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Supersymmetry – theory overview

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The SUSY paradigm

- The SM (without neutrino masses) has only one mass scale but it is arbitrary and not protected when we couple to any New Physics.
- In SUSY, we introduce a (spontaneously broken) symmetry between fermions and bosons. The bosons acquire the chiral symmetry protecting the fermion masses from quantum corrections.
- It is required (at some level) for String Theory.
- The scale of SUSY breaking is then automatically protected and sets the mass scale for the SM too (may therefore have a *little* hierarchy problem).
- This is true ***whatever new matter*** we add: SUSY is a framework, and not just one model.
- It also allows us to calculate the Cosmological Constant (zero for unbroken SUSY/R-symmetry).

We then obtain for free:

- Gauge coupling unification! (is it just a cruel joke of nature?)
- Stability for the Higgs potential.
- Provides dark matter candidates and can readily address baryogenesis.

Where are we now?

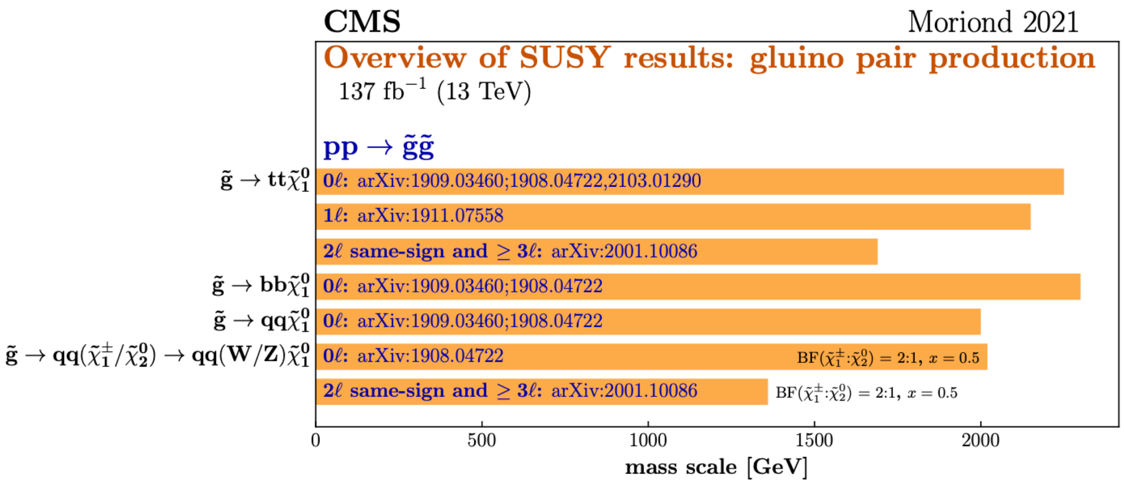
- Colourful sparticles did not appear immediately below a TeV
- Limits on colourful particles in simple MSSM scenarios around 2 TeV (BUT)
- No DM particle found (yet) either

BUT:

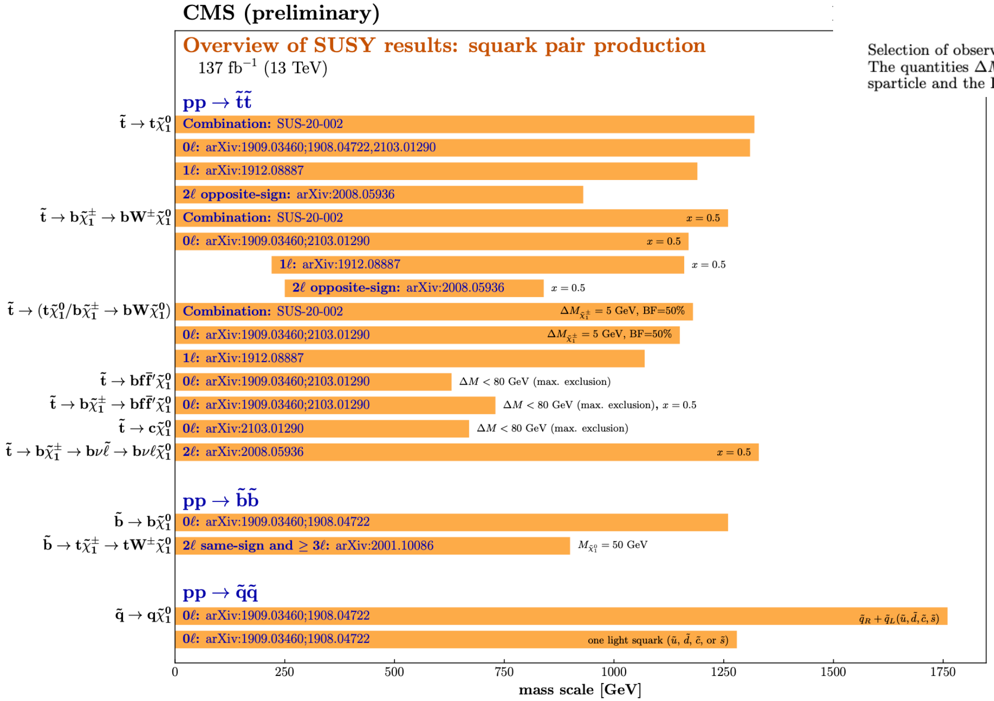
- No colourful particles actually sits well with Higgs mass, flavour …
- Direct searches for electroweakinos actually have poor reach
- Still best-motivated BSM **framework** (no compelling alternative)

Even minimal scenarios could still be hiding in plain sight!

Gluinos excluded below about 2 TeV



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

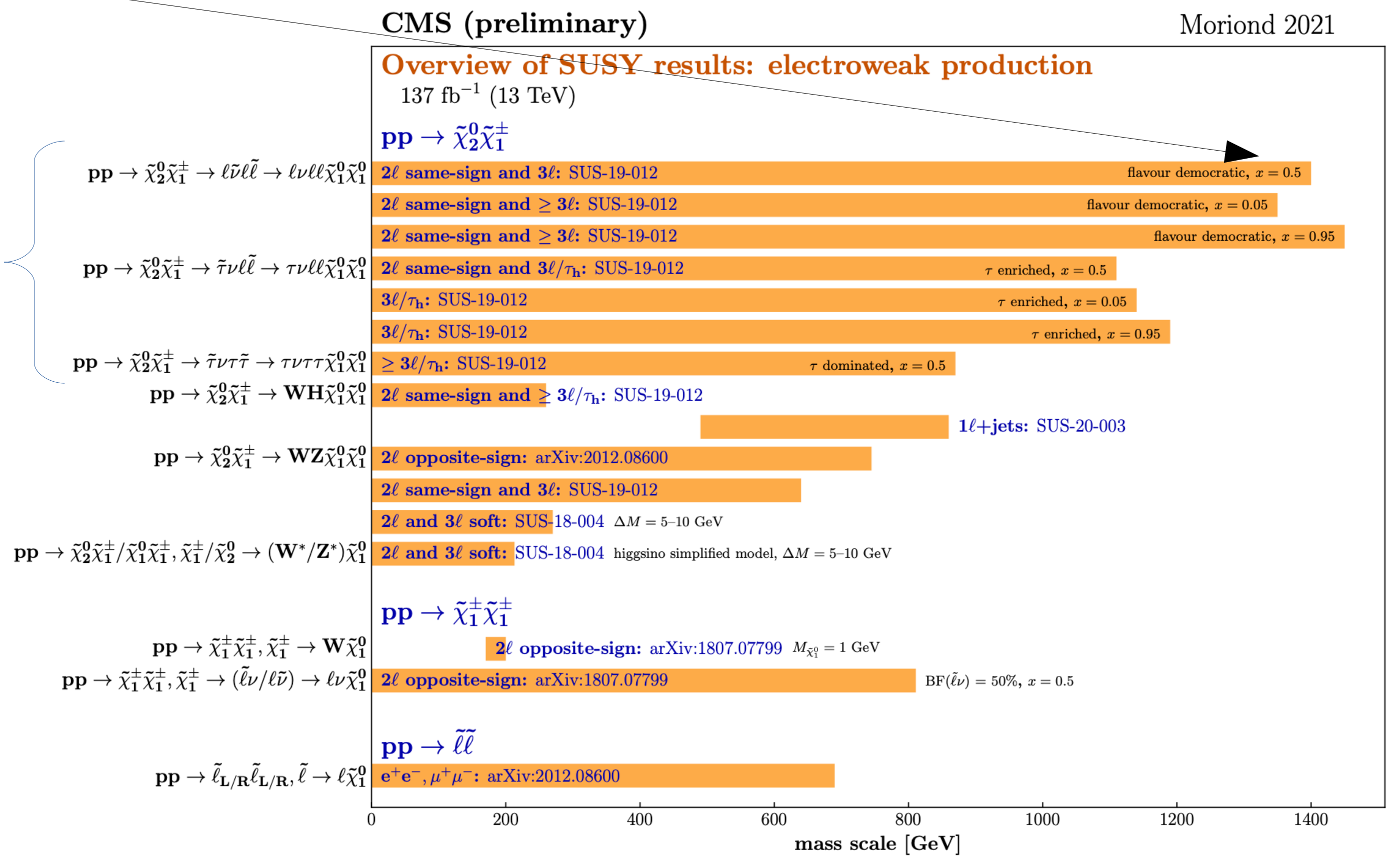
Limits on stops/sbottoms at best about 1300 GeV, but model dependent and holes remain

1[st] generation squarks excluded below 1250 GeV or even beyond 2 TeV depending on assumptions

Limits on electroweak production have big headline numbers

… but rely on light sleptons

… and even the direct production limits are best cases:



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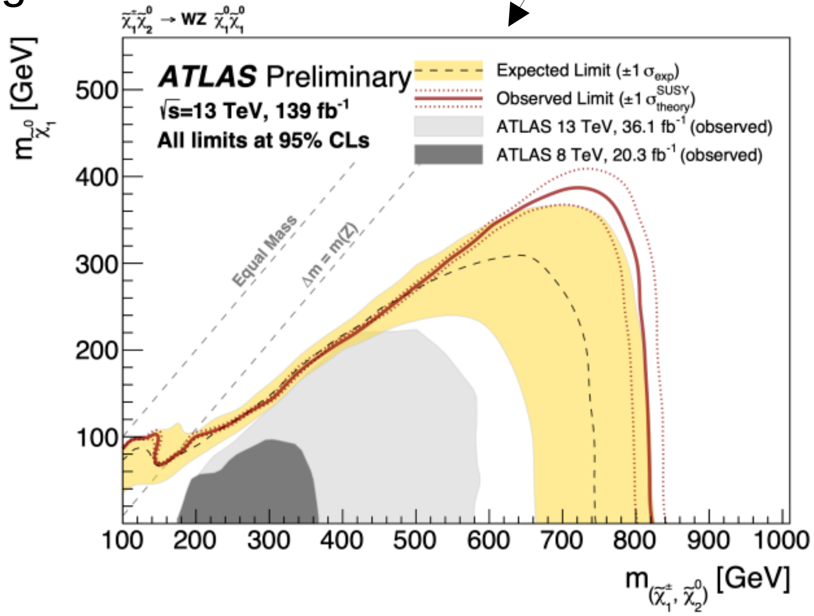
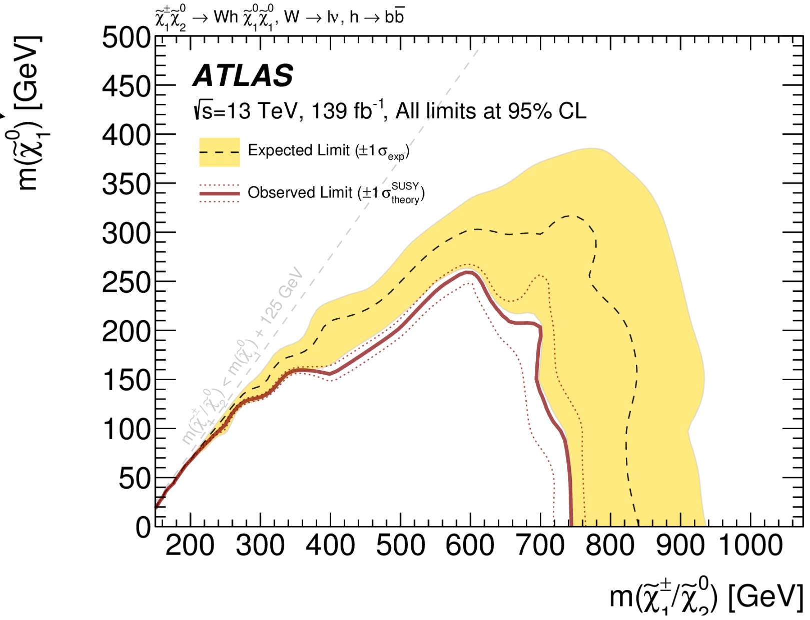
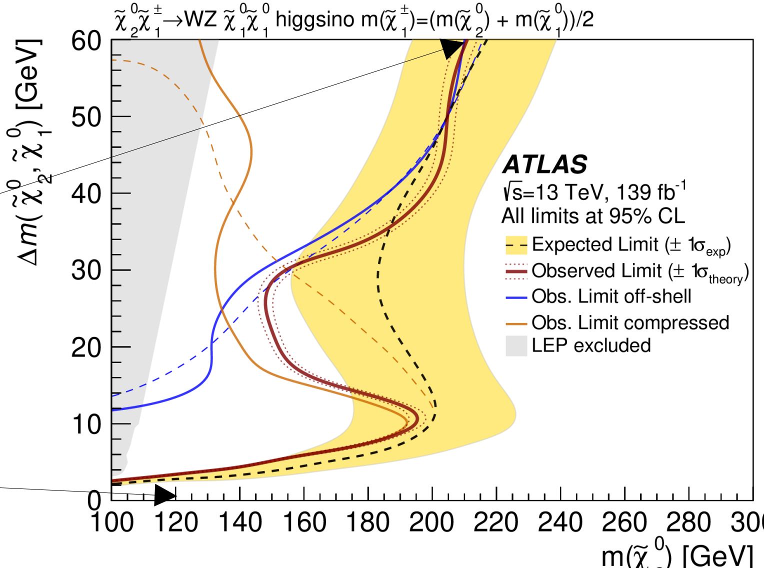
Limits up to 800 GeV are for wino-like charginos:



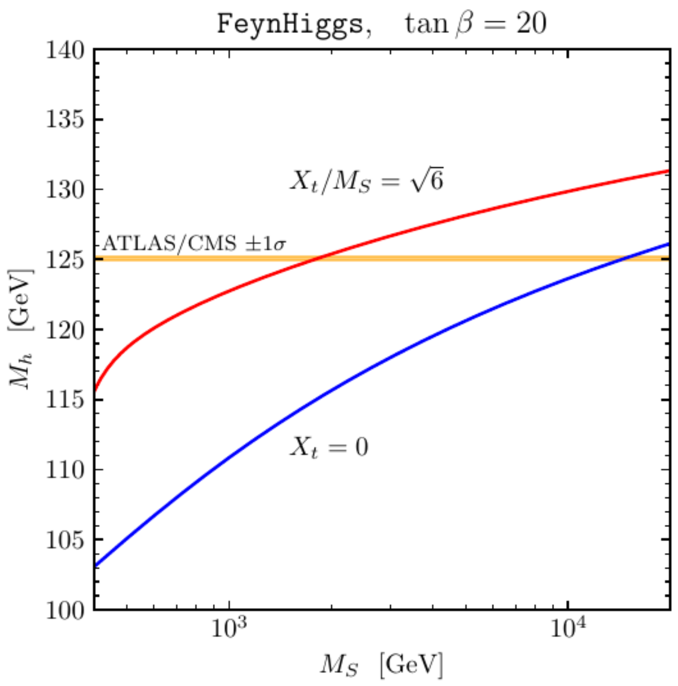


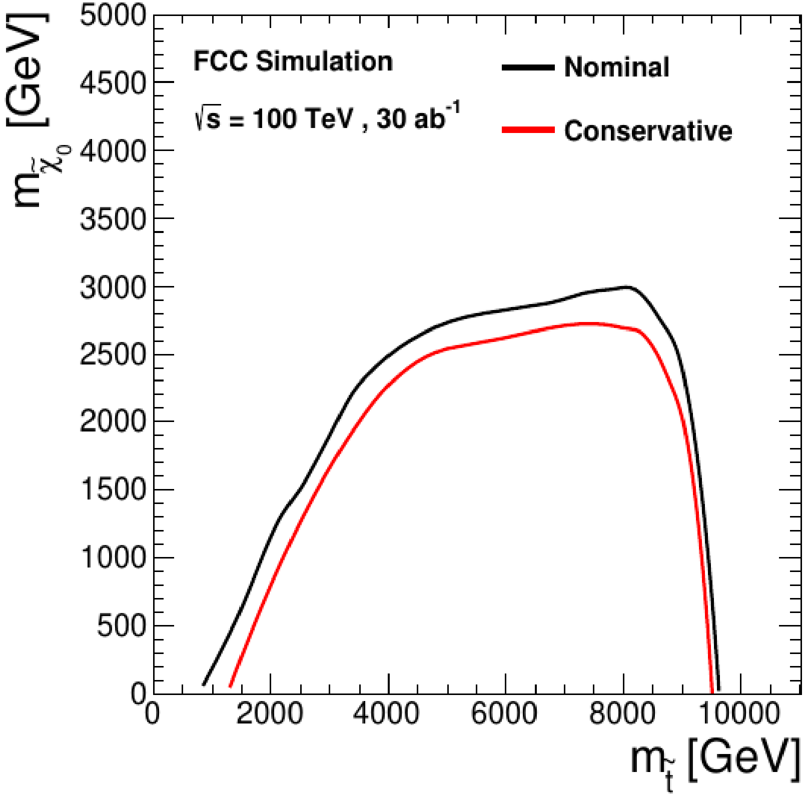
But only 210 GeV for higgsinos – with a big mass splitting:

Pure higgsinos still very hard to limit … except when we have LLPs!



On the other hand, precision computations of the MSSM Higgs mass show that we expect stops to be heavy; only for moderate to high tan β, stops should be within reach of the FCC:

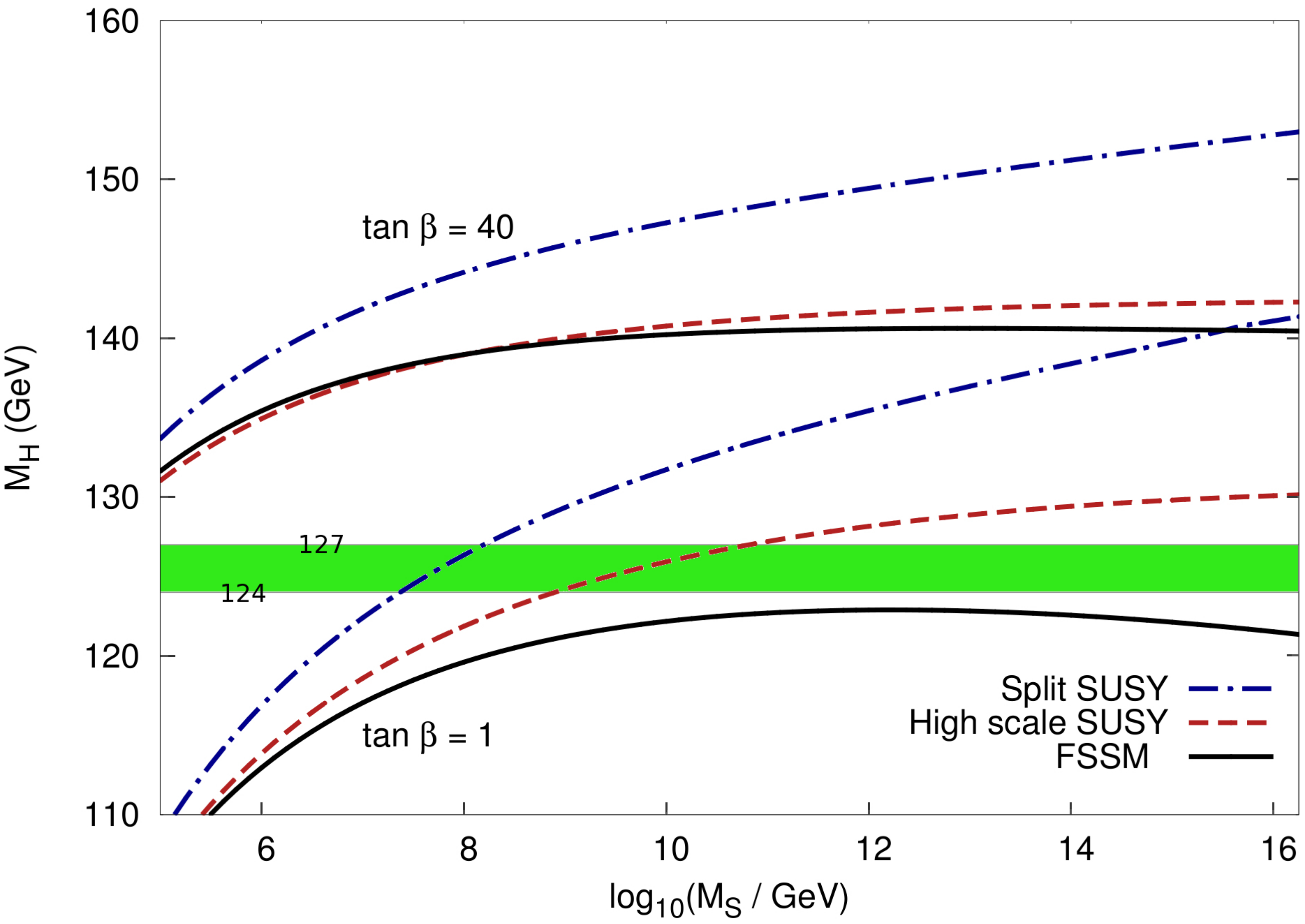




Different SUSY scenarios scenarios give various predictions for the Higgs mass:

It can be used to put an upper limit on the SUSY scale!

OR: the Higgs mass is exactly in the range that SUSY predicts ...



Leads to a reasonable set of hypotheses:

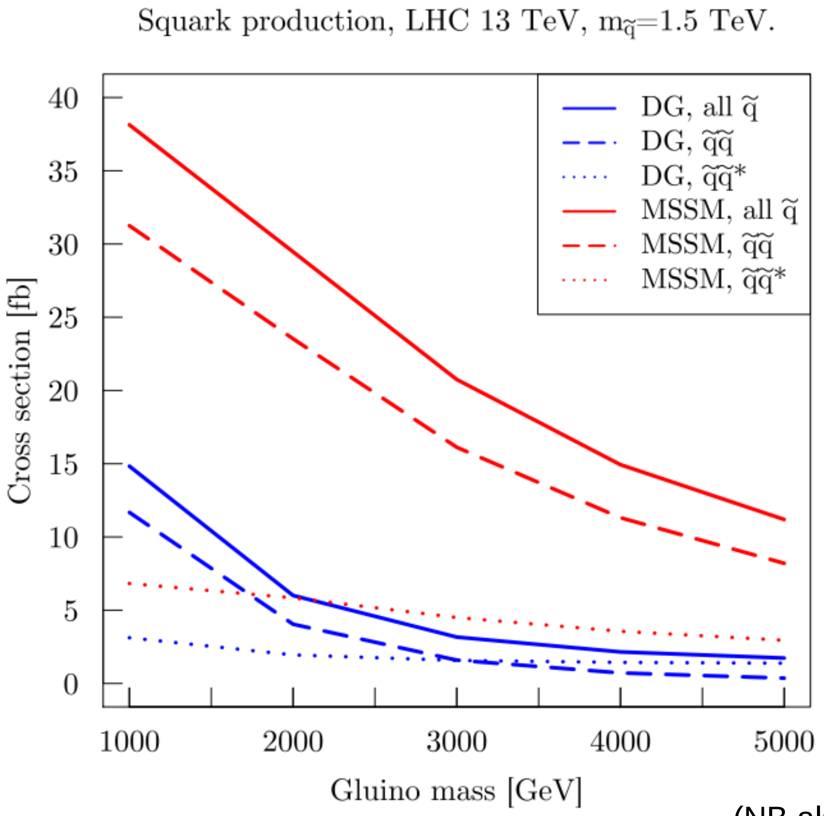
- Worst case scenario is heavy SUSY with non-WIMP DM, and **no gauge coupling unification**
- Split SUSY (all scalars heavy except the Higgs) allows WIMP DM, but the Higgs mass + gauge coupling unification favour a mini-split of masses up to 100 TeV. This logic seems increasingly compelling.
- SUSY could easily be lurking in plain sight, or with colourful states just above the LHC reach.
- **Non-minimal SUSY scenarios** (beyond the MSSM) may be even lighter and salvage naturalness (vs little hierarchy problem).
- Optimistic picture is made more likely by anomalies (W mass, g-2 etc)

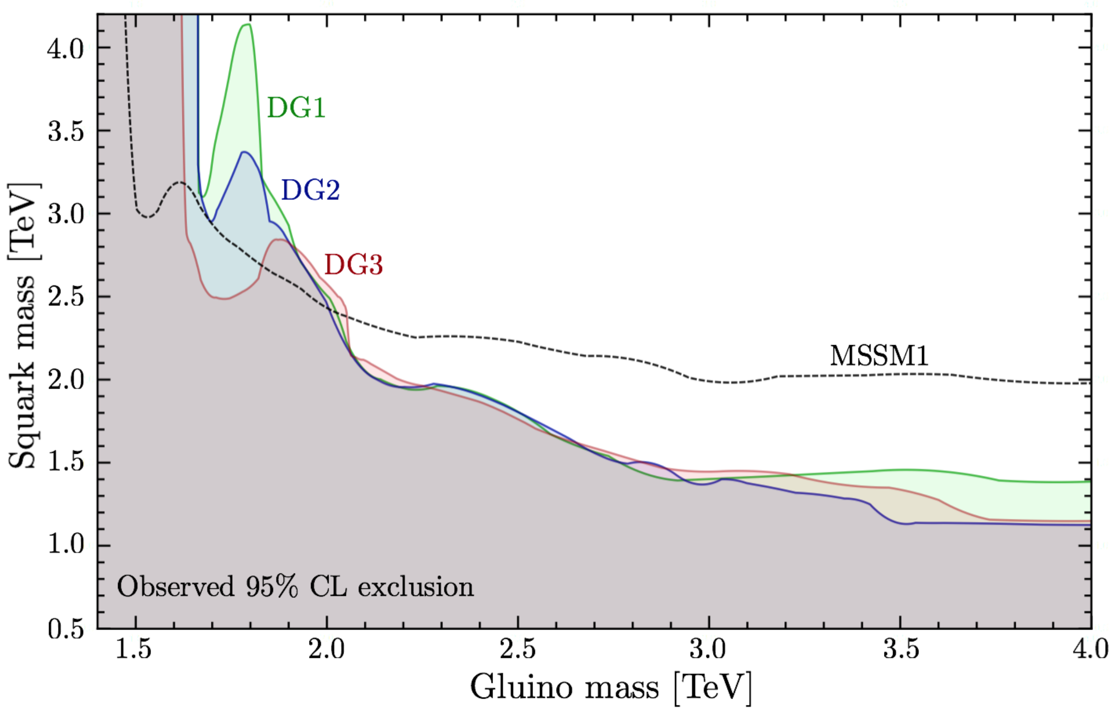
[Chalons, Kraml, MDG, ReyesGonzález, Williamson: 1812.09293]

Example: Dirac gaugino models are 'supersafe'

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

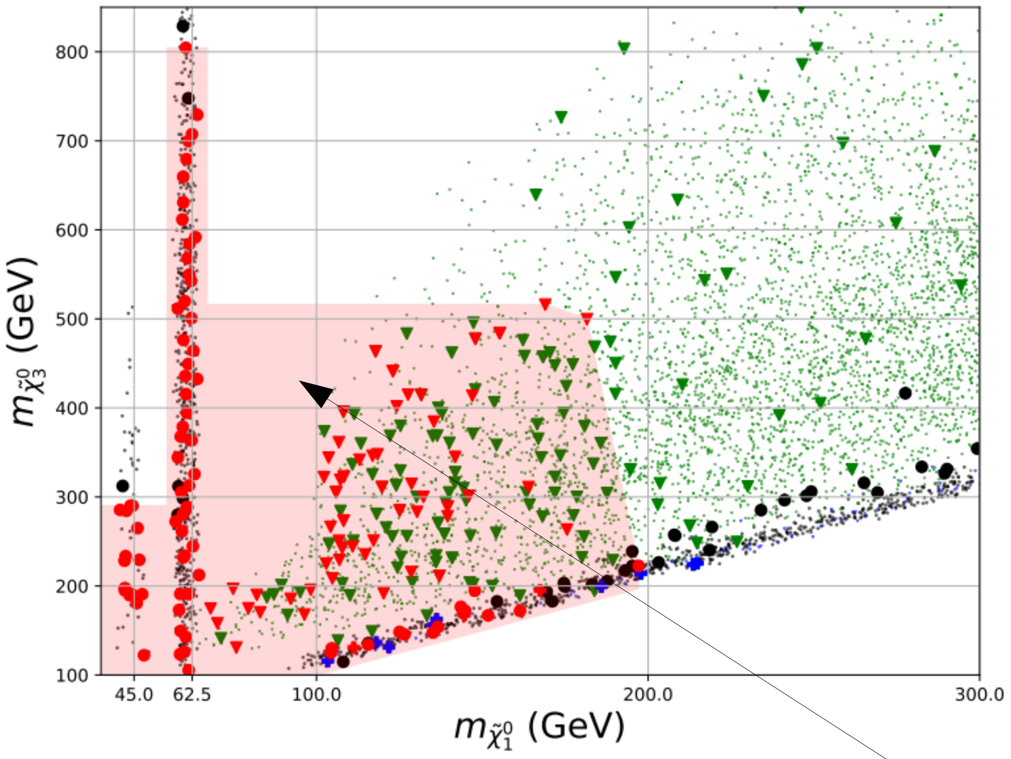




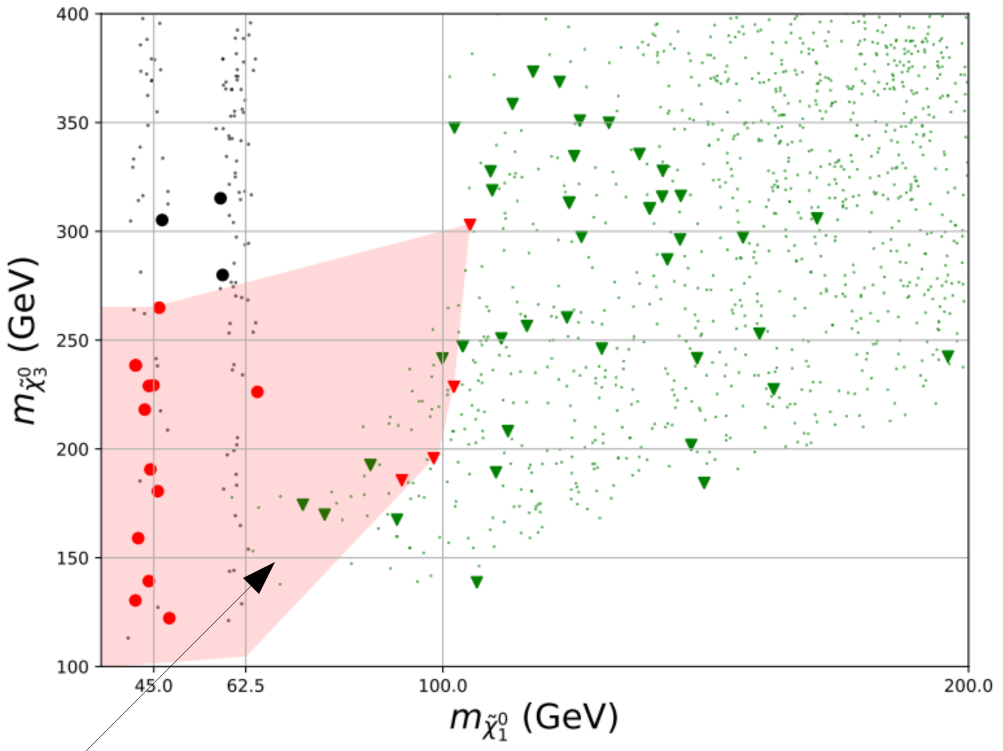
(NB also looked for the scalar octets with L. Darmé and B. Fuks in [1805.10835])

But for the EW sector:

MD2 < 900 GeV: some Wino fraction



MD2 > 700 GeV: small Wino fraction



Regions we find excluded points

Recent theory activities

- Precision computations are vital, since SUSY makes predictions! Higgs mass, triple Higgs couplings, g-2, W mass, EDMs … Recent workshop(s) e.g. KUTS initiative and MW Days 23. The results can often be applied to other models (see e.g. the Higgs Mass white paper 2012.15629)
- Hand in hand goes tools development: dedicated/generic spectrum generators, GM2Calc, Machine Learning LHC cross-sections/limits, etc
- **Attempts to recast as many LHC searches as possible**!
- Benchmark scenarios for future runs/colliders, dark-matter/collider complementarity, **global fits** (e.g. CMSSM fit 2210.16337, or GAMBIT, e.g. 2303.09082 EWinos).
- New models/scenarios: SUSY twin Higgs, ...
- Models for g-2.
- **Models for the W mass!**

Main technical problems now:

- How to make things run faster?
  - Spectrum generation/decays ~ 1s
  - Low energy/dark matter/Higgs constraints ~ few s
  - Collider constraints ~ hour(s)!!
- How to have same accuracy everywhere?
  - Transition to NLO for MadGraph (not yet easy for any model)
  - Tree vs 1-loop vs 2-loop for Higgs mass, EWPT, EDMs, decays, …
- What constraints are we missing?
- How to combine constraints from different observables – or even different signal regions in the same LHC analysis!
- **How to add more LHC analyses?!**
  - **Not everything works/is available for every model**
  - **Most LHC analyses not yet recast!**

E.g. all the CMS analyses available in GAMBIT:

Only 4 full run 2!

```
Analysis_CMS_13TeV_0LEP_137invfb.cpp
Analysis_CMS_13TeV_0LEP_13invfb.cpp
Analysis_CMS_13TeV_0LEP_36invfb.cpp
Analysis_CMS_13TeV_1LEPbb_36invfb.cpp
Analysis_CMS_13TeV_1LEPStop_36invfb.cpp
Analysis_CMS_13TeV_1Photon1Lepton_36invfb.cpp
Analysis_CMS_13TeV_2LEPsoft_36invfb.cpp
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Analysis_CMS_13TeV_2OSLEP_137invfb.cpp
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Analysis_CMS_13TeV_2OSLEP_chargino_stop_36invfb.cpp
Analysis_CMS_13TeV_2OSLEP_confnote_36invfb.cpp
Analysis_CMS_13TeV_2Photon_GMSB_36invfb.cpp
Analysis_CMS_13TeV_2SSLEP_Stop_137invfb.cpp
Analysis_CMS_13TeV_2SSLEP_Stop_36invfb.cpp
Analysis_CMS_13TeV_MONOJET_36invfb.cpp
Analysis_CMS_13TeV_MultiLEP_137invfb.cpp
Analysis_CMS_13TeV_MultiLEP_36invfb.cpp
Analysis_CMS_13TeV_MultiLEP_Full_36invfb.cpp
Analysis_CMS_13TeV_Photon_GMSB_36invfb.cpp
Analysis_CMS_8TeV_1LEPDMTOP_20invfb.cpp
Analysis_CMS_8TeV_2LEPDMTOP_20invfb.cpp
Analysis_CMS_8TeV_MONOJET_20invfb.cpp
Analysis_CMS_8TeV_MultiLEP_20invfb.cpp
```

E.g. 13 TeV CMS analyses available in MadAnalysis (6 full run 2)

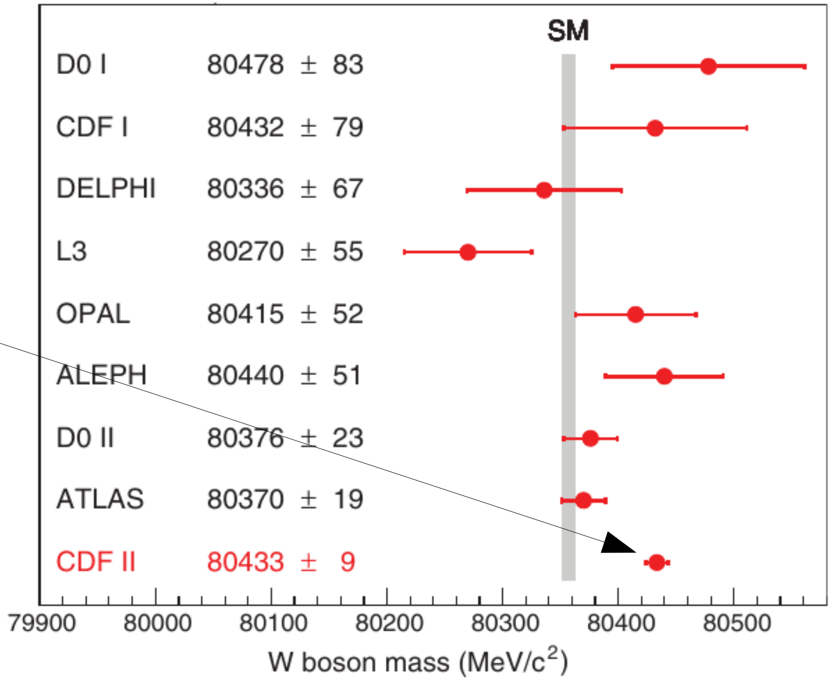
CMS analyses, 13 TeV

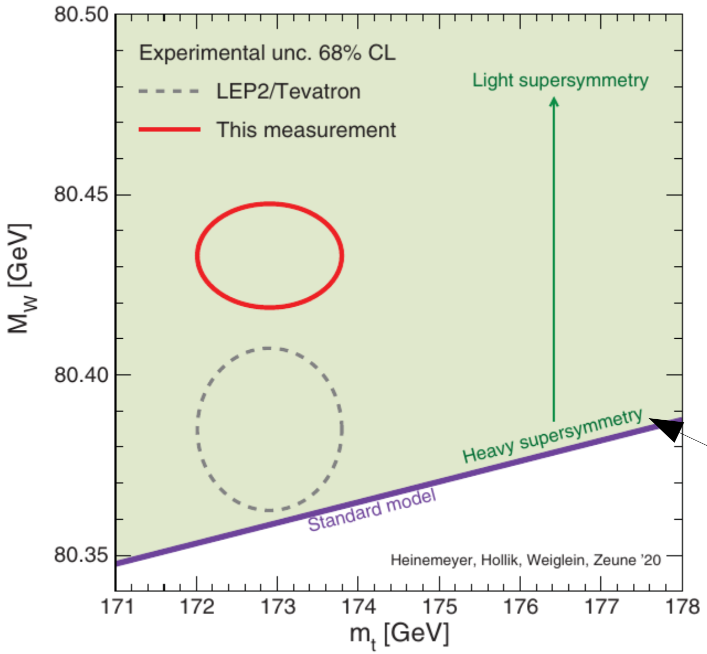
Analysis	Short Description	Implemented by
CMS-SUS-16-033	Supersymmetry in the multijet plus missing energy channel (35.9 fb-1)	F. Ambrogi and J. Sonneveld
CMS-SUS-16-039	Electroweakinos in the SS2L, 3L and 4L channels (35.9 fb-1)	B. Fuks and S. Mondal
CMS-SUS-16-048	Compressed electroweakinos with soft leptons (35.9 fb-1)	B. Fuks J.Y. Araz
CMS-SUS-16-052	SUSY in the 1l + jets channel (36 fb-1)	D. Sengupta
CMS-SUS-17-001	Stops in the OS dilepton mode (35.9 fb-1)	S.-M. Choi, S. Jeong, D.-W. Kang *et al.*
CMS-SUS-19-006	SUSY in the HT/missing HT channel (137 fb-1)	M. Mrowietz, S. Bein, J. Sonneveld
CMS-B2G-17-014	Vector-like quarks with charge 5/3 with same-sign dileptons (35.9/fb)	J. Salko, L. Panizzi
CMS-EXO-16-010	Mono-Z-boson (2.3 fb-1)	B. Fuks
CMS-EXO-16-012	Mono-Higgs (2.3 fb-1)	S. Ahn, J. Park, W. Zhang
CMS-EXO-16-022	Long-lived leptons (2.6 fb-1)	J. Chang M. Ustch, M. Goodsell
CMS-EXO-17-009	Leptoquark pair production in the electron(s)+jets channel (35.9 fb-1)	T. Murphy
CMS-EXO-17-011	WR and heavy neutrino in the 2l2j mode (35.9 fb-1)	A. Jueid, B. Fuks
CMS-EXO-17-015	Leptoquarks + dark matter in the 1mu+1jet+met channel (77.4 fb-1)	A. Jueid and B. Fuks
CMS-EXO-17-030	Pairs of trijet resonances (35.9 fb-1)	Y. Kang, J. Kim, J. Choi, S. Yun
CMS-EXO-19-002	Type-III seesaw and top-philic scalars with multileptons (137/fb)	E. Conte, R. Ducrocq
CMS-EXO-19-010	CMS disappearing tracks (139/fb)	M. Goodsell
CMS-EXO-20-002	WR and heavy neutrino in the 2l2j mode (138 fb-1)	A. Jueid, B. Fuks
CMS-EXO-20-004	Dark matter in the multi-jet+met channel (137 fb-1)	A. Albert
CMS-HIG-18-011	Exotic Higgs decay in the 2 muons + 2 b-jet channel via 2 pseudoscalars (35.9 fb-1)	J.B. Lee and J. Lee
CMS-TOP-17-009	SM four-top analysis (35.9 fb-1)	L. Darmé and B. Fuks
CMS-TOP-18-003	SM four-top analysis (137 fb-1)	L. Darmé and B. Fuks

Some groups are commendably *adding the code for their own analyses:* **please make this standard practice!**

W boson mass

The biggest reaction from the theory community in the last year was the CDF II W boson mass measurement





They directly referred to longstanding SUSY predictions of an enhancement compared to SM

Models to enhance the W mass

Currently > 375 citations to the CDF paper from last year!

Explanations generally one or more of:

- EFT fits
- Models with extra SU(2) reps (e.g. triplet) with a vev
- Models with light EW states (loops)
- Models with a Z' that mixes with the Z (we fix the Z mass and the weak mixing angles from observations)

$$\rho \equiv 1 + \Delta\rho_{\text{tree}} + \Delta\rho = 1 + 4\frac{v_T^2}{v^2} + \Delta\rho.$$

$$\Delta_{\text{tree}} M_W^2 = \frac{c_W^2}{c_W^2 - s_W^2} (M_W^2)_{\text{SM}} \Delta\rho_{\text{tree}},$$

$$\Delta_{\text{tree}} s_W^2 = -\frac{s_W^2 c_W^2}{c_W^2 - s_W^2} \Delta\rho_{\text{tree}},$$

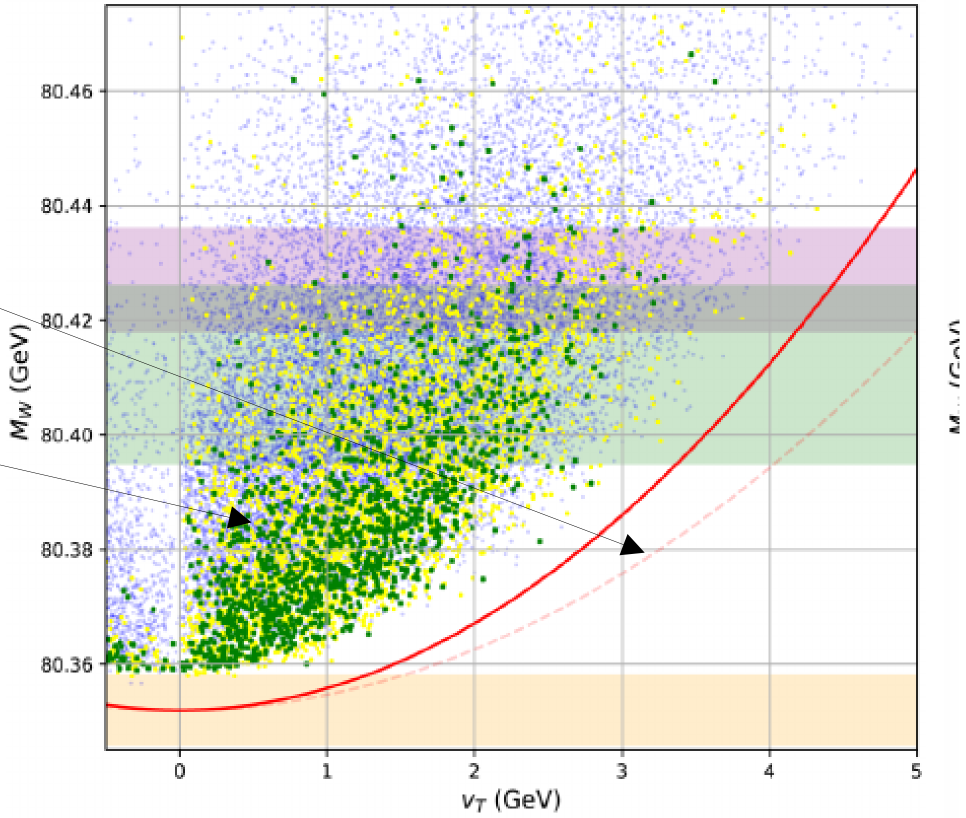
MSSM can obviously accommodate extra light EW-charged multiplets (sleptons, higgses etc) – more general SUSY models can include all of the above.

E.g. Dirac gaugino enhancements to the W mass

'Natural' non-minimal SUSY model. Add: a singlet $\mathbf{S}$, an $SU(2)_W$ triplet $\mathbf{T}^a$, and an $SU(3)_C$ octet $\mathbf{O}^a$

$$\rho \equiv 1 + \Delta\rho_{\rm tree} + \Delta\rho = 1 + 4\frac{v_T^2}{v^2} + \Delta\rho.$$

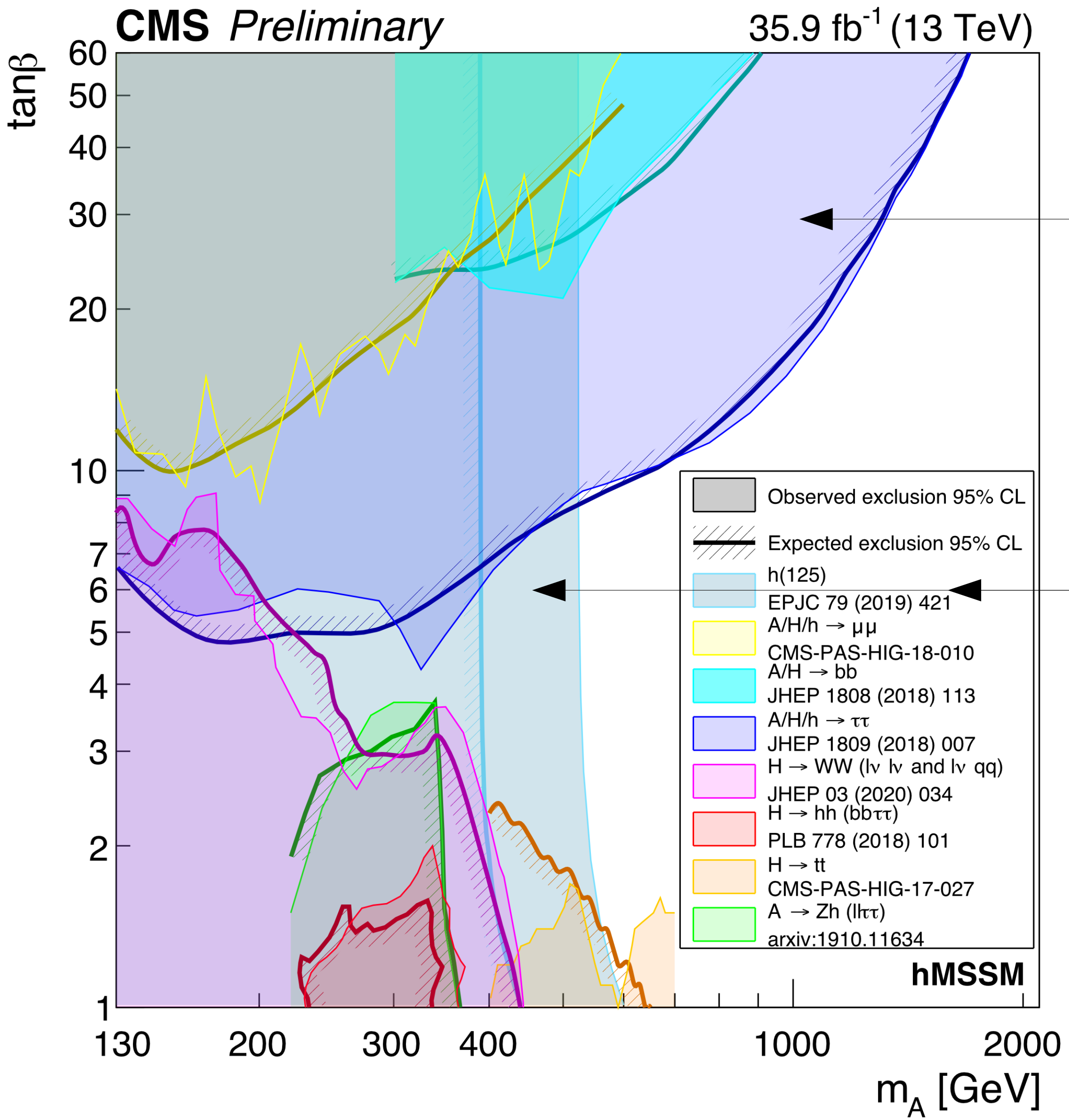
Get additional one-loop enhancement from light (collider-safe) pseudo-Dirac electroweakinos $\mathcal{O}(300\,\mathrm{GeV})$



Conclusions

- SUSY is still the best motivated framework, but there is no clear indication at what scale – unless low energy anomalies are confirmed.
- Electroweakinos are underexploited (very low limits) and may present the best chance of discovery: new techniques, LLPs, …
- Much to be done in precision computations and recasting.
- Scenarios beyond the MSSM (NMSSM, Dirac Gauginos, …) may have new interesting features … but even the CMSSM is not dead!

BACKUP



MSSM Higgs searches

Only reach about 500 GeV, although up to 2 TeV for high $\tan\beta$

$\tan\beta$ enhanced decays to taus

SM Higgs-like couplings

NB also have a limit of about 560 GeV from $B \to s\gamma$

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:

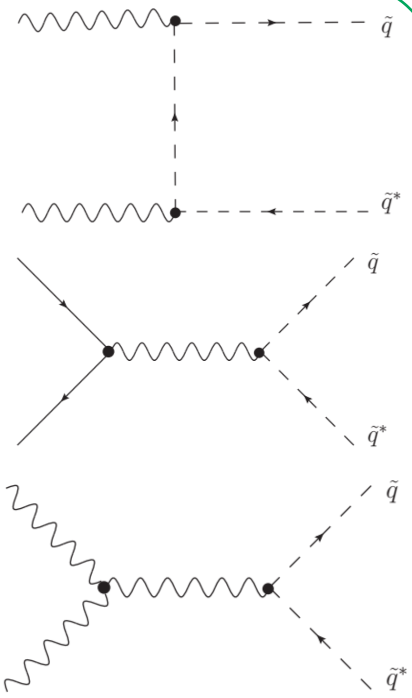
$$m_{DY}(S+\overline{S})(|H_u|^2 - |H_d|^2)$$

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

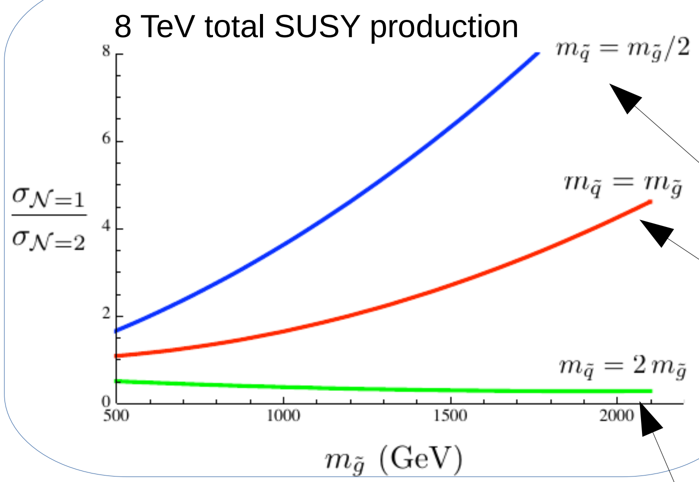
$$m_{DO}(O^a+\overline{O}^a)\sum \tilde{q}^* T^a \tilde{q}$$

And supersafe!

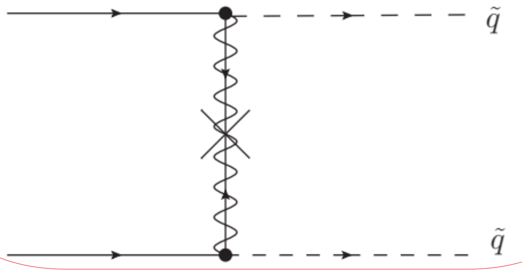
From 1111.4322 by Heikenheimo, Kellerstein, Sanz

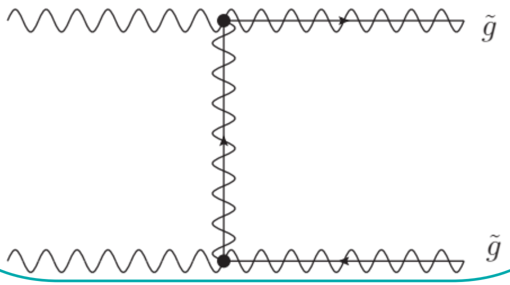


Diagrams common to Majorana/Dirac case



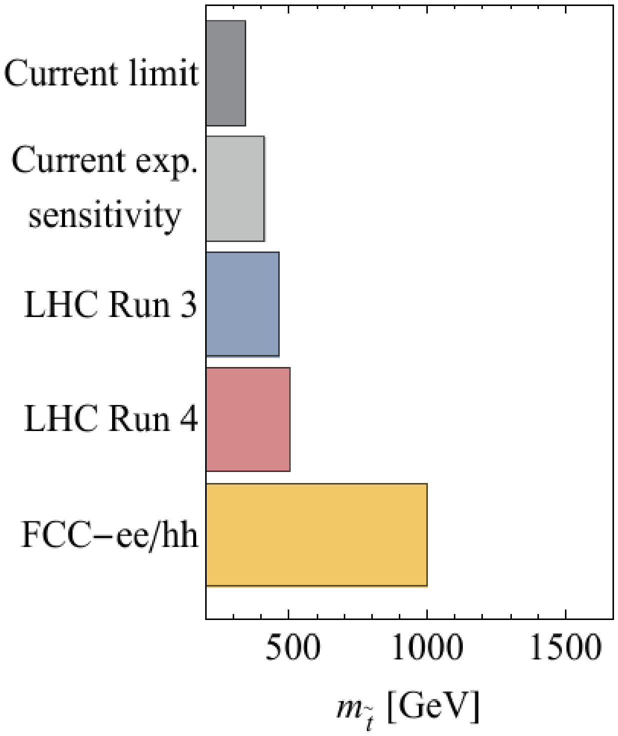
Chirality-flip diagram for squark production dominates in Majorana case, absent for Dirac

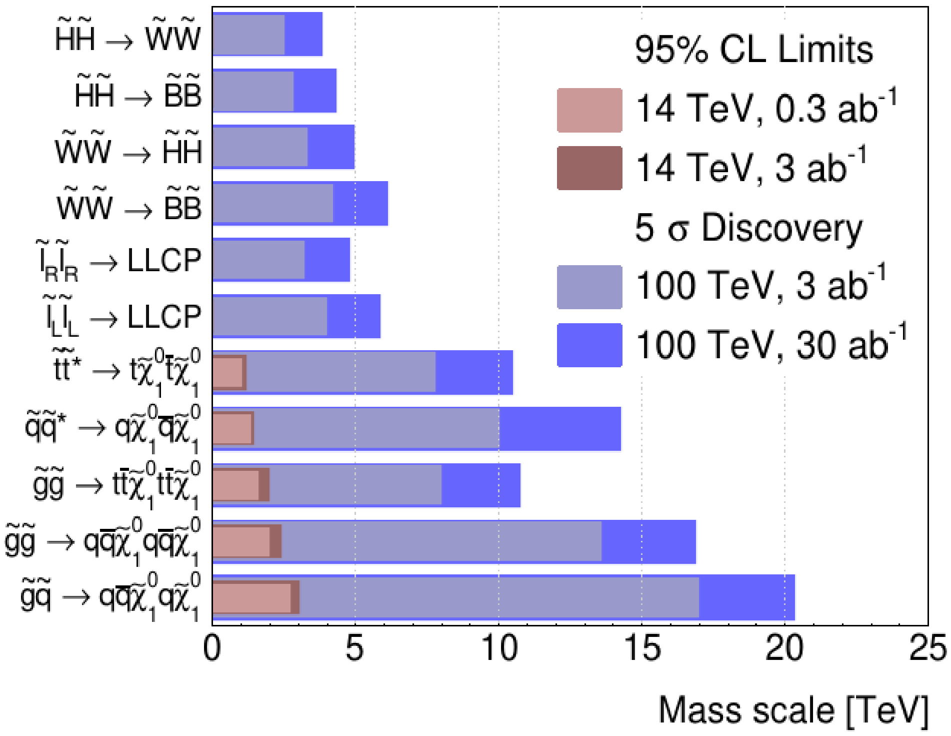




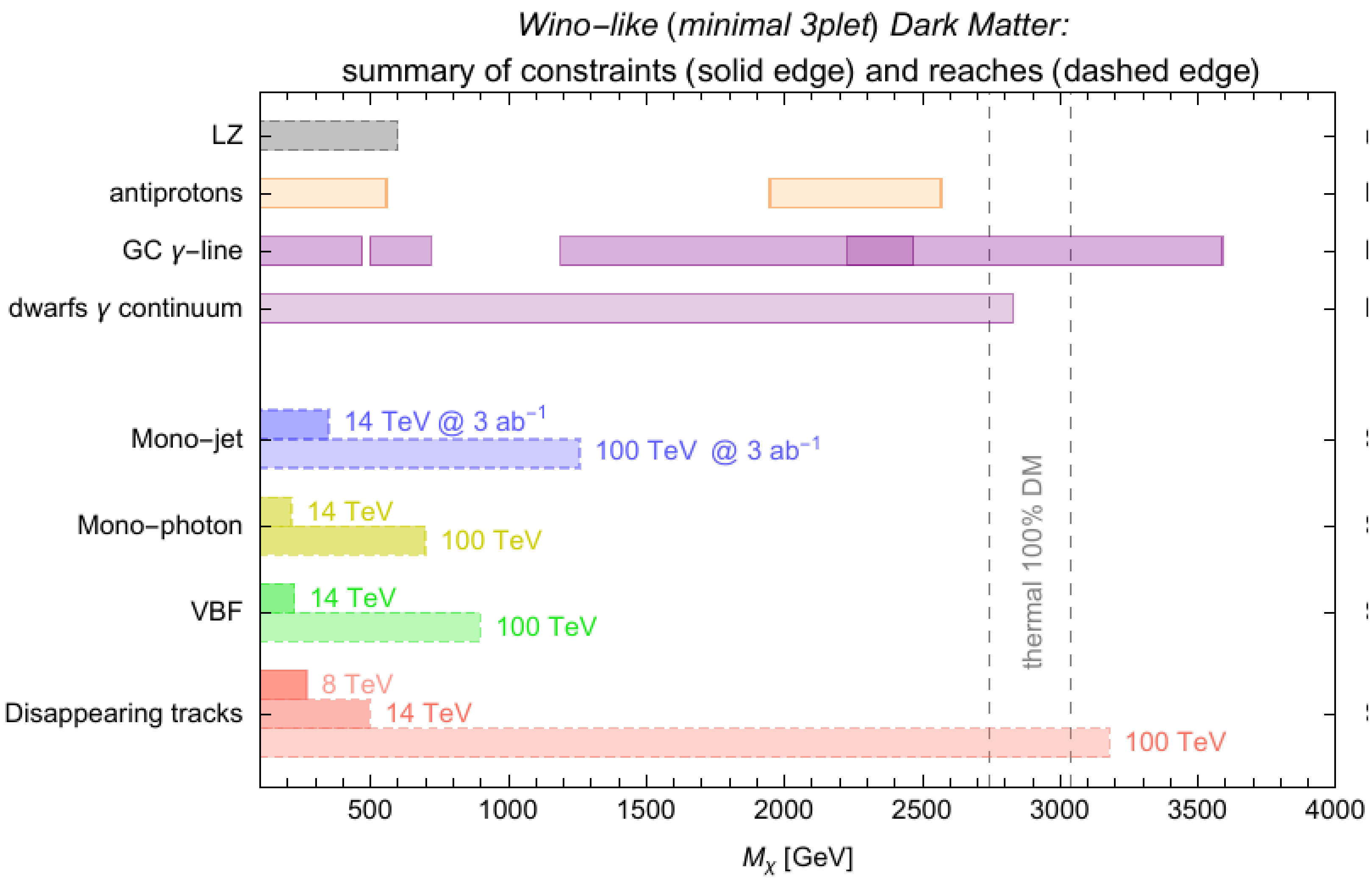
Production of gluinos ~ twice as large in Dirac case

FCC Projections for SUSY searches



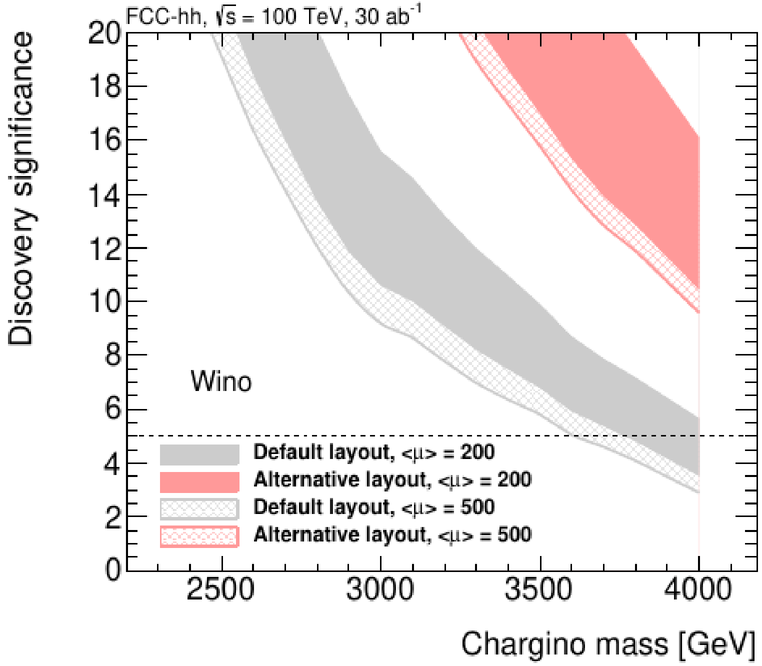


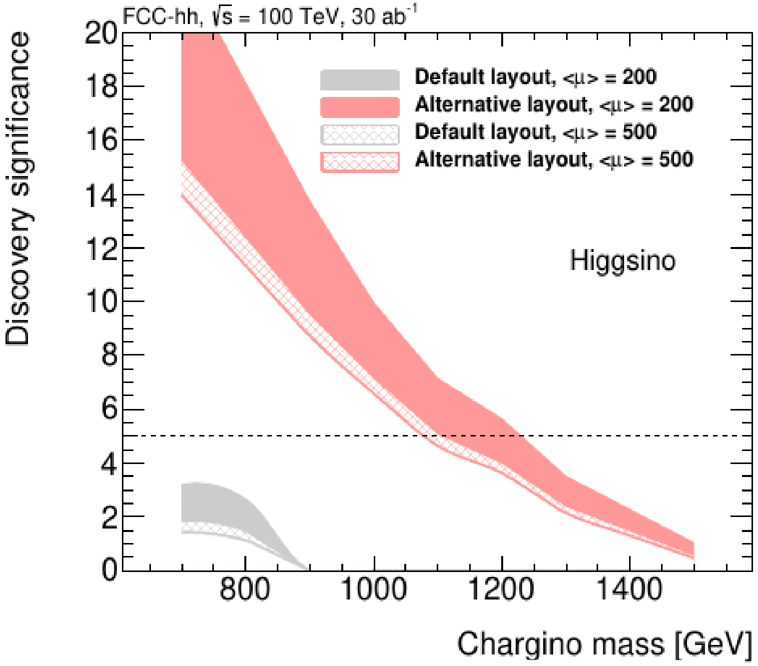
See Physics at a 100 TeV pp collider: beyond the Standard Model phenomena and FCC Physics Opportunities : Future Circular Collider Conceptual Design Report Volume 1



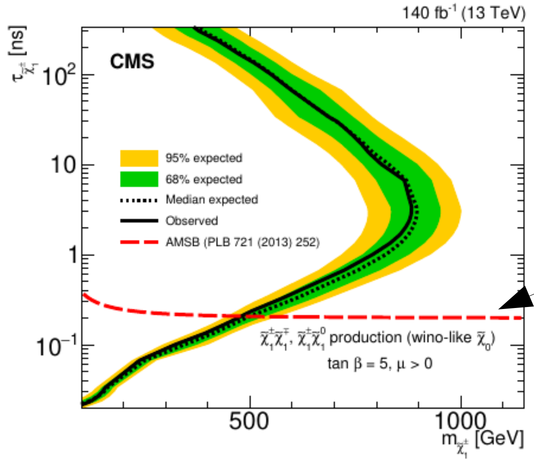
Wino−like (minimal 3plet) Dark Matter:
summary of constraints (solid edge) and reaches (dashed edge)
LZ
antiprotons
GC γ−line
dwarfs γ continuum
Mono−jet
14 TeV @ 3 ab⁻¹
100 TeV @ 3 ab⁻¹
Mono−photon
14 TeV
100 TeV
VBF
14 TeV
100 TeV
Disappearing tracks
8 TeV
14 TeV
100 TeV
thermal 100% DM
500
1000
1500
2000
2500
3000
3500
4000
Mχ [GeV]

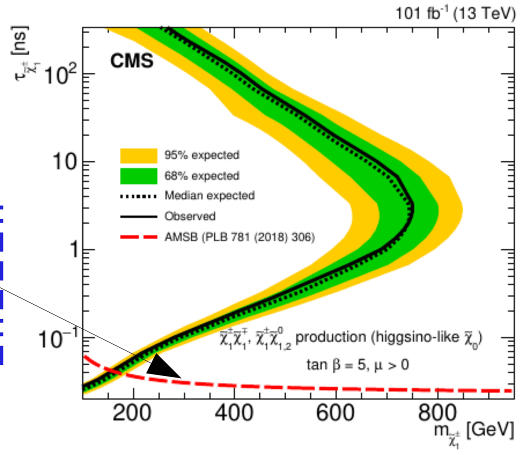
Disappearing tracks projections at FCC-hh:





c.f.
LHC:





Prediction for lifetime of pure wino/higgsino