UNIVERSITÀ DEGLI STUDI
DI GENOVA

Constraining the Minimal Dirac Gaugino Model

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Based on: arXiv:1812.09293 and arXiv:2007.08498.
In collab with M. Goodsell, S. Kraml, S. Williamson, G. Chalons.

Genova, Italy, 16 December 2020

General outline.

- **Introduction: Searching new physics at the LHC.**
- **Constraining the Minimal Dirac Gaugino Model.**

  - The model.

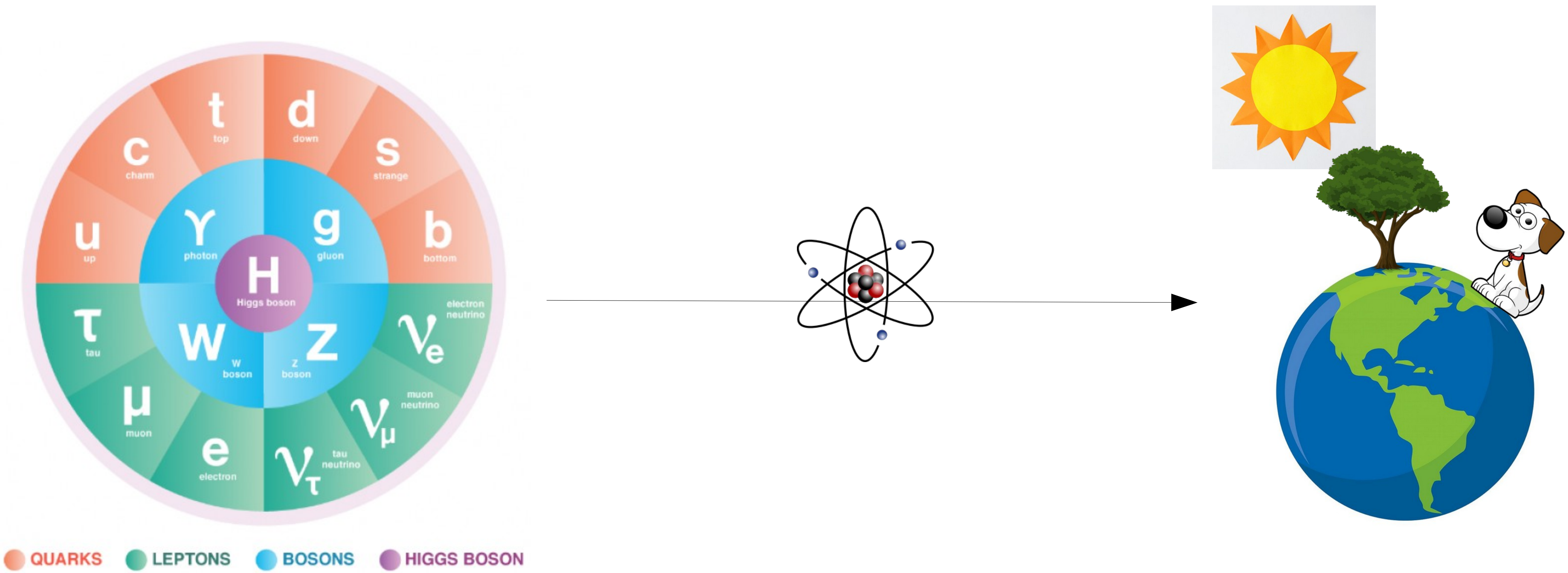
  - LHC limits on gluinos and squarks.

  - Constraining the electroweakino sector.
- **Conclusion.**

Introduction.

Searching new physics at the LHC.

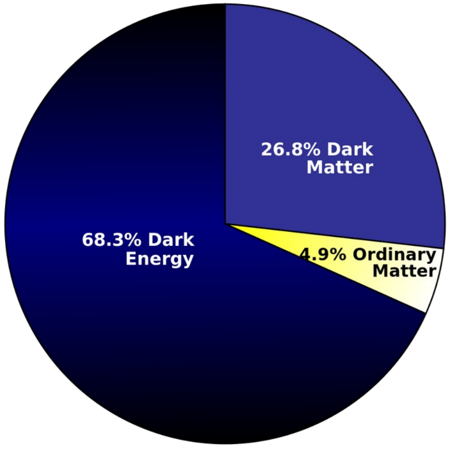
The Standard Model of particle physics



Why new physics?

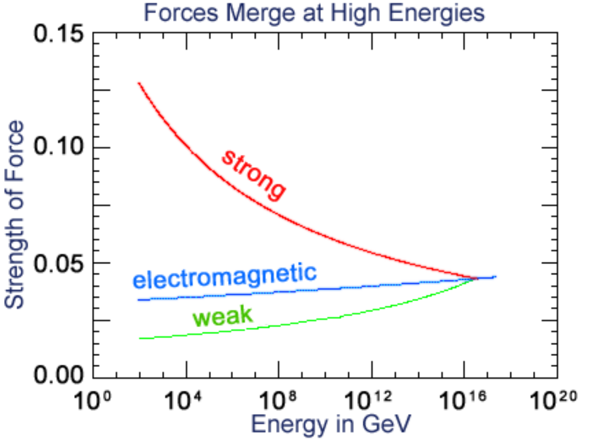
Astrophysics and cosmology

- Dark Matter
- Dark energy
- Matter-antimatter asymmetry
- Neutrino masses

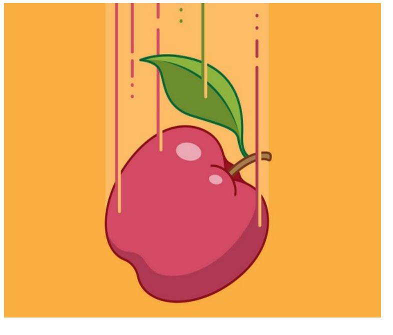


Intrinsic questions.

- The hierarchy problem
- Gauge coupling unification
- Strong CP problem
- Why three families?

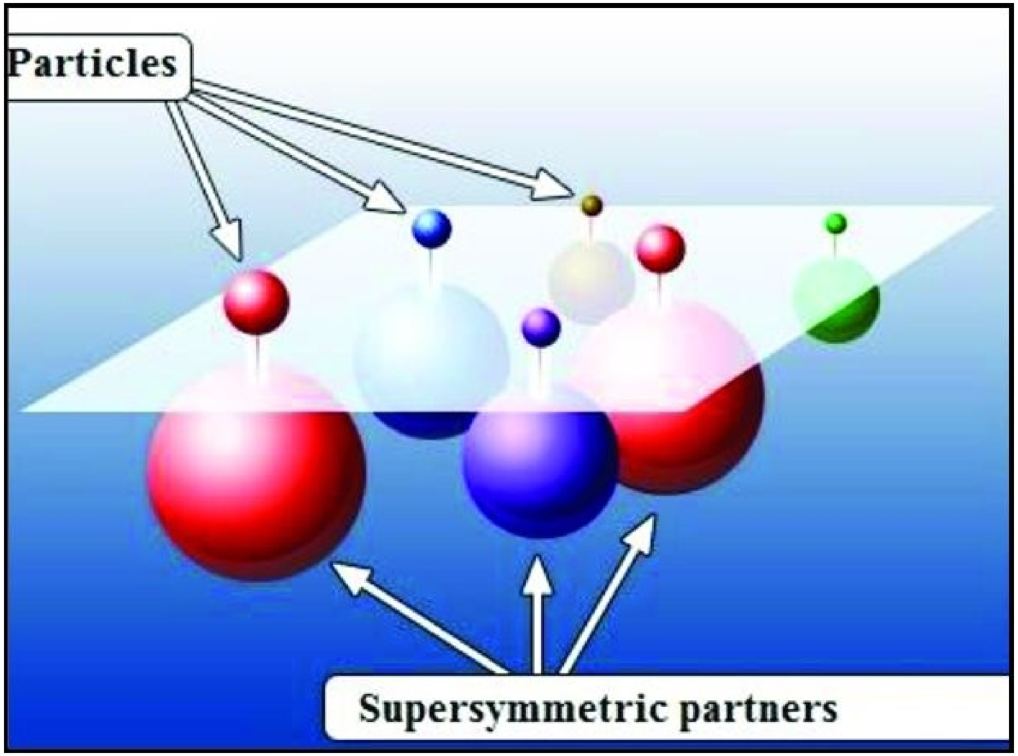


- **Gravity**



Where to go? Supersymmetry*

- In supersymmetry (SUSY), fermionic generators transform the spin of the fields by ½.
- Thus, ***for each fermion there is a bosonic superpartner and viceversa.***

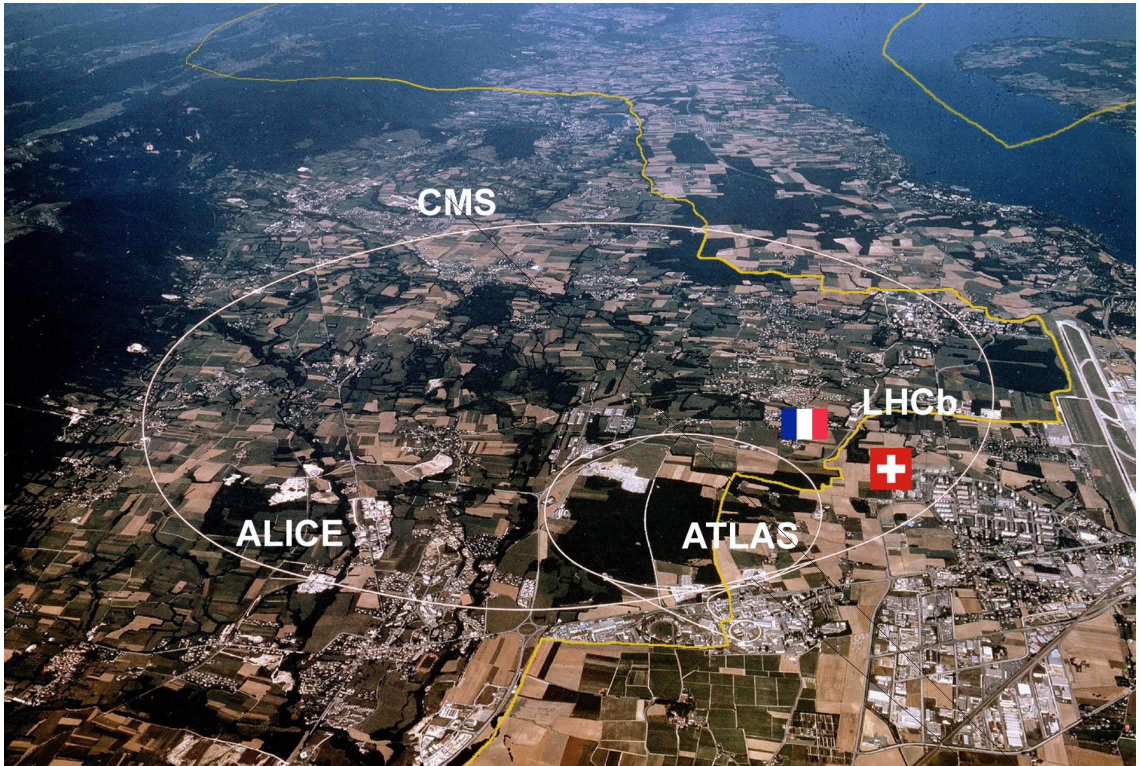


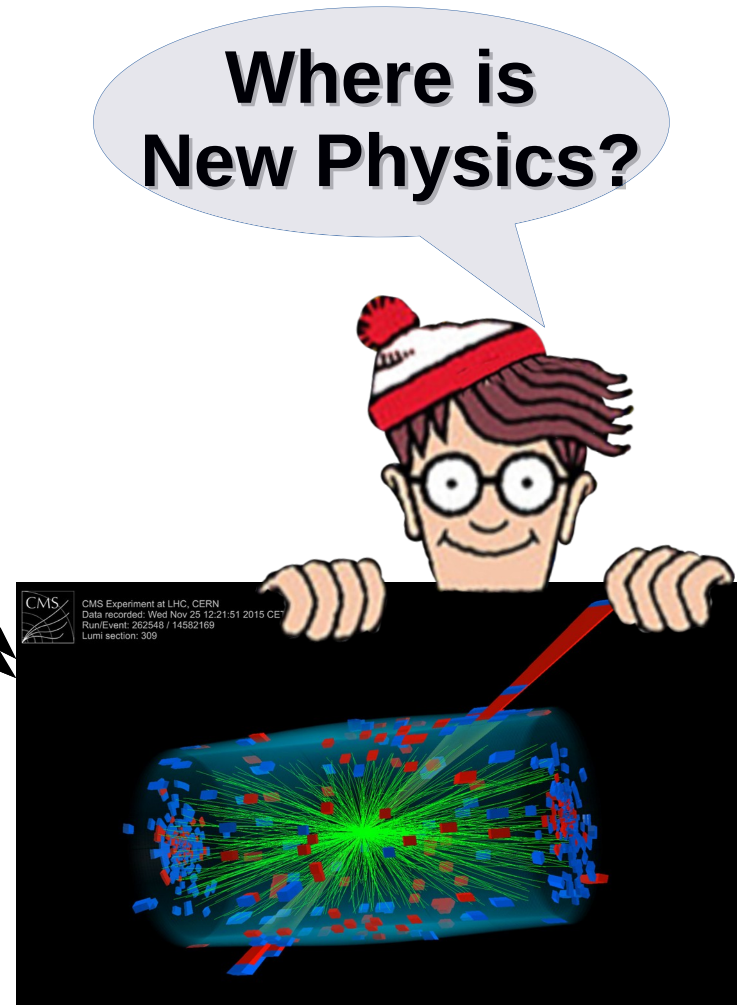
MOTIVATIONS:

- Only way to extend the Poincaré space-time symmetries.
- Natural solution to hierarchy problem.
- Unification of electroweak and strong forces.
- Can include Dark Matter candidates.
- Connection with quantum gravity.

***Other possibilities are: Extra dimensions, Multi-Higgs models, Axions,...**

The Large Hadron Collider.





- Run 1 (2009-2013): 7-8 TeV c.o.m.; 30/fb t.i.l
- Run 2 (2015-2018): 13 TeV c.o.m. ; 150/fb t.i.l.
- Run 3: Under preparation.

New physics searches at LHC.

SUSY searches

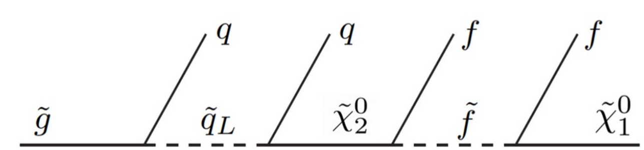
SUSY theories have a rich phenomenology which inspire searches in multiple signal regions!

- Is commonly assumed that they conserve R-parity

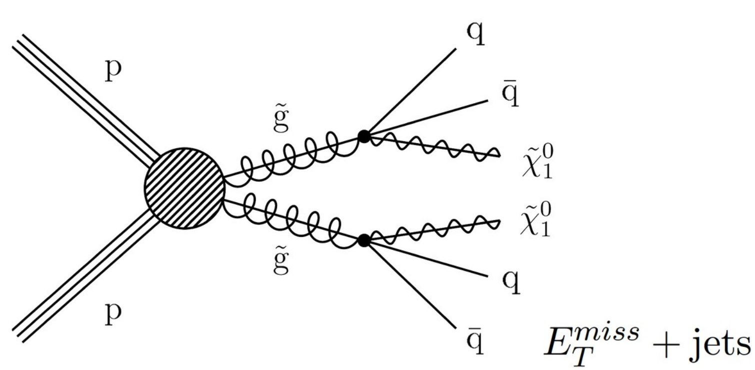
$$R = (-1)^{3(B-L)+2s} \longrightarrow$$

(Imposed for baryon B and lepton L number conservation.)

As a consequence
- SUSY particles would always be pair produced at LHC .
- They cascade decay into the Lightest SUSY Particle LSP.
- The LSP is stable.
- If neutral, the LSP can be Dark Matter candidate.
- A neutral LSP leaves a missing energy E_T^{miss} signature.



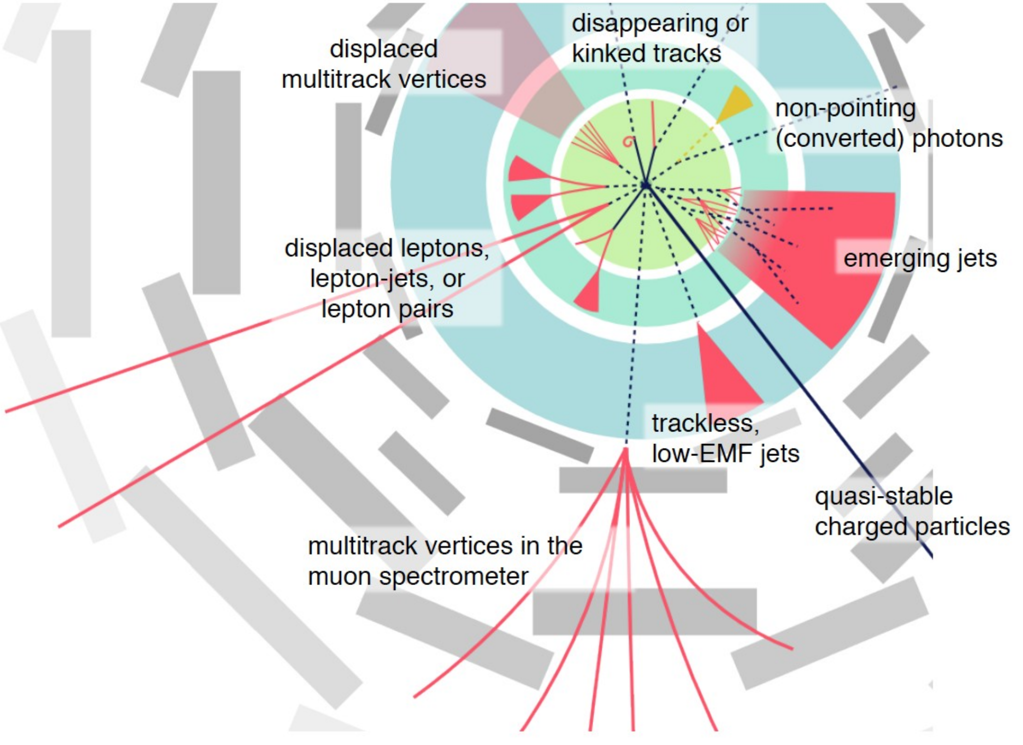
→ **SUSY would be observed as SM final states plus missing energy:**



New physics searches at LHC.

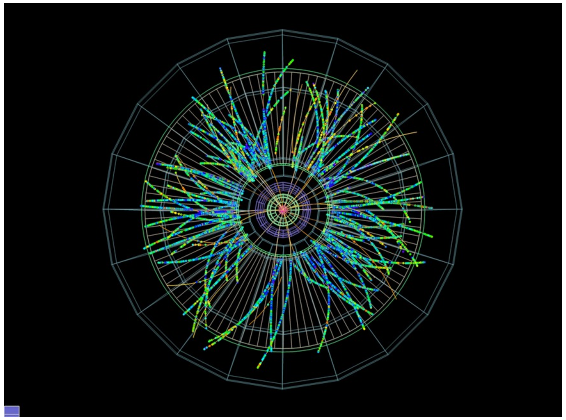
LLP searches

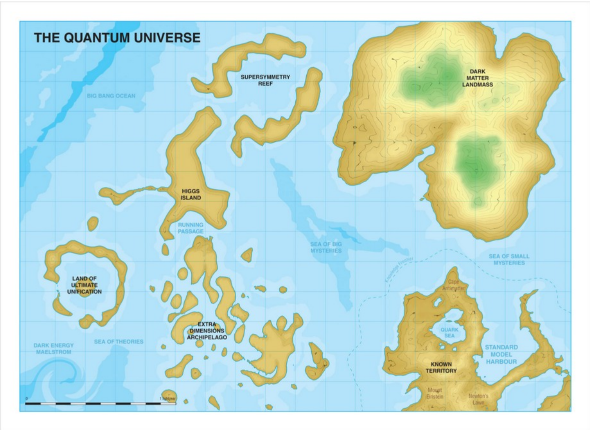
- Long Lived Particles (LLP) are BSM particles with lifetimes >= of the order of the detector.
- They are realized in SUSY theories with approximate R-symmetry, models with quasi-degenerate mass spectra, in FIMP dark matter theories, etc.
- Impose new challenges for their observation.
- Distinctive signatures expected from those of SM.



Why beyond vanilla?

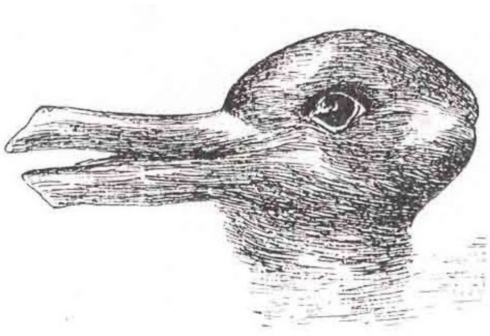
- ATLAS and CMS has an extensive program of searches for new physics.
- Experimental analyses are often optimized and interpreted for popular or ‘vanilla’ BSM models.





- However, there is a sea of proposed theories/scenarios for new physics,
- Many are non-minimal, less-known, not-thought-of-yet… theories that are not directly interpreted by LHC searches.
- We call them **beyond vanilla new physics.**

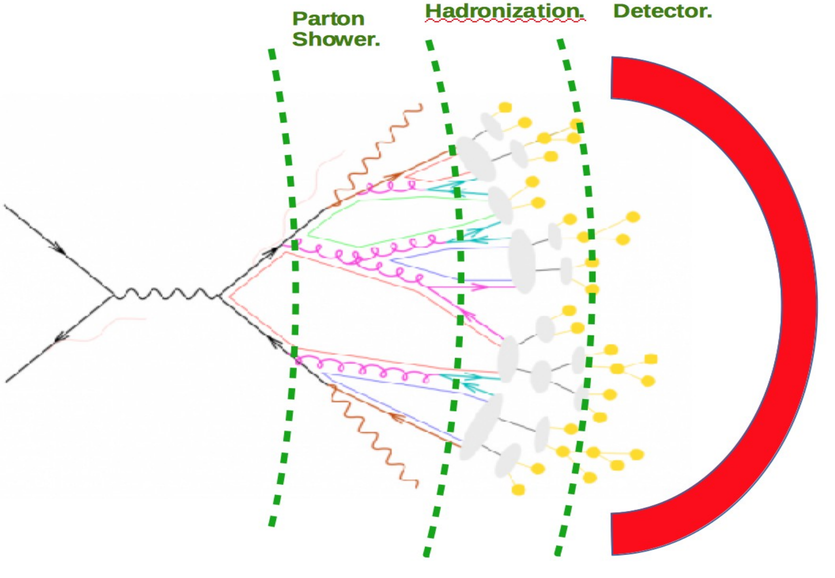
- The aim of the **LHC reinterpretation framework** is to be able to test any BSM theory against LHC results.
- A very active field with strong communication between theorists and experimenters.



Reinterpretation of LHC searches

Full recasting approach.

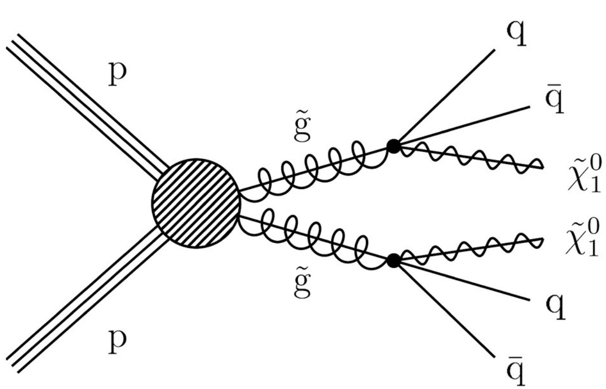
- Full event simulation with MC event generators and emulation of detector response. Dedicated tools: **Madgraph, Pythia, Herwig, Delphes,...**
- implementation of analyses cuts, statistical interpretation. Tools: **Madanalysis5, CheckMATE, ColliderBit, Rivet, …**
- Each tool with a growing number of implemented searches.
- **Needed from the experiment:** object definitions, cuts,… (for implementation), benchmarks, cutflows….(for validation), observed and expected events…(for interpretation).



Reinterpretation of LHC searches

Simplified model approach.

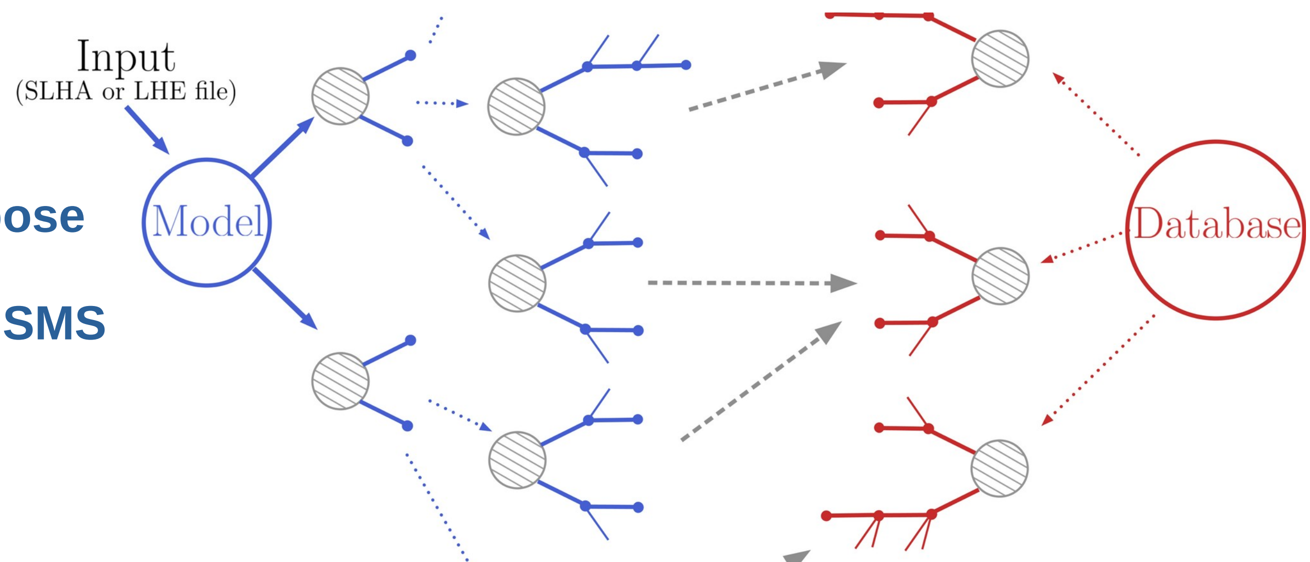
Most LHC new physics searches present their results in the context of simplified model spectra (SMS):



- Reduction of full models to subsets with few final states.
- Direct comparison of $\sigma \times \mathcal{B}$ of theory vs corresponding $[\sigma \times \mathcal{B}]_{UL}$ from exp.
- SMS results are relatively straightforward to reinterpret.

SModelS

General procedure to decompose BSM collider signatures presenting Z2 symmetry into SMS topologies,
Direct confrontation with experimental constraints implemented in the SmodelS database.



https://smodels.github.io/

Constraining the Minimal Dirac Gaugino Model

1. ***The model***

The model.

- Most of SUSY searches at the LHC are optimized for the MSSM, where gauginos are Majorana particles.

- We can introduce Dirac gaugino states by adding a Weyl fermion in the adjoint representation of each gauge group. Embedded in a scalar **S**, triplet **T** and octet **O** superfields.

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

Properties:

- Only *supersoft* terms that don’t appear in the RG equations of the other operators.

- Only a finite shift is induced to the sfermion masses.

- Tree level enhancement of Higgs mass

->Here we consider the **Minimal Dirac Gaugino Supersymmetric Standard Model (MDGSSM)** where

- The only added superfields are **S**, **T** and **O**.

- Explicit R-symmetry breaking in the Higgs sector.

MDGSSM particle content

Names		Spin 0	Spin 1/2	Spin 1	$SU(3)$, $SU(2)$, $U(1)_Y$
Quarks	$\mathbf{Q}$	$\tilde{Q} = (\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)		$(\mathbf{3},\ \mathbf{2},\ 1/6)$
	$\mathbf{u^c}$	$\tilde{u}^c_R$	u^c_R		$(\overline{\mathbf{3}},\ \mathbf{1},\ \text{-}2/3)$
($\times 3$ families)	$\mathbf{d^c}$	$\tilde{d}^c_R$	d^c_R		$(\overline{\mathbf{3}},\ \mathbf{1},\ 1/3)$
Leptons	$\mathbf{L}$	$(\tilde{\nu}_{eL}, \tilde{e}_L)$	(ν_{eL}, e_L)		$(\mathbf{1},\ \mathbf{2},\ \text{-}1/2)$
($\times 3$ families)	$\mathbf{e^c}$	$\tilde{e}^c_R$	e^c_R		$(\mathbf{1},\ \mathbf{1},\ 1)$
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^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$		$(\mathbf{1},\ \mathbf{2},\ \text{-}1/2)$
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	$(\mathbf{1},\ \mathbf{1},\ 0)$
DG-octet	$\mathbf{O_g}$	O_g	$\tilde{g}'$		$(\mathbf{8},\ \mathbf{1},\ 0)$
DG-triplet	$\mathbf{T}$	$\{T^0, T^\pm\}$	$\{\tilde{W}'^\pm, \tilde{W}'^0\}$		$(\mathbf{1}, \mathbf{3},\ 0)$
DG-singlet	$\mathbf{S}$	S	$\tilde{B}'$		$(\mathbf{1},\ \mathbf{1},\ 0)$

MSSM

MDGSSM

Extra spin zero states.
See e.g. arXiv:1805.10835
for sgluons.

Extra Gluinos

Extra Binos and Winos.

Here we focus on these.

MDGSSM electroweakino spectrum.

In the MDGSSM we have 6 neutralinos and 3 charginos:

$$\begin{pmatrix} 0 & M_{DB} & 0 & 0 & -\frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W s_\beta & -\frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W c_\beta \\ M_{DB} & 0 & 0 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & 0 & 0 & M_{DW} & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W s_\beta & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W c_\beta \\ 0 & 0 & M_{DW} & 0 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -\frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W s_\beta & -m_Z s_W c_\beta & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W s_\beta & m_Z c_W c_\beta & 0 & -\mu \\ -\frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W c_\beta & m_Z s_W s_\beta & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W c_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

Neutralinos

$$\begin{pmatrix} 0 & M_{DW} & \frac{2\lambda_T}{g} m_W c_\beta \\ M_{DW} & 0 & \sqrt{2} m_W s_\beta \\ -\frac{2\lambda_T}{g} m_W s_\beta & \sqrt{2} m_W c_\beta & \mu \end{pmatrix}$$

Charginos

Binos
Winos
Higgsinos

λ_S and λ_T are the couplings between the scalar and triplet DG-adjoint fermions and the Higgs superfields

$$W \supset \lambda_S \mathbf{S}\,\mathbf{H_u}\cdot\mathbf{H_d} + 2\lambda_T\,\mathbf{H_d}\cdot\mathbf{T}\mathbf{H_u}$$

They induce small-mass splittings between binos and winos, e.g. if M_{DB} << M_{DW}, μ

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

Constraining the Minimal Dirac Gaugino Model.

2. ***LHC limits on gluinos and squarks.***

Gluino and squark production.

- **Squark production.**

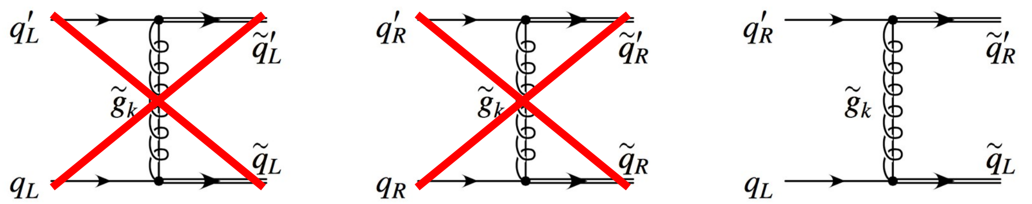
  t-channel exchange via Dirac gluino forbids final states of same helicity, reducing squark production cross sections.

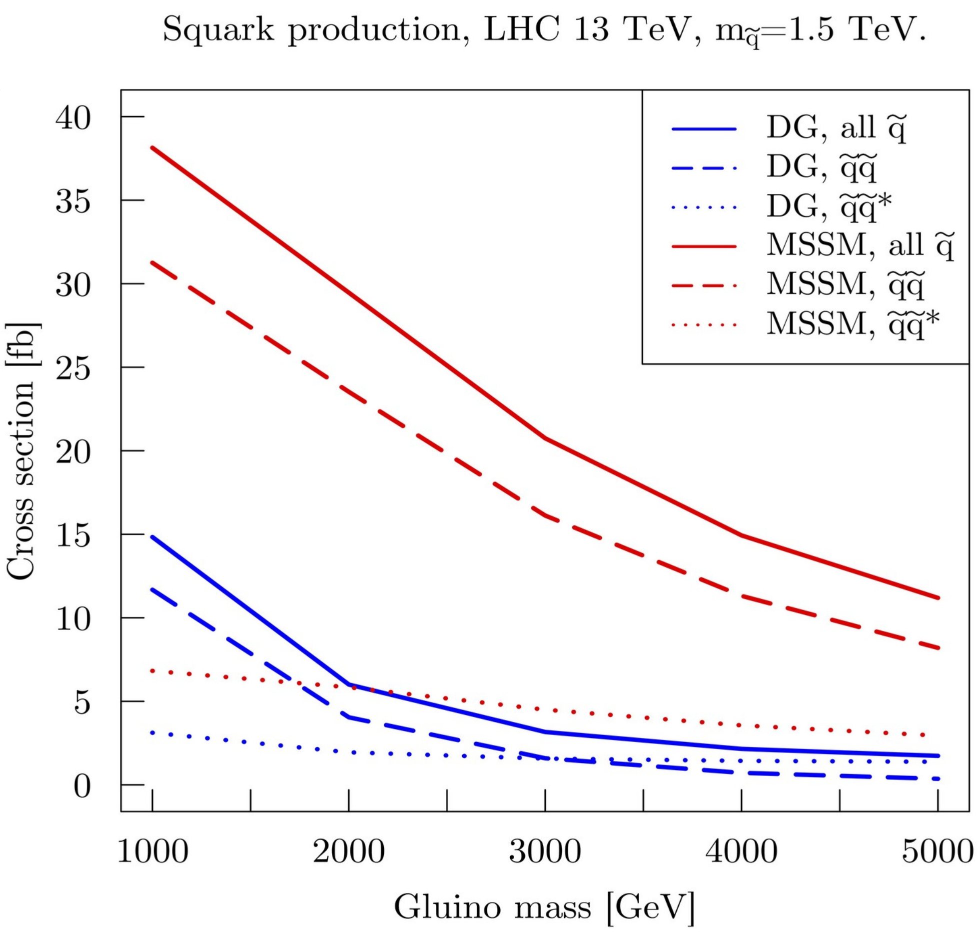
- **Gluino production.**

  Augmented number of gluino degrees of freedom enhance their production cross sections.

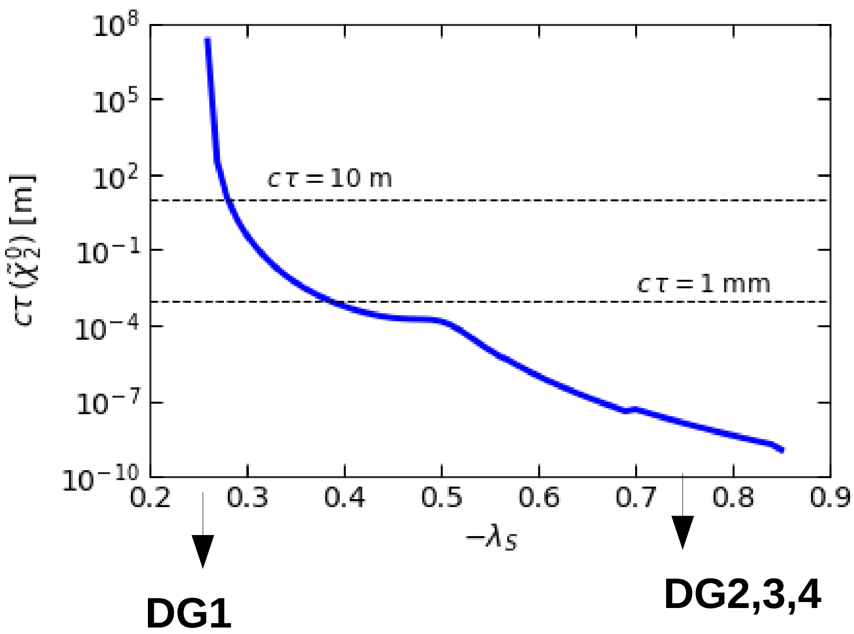
- **Gluino-squark production**

  Similar to Majorana case.

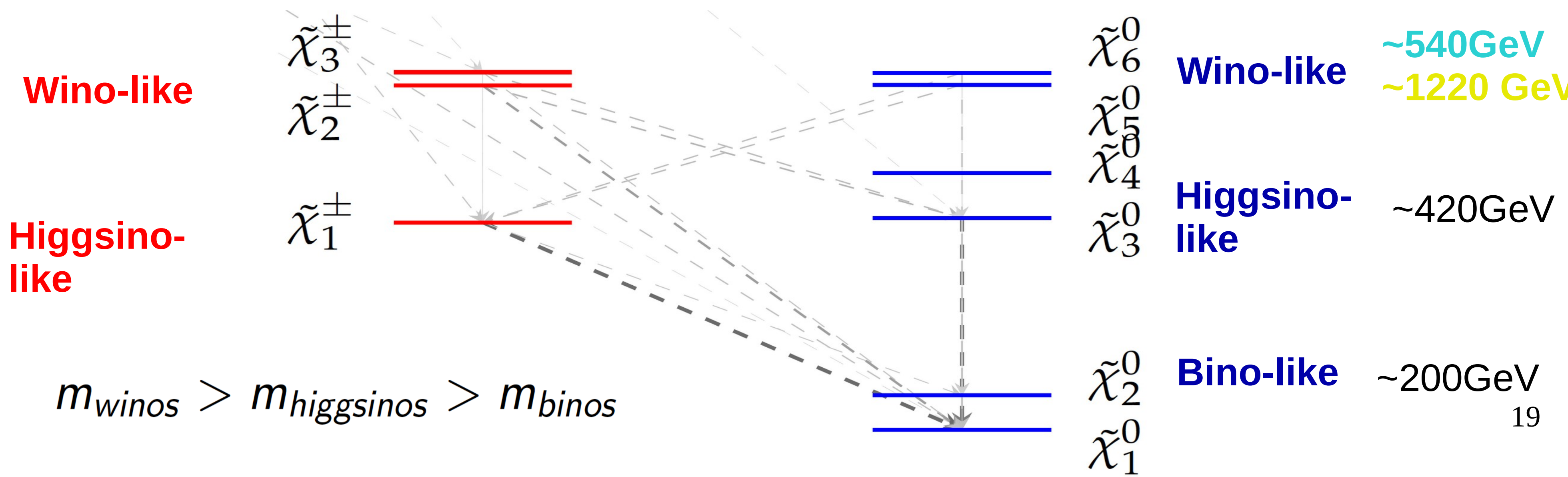




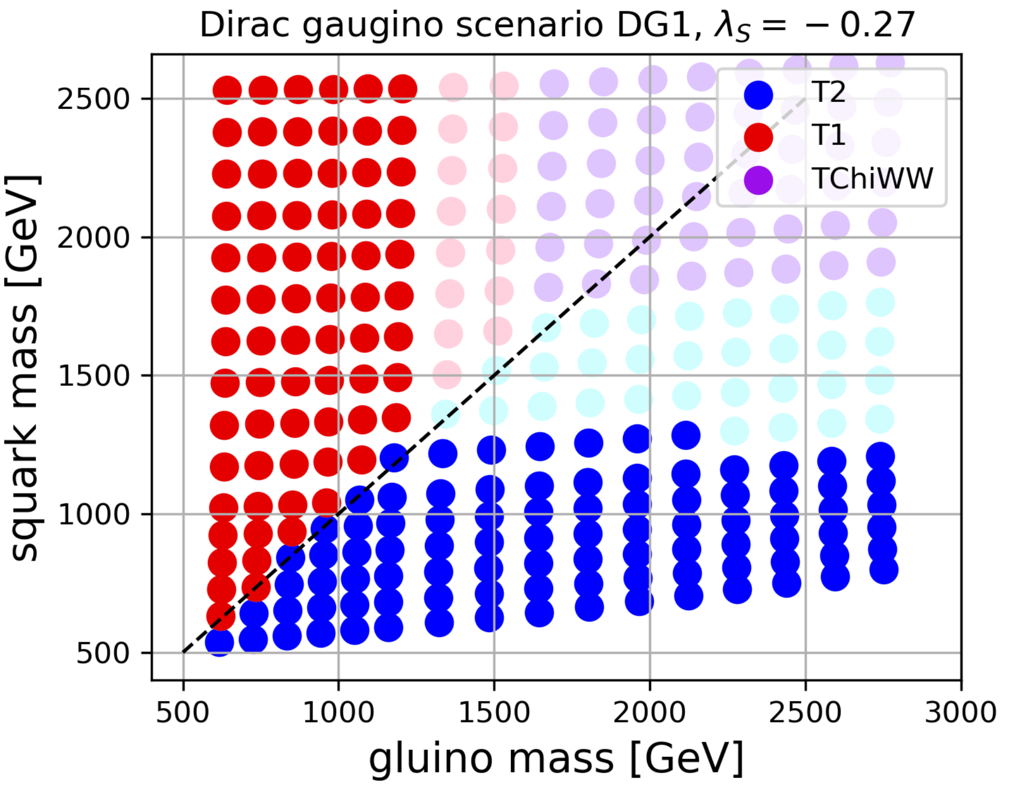
Benchmark scenarios.

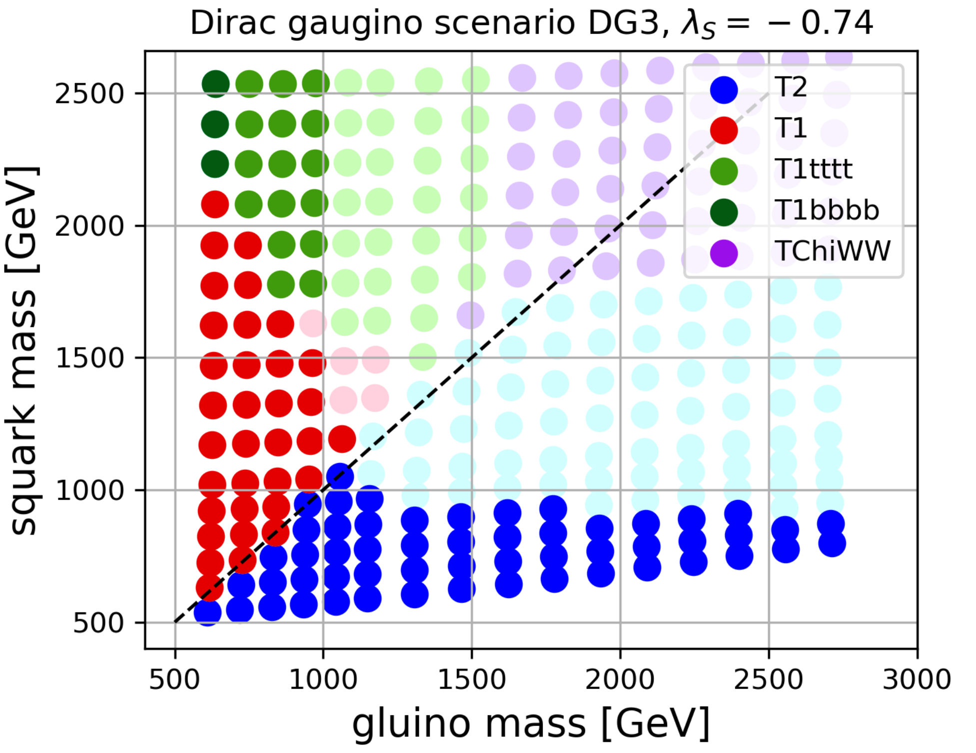


	Bino mass-splitting	NLSP lifetime	3rd gen squark mass
DG1	small	large	3.6 TeV
DG2	large	small	2.6 TeV
DG3	large	small	1.6 TeV
DG4	large	small	2.9 TeV

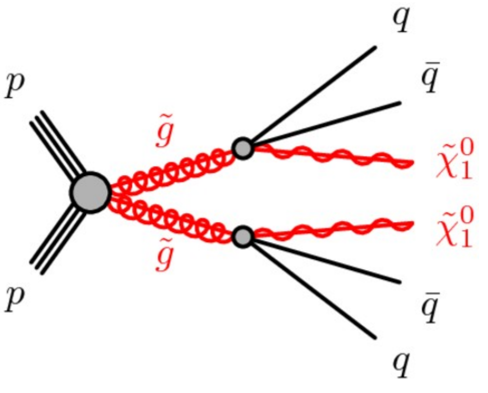


Results from simplified models.

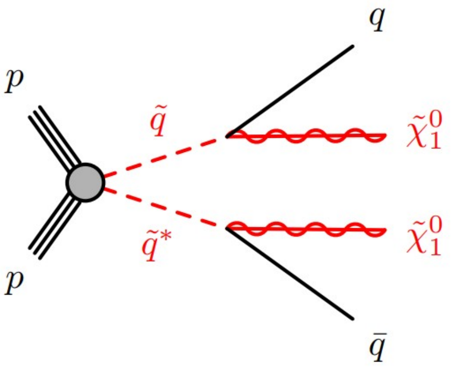




T1XXXX:



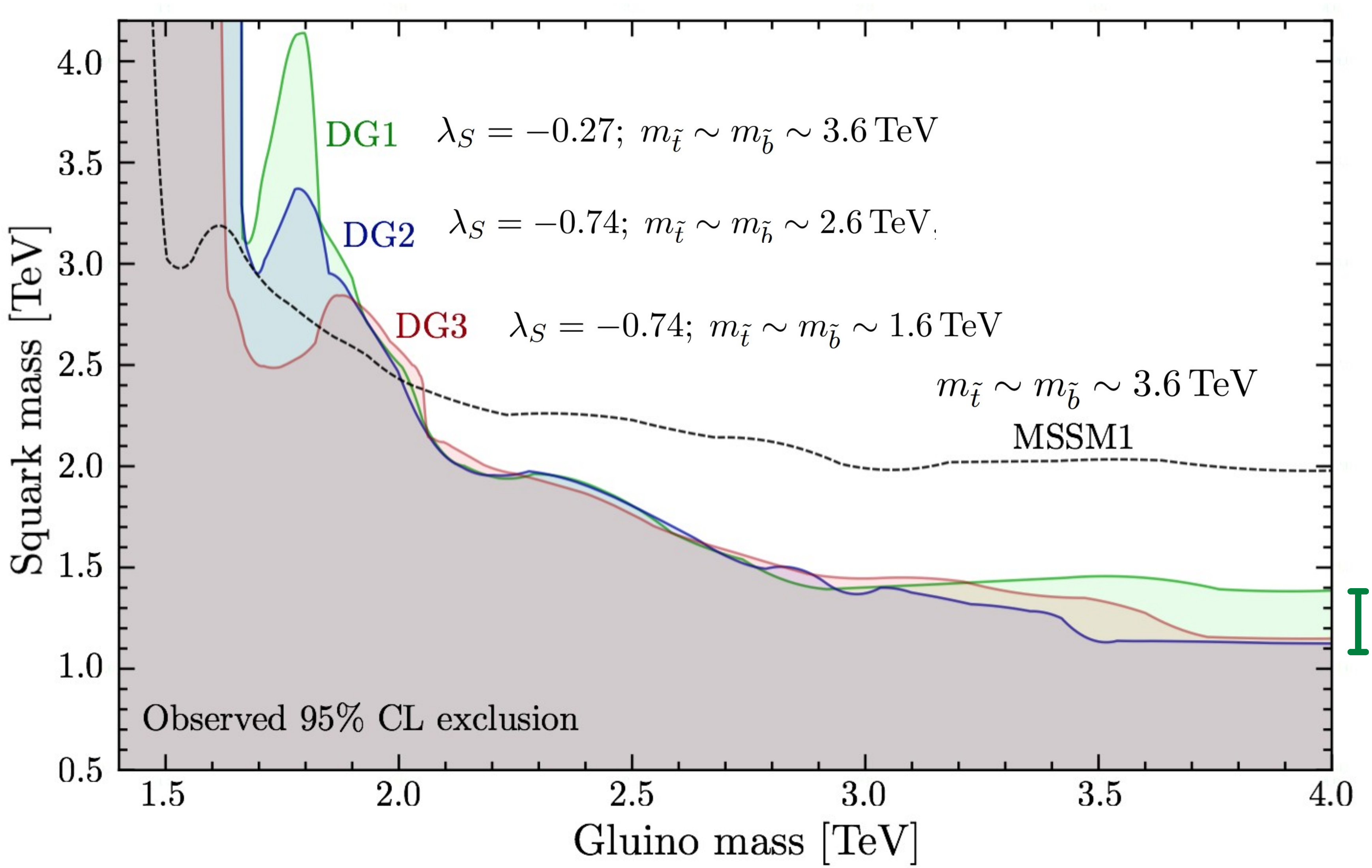
T2:



Results from full recasting: light winos.

Analysis: ATLAS 13TeV Multijet+MET (36/fb) search

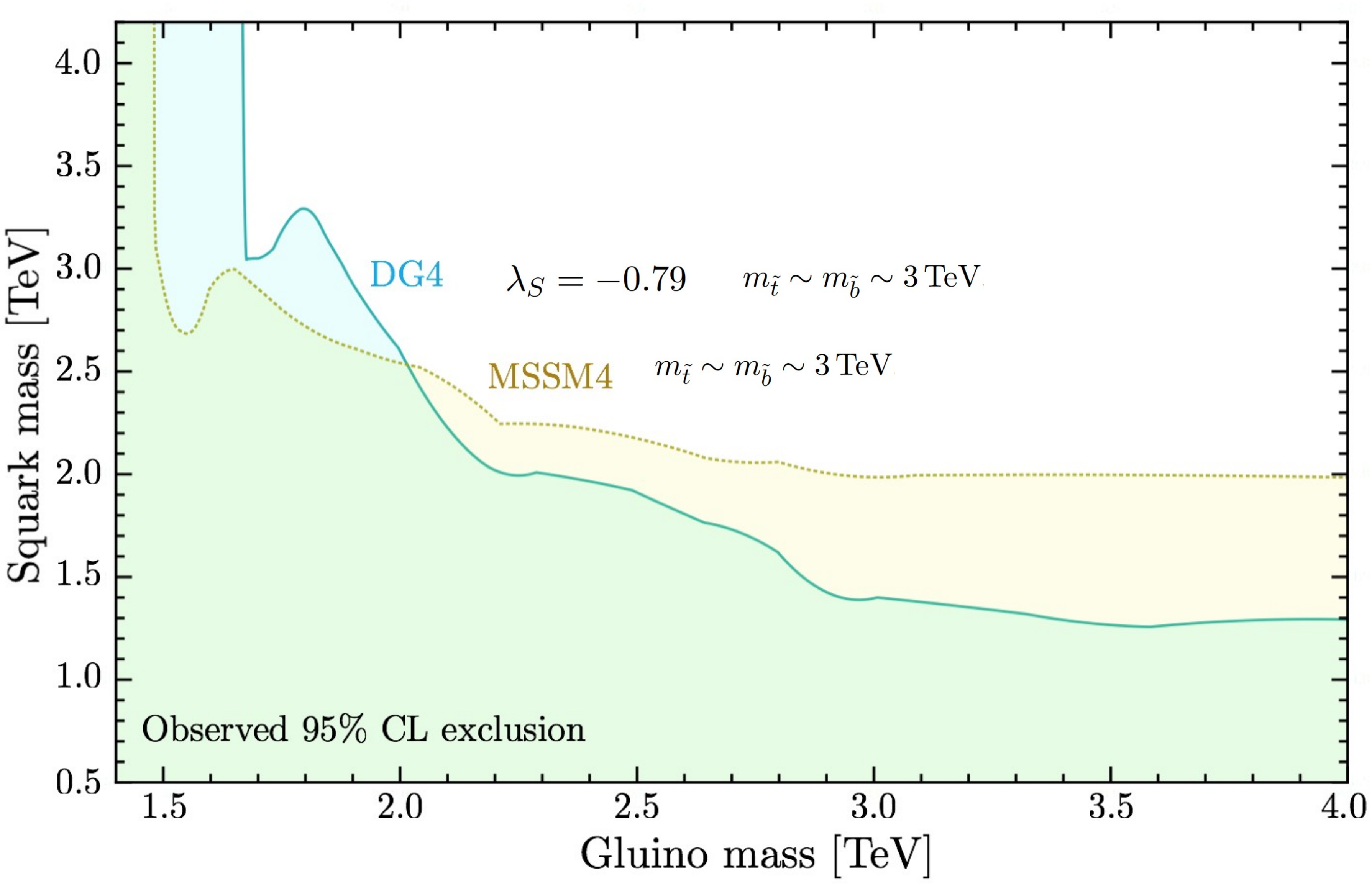
Recasted in MadAnalysis PAD → *http://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase*



Due to difference in bino mass spliting.

Dashed line (MSSM1) is the limit one finds in the MSSM.

Results from full recasting: heavy winos.



Constraining the Minimal Dirac Gaugino Model.

3. ***Electroweak-ino sector.***

Finding region with DM candidates.

$$0 < M_{DB}, M_{DW}, \mu < 2 \text{ TeV}; \quad 1.7 < \tan\beta < 60; \quad -3 < \lambda_S, \lambda_T < 3.$$

We implemented an MCMC Metropolis-Hastings algorithm (with a small probability of random uniform jump) that walks toward the minimum of

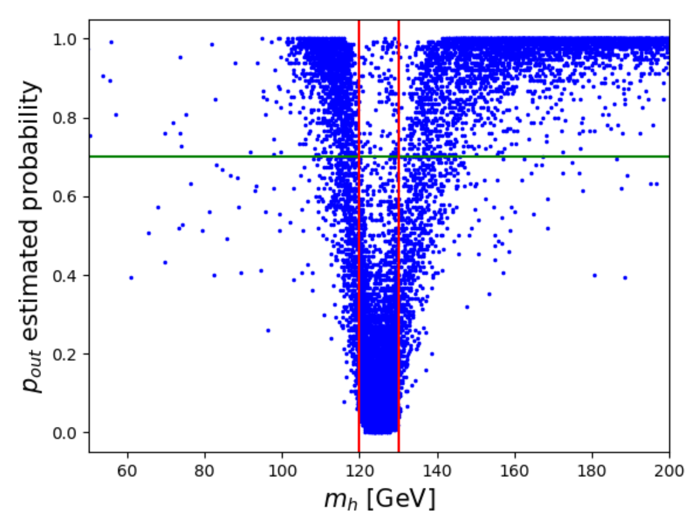
$$-\log(L) = \chi^2_{\Omega h^2} - \log(p_{\mathrm{X1T}}) + \log(m_{\mathrm{LSP}})$$

$$\chi^2_{\Omega h^2} = \frac{(\Omega h^2 - \Omega h^2_{\mathrm{Planck}})^2}{\Delta^2_\Omega}$$

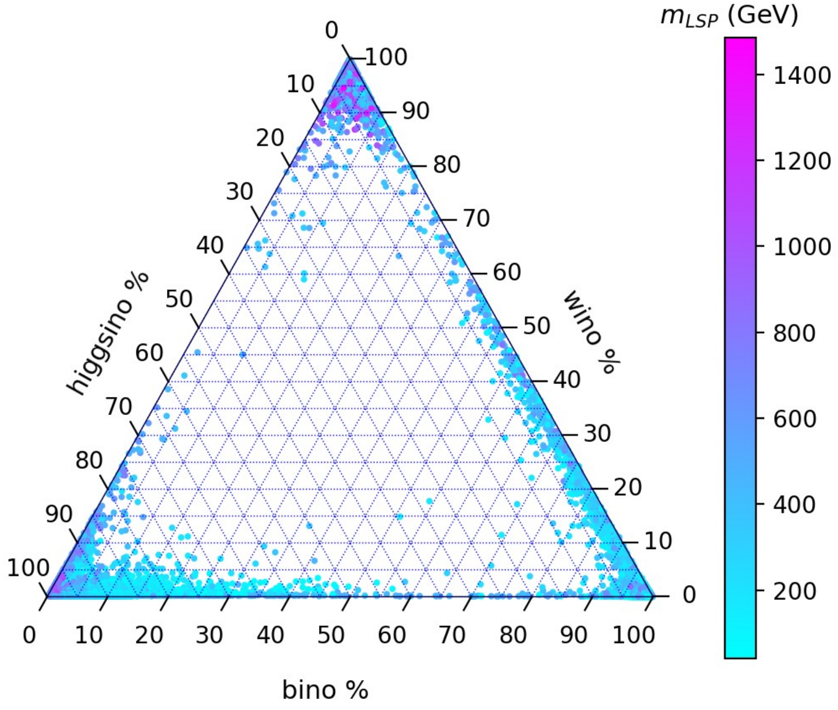
P-value of Xenon1T exclusion

Mass of LSP

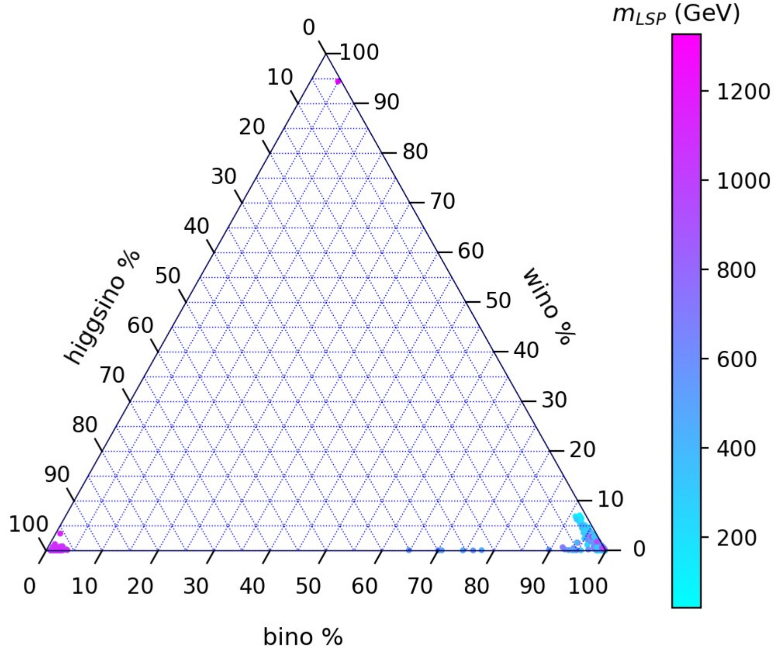
To efficiently find the points with A Higgs mass in good range we Implemented a Random Forest Classifier **yielding a ~4 times faster scan!**



Scan results.



$$\Omega h^2 < 1.1\,\Omega h^2{}_{\mathrm{Planck}}$$



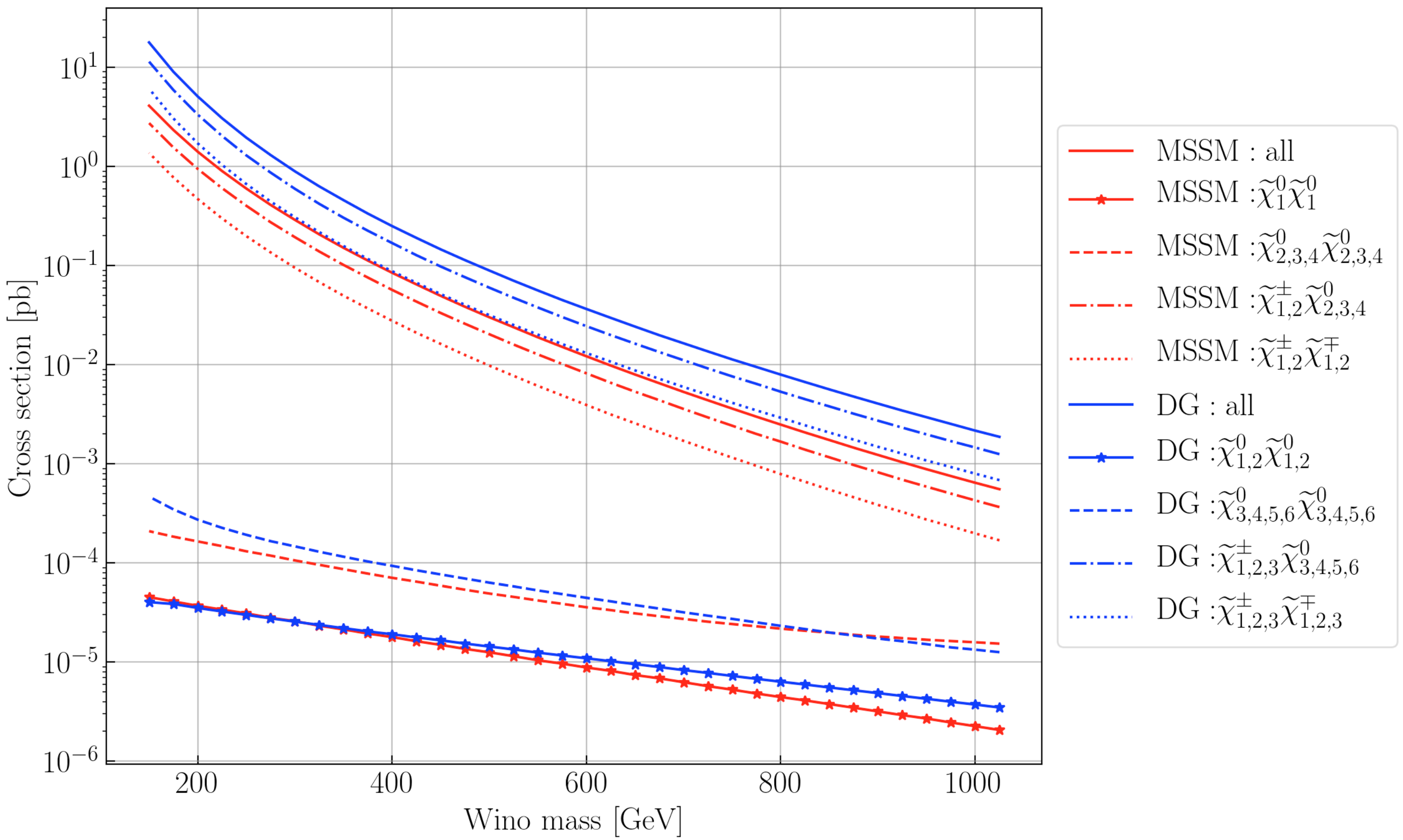
$$\Omega h^2 = \Omega h^2{}_{\mathrm{Planck}} \pm 10\%$$

Constraints included so far:

- LSP is at least a fraction of observed DM content.
- LEP limits
- Z invisible decays
- H invisible decays
- XENON1T direct detection constraints.

Electroweakino collider signals.

3-4 times larger chargino-neutralino and chargino-chargino production xsections



$$m_{D2} = 1.2\, m_{DY} \text{ (MDGSSM) and } M_2 = 1.2\, M_1 \text{ (MSSM)}$$

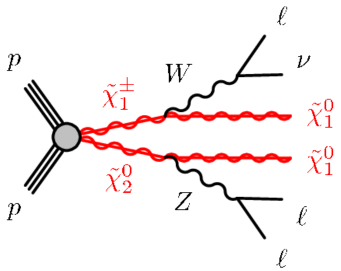
$$\mu \simeq 1400 \text{ GeV}, \tan\beta \simeq 10,\ \lambda_S \simeq -0.29 \text{ and } \sqrt{2}\lambda_T \simeq -1.40.$$

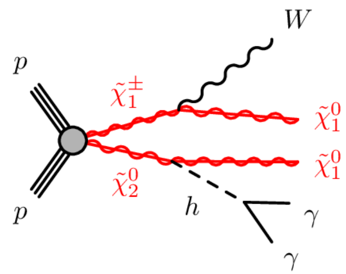
LHC constraints. Prompt searches.

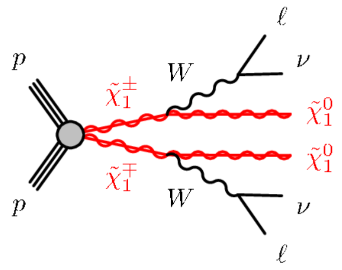
- Limits derived from simplified model reinterpretation using SModelS.

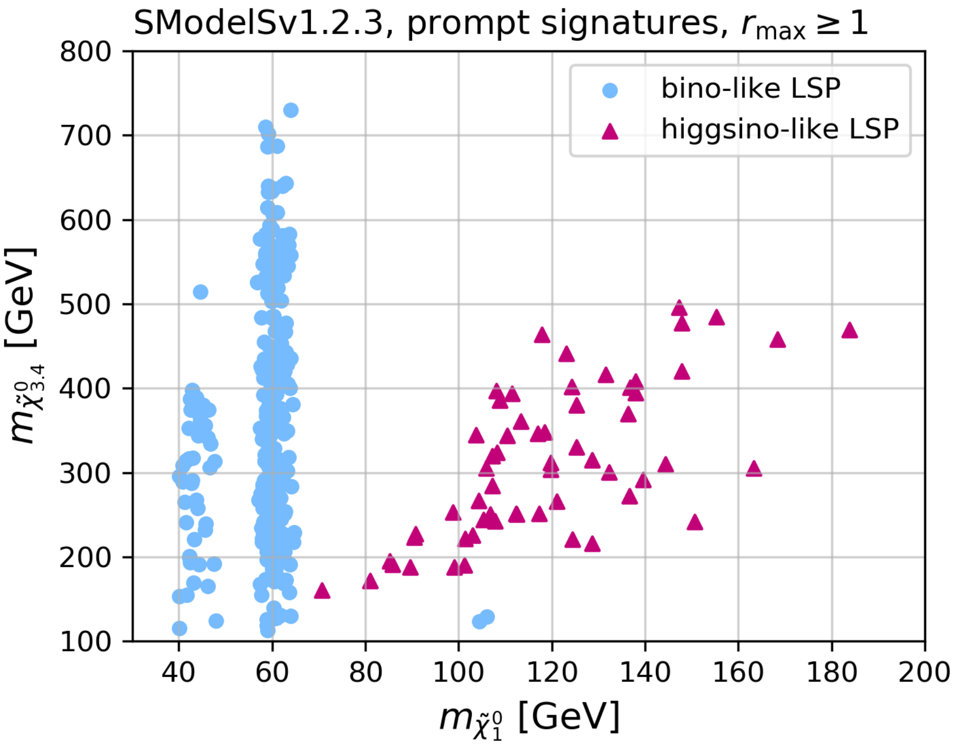
Relevant analyses:

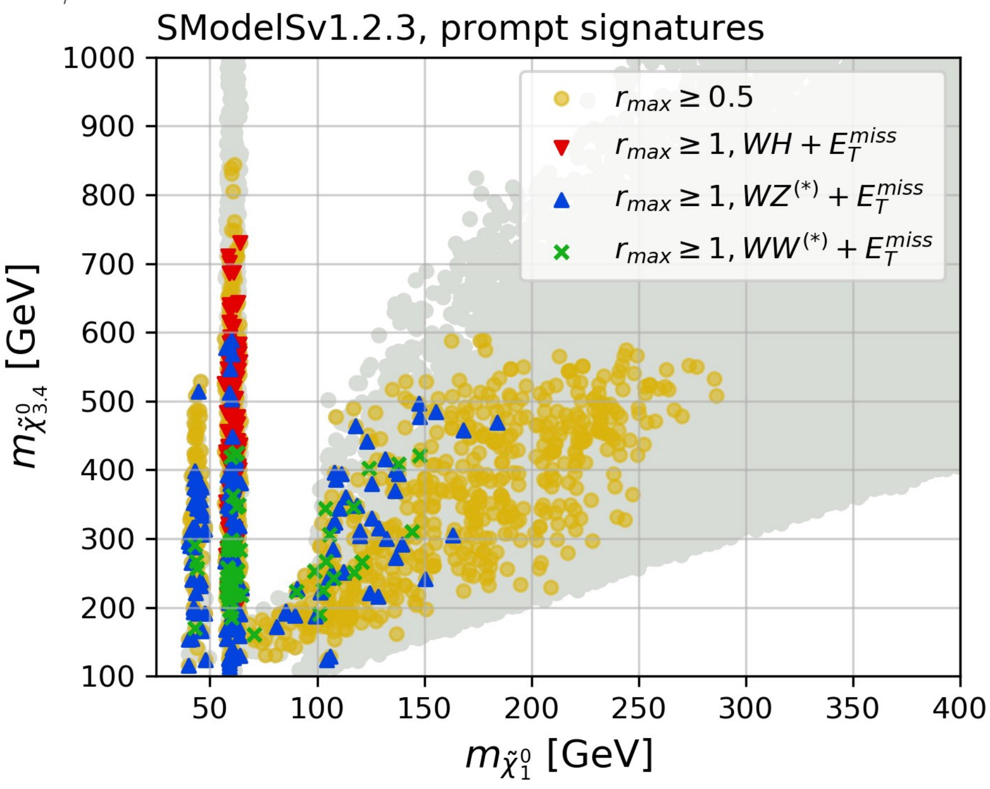
- ATLAS EW-ino searches with 139/fb, constraining WZ(*), WH, WW(*)+ MET signatures.
- CMS EW-ino combination from 35/fb, constraining WZ(*) and WH + MET signatures.





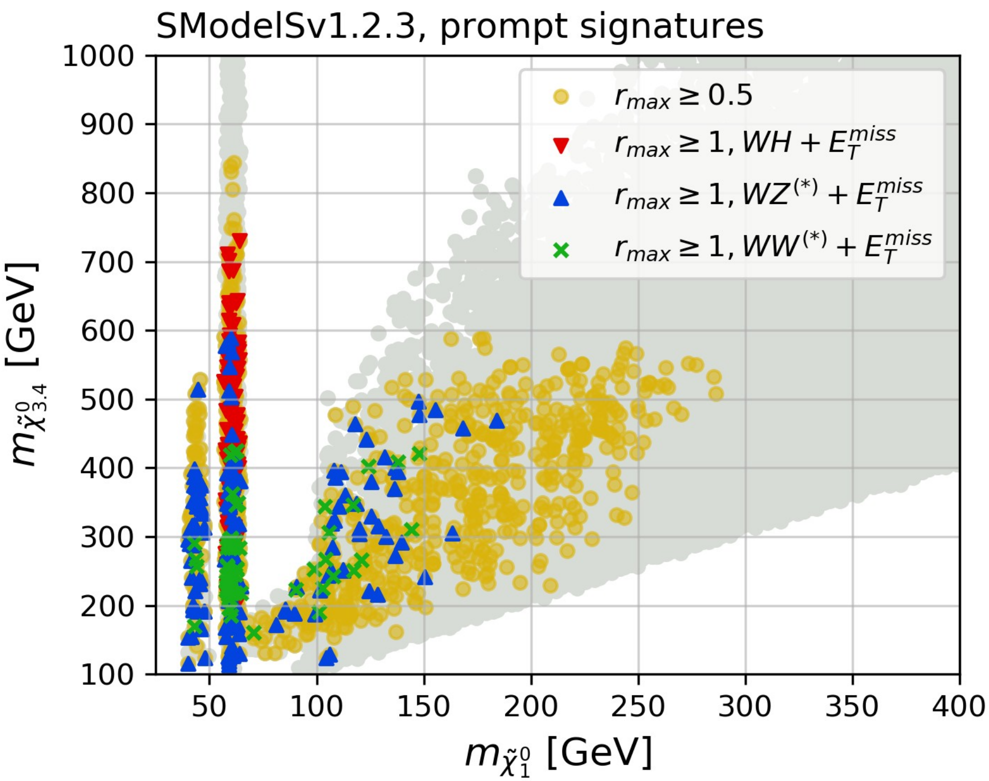


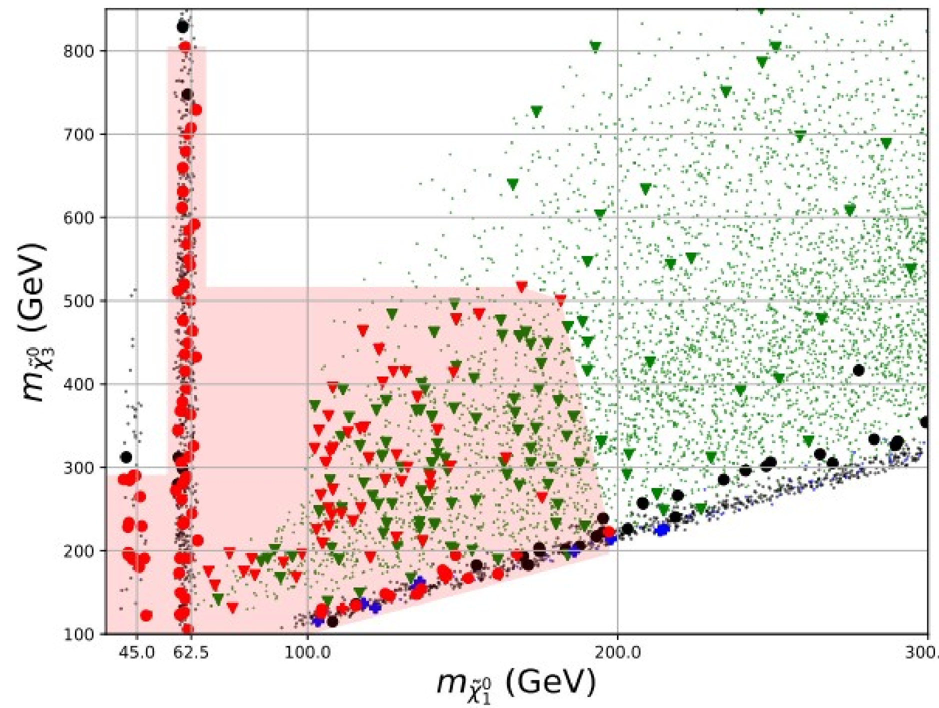




LHC constraints. Prompt searches.

Comparing reinterpretation approaches… surprisingly good agreement!





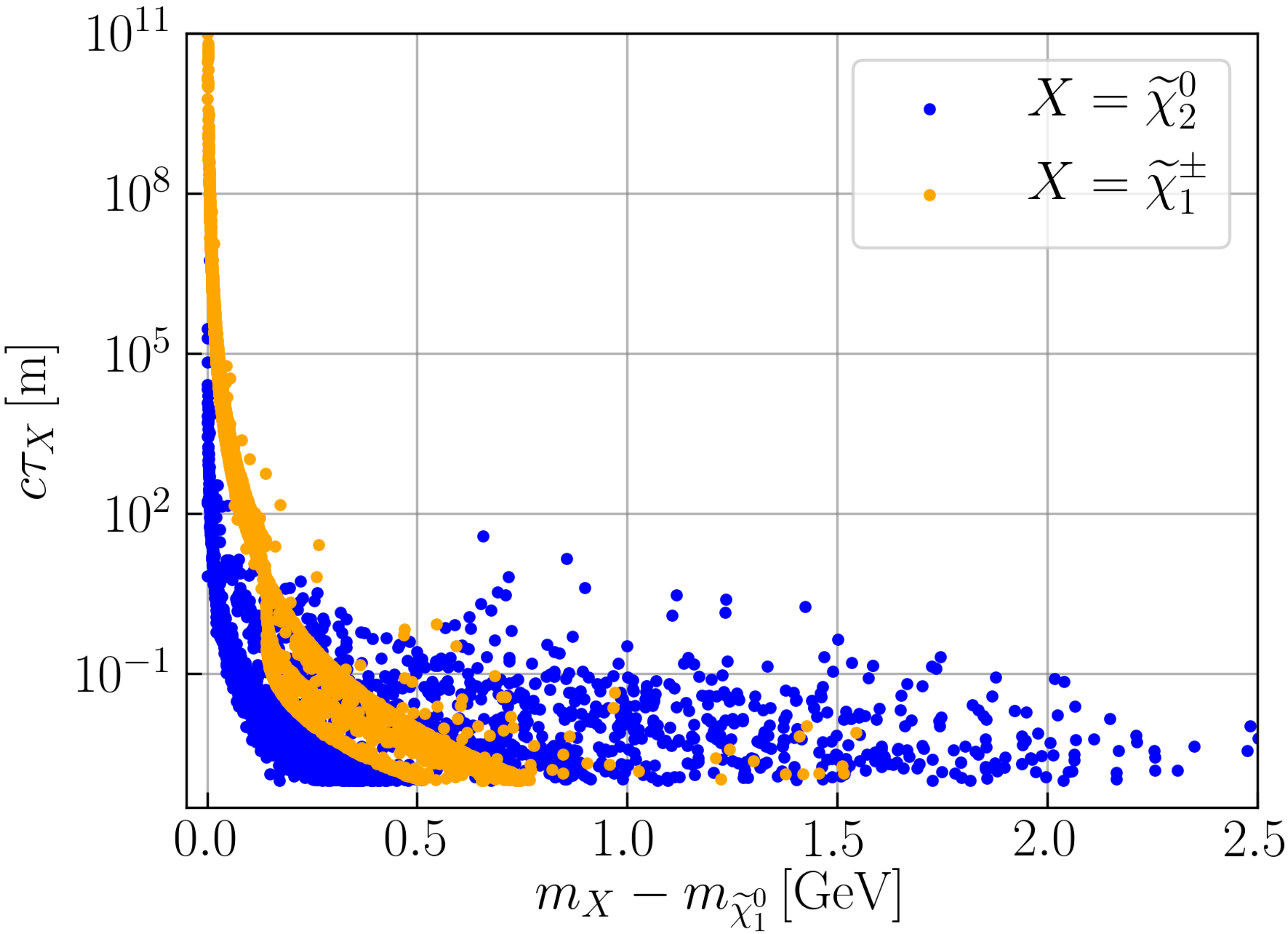
M_{DW} <900GeV

Simplified model approach

Full recasting approach (with MadAnalysis5)

LLP scenarios.

~20% of scenarios contain LLPs.



Decays of LL charginos treated as:

$$\Gamma(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 \pi^-)$$

$$\Gamma(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 \pi^- \pi^0)$$

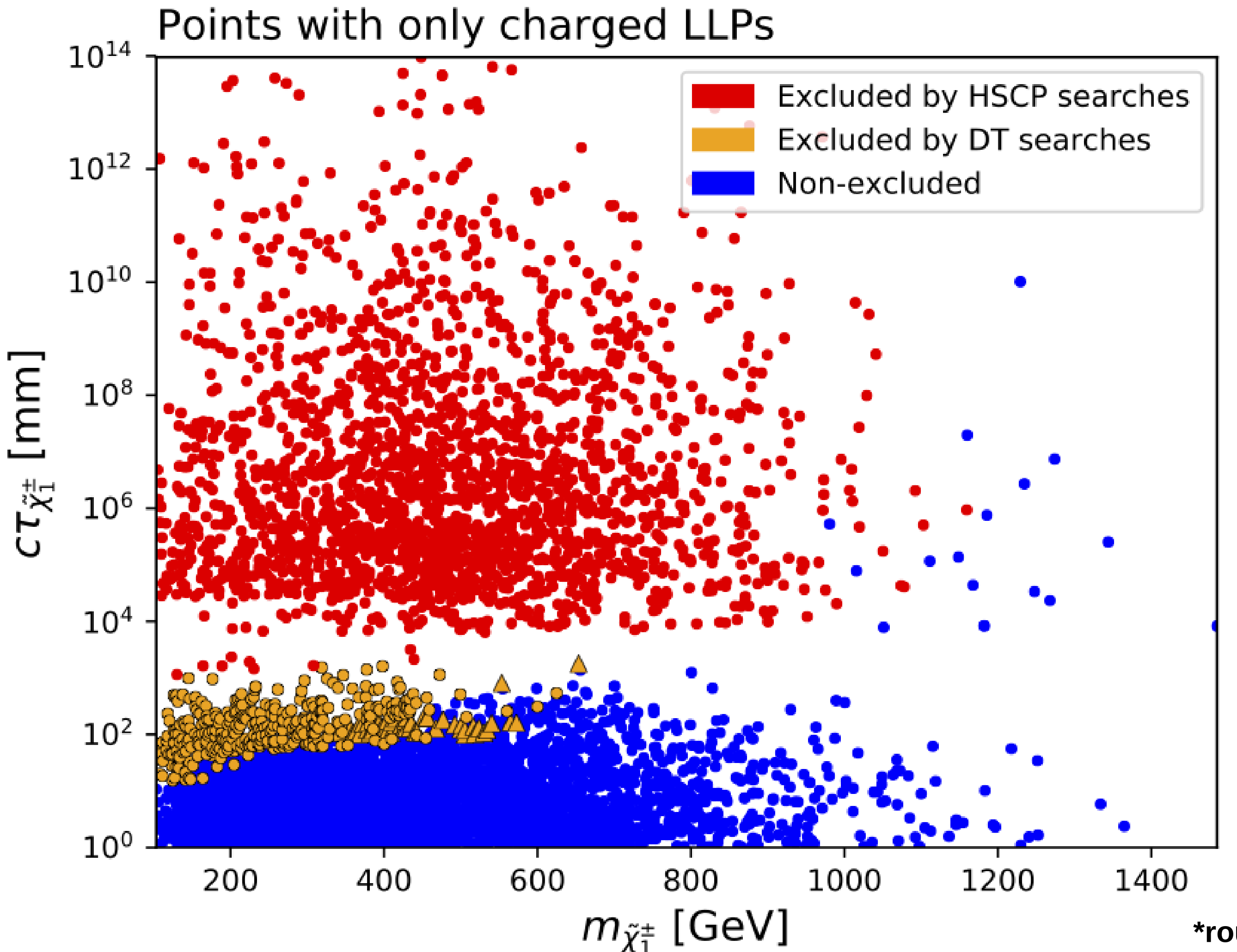
$$\Gamma(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 3\pi)$$

LL neutralinos predominantly decay as:

$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + \gamma$$

LHC constrains. Charged LLPs.

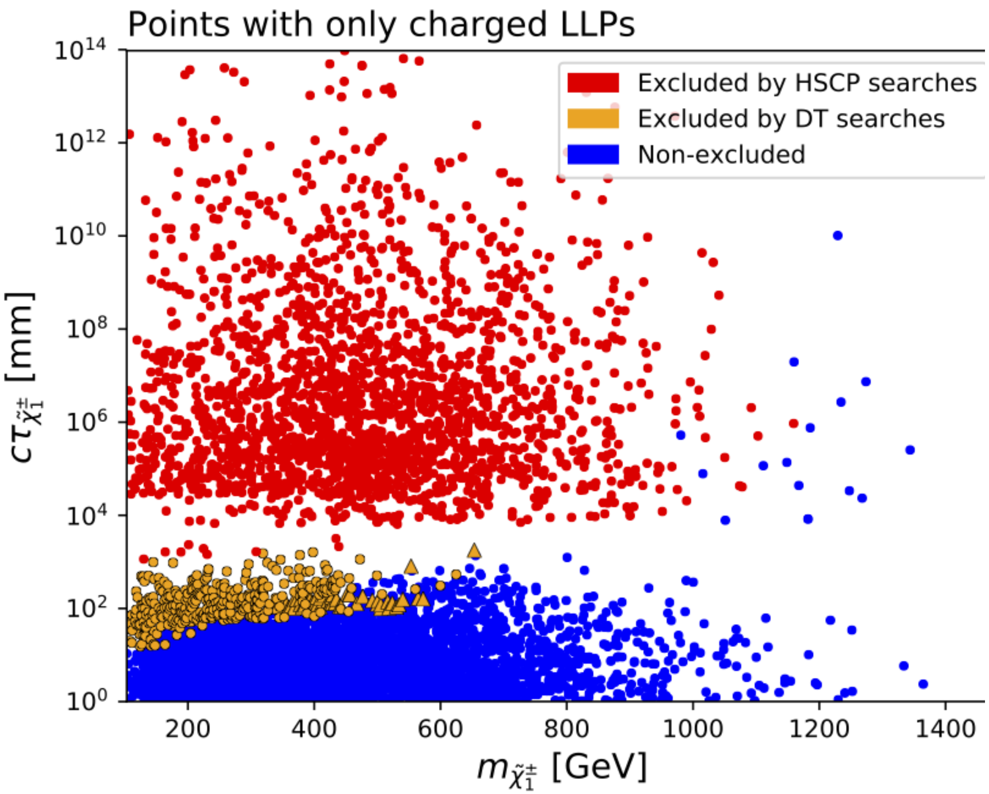
- Heavy Stable Charged Particle (HSCP) limits derived using SModelS (CMS 8TeV and 13TeV-13/fb).
- Disappearing Track (DT) limits derived using independent interpolation of upper limits (ATLAS and CMS 13TeV-36/fb, CMS 13TeV-140/fb*).



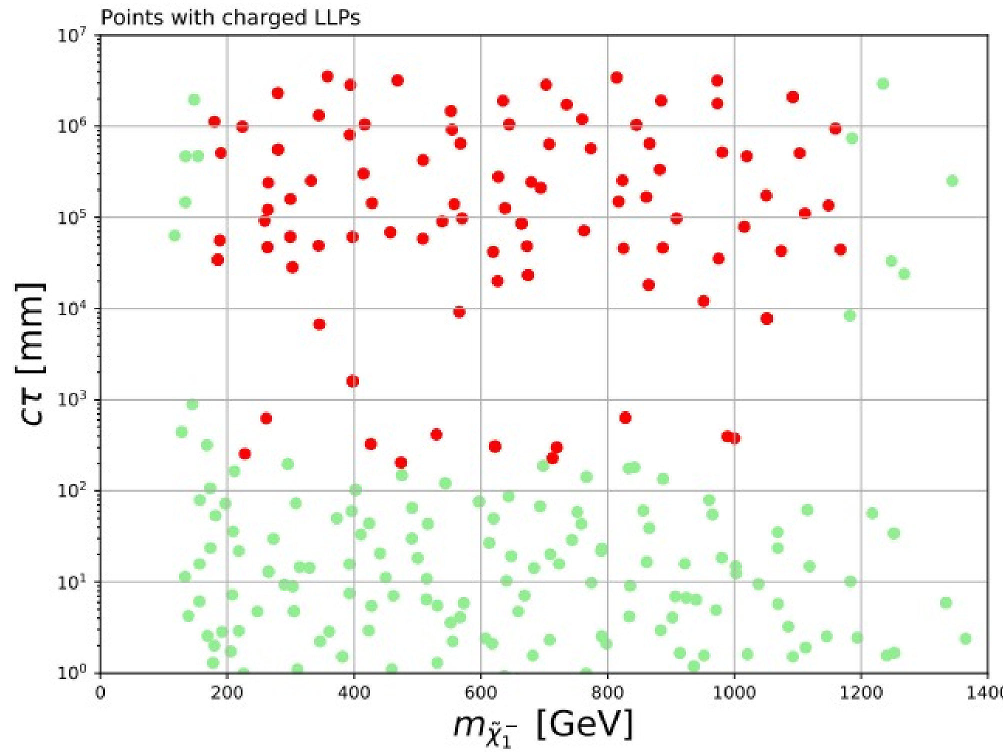
*rough interpolation, no full info provided yet.

LHC constrains. Charged LLPs.

Comparing reinterpretation approaches (HSCP search):
Good agreement, not so surprising since search is very sensitive.

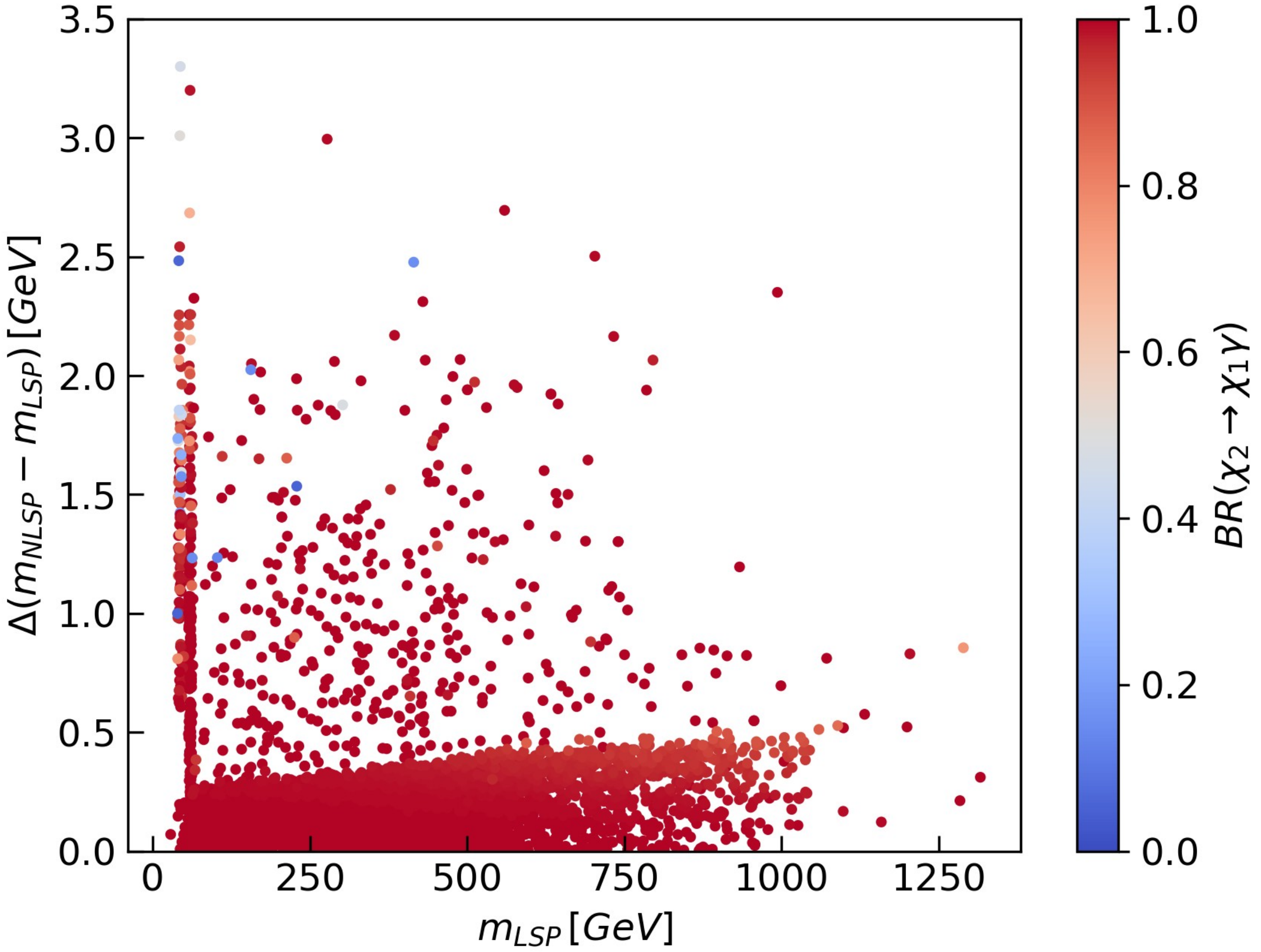


Simplified models



Full recasting (using A. Lessa´s HSCP ATLAS implementation:
https://github.com/llprecasting/recastingCodes)

Neutral LLP signatures.



- Loop decays into soft photons dominate.
- Signature not covered at LHC!

Conclusions.

Constraining the MDGSSM

Gluinos and squarks:

- Results were as expected from the differences between MDGSSM and MSSM regarding gluino and squark production.
- Stronger constrains when gluino production is dominant and weaker ones in the region where squark production dominates.
- We observed relaxed constraints in the scenarios with large bino mass-splitting due to extra steps in the decay chain.

Electroweakino sector.

- We found a significant number of scenarios with long-lived charginos and/or neutralinos which survive DM constraints.
- Prompt searches only excluded certain points with LSP masses below 200 GeV.
- HSCP and DT searches provide strong constraints on scenarios with charged LLPs.
- Scenarios with neutral LLPs currently escape exclusion as their distinctive signature (soft photons plus missing energy) is not covered at the LHC.

Reinterpretation of LHC results.

- There are a number of reasons to journey beyond the Standard Model.
- A plethora of theories on the market.
- Reinterpretation of LHC data is a very active and relevant field composed by a large community of theorist and experimenters.
- Forum: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/InterpretingLHCresults
- Current hot topics:

  -Implementation of full likelihoods

  -Reinterpretation of LLP searches.

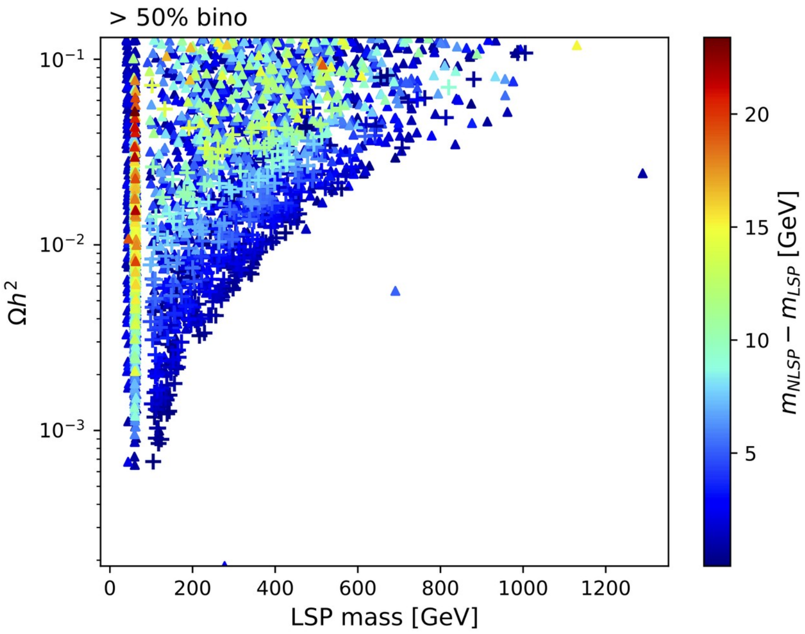
  -Implementation of ML based searches.

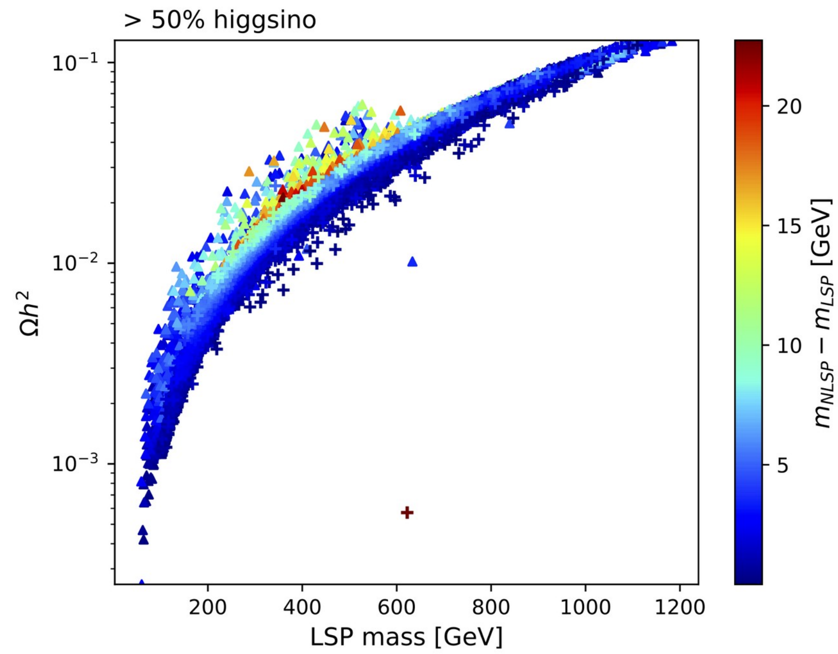
  -...

Thank you!!!

Back up

Scan results.

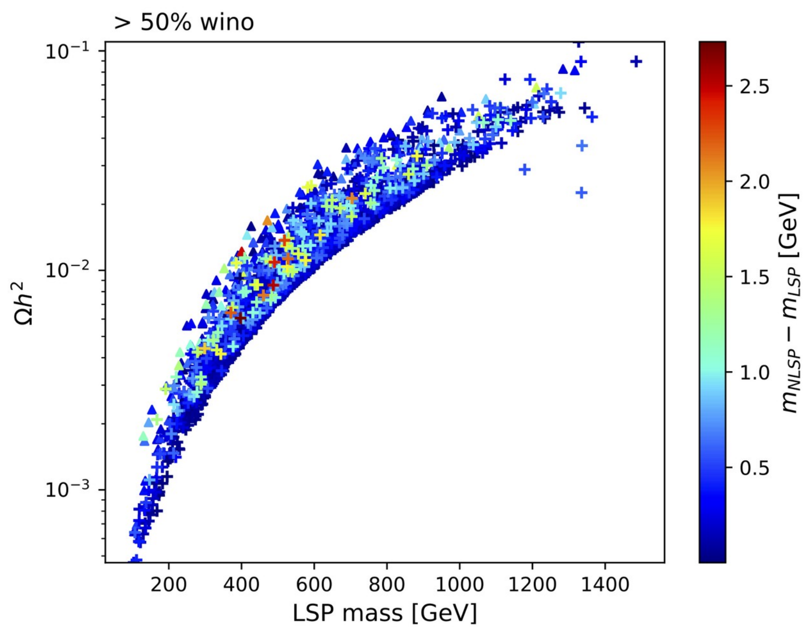




- General small NLSP-LSP mass splittings.
- Two possible mass orderings

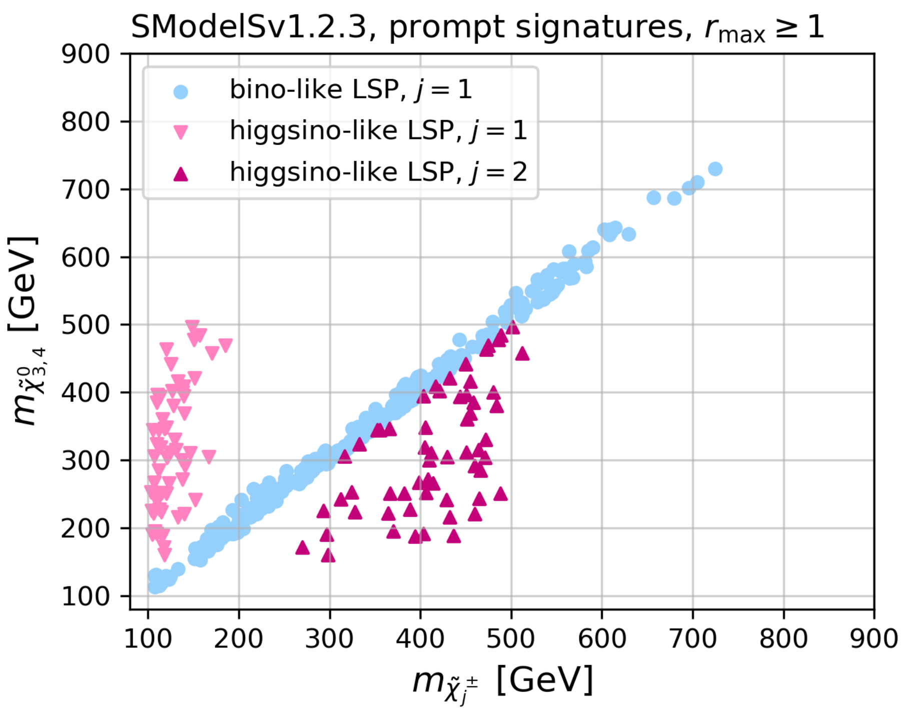
$$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0$$

$$\tilde{\chi}_1^0 < \tilde{\chi}_2^0 < \tilde{\chi}_1^\pm$$

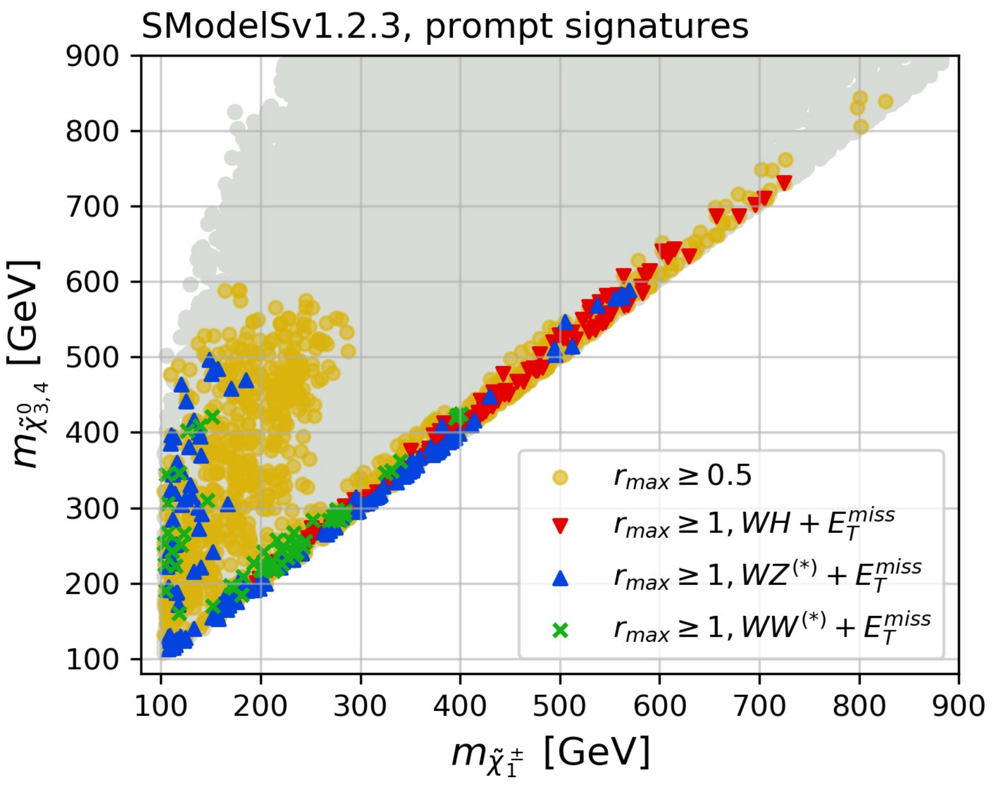


▲ neutral NLSP

\+ charged NLSP



SModelSv1.2.3, prompt signatures, $r_{\max} \geq 1$
bino-like LSP, $j = 1$
higgsino-like LSP, $j = 1$
higgsino-like LSP, $j = 2$
$m_{\tilde{\chi}^0_{3,4}}$ [GeV]
$m_{\tilde{\chi}^\pm_j}$ [GeV]



SModelSv1.2.3, prompt signatures
$r_{max} \geq 0.5$
$r_{max} \geq 1, WH + E_T^{miss}$
$r_{max} \geq 1, WZ^{(*)} + E_T^{miss}$
$r_{max} \geq 1, WW^{(*)} + E_T^{miss}$
$m_{\tilde{\chi}^0_{3,4}}$ [GeV]
$m_{\tilde{\chi}^\pm_1}$ [GeV]

Scan results.

$$\Omega h^2 = \Omega h^2{}_{\text{Planck}} \pm 10\%$$