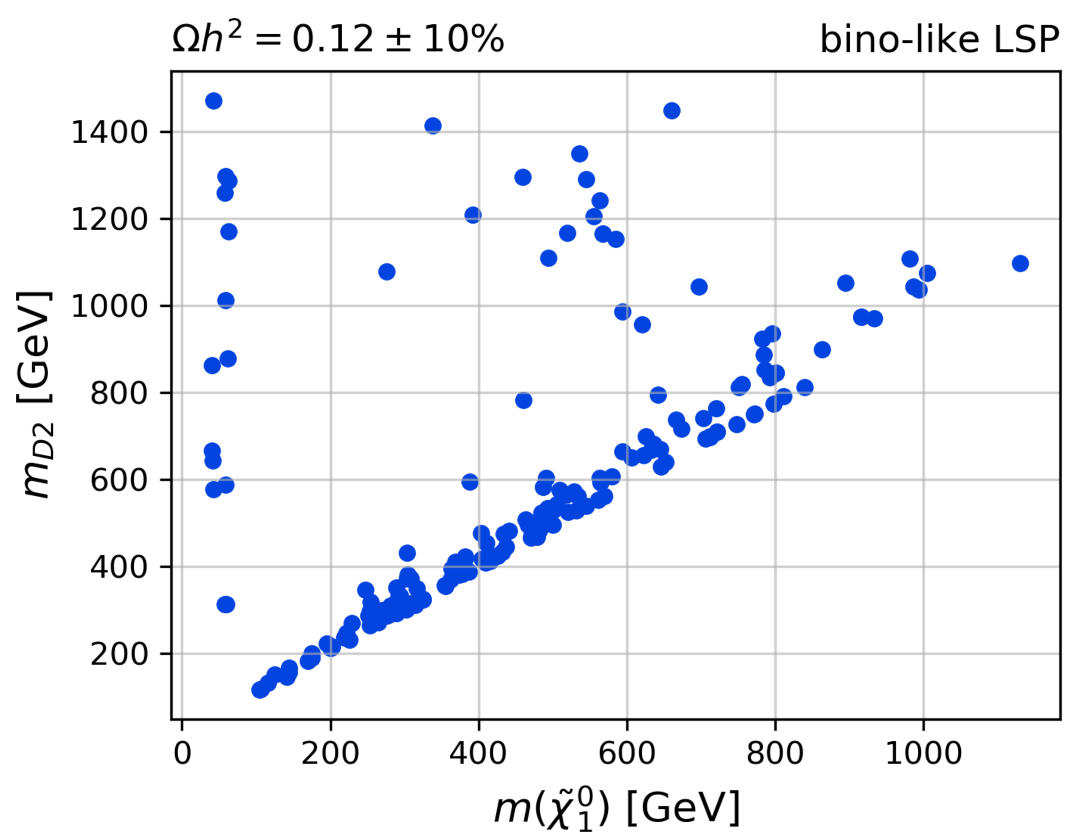
TO CONCLUDE

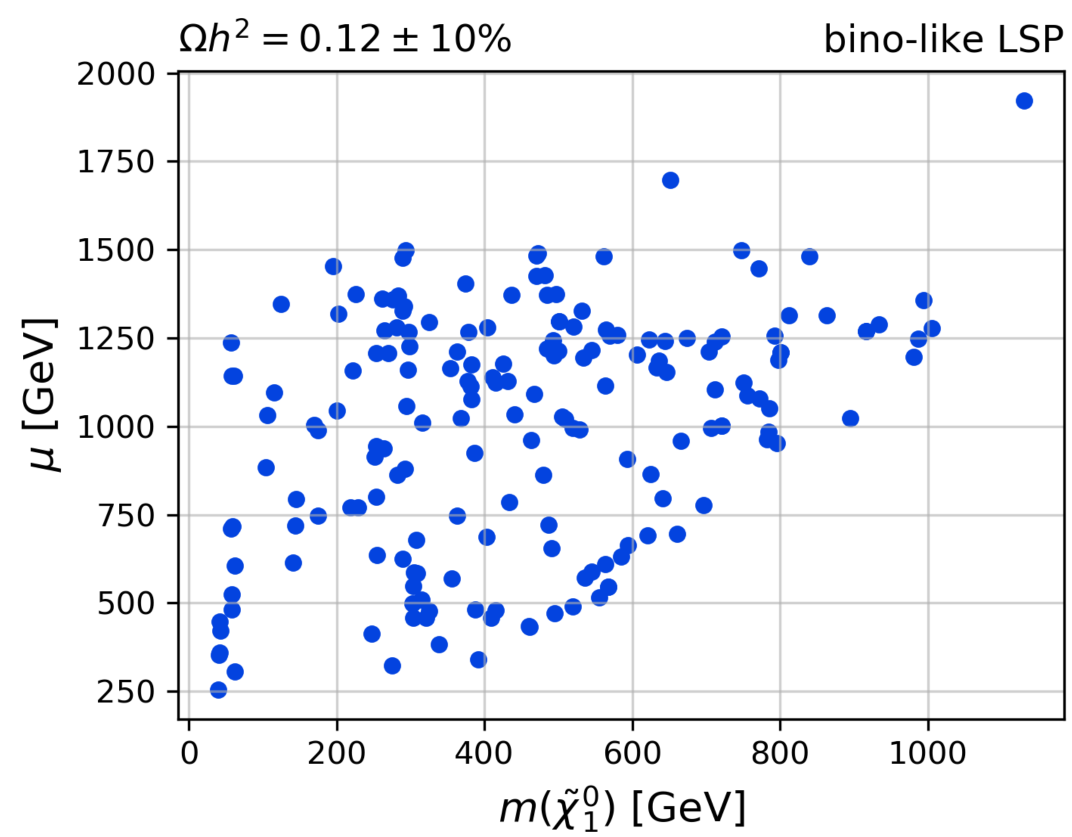
- MDGSSM provides bino coannihilation scenarios with potentially rich collider phenomenology, different from MSSM.
- We are currently investigating LHC limits from Run 2 searches.
- Constraints from EW-ino searches at Run 2 (WZ+MET, WH+MET) don't seem very strong.
- For Snowmass 2021 process: interesting to explore the potential of future experiments to discover / unravel DG DM scenarios.
- One way to differentiate MDGSSM vs MSSM would be to detect the $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + \gamma$ decay (with or w/o displacement).

BACKUP

Goodsell, SK, Reyes-Gonzalez, Williamson, in progress

MDGSSM: BINO DM PARAMETER SPACE





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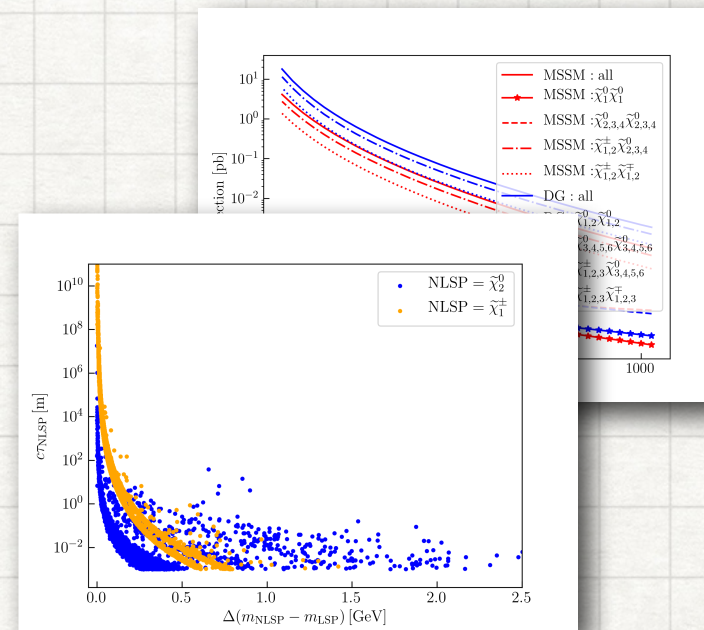

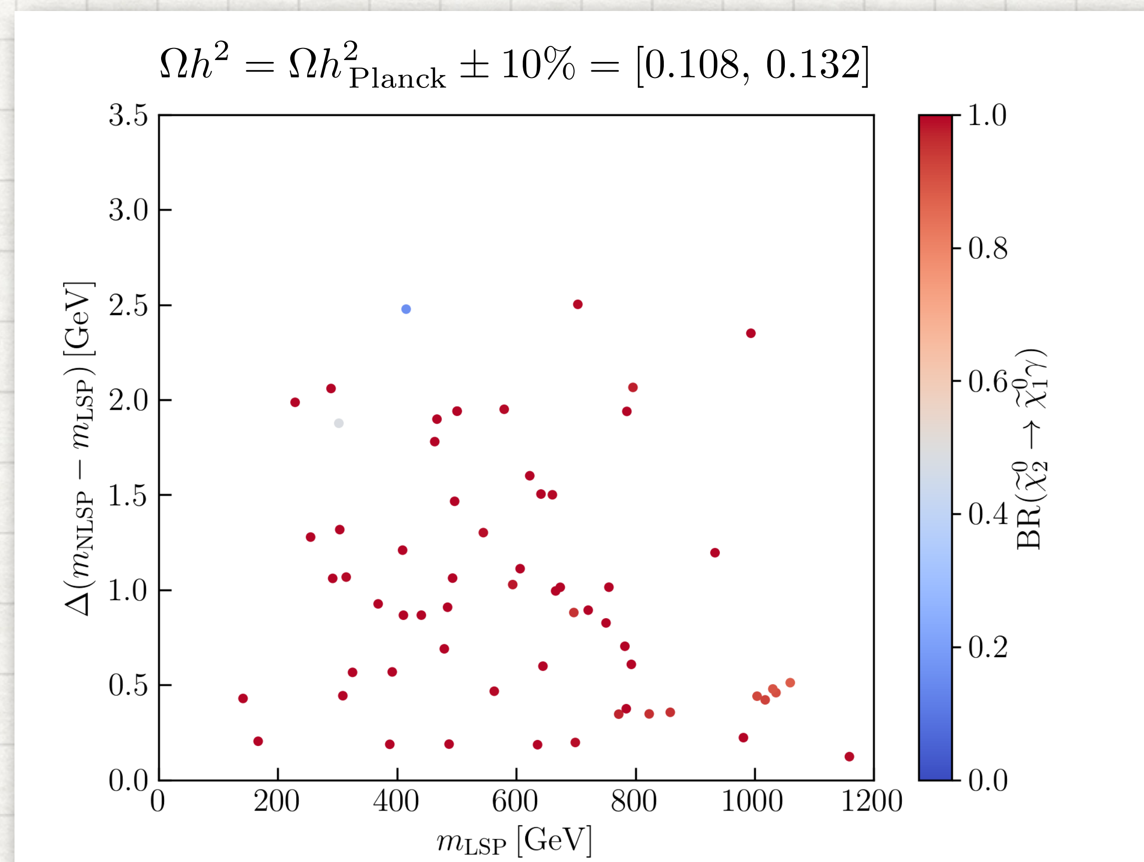

MINIMAL R-SYMMETRIC MODEL

MRSSM

- U(1) R-symmetry preserved after EWSB
- Need additional partner fields $\mathbf{R}_{u,d}$ for the Higgs scalars so that higgsinos can obtain a mass (analogous to MSSM μ-term)

Names		Spin 0, $R=0$	Spin 1/2, $R=-1$		$SU(3), SU(2), U(1)_Y$
Higgs	$\mathbf{H_u}$	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$		$(\mathbf{1}, \mathbf{2}, 1/2)$
	$\mathbf{H_d}$	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$		$(\mathbf{1}, \mathbf{2}, -1/2)$
DG-octet	$\mathbf{O}$	O	χ_O		$(\mathbf{8}, \mathbf{1}, 0)$
DG-triplet	$\mathbf{T}$	$\{T^0, T^\pm\}$	$\{\chi_T^\pm, \chi_T^0\}$		$(\mathbf{1}, \mathbf{3}, 0)$
DG-singlet	$\mathbf{S}$	S	χ_S		$(\mathbf{1}, \mathbf{1}, 0)$
Names		Spin 0, $R=2$	Spin 1/2, $R=1$	Spin 1, $R=0$	$SU(3), SU(2), U(1)_Y$
Gluons	$\mathbf{W}_{3\alpha}$		$\tilde{g}_\alpha$	g	$(\mathbf{8}, \mathbf{1}, 0)$
W	$\mathbf{W}_{2\alpha}$		$\tilde{W}^\pm, \tilde{W}^0$	$W^\pm, W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
B	$\mathbf{W}_{1\alpha}$		$\tilde{B}$	B	$(\mathbf{1}, \mathbf{1}, 0)$
R-Higgs	$\mathbf{R_d}$	(R_d^+, R_d^0)	$(\tilde{R}_d^+, \tilde{R}_d^0)$		$(\mathbf{1}, \mathbf{2}, 1/2)$
	$\mathbf{R_u}$	(R_u^0, R_u^-)	$(\tilde{R}_u^0, \tilde{R}_u^-)$		$(\mathbf{1}, \mathbf{2}, -1/2)$

See e.g., Diessner, Kalinowski, Kotlarski, Stöckinger, 1410.4791

MINIMAL R-SYMMETRIC MODEL

MRSSM

$$W^{\mathrm{MRSSM}} = \mu_u \, \mathbf{R_u} \cdot \mathbf{H_u} + \mu_d \, \mathbf{R_d} \cdot \mathbf{H_d} + \lambda_{S_u} \mathbf{S} \, \mathbf{R_u} \cdot \mathbf{H_u} + \lambda_{S_d} \mathbf{S} \, \mathbf{R_d} \cdot \mathbf{H_d} + 2\lambda_{T_u} \, \mathbf{R_u} \cdot \mathbf{T H_u} + 2\lambda_{T_d} \, \mathbf{R_d} \cdot \mathbf{T H_d} \, .$$

$$\mathcal{L}_{\mathrm{MRSSM}} \supset (\tilde{B}, \tilde{W}^0, \tilde{R}_d^0, \tilde{R}_u^0) \begin{pmatrix} m_{DY} & 0 & -\frac{1}{2} g_Y v_d & \frac{1}{2} g_Y v_u \\ 0 & m_{D2} & \frac{1}{2} g_2 v_d & -\frac{1}{2} g_2 v_u \\ -\frac{1}{2} \lambda_{S_d} v_d & -\frac{1}{2} \lambda_{T_d} v_d & -\mu_d^{\mathrm{eff},+} & 0 \\ \frac{1}{2} \lambda_{S_u} v_u & -\frac{1}{2} \lambda_{T_u} v_u & 0 & \mu_u^{\mathrm{eff},-} \end{pmatrix} \begin{pmatrix} \chi_S^0 \\ \chi_T^0 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix}$$

$$\boxed{\mu_{u,d}^{\mathrm{eff},\pm} \equiv \mu_{u,d} + \frac{1}{\sqrt{2}} \lambda_{S_{u,d}} v_S \pm \frac{1}{\sqrt{2}} \lambda_{T_{u,d}} v_T}$$

- EW gauginos and (R-)higgsinos form four Dirac neutralinos
- Interesting consequences for DM freeze-out and direct detection *
  (LSP is not it's own anti-particle)

*) Majorana case: scalar and axial-vector interactions; Dirac case: also vector interactions