Testing Yukawa Unification at LHC and Dark Matter Experiments

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Outline

- The Standard Model
- SUSY and MSSM
- Pati-Salam Model
- Yukawa Unification
- LHC Implications
- Dark Matter Implications
- Conclusion

The Standard Model

- The SM is a gauge theory of fields of spin 0, 1/2 and 1 based on $SU(3)_c \times SU(2)_L \times U(1)_Y$

  $SU(3)_c \to$ QCD, confinement

  $SU(2)_L \times U(1)_Y \to$ electroweak interactions, chiral, spontaneous symmetry breaking

$$SU(2)_L \times U(1)_Y \to U(1)_{\mathrm{em}}$$

- The SM is one of the most successful theories in physics. It has been tested rigorously.

  $W^{\pm}, Z$ bosons

  Rare B-meson decays: $B_s \to \mu^+\mu^-$, $b \to s\gamma$

  The Higgs Boson

Standard Model

SM is not a fundamental theory!

- Gauge Hierarchy problem: $\delta m_h^2 \propto \Lambda^2$
- The Higgs vacuum stability: $\lambda < 0$ for $\Lambda \gtrsim 10^{10}$ GeV

  Stability Condition: $m_h > (129.6 \pm 1.5)$ GeV
- The gauge symmetry
- Neutrino masses and mixings
- Dark matter

SUSY and MSSM

SUSY is a symmetry that relates fermions and bosons

$$Q\,|fermion\rangle = |boson\rangle\,, \quad Q\,|boson\rangle = |fermion\rangle$$

- **Resolution to the gauge hierarchy problem.**
- **Fast proton decay** $\Rightarrow$ **R-parity conservation**
  Stable LSP and DM: neutralino, sneutrino, gravitino
- $h \sim H_{\rm SM}$ when $m_h \ll m_H \sim m_A \sim m_{H^\pm}$ (Decoupling Limit)
- Radiative Electroweak Symmetry Breaking
- Gauge Coupling Unification: SUSY GUTs

Pati-Salam Model

- Based on $SU(4)_c \times SU(2)_L \times SU(2)_R$

$$M_1 = \frac{3}{5} M_{2R} + \frac{2}{5} M_3$$

- $U(1)_{B-L} \in SU(4)_c$: R-Parity, Proton decay ...
- The matter fields are in $\psi(4,2,1)$ and $\psi(\bar{4},1,2)$.
- MSSM Higgs doublets can solely be included in $H(1,2,2)$
- Yukawa Unification arises from

$$\psi_c \psi H \quad \Rightarrow \quad y_t = y_b = y_\tau$$

- Right-handed neutrinos are required: See-saw mechanisms

Fundamental Parameters

$0.1 \leq$	m_L	≤ 10 TeV	SSB mass for LH scalars
$0.05 \leq$	M_{2L}	≤ 5 TeV	SSB mass for $SU(2)_L$ gaugino
$-3 \leq$	M_3	≤ 5 TeV	SSB mass for $SU(3)_c$ gaugino
$-3 \leq$	A_0/m_L	≤ 3	SSB Trilinear Scalar Coupling
$2 \leq$	$\tan\beta$	≤ 60	$\tan\beta \equiv v_u/v_d$
$-3 \leq$	$\mathrm{x_{RL}}$	≤ 3	$m_R = x_{RL} m_L$
$-3 \leq$	$\mathrm{y_{RL}}$	≤ 3	$M_{2R} = y_{RL} M_{2L}$
$0 \leq$	$\mathrm{x_d}$	≤ 3	$m_{H_d} = x_d m_L$
$-1 \leq$	$\mathrm{x_u}$	≤ 2	$m_{H_u} = x_u m_L$

Experimental Constraints

LHC constraints

$$123 \leq m_h \leq 127 \text{ GeV}$$

$$m_{\tilde{g}} \geq 2100 \text{ GeV} \quad (800 \text{ GeV, if NLSP})$$

$$0.8 \times 10^{-9} \leq \text{BR}(B_s \to \mu^+\mu^-) \leq 6.2 \times 10^{-9}$$

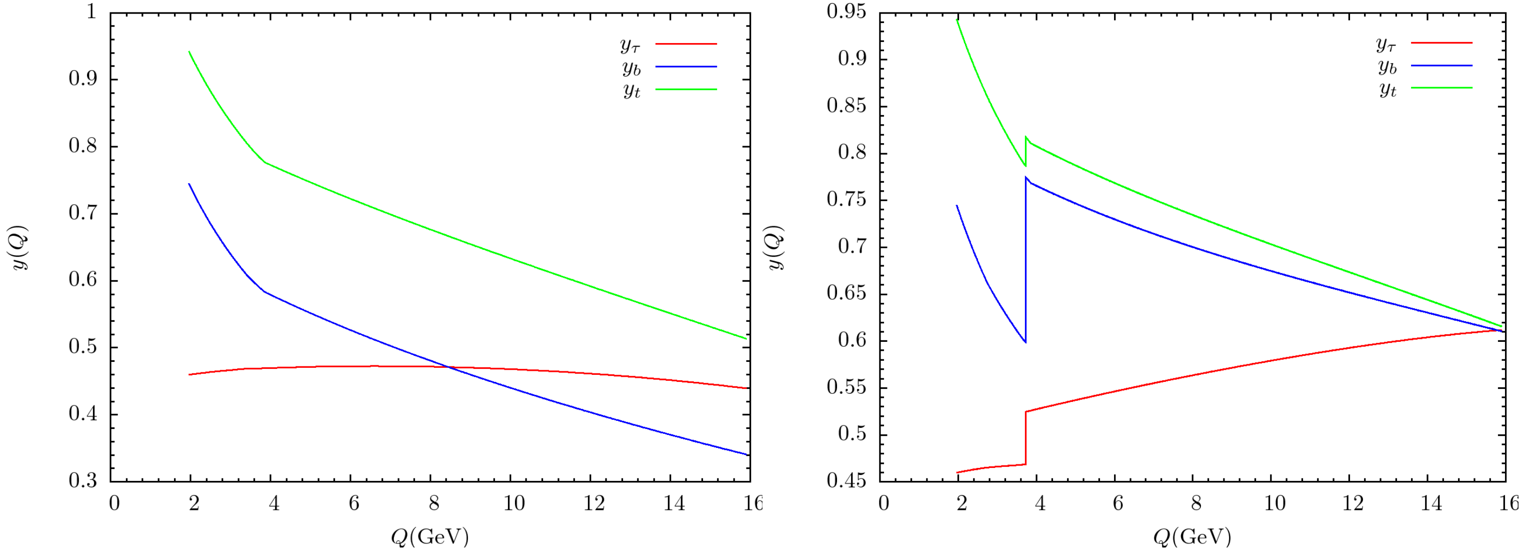
$$2.9 \times 10^{-4} \leq \text{BR}(b \to s\gamma) \leq 6.2 \times 10^{-9}$$

$$0.114 \leq \Omega h^2(\text{Planck}) \leq 0.126$$

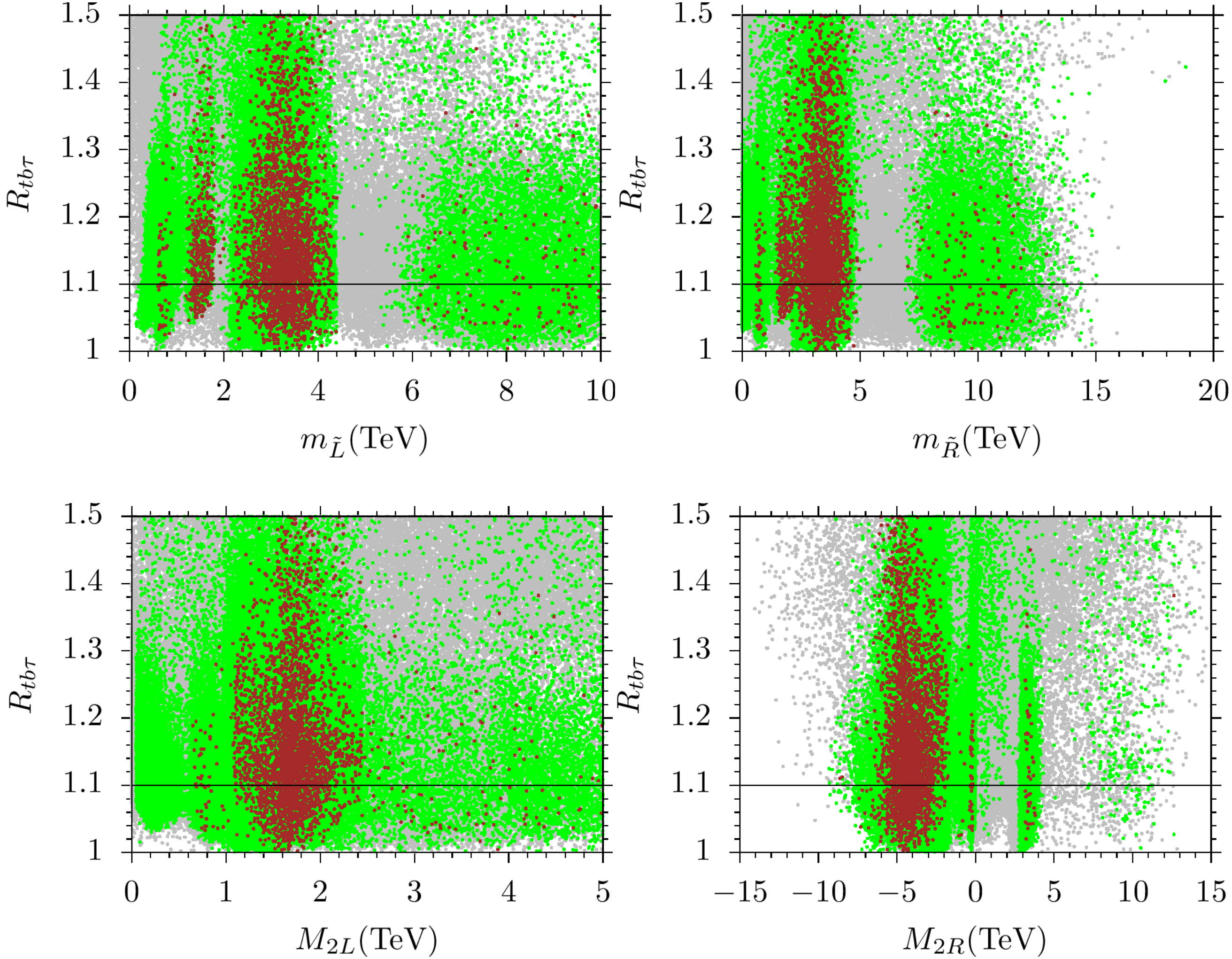
$$\mu > 0 \qquad m_t = 173.3 \text{ GeV}$$

$$R_{tb\tau} \equiv \frac{\text{Max}(y_t, y_b, y_\tau)}{\text{Min}(y_t, y_b, y_\tau)} \leq 1.1$$

YU needs threshold corrections



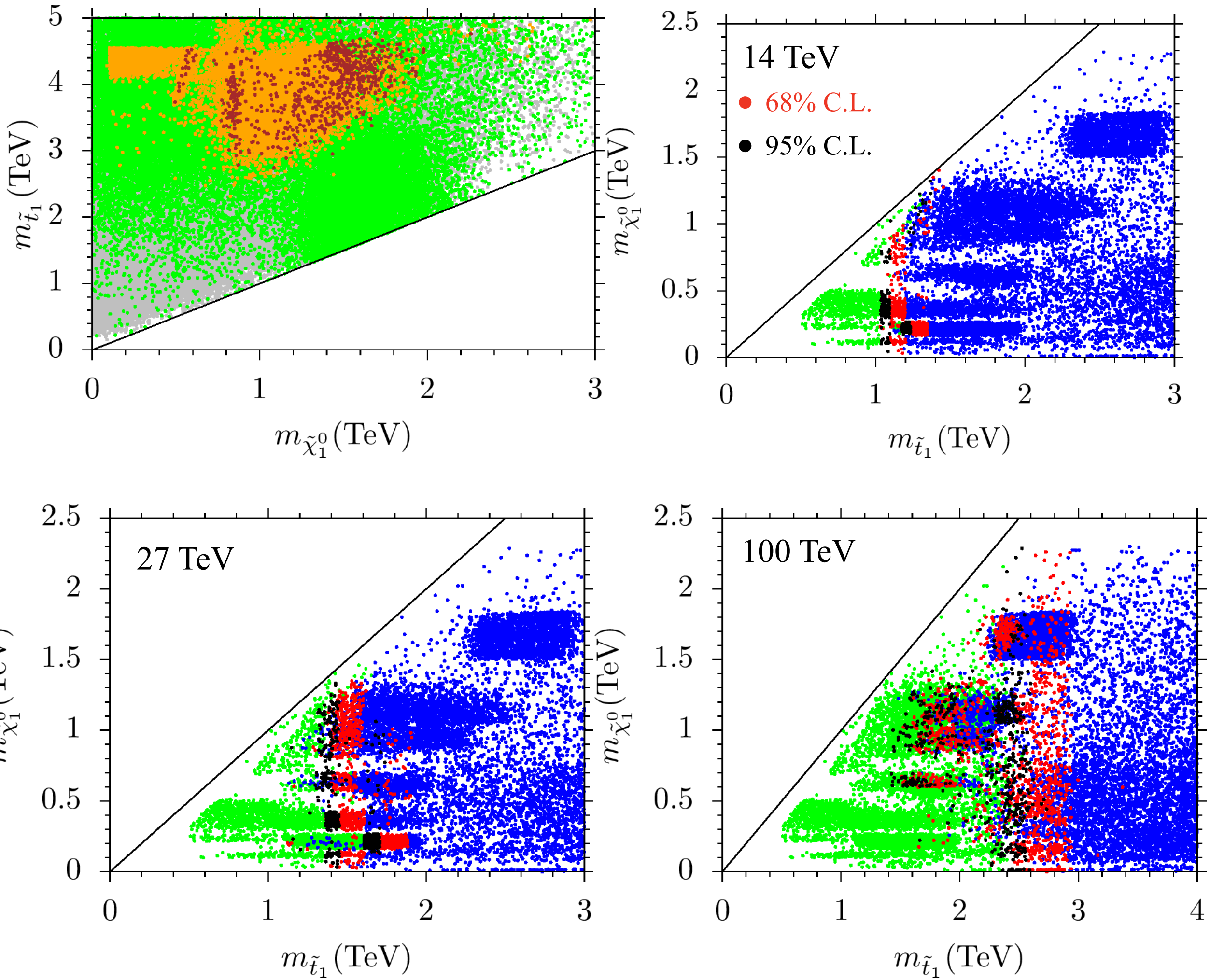
$$\delta y_b = \frac{g_3^2}{12\pi^2}\frac{\mu m_{\tilde{g}} \tan\beta}{m_1^2} + \frac{y_t^2}{32\pi^2}\frac{\mu A_t \tan\beta}{m_2^2} + \ldots$$



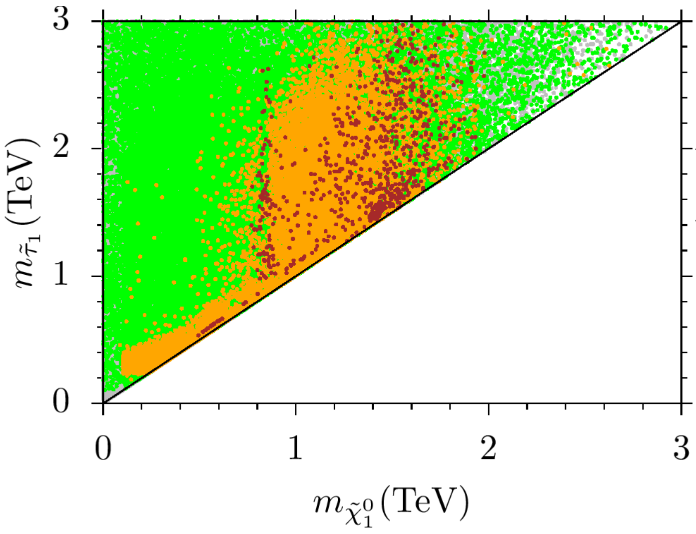
All points are consistent with the REWSB and LSP neutralino conditions. Green points satisfy the mass bounds and constraints from rare $B-$meson decays. Brown points form a subset of green and they represent relic abundance of LSP neutralino consistent with the Planck bound within 5σ. The horizontal lines indicate $R_{tb\tau} = 1.1$ and the regions below these lines are considered to be compatible with the YU condition.

LHC Implications

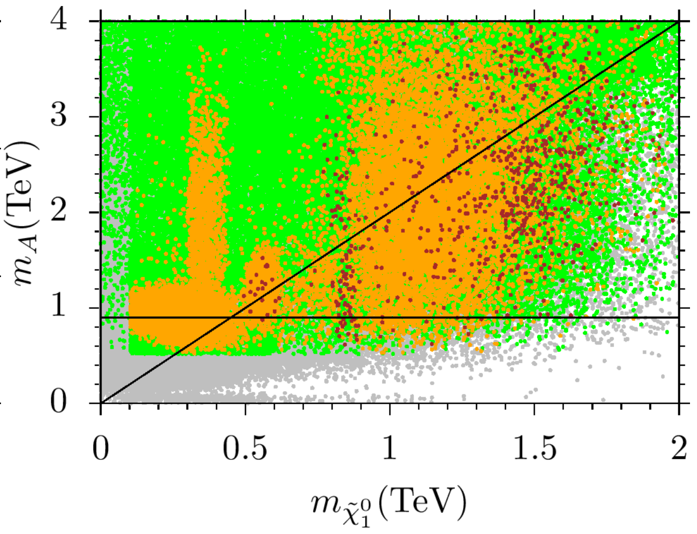
(Z. Altin, Z. Kirca, T. Tanimak, C.S. Un, Eur.Phys.J. C80 (2020),818.)



LHC Implications:

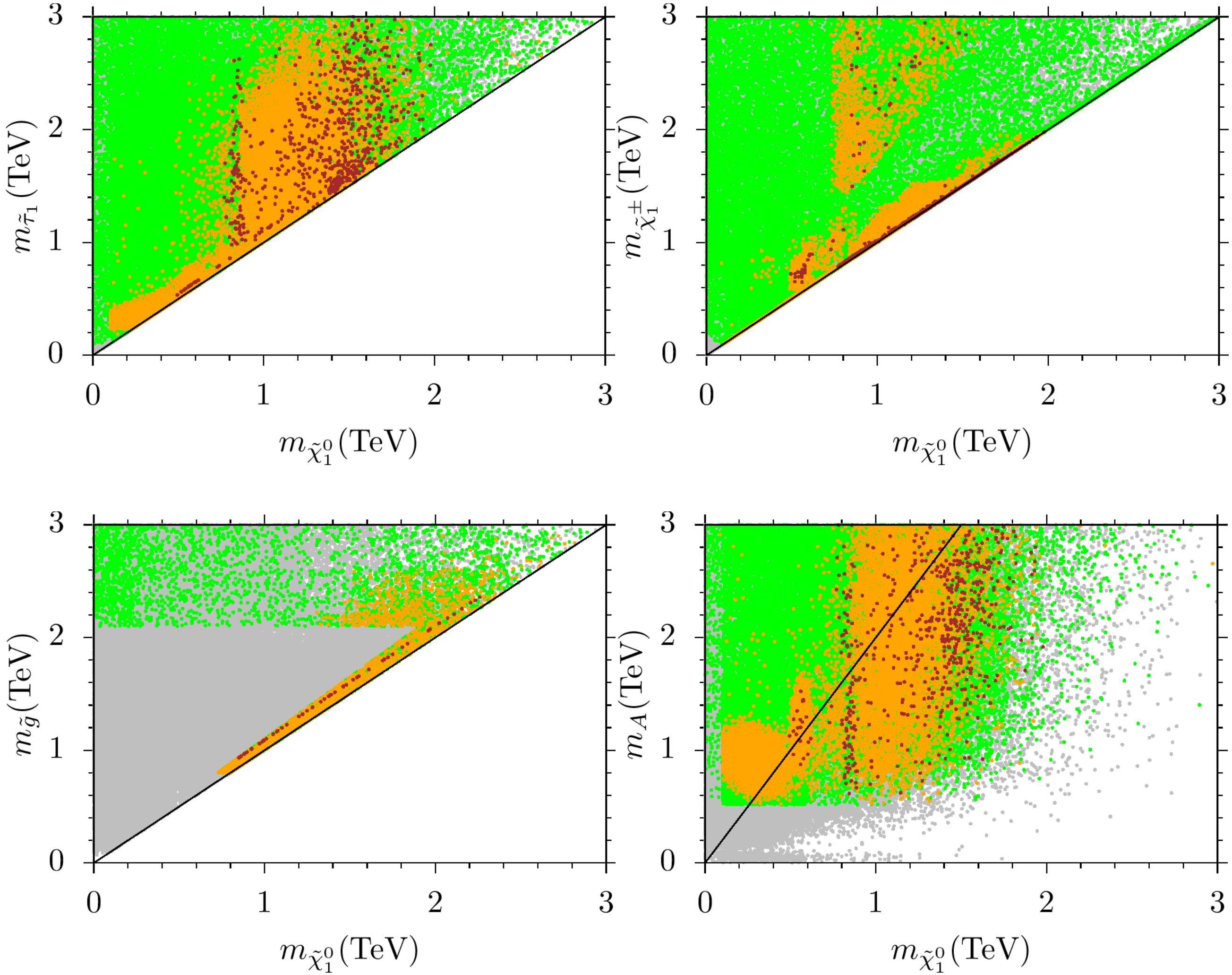


(a) $\tilde{\tau}$ through $\tilde{\chi}^0$ and $\tilde{\chi}^\pm$

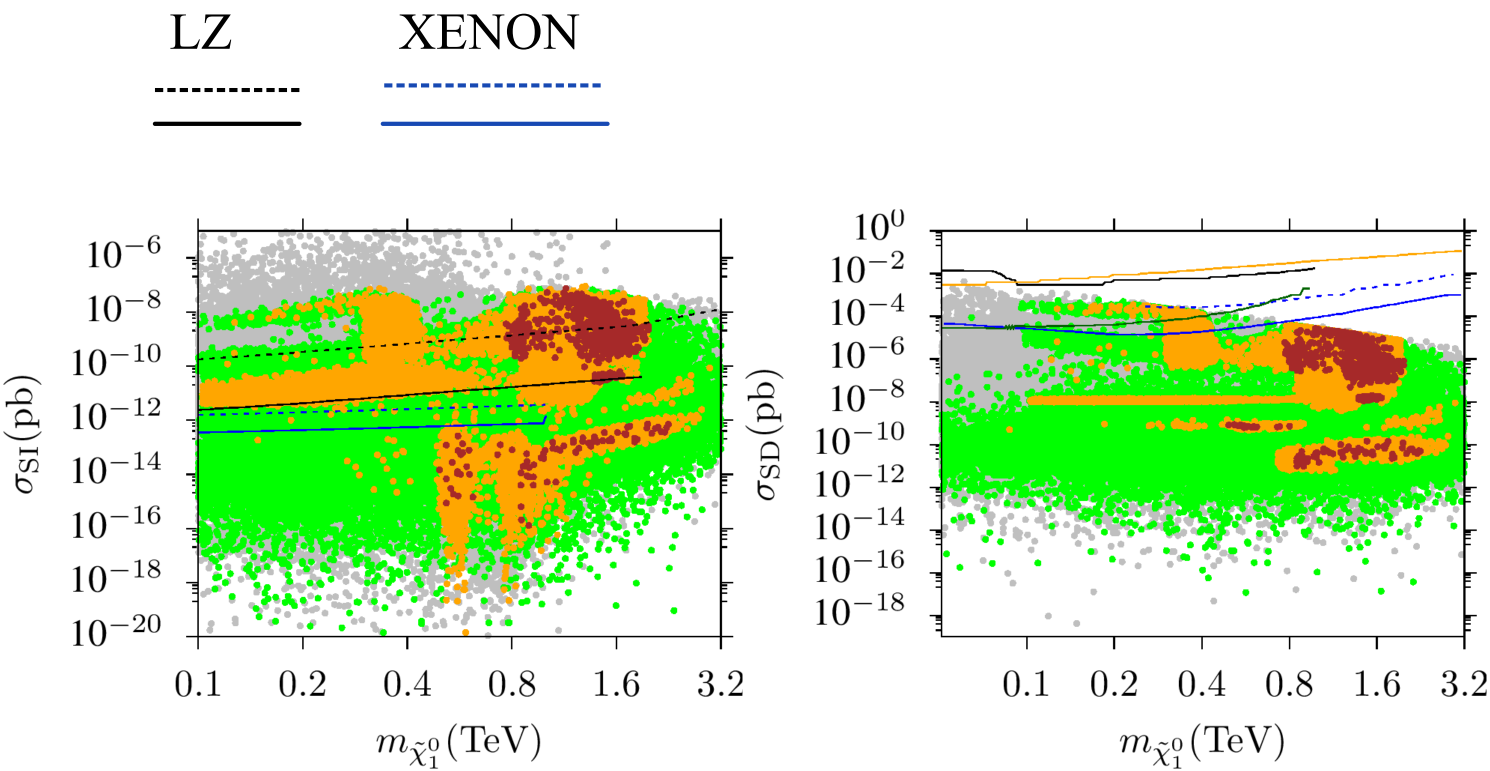


(b) A through its hadronic decays

Dark Matter Implications: Coannihilation Scenarios



Dark Matter Implications: Direct Detection



Conclusion

- $m_{\tilde{t}} \gtrsim 3TeV$ can be probed in the HL-LHC and HE-LHC experiments,
- $m_{\tilde{g}}$ NLSP in $\sim [0.8 - 2.4]$ TeV: about to be probed in LHC Run-3,
- $A-$boson with $m_A \gtrsim 1$ TeV is about to be probed through its hadronic decays,
- $m_{\tilde{\tau}} \gtrsim 500$ GeV can be probed through $\tilde{\chi}^0, \tilde{\chi}^{\pm}$ productions,
- LSP neutralino coannihilations (stau, gluino and chargino scenarios) and $A-$resonance solutions.
- Bino-like DM: Further upgrades in XENONnT
- Wino-like and Higgsino-like DM: Testable at the LUX-Zeplin and XENON1T experiments.