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Status and Prospects for Supersymmetry at the FCC

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LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

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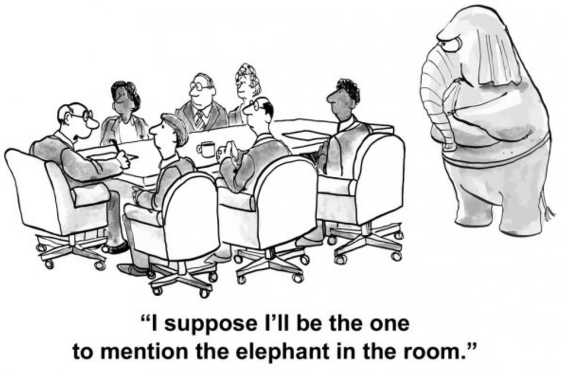
PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR

Overview

- Status of SUSY going into run 3
- Theory perspective on SUSY at the FCC
- Prospects

Isn't SUSY already dead?



- 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**

Even minimal scenarios could still be hiding in plain sight!

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2022

ATLAS Preliminary

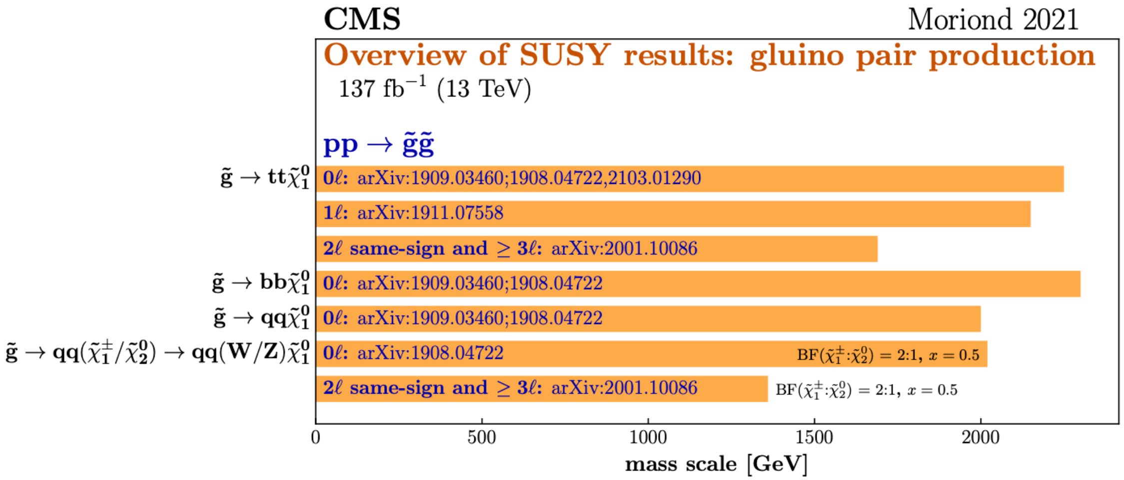
$\sqrt{s}$ = 13 TeV

	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{q}$ [1×, 8× Degen.]	1.0 / 1.85	m($\tilde{\chi}^0_1$)<400 GeV	2010.14293
		mono-jet	1-3 jets	$E_T^{\rm miss}$	139	$\tilde{q}$ [8× Degen.]	0.9	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{g}$	2.3	m($\tilde{\chi}^0_1$)=0 GeV	2010.14293
						$\tilde{g}$	Forbidden 1.15-1.95	m($\tilde{\chi}^0_1$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}^0_1$	1 e,μ	2-6 jets		139	$\tilde{g}$	2.2	m($\tilde{\chi}^0_1$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	139	$\tilde{g}$	2.2	m($\tilde{\chi}^0_1$)<700 GeV	CERN-EP-2022-014
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	139	$\tilde{g}$	1.97	m($\tilde{\chi}^0_1$) <600 GeV	2008.06032
		SS e,μ	6 jets		139	$\tilde{g}$	1.15	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde{g}$	2.25	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1909.08457
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	1.255	m($\tilde{\chi}^0_1$)<400 GeV	2101.12527
						$\tilde{b}_1$	0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}^0_1$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	Forbidden 0.23-1.35	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	1908.03122
		2 τ	2 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	0.13-0.85	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{t}_1$	1.25	m($\tilde{\chi}^0_1$)=1 GeV	2004.14060,2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$	Forbidden 0.65	m($\tilde{\chi}^0_1$)=500 GeV	2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$	Forbidden 1.4	m($\tilde{\tau}_1$)=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	139	$\tilde{t}_1$	0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_2$, $\tilde{\chi}^0_2\to Z/h\tilde{\chi}^0_1$	1-2 e,μ	1-4 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$	0.067-1.18	m($\tilde{\chi}^0_2$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	$E_T^{\rm miss}$	139	$\tilde{t}_2$	Forbidden 0.86	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	Multiple ℓ/jets		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.96	m($\tilde{\chi}^0_1$)=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.205	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	0.42	m($\tilde{\chi}^0_1$)=0, wino-bino	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	Multiple ℓ/jets		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	Forbidden 1.06	m($\tilde{\chi}^0_1$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		$E_T^{\rm miss}$	139	$\tilde{\tau}$ [$\tilde{\tau}_{\rm L}$, $\tilde{\tau}_{\rm R,L}$]	0.16-0.3 / 0.12-0.39	m($\tilde{\chi}^0_1$)=0	1911.06660
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\ell}$	0.7	m($\tilde{\chi}^0_1$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\ell}$	0.256	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	$E_T^{\rm miss}$	36.1	$\tilde{H}$	0.13-0.23 / 0.29-0.88	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{H}$	0.55	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	$\geq$ 2 large jets	$E_T^{\rm miss}$	139	$\tilde{H}$	0.45-0.93	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2108.07586
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	0.66	Pure Wino	2201.02472
						$\tilde{\chi}^\pm_1$	0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		$E_T^{\rm miss}$	139	$\tilde{g}$	2.05		CERN-EP-2022-029
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$	pixel dE/dx		$E_T^{\rm miss}$	139	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns]	2.2	m($\tilde{\chi}^0_1$)=100 GeV	CERN-EP-2022-029
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		$E_T^{\rm miss}$	139	$\tilde{e}$,$\tilde{\mu}$	0.7	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
						$\tilde{\tau}$	0.34	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
		pixel dE/dx		$E_T^{\rm miss}$	139	$\tilde{\tau}$	0.36	$\tau(\tilde{\ell})$ = 10 ns	CERN-EP-2022-029
RPV	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$ [BR($Z\tau$)=1, BR(Ze)=1]	0.625 / 1.05	Pure Wino	2011.10543
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$]	0.95 / 1.55	m($\tilde{\chi}^0_1$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$		4-5 large jets		36.1	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV]	1.3 / 1.9	Large λ''_{112}	1804.03568
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2]	0.55 / 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}^\pm_1$, $\tilde{\chi}^\pm_1\to bbs$		$\geq 4b$		139	$\tilde{t}$	Forbidden 0.95	m($\tilde{\chi}^\pm_1$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs]	0.42 / 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 / 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2/\tilde{\chi}^0_1$, $\tilde{\chi}^0_{1,2}\to tbs$, $\tilde{\chi}^+_1\to bbs$	1-2 e,μ	$\geq$6 jets		139	$\tilde{\chi}^0_1$	0.2-0.32	Pure higgsino	2106.09609

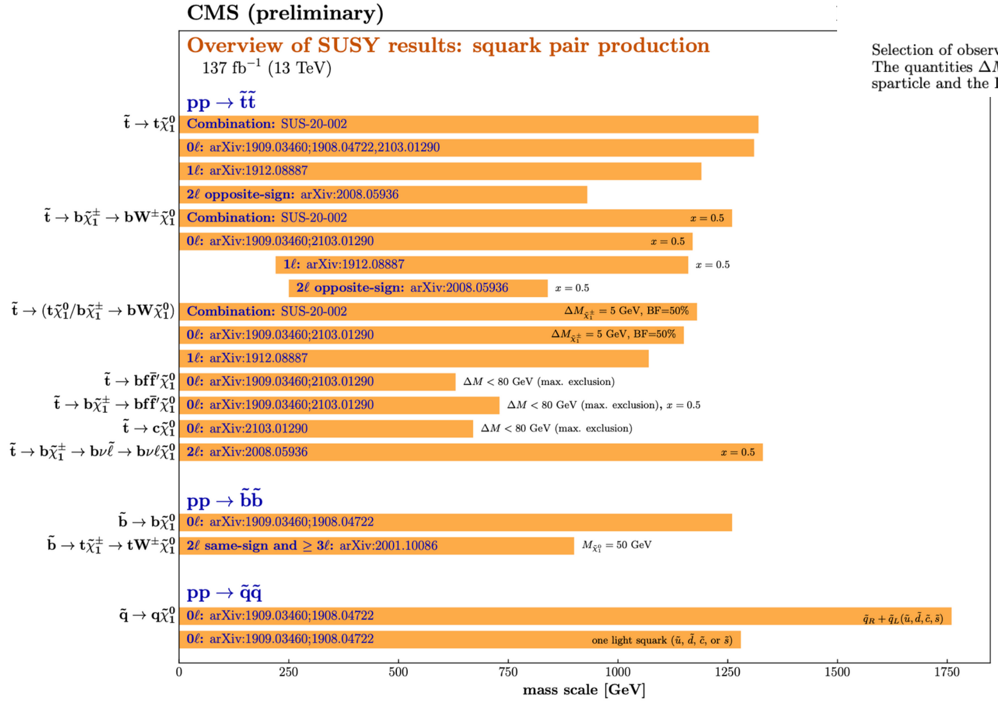
10^{-1} — 1 — Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

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.

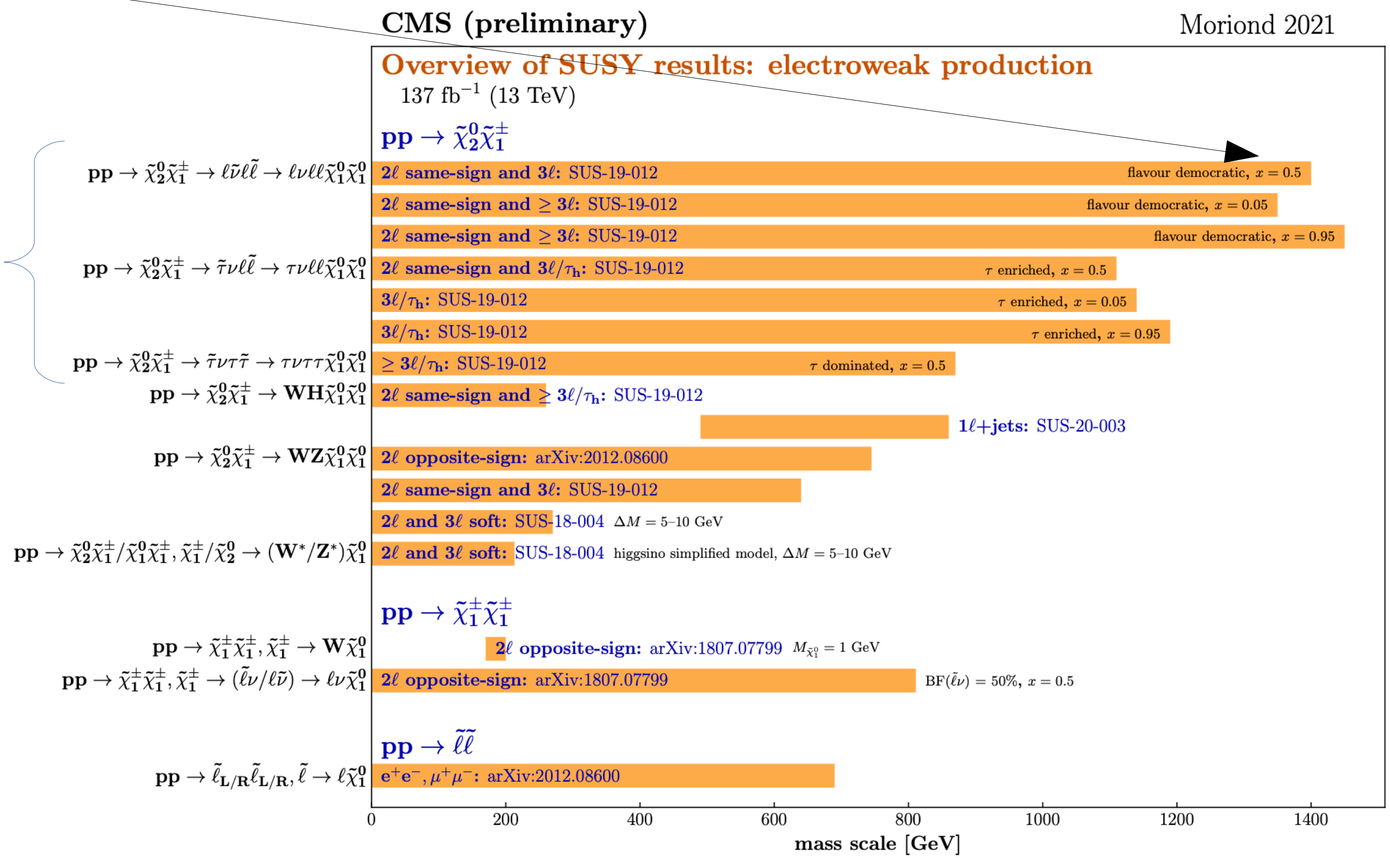
Limits on stops/sbottoms at best about 1300 GeV, but model dependent and holes remain

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

Limits on electroweak production have big headline numbers

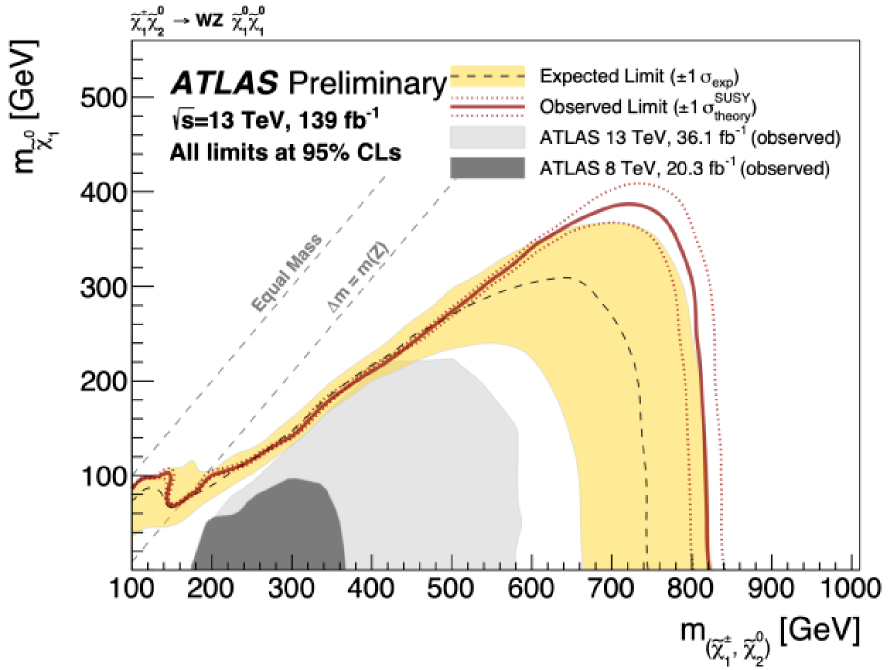
… but rely on light sleptons

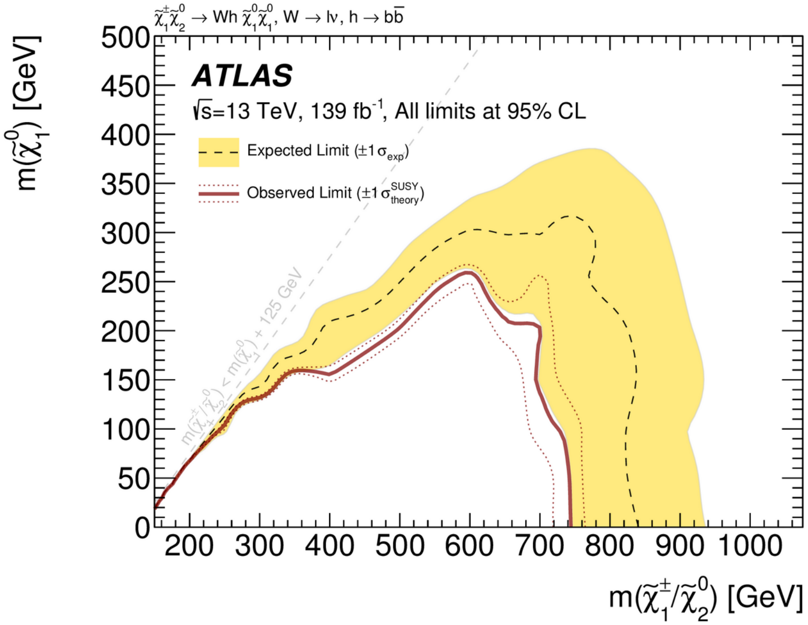
… and even the direct production limits are best cases:



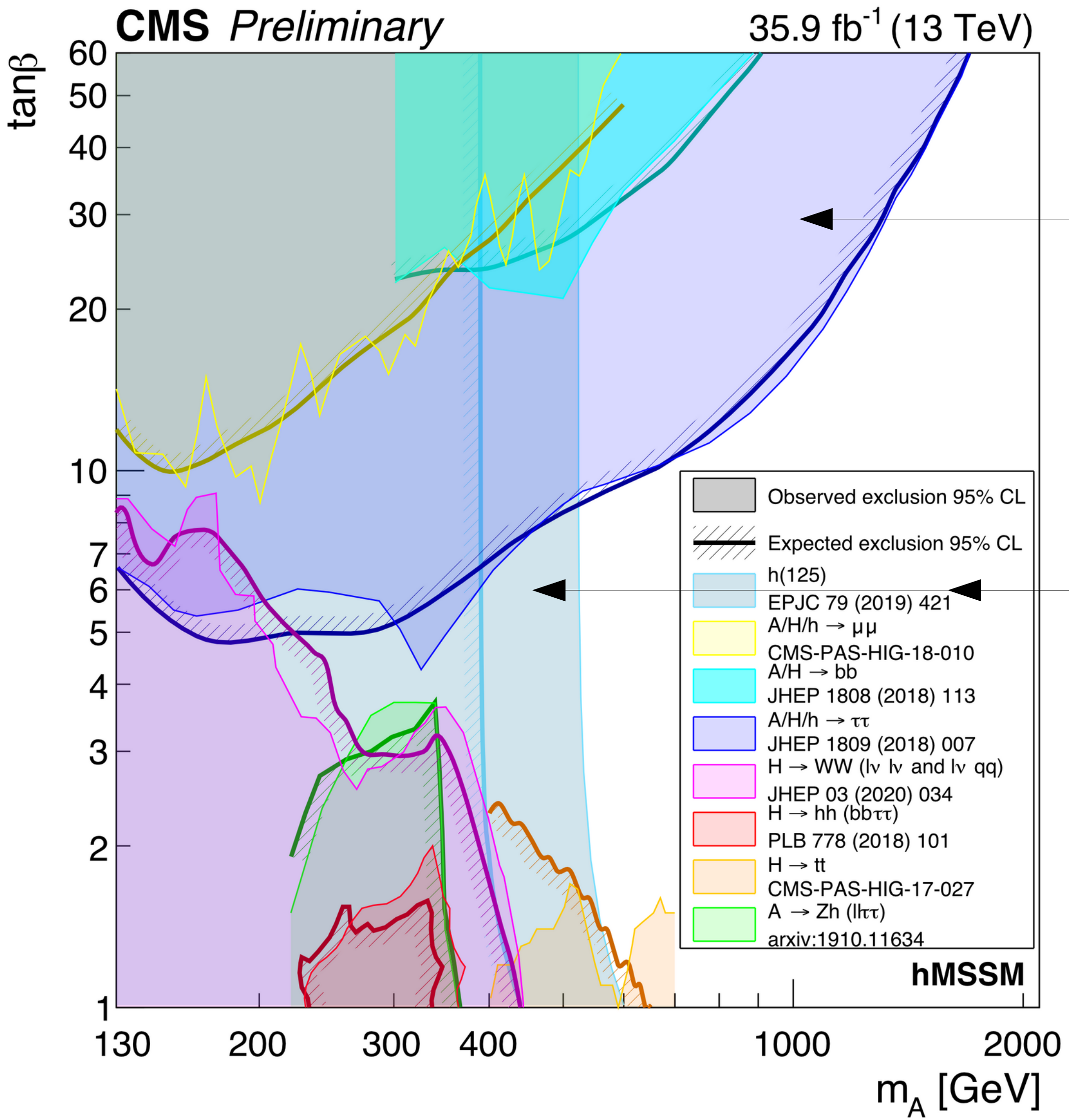
Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate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

These limits up to 800 GeV are for wino-like charginos:





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 $B \to s\gamma$

- Early LHC searches were for promptly decaying particles, LLPs have gained a lot of ground recently
- Huge number of BSM searches from runs 1 and 2 applicable to SUSY
- … but SUSY is more a framework than one model (even the MSSM can have hugely varied pheno).
- Need to test a given model against latest data, but this is far from automatic.
- HiggsSignals/HiggsBounds – and now **HiggsTools** – do a good job for the Higgs-like searches
- Various subsets of analyses have been reinterpreted in codes – can then be applied to different models with same signature
- Main frameworks are **MadAnalysis** (MA5), CheckMATE and ColliderBit (part of GAMBIT); **SModelS** uses a different fast approach.
- About 40 13 TeV analyses have been done for MA5; only 5 of these are full Run 2 datasets relevant for SUSY.

Definitive statements about current limits are not possible; even checking a given model point is still not automatic for SUSY

Heavy SUSY/split SUSY/minimal DM are classic examples which may be hiding under our noses

Why SUSY at the FCC?

- Is apparent gauge coupling unification just a cruel joke of nature?
- SUSY reduces the Hierarchy problem to the Little Hierarchy problem
- It also allows us to address the cosmological constant problem
- It provides dark matter candidates and can readily address baryogenesis
- It seems to be necessary for string theory → quantum gravity

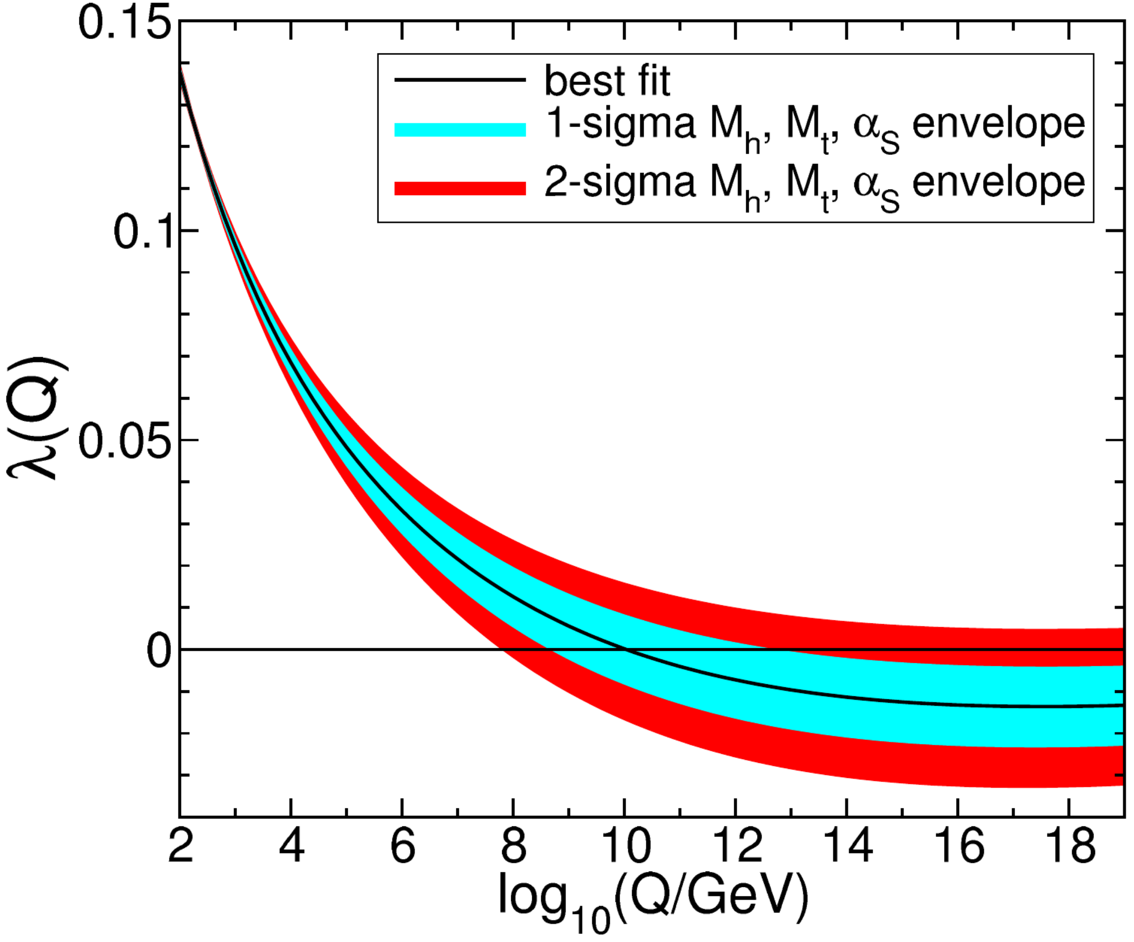
- A 125 GeV Higgs implies somewhat heavy colourful superpartners
- Flavour physics constraints indirectly imply heavy colourful states – except for the B anomalies!
- For a WIMP neutralino DM candidate, a pure Wino should have mass of ~ 2.7 TeV, and a Higgsino around a TeV:

$$\Omega h^2(\text{wino}) \sim 0.11 \left(\frac{m}{2.7\,\text{TeV}}\right)^2 \qquad \Omega h^2(\text{higgsino}) \sim 0.1 \left(\frac{m}{\text{TeV}}\right)^2$$

- The heavier the colourful states, if we want a wimp DM candidate we cannot have arbitrarily heavy electroweak states: they should be in reach of the FCC!

SM quartic coupling, taken from Martin and Robertson, 2019:

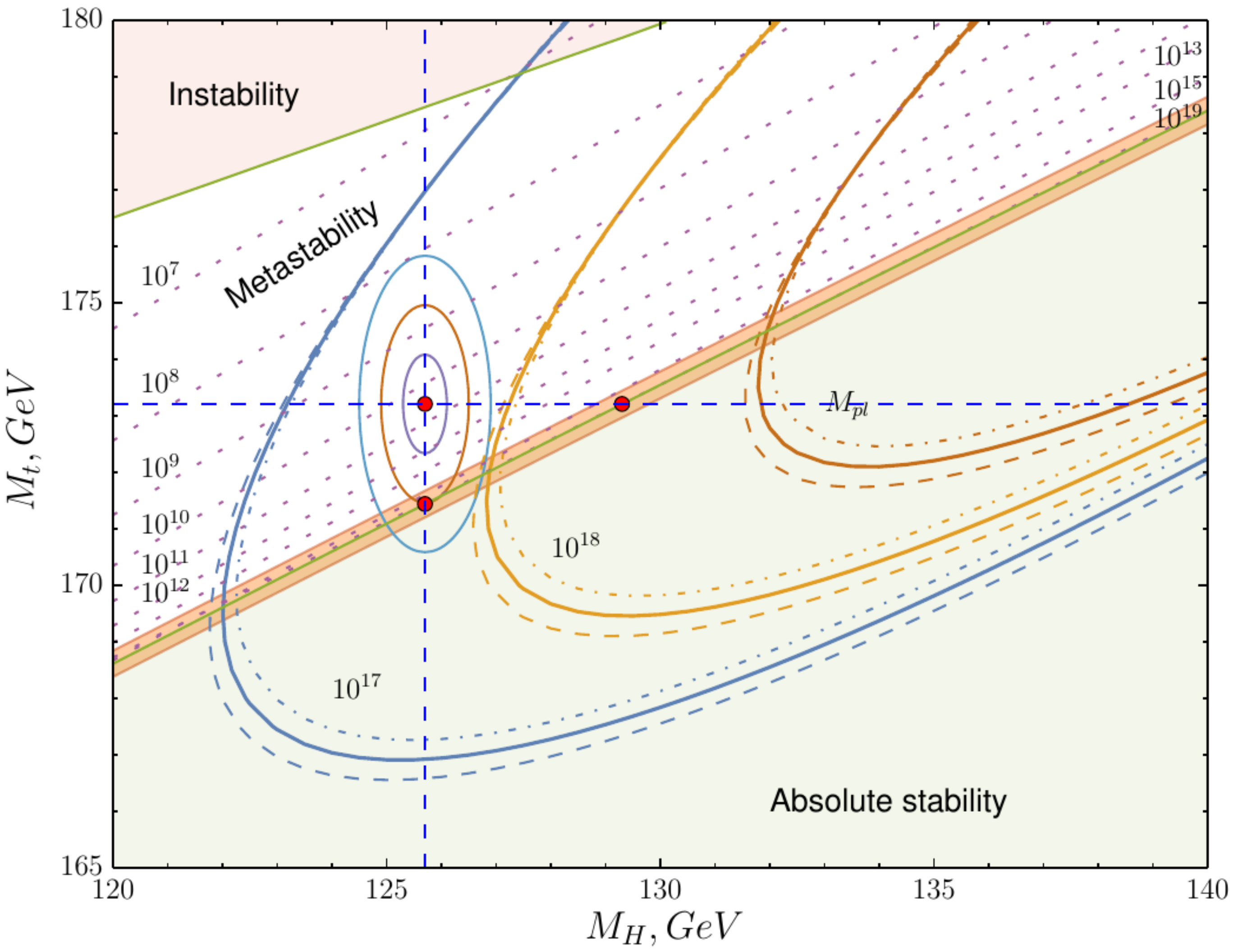
Implies an upper bound on the SUSY scale



Biggest source of uncertainty is the top quark mass

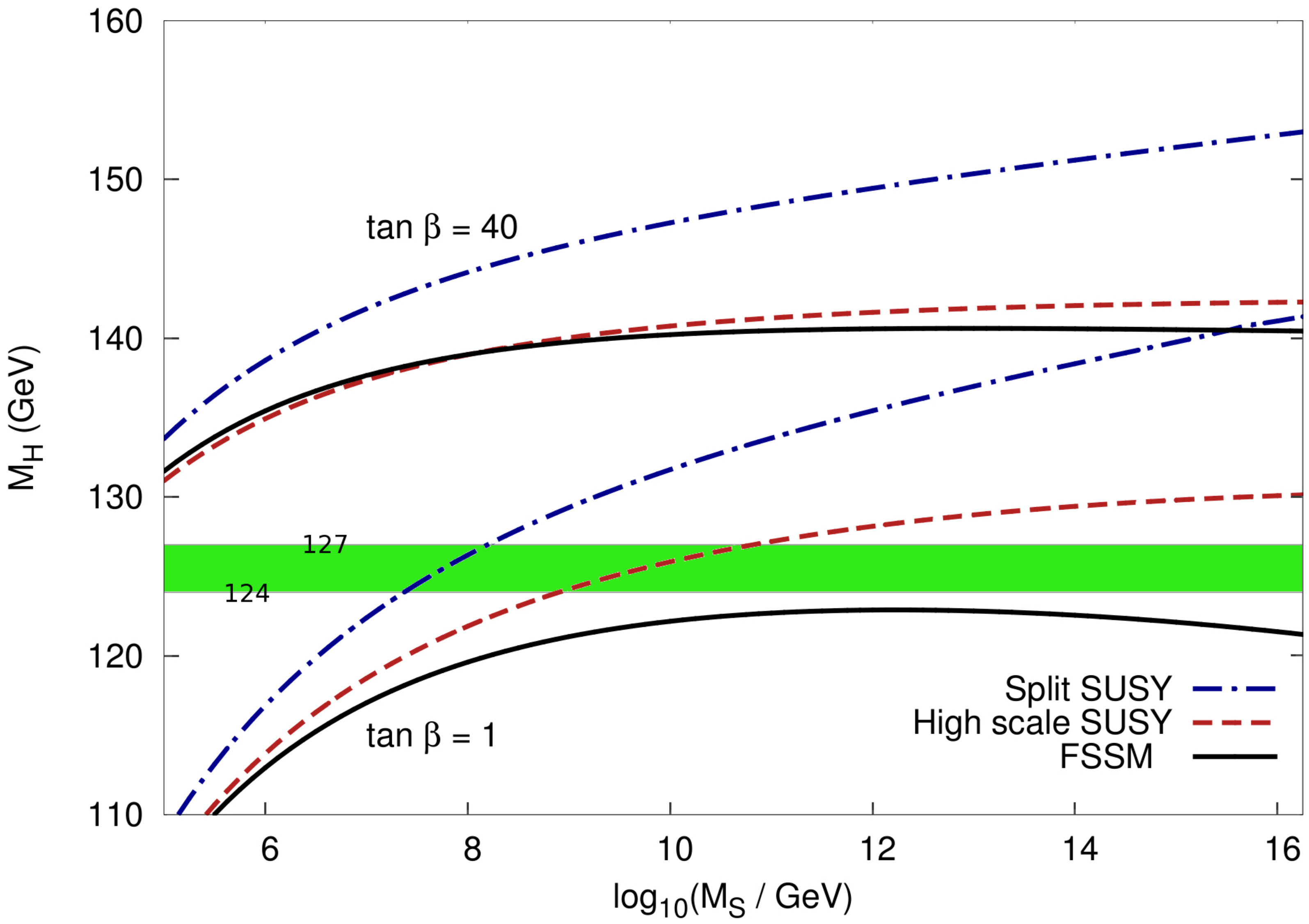
SM stability

Taken from the website of the code MR: http://apik.github.io/mr/



But we can do better!

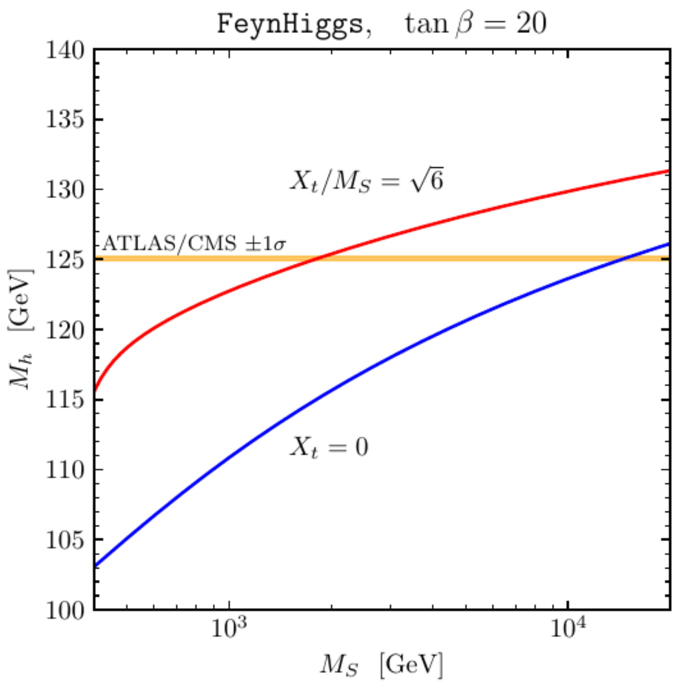
Predictions for the Higgs mass in different SUSY scenarios:

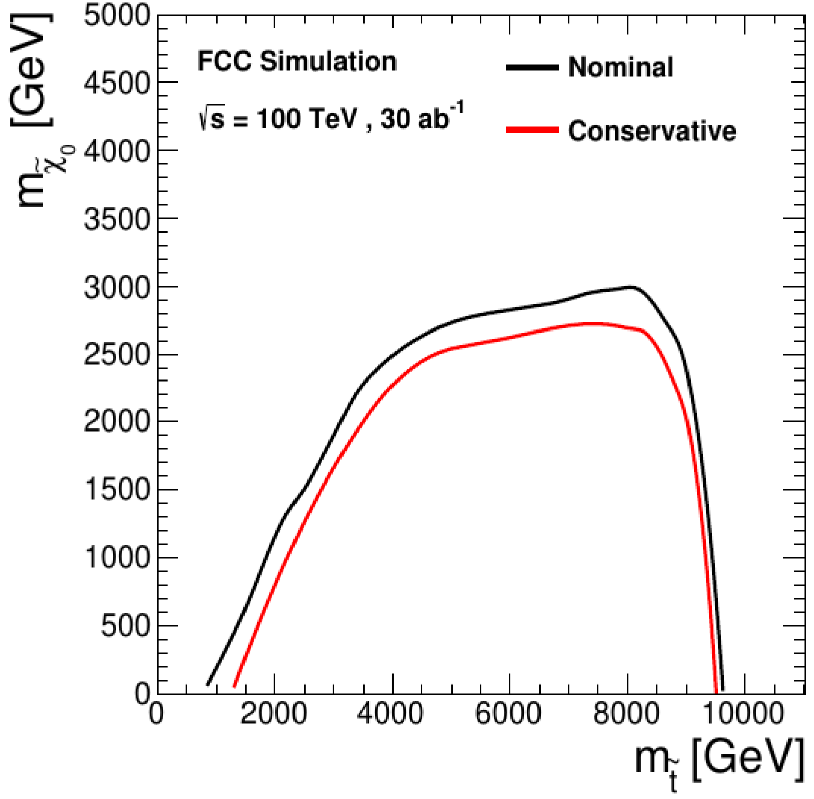


The Higgs mass can be used to put an upper limit on the SUSY scale!

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

Precision computations of the MSSM Higgs mass show, for moderate to high tan β, stops should be within reach of the FCC:

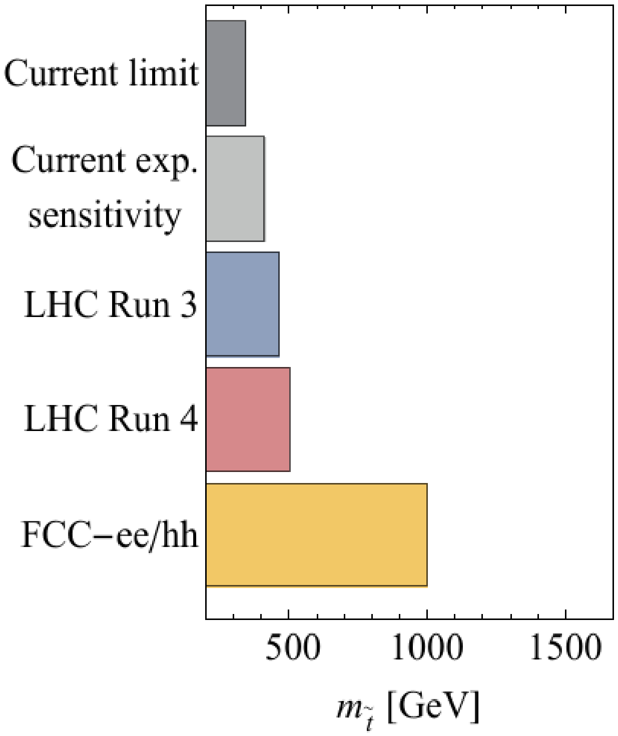


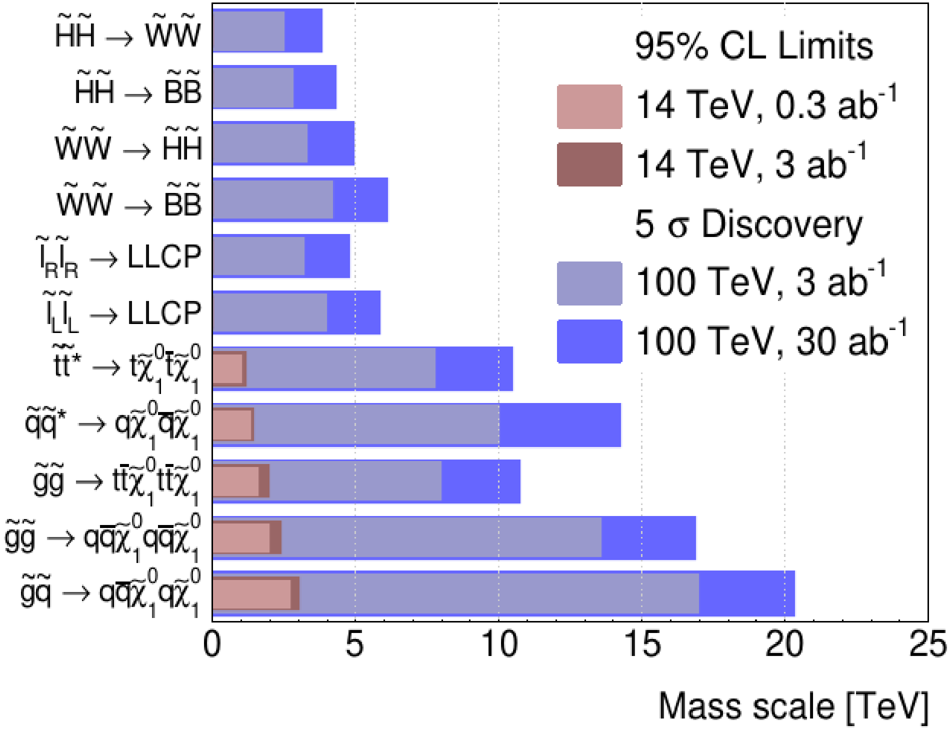


Leads to a reasonable set of hypotheses:

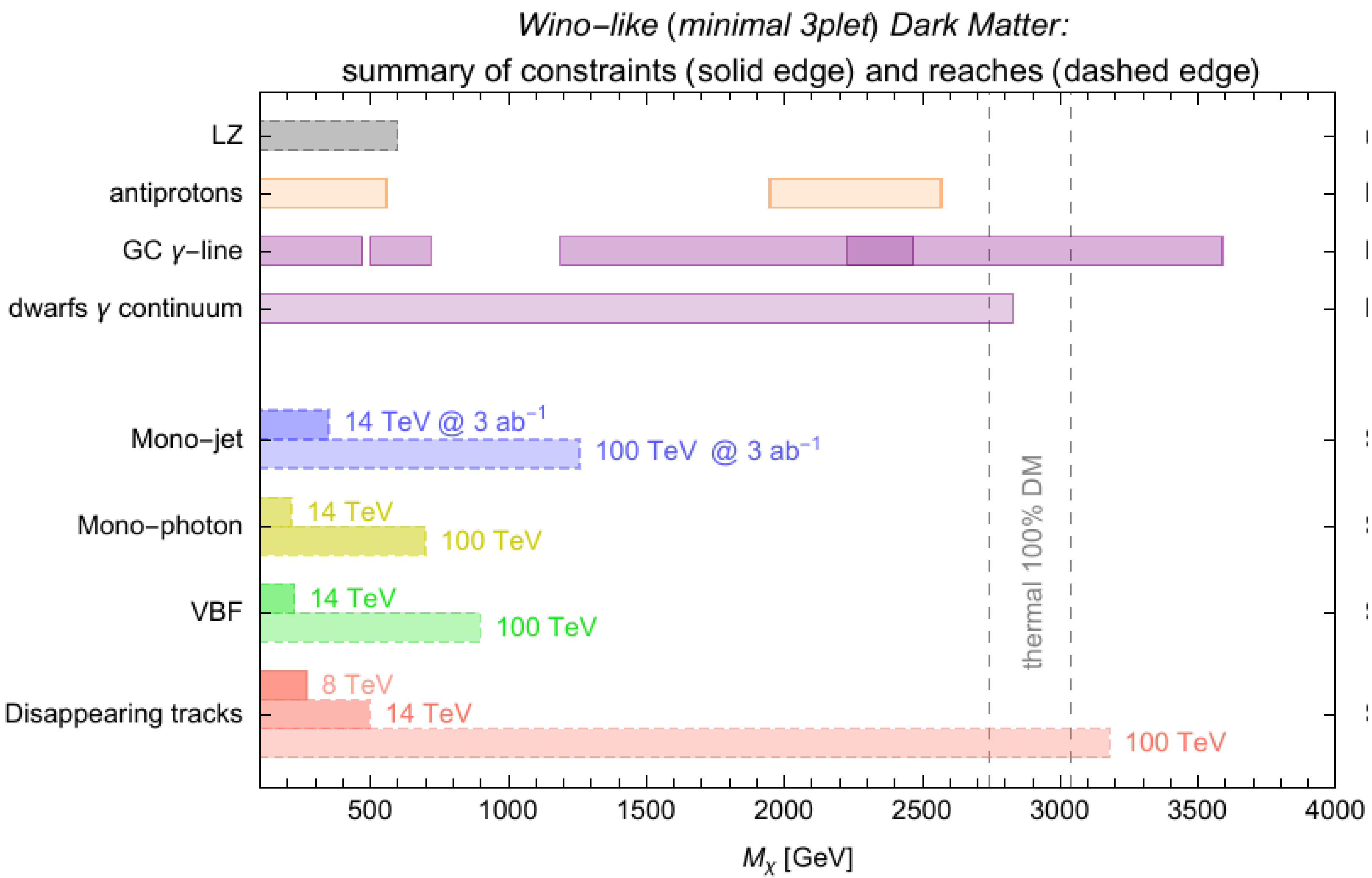
- Worst case scenario is heavy SUSY with non-WIMP DM, and **no gauge coupling unification**
- Split SUSY (all scalars heavy except the Higgs) allows WIMP DM, but the Higgs mass + gauge coupling unification favour a mini-split of masses up to 100 TeV
- SUSY could easily be lurking in plain sight, or with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

FCC Projections for SUSY searches

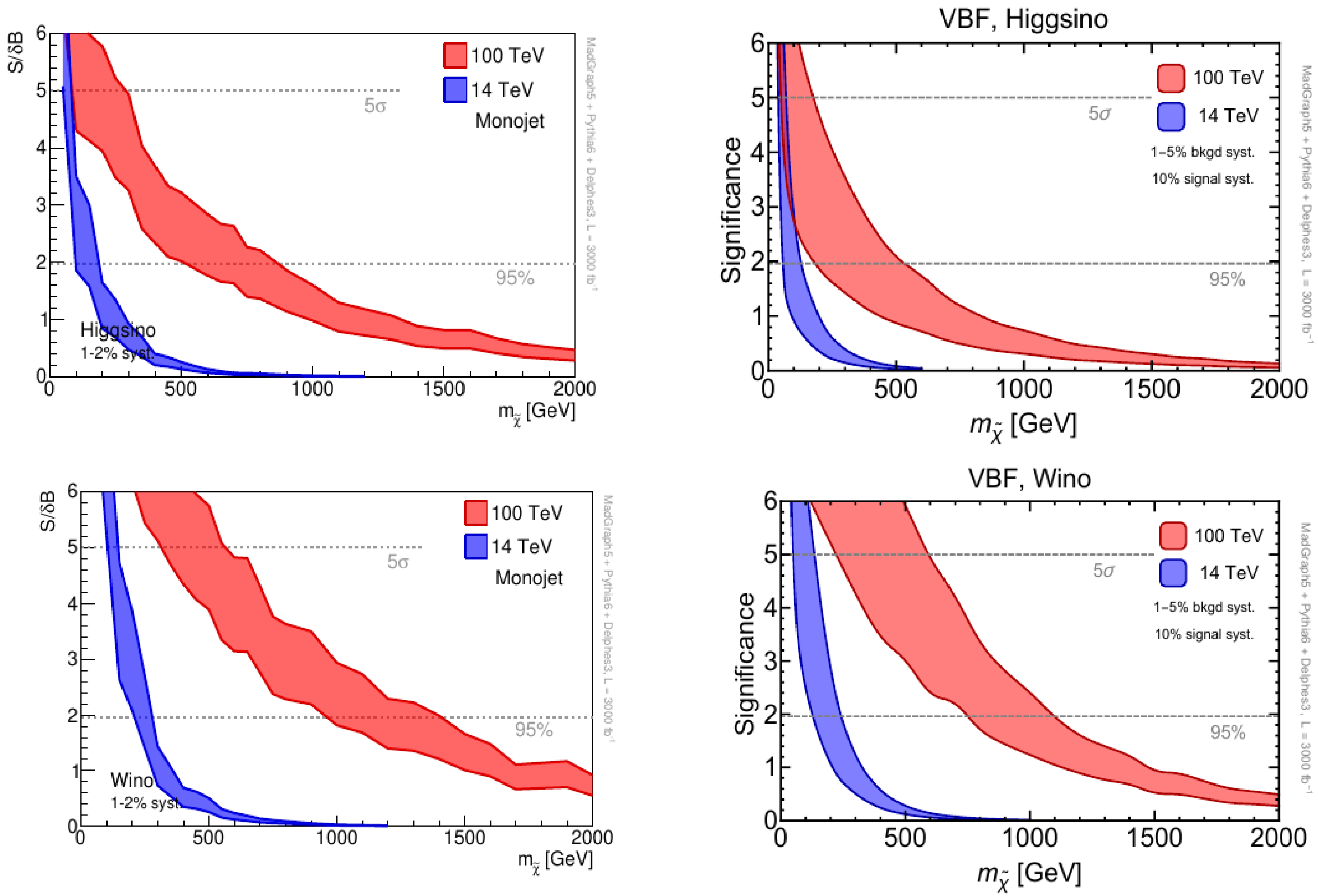




See Physics at a 100 TeV pp collider: beyond the Standard Model phenomena and
FCC Physics Opportunities : Future Circular Collider Conceptual Design Report Volume 1

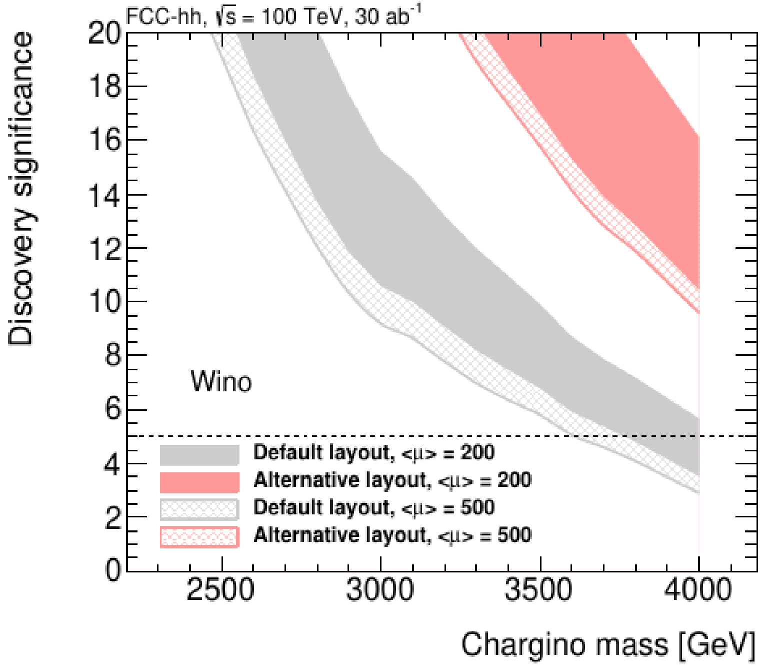


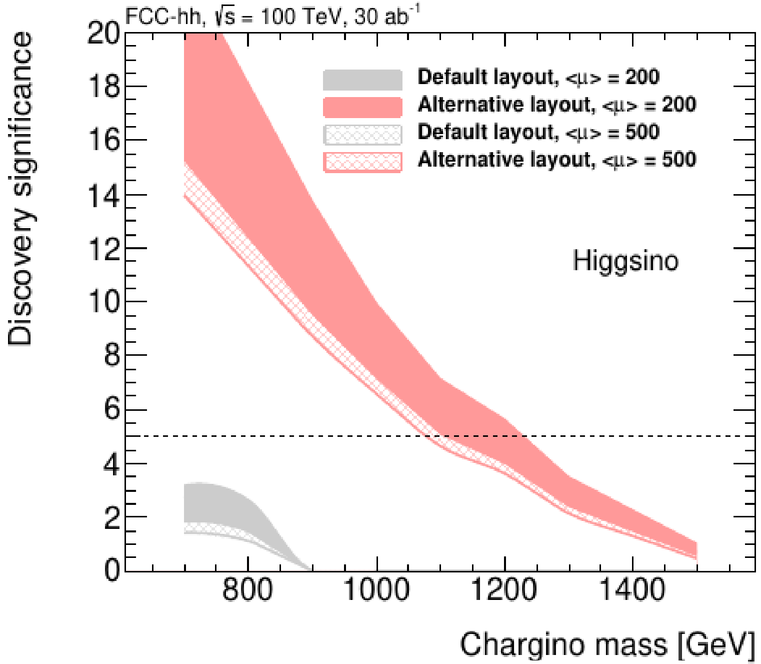
Wino−like (minimal 3plet) Dark Matter:
summary of constraints (solid edge) and reaches (dashed edge)
LZ
antiprotons
GC γ−line
dwarfs γ continuum
Mono−jet
14 TeV @ 3 ab−1
100 TeV @ 3 ab−1
Mono−photon
14 TeV
100 TeV
VBF
14 TeV
100 TeV
Disappearing tracks
8 TeV
14 TeV
100 TeV
thermal 100% DM
500
1000
1500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



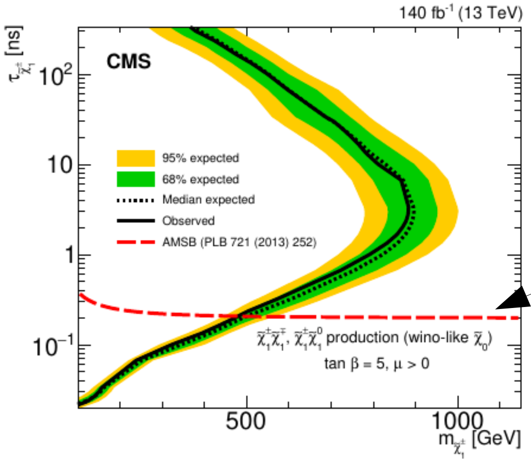
S/δB
100 TeV
14 TeV
Monojet
5σ
95%
Higgsino
1-2% syst.
m_χ̃ [GeV]
MadGraph5 + Pythia6 + Delphes3, L = 3000 fb⁻¹
VBF, Higgsino
Significance
100 TeV
14 TeV
1–5% bkgd syst.
10% signal syst.
5σ
95%
m_χ̃ [GeV]
MadGraph5 + Pythia6 + Delphes3, L = 3000 fb⁻¹
S/δB
100 TeV
14 TeV
Monojet
5σ
95%
Wino
1-2% syst.
m_χ̃ [GeV]
MadGraph5 + Pythia6 + Delphes3, L = 3000 fb⁻¹
VBF, Wino
Significance
100 TeV
14 TeV
1–5% bkgd syst.
10% signal syst.
5σ
95%
m_χ̃ [GeV]
MadGraph5 + Pythia6 + Delphes3, L = 3000 fb⁻¹

Disappearing tracks projections at FCC-hh:

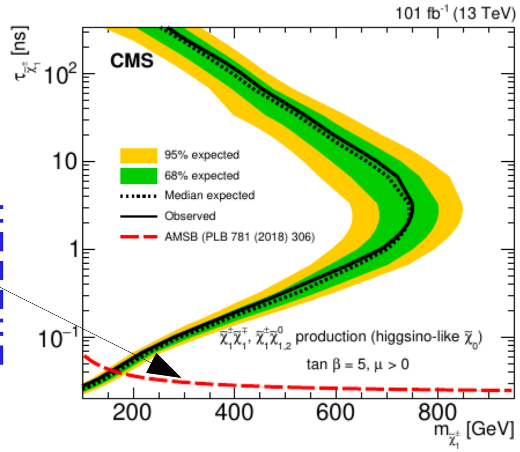




c.f. LHC:



Prediction for lifetime of pure wino/higgsino



Conclusions

- Search strategies for the FCC seem to mimic LHC ones: monojet, pair production, disappearing tracks
- New searches are being developed for run 3 (displaced vertices, machine learning) which might also help FCC strategies …
- … I didn’t find much activity on this recently
- Also tools for projections for the FCC are needed! (notably cross-section calculators exist, key4HEP is a very encouraging development – need more automation for theorists too!)