Constraining Electroweakinos in the minimal Dirac Gaugino Model

Mark Goodsell

With: Sabine Kraml, Humberto Reyes-González and Sophie Williamson

Based on [2007.08498] (and [1812.09293 + Guillaume Chalons]); and [MDG: doi:10.14428/DVN/BUN2UX]

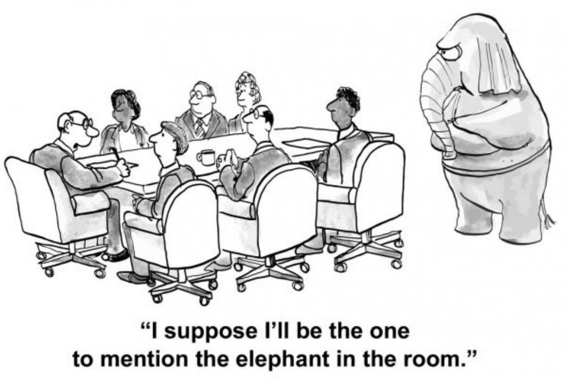
LPTHE
LABORATOIRE DE PHYSIQUE
THEORIQUE ET HAUTES ENERGIES

SORBONNE UNIVERSITÉ

cnrs

PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR
ANR

Isn't SUSY already dead?



- Limits on colourful particles in simple MSSM scenarios around 2 TeV (sits well with Higgs mass, flavour …)
- No DM particle (yet)
- BUT direct searches for electroweakinos actually have poor reach
- Still best-motivated BSM **framework**

Non-minimal scenarios could still be hiding in plain sight

Dirac gauginos: supersoft

- In SUSY, have a gaugino λ in adjoint rep of every gauge group (singlet, triplet, octet).
- When we break SUSY, in MSSM can only write a Majorana mass – breaks R-symmetry.
- BUT if we add chiral superfields **Σ = (**Σ,χ) can write a Dirac mass via the *supersoft* operator

$$\mathcal{L} \supset \int \mathrm{d}^2\theta 2\sqrt{2} m_D \theta^\alpha \mathrm{tr}(W_\alpha \Sigma) \supset -m_D \lambda\chi + \sqrt{2} m_D \Sigma D$$

This operator doesn't appear in RGEs, unlike Majorana mass

D-term interaction leads to new Higgs trilinears and octet couplings to squarks:

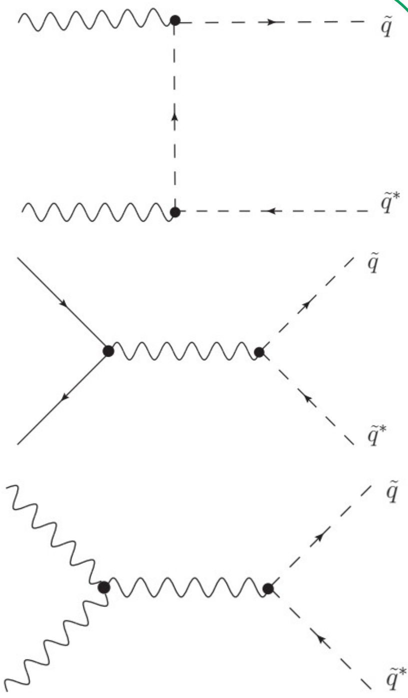
$$m_{DY}(S+\overline{S})(|H_u|^2 - |H_d|^2)$$

$$m_{D2}(T^0 + \overline{T}^0)(|H_u^0|^2 - |H_d^0|^2)$$

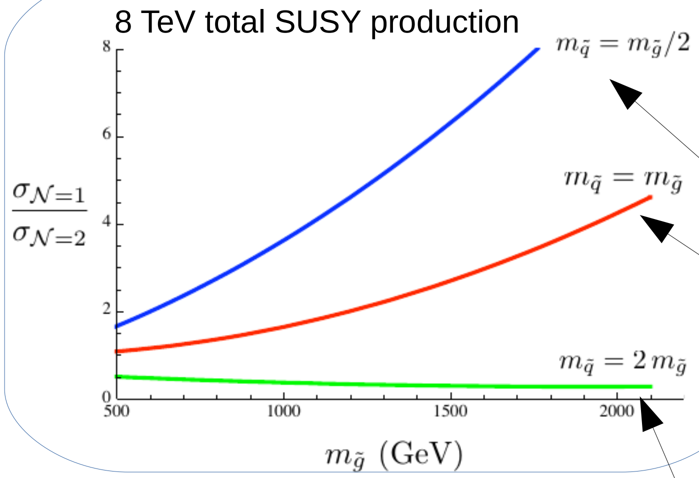
$$m_{DO}(O^a + \overline{O}^a)\sum \tilde{q}^* T^a \tilde{q}$$

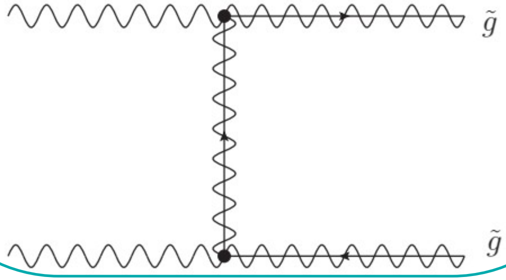
And supersafe!

From 1111.4322 by Heikenheimo, Kellerstein, Sanz



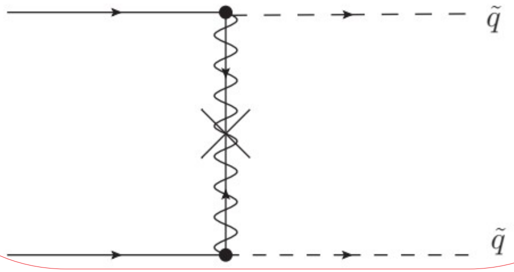
Diagrams common to Majorana/Dirac case





Production of gluinos ~ twice as large in Dirac case

Chirality-flip diagram for squark production dominates in Majorana case, absent for Dirac

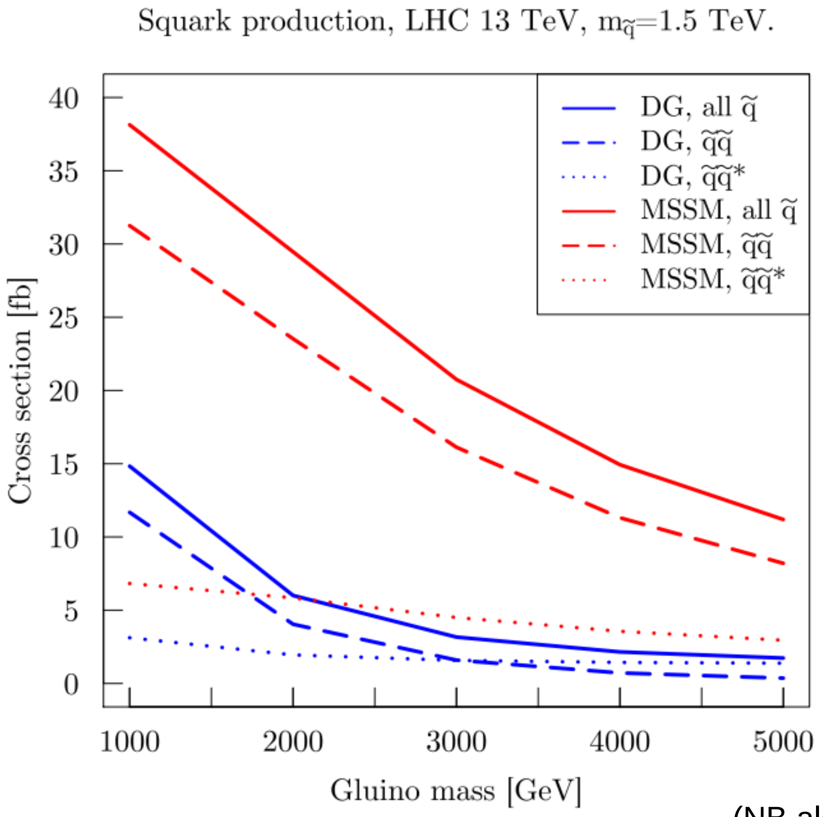


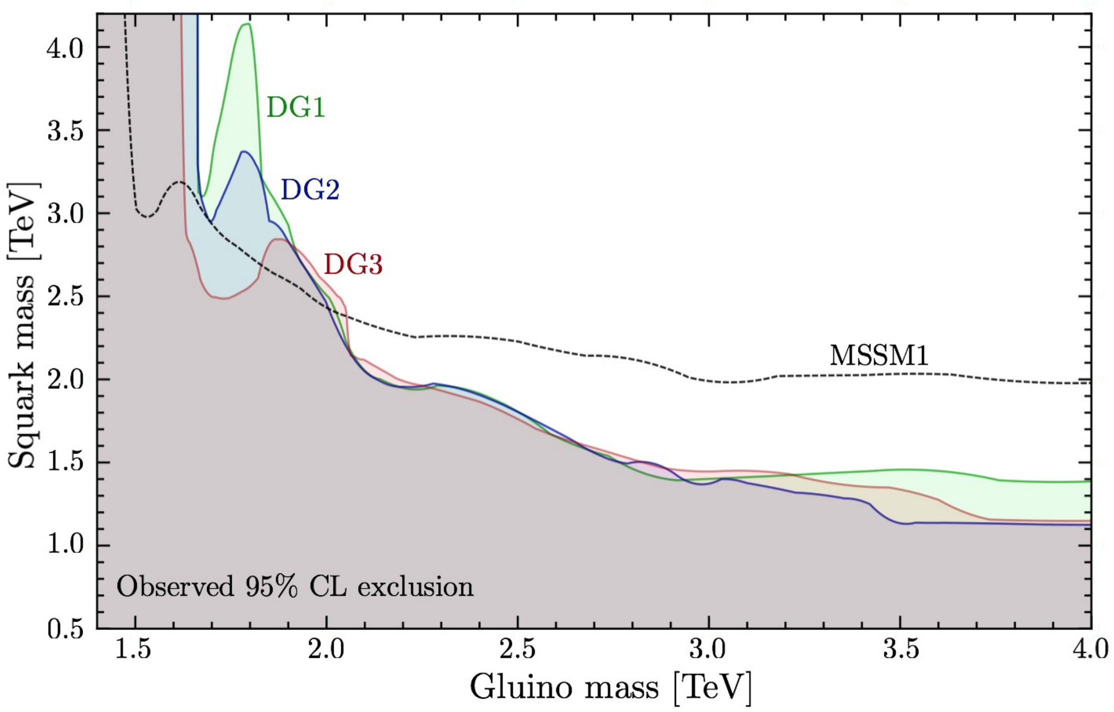
[Chalons, Kraml, MDG, ReyesGonzález, Williamson: 1812.09293]

Our full recasting results at 13 TeV

Also compared the recasting with SModelS v1.1

Used MadAnalysis 5 implementation of ATLAS-SUSY-2016-07 search for squarks and gluinos with 36 fb^{-1} @ 13TeV





(NB also looked for the scalar octets with L. Darmé and B. Fuks in [1805.10835])

So what about the electroweakino sector?

Two main classes of models:

- Preserve global U(1) R-symmetry: MRSSM – EWinos exactly Dirac, needs extra fields
- R-symmetry broken in EW sector: MDGSSM (this talk)

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

Broken R-symmetry leads to splitting of Dirac gauginos into pseudo-Dirac Majorana pairs

The MDGSSM is "minimal" because we only add the adjoint superfields S,T,O to the MSSM

End up with 6 ***pseudo-Dirac*** neutralinos and **three** charginos

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

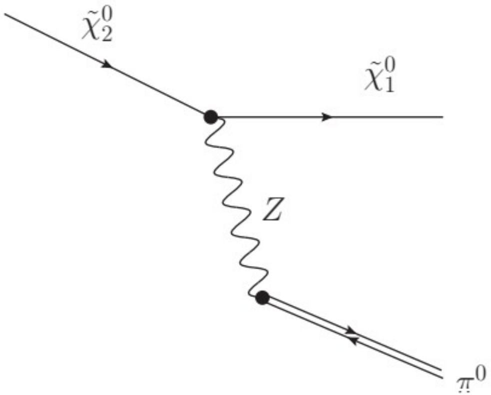
$$\tilde{B}', \quad \tilde{B}, \quad \tilde{W}'^0, \quad \tilde{W}^0, \quad \tilde{H}_d^0, \quad \tilde{H}_u^0$$

Pseudo-Dirac leads to LLPs!

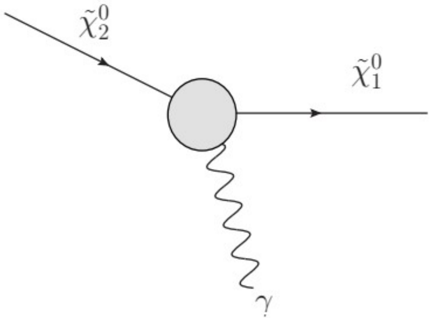
e.g. for bino LSP with higgsino NLSP:

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

If mass splitting large enough, decay to pions:



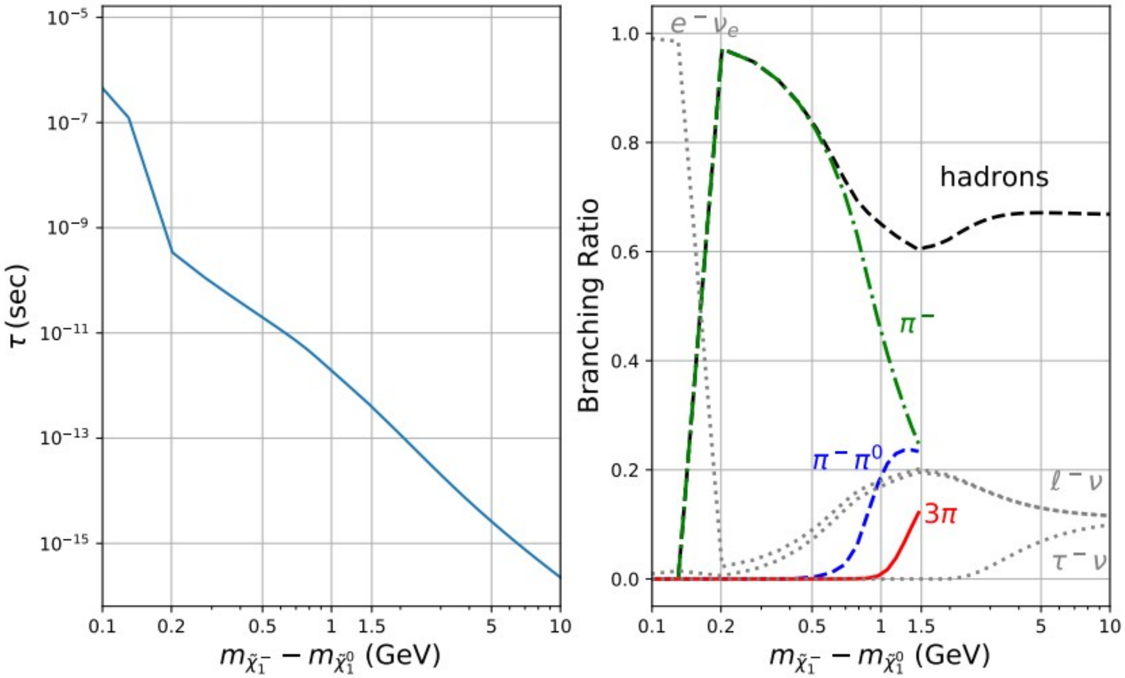
Or for smaller splittings, only photon channel is open:

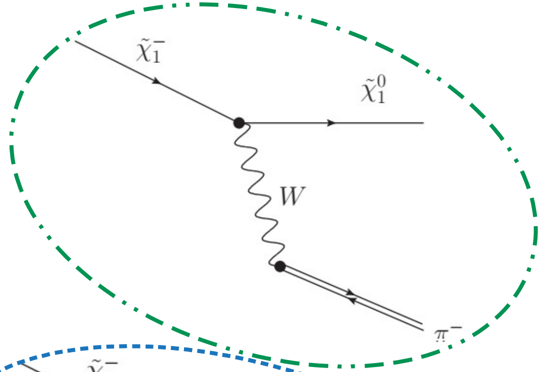


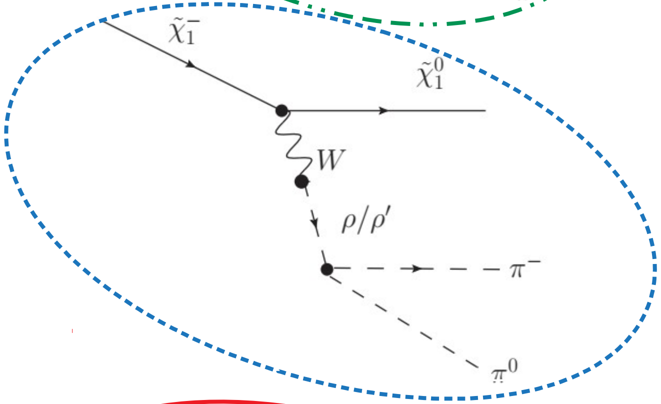
Needed to upgrade SARAH to calculate these (accurately)

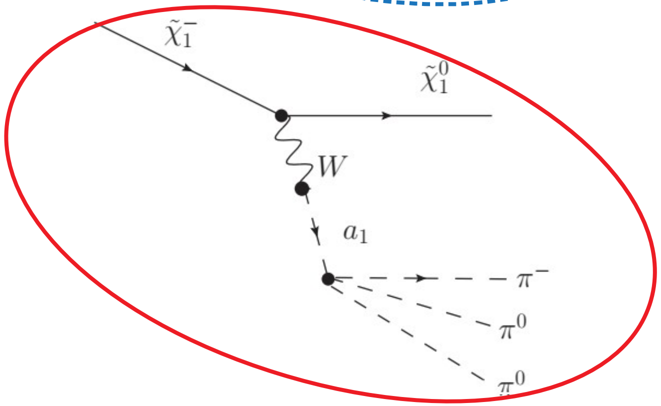
Similar story for charginos:

Large $|\mu|$ limiting case, MDGSSM



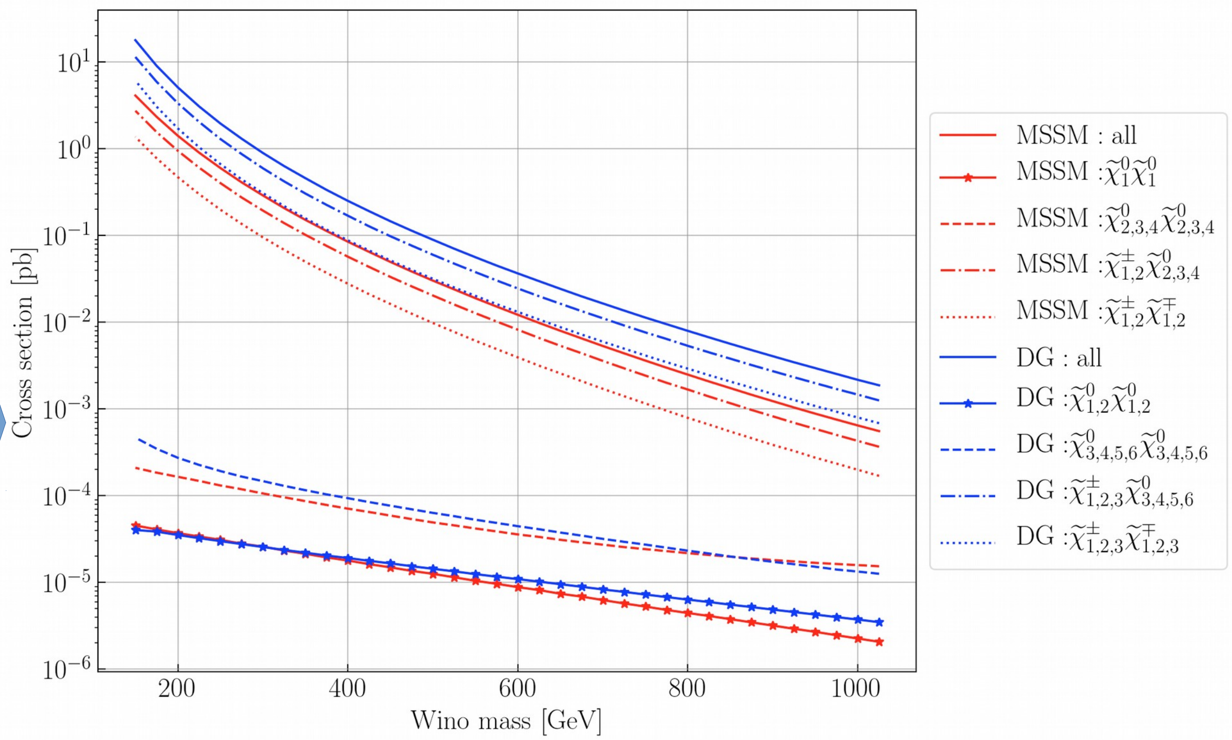




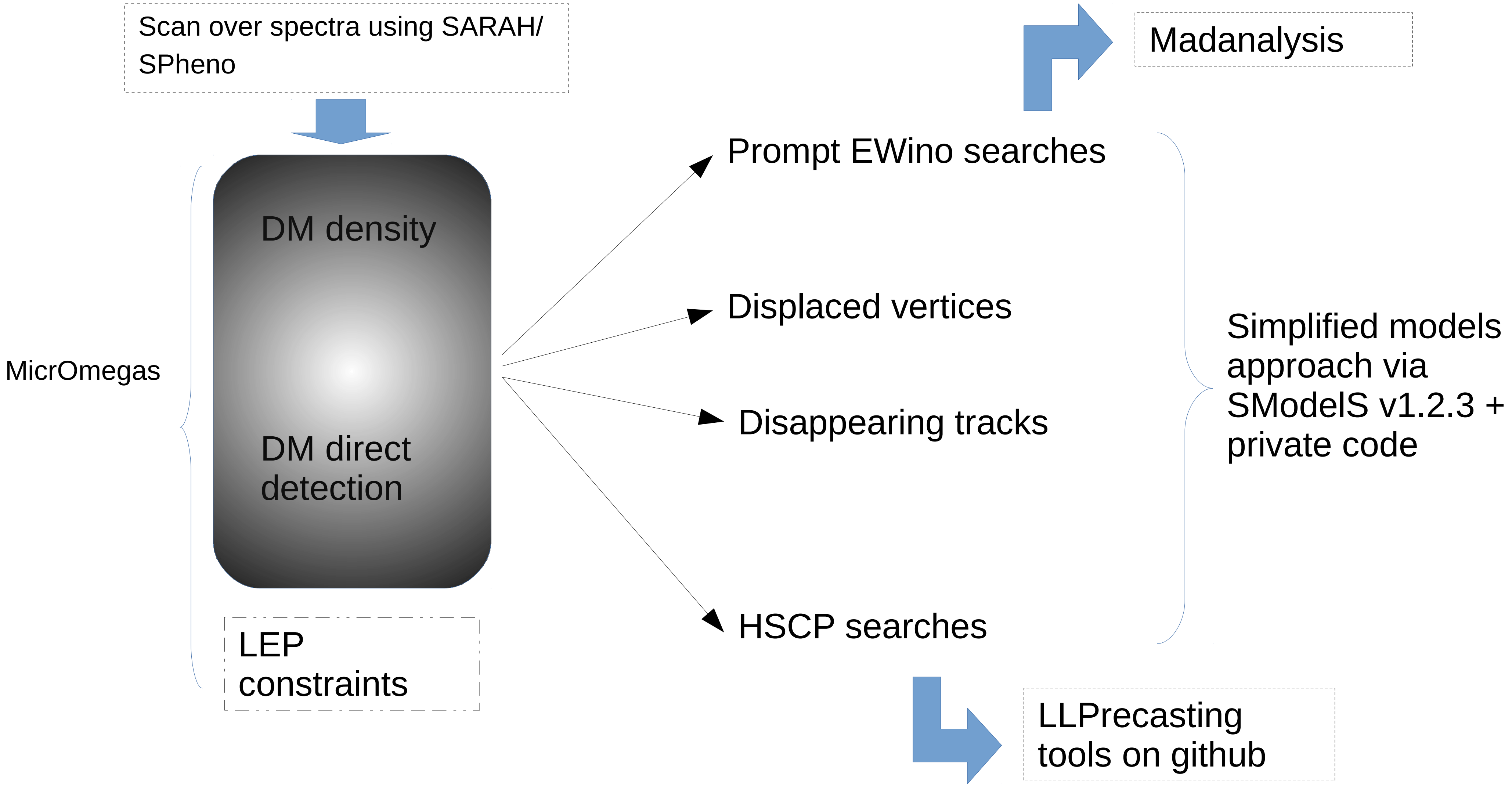


- EWinos make up DM, so can study DM-collider complementarity.
- MDGSSM Higgsinos are similar to MSSM: hard to produce, hard to find … and can only be 100% of dark matter if around a TeV
- Winos are produced much more copiously, but would be around 2.5 TeV

- An admixture with Bino LSP seems most plausible and easier to find … but signals of the mixed states can be more complicated than MSSM
- Here: Wino Dirac mass 20% greater than Bino mass
- We also have possible charged and neutral LLPs!



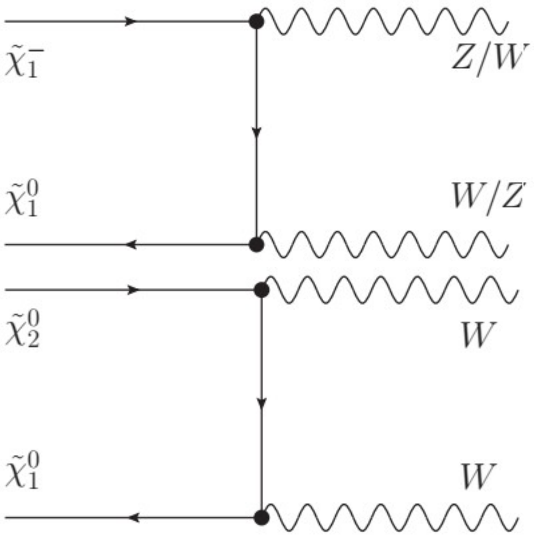
Search strategies



Pseudo-Dirac DM

Perfect for coannihilation while relaxing direct detection constraints

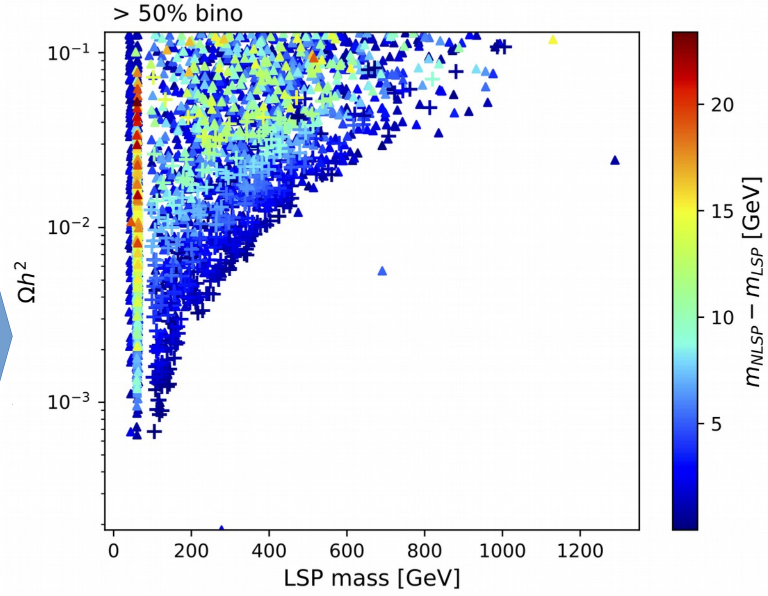
Richer EWino sector means more states to coannihiliate with



Some previous studies of the same/similar model analysed

DM parameter space: Hsieh (2007);
Belanger, Benakli, MDG, Moura, Pukhov (2009);
Chun, Park, Scopel (2009);
Simone, Sanz, Sato (2010);
MDG, Krauss, Müller, Porod, Staub (2015) ...

With latest codes we could do a large MCMC scan over EWino masses (fixing squarks/sleptons heavy, keeping only correct Higgs mass)

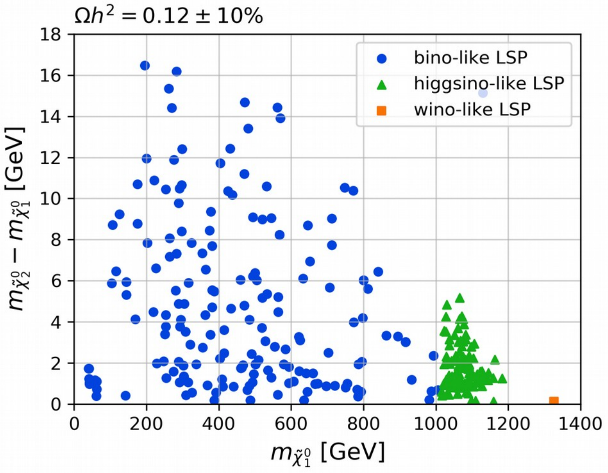


(these points are those with >50% bino fraction, for Higgsinos/Winos we find typical curves and they are underdense unless very heavy)

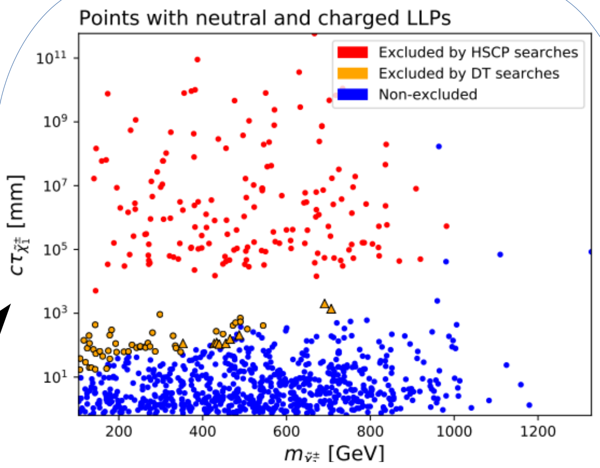
LLP constraints

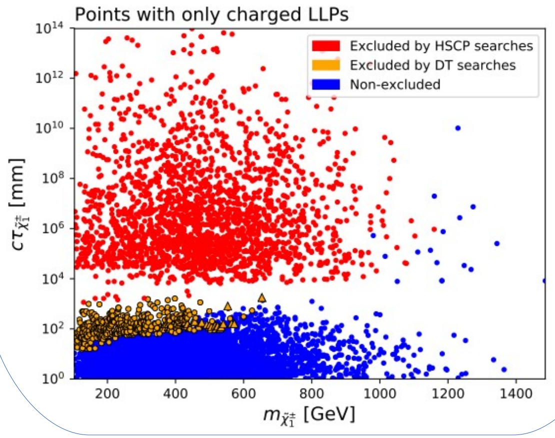
Most good points
do not have
LLPs ...

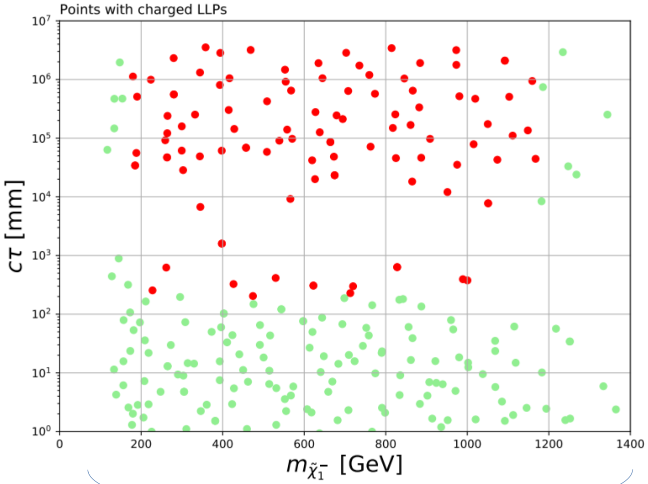
… except for (some) with
$\Delta m < 2.5$ GeV



LLPs stick out like a sore thumb below 1 TeV







Recasting using modified version of code by A. Lessa in Pythia 8

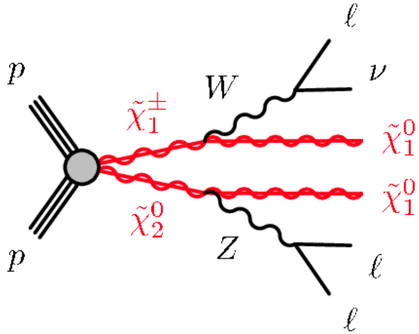
Recasting done in (private) simplified model approach

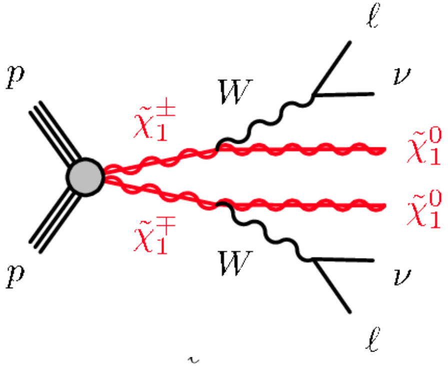
LHC constraints: simplified models

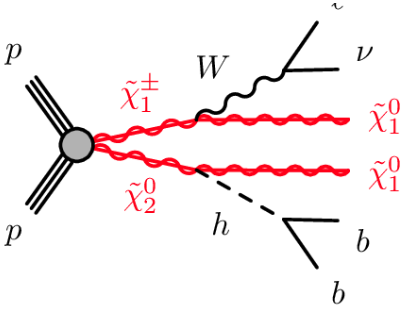
- SModelS contains a huge database of simplified model analyses, including many at 139 fb^{-1}
- Works very well when the model looks simple …
- … but even if not, can see which are the most important channels very easily

In our case, they are:

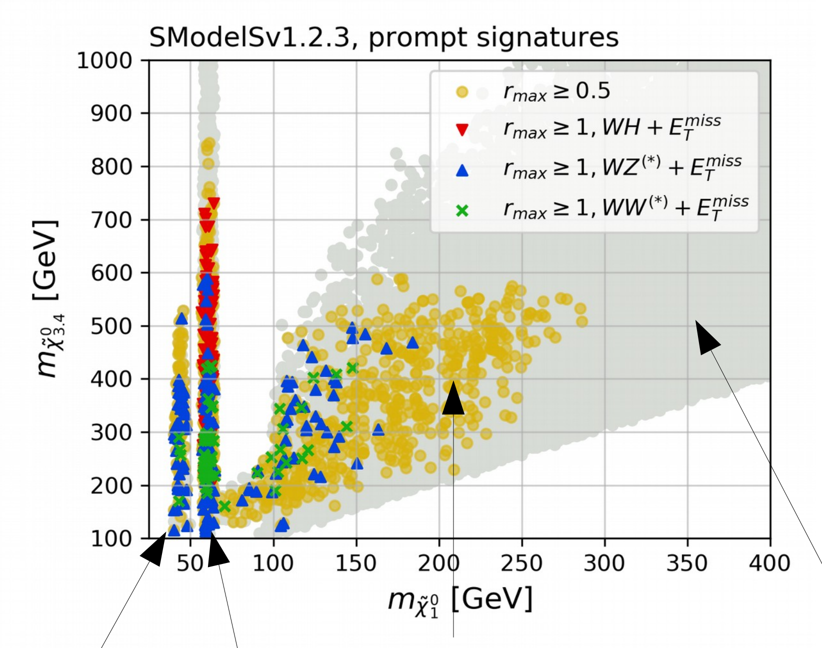
- ATLAS EWino searches at 139 fb^{-1}: WZ + MET ATLAS-SUSY-2018-06,
- WW+MET ATLAS-SUSY-2018-32,
- WH+MET ATLAS-SUSY-2019-08,
- CMS EWino combination at 35.9 fb^{-1}: CMS-SUS-17-004.

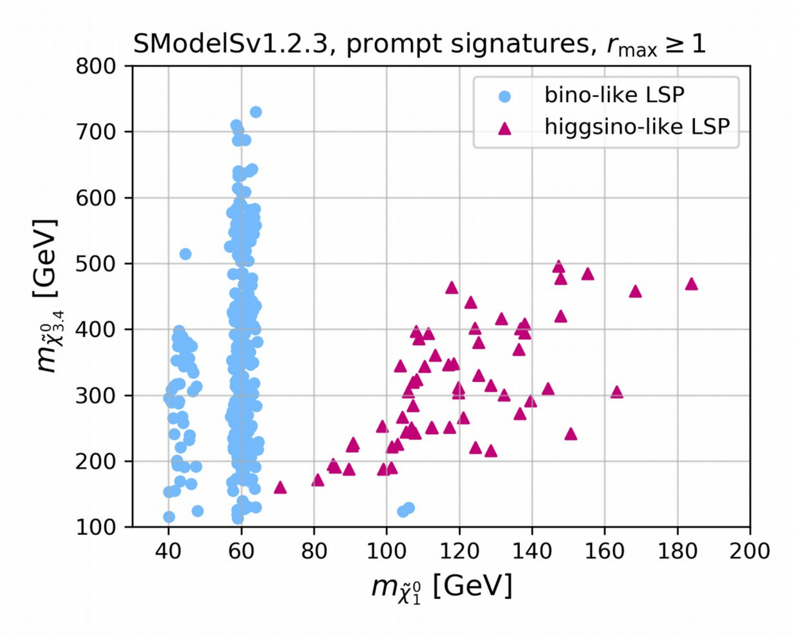






Results from SModelS recasting show Higgs/Z funnel strongly constrained and rather poor LHC reach elsewhere:





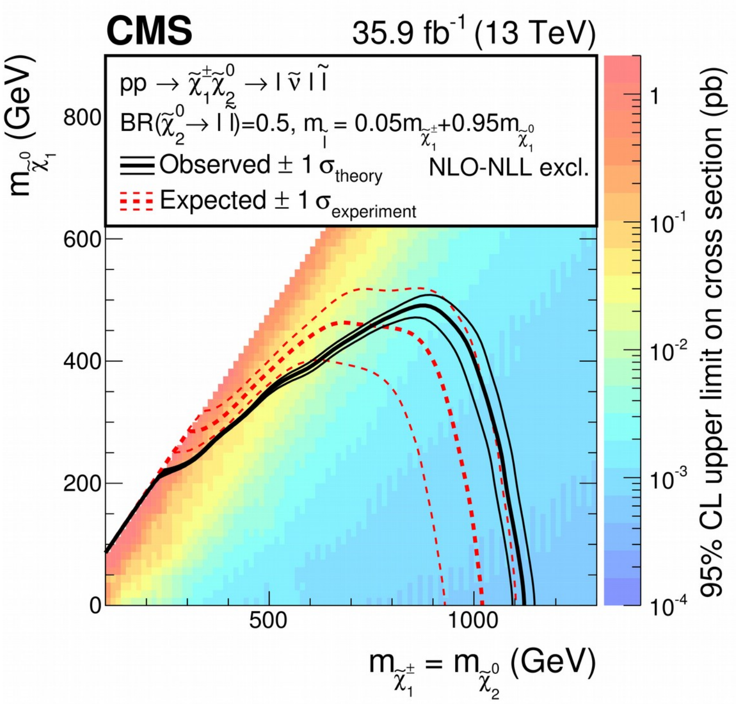
Z funnel

H funnel

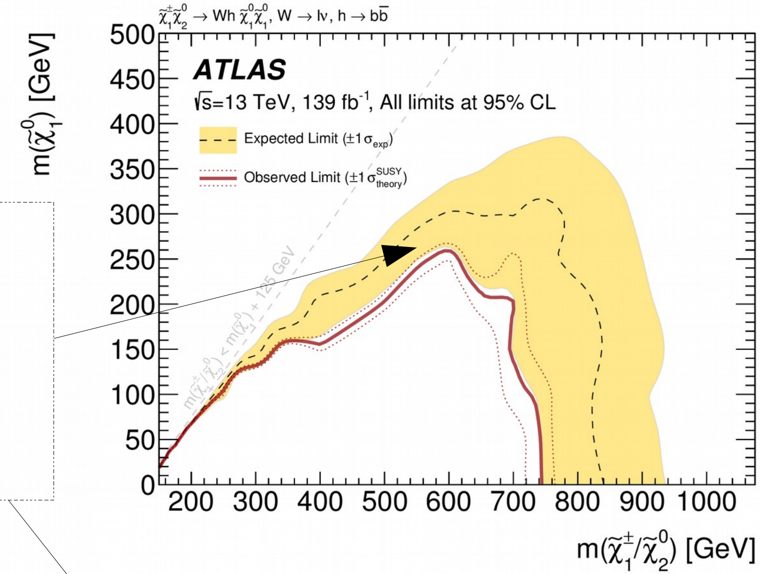
Points that may be probed in future runs

Safe points

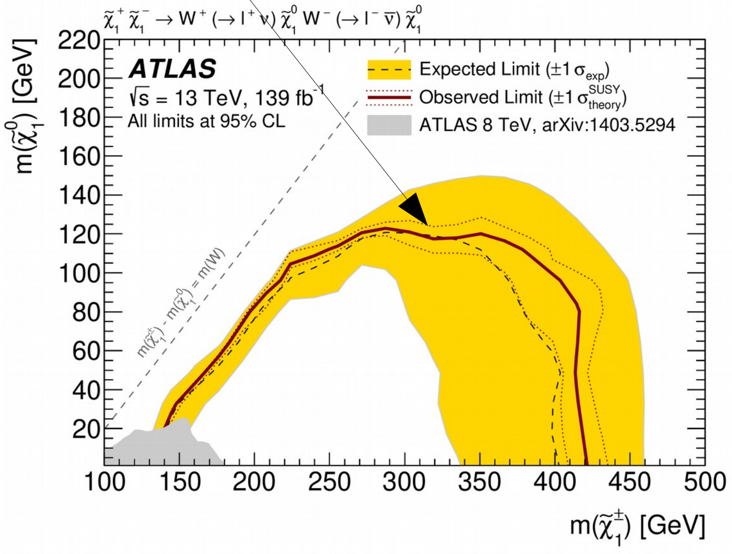
Compare to headline plots in MSSM from ATLAS/CMS:



A very optimal case with light sleptons!



Actually rather weak limits on the LSP, and these are the best cases!



LHC constraints: MadAnalysis

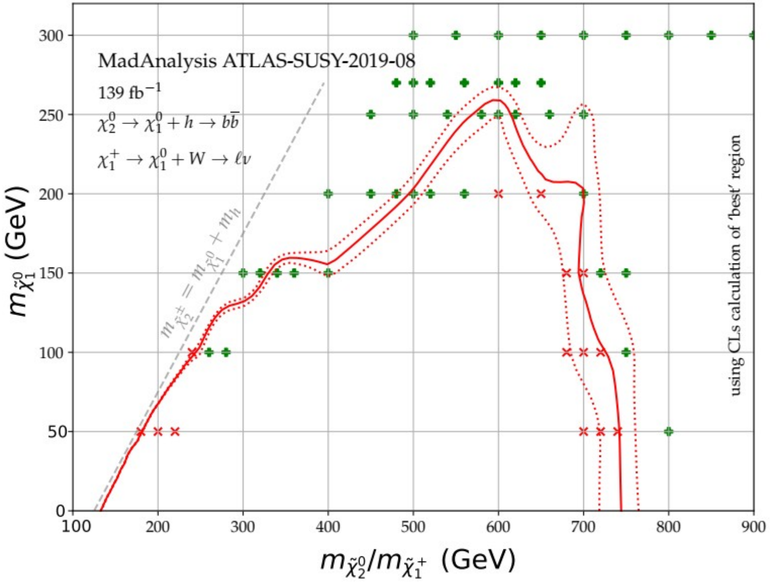
- Several “full” recasting tools available: ColliderBit, CheckMATE, MadAnalysis
- Roughly equivalent sets available for EWinos: chose MA5 which had CMS-SUS-16-039 and CMS-SUS-16-048 …
- … includes covariance information and all three signatures (WZ, WW, WH)
- … In principle, should be more powerful than SModelS because can combine signals and signal regions (found this for squark/gluino search)
- BUT SModelS has more 139 fb^{-1} analyses
- So: implemented the 139 fb^{-1} ATLAS-SUSY-2019-08 (WH) analysis in MadAnalysis

(validation)

Recast of ATLAS-SUSY-2019-08

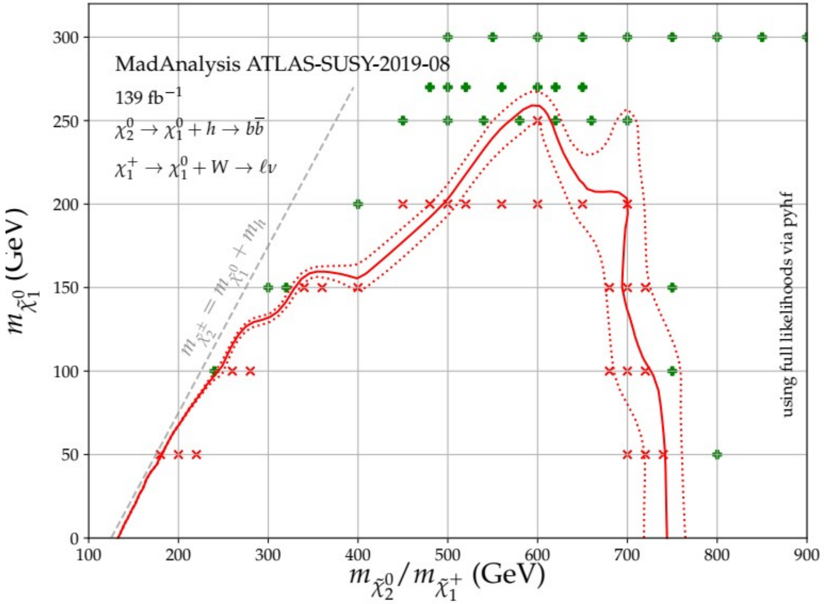
WH signature through Higgs to bb and W to leptons @ 139fb^{-1}

Looked for a Wino NLSP and Bino LSP in **MSSM**



Exclusions using 'best' region

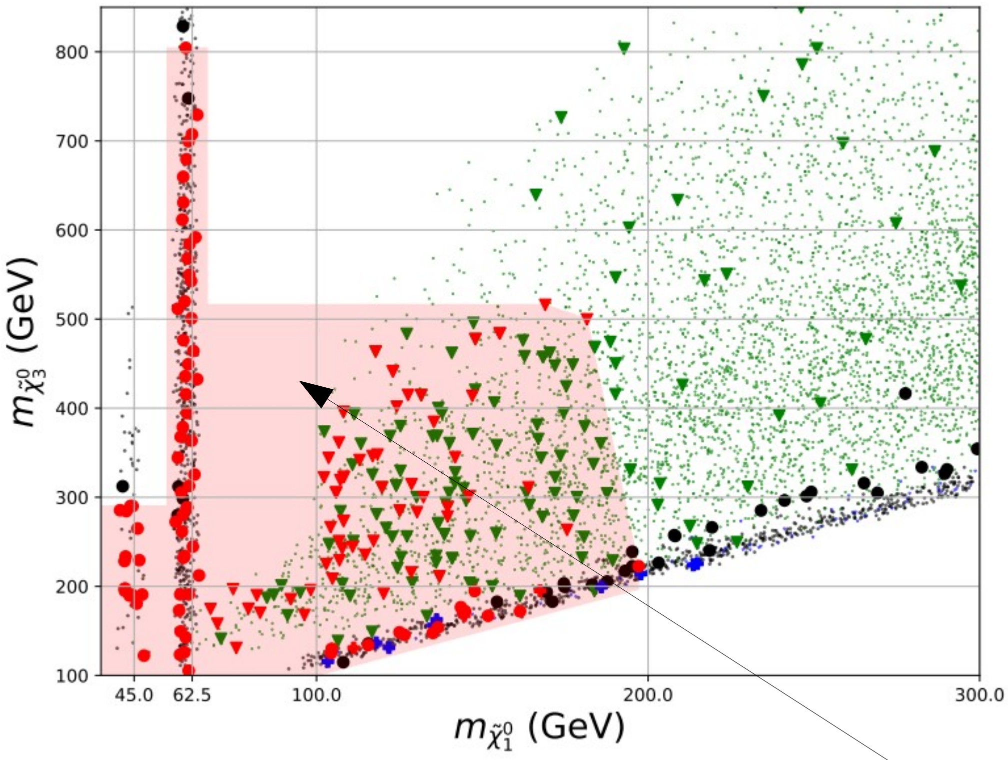
Recently provided full likelihoods in pyhf!



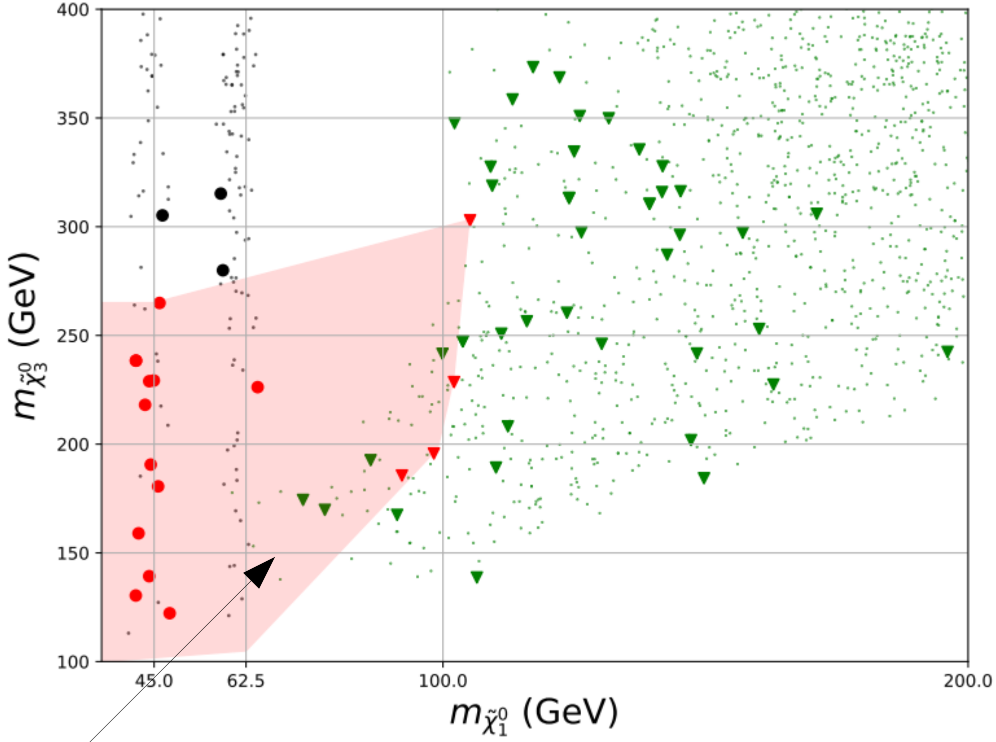
Exclusions using private implementation + pyhf – MA5 authors will (have) automate(d) this in future release

Results for MDGSSM

MD2 < 900 GeV: some Wino fraction



MD2 > 700 GeV: small Wino fraction



Regions we find excluded points

Excellent agreement with simplified models approach!

Conclusions

- Constraints on EW sector of full SUSY scenarios are still poor, but will substantially improve with more data.
- Or: DM in non-minimal models could still be hiding just round the corner!
- There is an effort to create new strategies to look for e.g. Higgsinos: will also apply here.
- Simplified models approach is very useful for this case, certainly showed its advantage in speed of implementation and application.
- Much work still to be done to improve the recasting chain: more full recasting analyses, faster codes, more efficient selection of points, NLO corrections, etc.
- More work needed for LLPs (in progress).
- Loop-induced (to photon) and pion decays were very important: more improvements needed here.
- Can apply the same toolbox SARAH-MicrOmegas-SmodelS-MadAnalysis (or equivalent tools) and workflow to other (complete) models.