NMSSM signatures at the LHC

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Why the NMSSM?

- Relatively heavy Higgs @ LHC $\Rightarrow$ fine-tuning in the MSSM
- μ-problem of the MSSM: SUSY conserving mass term for H_u, H_d
  - $\mu = 0$ ➠ experimentally excluded ($\mu \geq 100$ GeV)
  - $\mu = M_{\text{Planck}}$ ➠ hierarchy problem ($\mu \sim M_{\text{susy}}$)
- Solution: add a gauge singlet S coupled to H_u, H_d

$$W_{\text{MSSM}} = \mu H_u H_d + \ldots \quad \rightarrow \quad W_{\text{NMSSM}} = \lambda S H_u H_d + \frac{\kappa}{3} S^3 + \ldots$$

After minimisation of the potential $\mu_{\text{eff}} \equiv \lambda \langle S \rangle \sim M_{\text{susy}}$

- The NMSSM is the simplest SUSY extension of the SM where the electroweak scale originates from the SUSY breaking **only**
- $\lambda \sim \kappa \rightarrow 0,\ \mu_{\text{eff}} \neq 0$ ➠ effective MSSM + decoupled singlet sector

$\Rightarrow$ the parameter space of the NMSSM includes the MSSM **and more**

What's the NMSSM?

- Particle content:
  - $\widetilde{S}$: one more neutralino ➡ $\widetilde{\chi}^0_{i=1..5}$
  - S_R : one more neutral CP-even Higgs ➡ $h_{i=1..3}$
  - S_I : one more neutral CP-odd Higgs ➡ $a_{i=1..2}$

- **Parameters:** $V_{\text{Higgs}} = V_{\text{F}} + V_{\text{D}} + V_{\text{soft}}$

$$V_{\text{soft}} = \left(\lambda A_\lambda H_u H_d S + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.}\right) + m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_S|S|^2$$

+ 3 minimization equations:

$$\mu_{\text{eff}} = \lambda\langle S\rangle, \quad \tan\beta = \frac{\langle H^0_u\rangle}{\langle H^0_d\rangle}, \quad M^2_Z = g^2\left(\langle H^0_u\rangle^2 + \langle H^0_d\rangle^2\right)$$

$\Rightarrow$ **6 free parameters in the Higgs sector:** λ, κ, A_λ, A_κ, μ_{eff}, $\tan\beta$

Recall: in the MSSM, 2 free parameters in the Higgs sector (m_A, $\tan\beta$)

NB: A_λ, $A_\kappa \leftrightarrow m_A$, m_P (diagonal elements of the CP-odd mass matrix)

Parameters at the weak scale

- If $A_\lambda = A_\kappa = 0$, the Higgs sector is invariant under a U(1) R-symmetry explicitly broken by gaugino masses ⇒ a_1 is a **light pseudo-Goldstone**
  Light pseudoscalar also with PQ symmetry when $\kappa = 0$ (nMSSM)
  In this case the singlino is also very light ($m_{a_1} \simeq 2\, m_{\tilde{S}}$ for correct DM)
- In general: $\Delta W = \mu H_u H_d + \mu' S^2 + \xi_F S\,, \quad \Delta V_{\rm soft} = \left(m_3^2 H_u H_d + m_S'^2 S^2 + \xi_S S + {\rm h.c.} \right)$
  One can always put $\mu = 0$ by the field redefinition $S \longrightarrow S - \mu/\lambda$
  However assuming $\xi_F = \xi_S = \mu' = m_S' = m_3 = 0$ ⇔ Z_3 symmetry

⇒ <u>Domain wall problem:</u> anisotropies in CMB + wrong BBN

➥ Assume tiny ***Z*3-breaking** interactions (no impact on spectrum)

⇒ <u>Tadpole problem:</u> $\xi_F = \Lambda\, M_{\rm susy}$, $\xi_S = \Lambda\, M_{\rm susy}^2$ (hierarchy pb)

➥ Assume new **discrete R-symmetries** at the high scale such that tadpole terms are generated radiatively with small coefficients

NB: In nMSSM (where $\kappa = 0$), one needs ξ_F, $\xi_S \neq 0$

Parameters at the high scale

- mSUGRA: $M_{1/2}$, m_0, A_0 (at M_{GUT}) + λ, κ, $\tan\beta$, sgn(μ_{eff}) (at M_{weak}) **?**

  $\Rightarrow$ Z_3-NMSSM: **1** free parameter (μ_{eff}) for **3** min. equations (M_{weak})

  ➥ Solution: assume semi-universal singlet soft terms at M_{GUT}

  - Parameters: λ, $\tan\beta$, sgn(μ_{eff}), $M_{1/2}$, m_0, A_0, [A_λ, A_κ]
  - Minimization conditions $\Rightarrow$ μ_{eff}, κ, m_S (at M_{weak})
    - ✦ Guess M_{GUT} and κ, m_S at this scale
    - ✦ Run the RGEs down to M_{weak}, compute μ_{eff}, κ, m_S ←
    - ✦ Run the RGEs up to M_{GUT}, distance from universality (iterate)
  - Similar algorithm for GMSB (checking for correct m_S)
- cNMSSM: take $A_\lambda = A_\kappa = A_0$, keep only $m_S = m_0$ (very constrained)
- NUH-NMSSM: Non-Universal Higgs sector
  - Parameters: $M_{1/2}$, m_0, A_0, A_λ, A_κ, λ, κ, $\tan\beta$, μ_{eff}
  - Minimization conditions $\Rightarrow$ m_{H_u}, m_{H_d}, m_S (at M_{weak})

  ➥ Used to study the nMSSM ($\kappa = A_\kappa = 0$ but ξ_F, $\xi_S \neq 0$)

The NMSSMTools package

- Package that contains 4 programs:
  - **NMHDECAY** for general NMSSM with soft terms at M_{weak}
  - **NMHDECAYCPV** for Z_3-NMSSM with CPV soft terms at M_{weak}
  - **NMSPEC** for mSUGRA (non-universal) models with inputs at M_{GUT}
  - **NMGMSB** for GMSB (extended) models with inputs at M_{mes}

  <u>Each in 4 versions:</u> 1 point, random scan, grid scan or MCMC scan

- For a given set of input parameters, it computes:
  - (2 loop) RGEs for all parameters $M_{weak} \leftrightarrow M_{GUT}$
  - Sparticle/Higgs masses and mixings (2 loop LL or *à la* Slavich)
  - Higgs decay widths in 2/3 particles (QCD corrections as in **HDECAY**)
  - DM relic density + (in)direct detection (interface with **micrOMEGAs**)
  - B physics: $b \to s\gamma$, $B_s \to \mu^+\mu^-$, $B \to X_s\, l^+ l^-$, $B \to \tau\upsilon$, $\Delta M_{s(d)}$, $\Upsilon \to a\gamma$, $(g\text{-}2)_\mu$…

- I/O files in SLHA2 conventions + script: `run $PATH/$P{inp}$S`
  - ➡ `$PATH/$P{spectr}$S`, `$PATH/$P{omega}$S` (1 point)
  - ➡ `$PATH/$P{out}$S`, `$PATH/$P{err}$S` (scan versions)

Input files

inp.dat

```
# Input file for NMSSMTools
# Based on SUSY LES HOUCHES ACCORD II

BLOCK MODSEL
        3       1               # NMSSM particle content
        1       0               # IMOD (0=general NMSSM, 1=mSUGRA, 2=GMSB)
        10      0               # ISCAN (0=no scan, 1=grid scan, 2=random scan)
        9       0               # Call micrOmegas (default 0=no, 1=relic density only,
#                                 2=dir. det. rate, 3=indir. det. rate, 4=both det. rates)
        8       0               # Precision for Higgs masses (default 0: as before,
#                                 1: full 1 loop + full 2 loop from top/bot Yukawas
#                                 2: as 1 + pole masses - 1&2 by courtesy of P. Slavich)
BLOCK SMINPUTS
        1       127.92D0        # ALPHA_EM^-1(MZ)
        2       1.16639D-5      # GF
        3       .1172D0         # ALPHA_S(MZ)
        4       91.187D0        # MZ
        5       4.214D0         # MB(MB) (running mass)
        6       171.4D0         # MTOP (pole mass)
        7       1.777D0         # MTAU

BLOCK MINPAR
#       0       1000.D0         # MSUSY (If =/= SQRT(2*MQ1+MU1+MD1)/2)
        3       2.D0            # TANB

BLOCK EXTPAR
#       1       100.D0          # M1 (If =/= M2/2)
        2       200.D0          # M2
#       3       600.D0          # M3 (If =/= 3*M2)
        11      -2500.D0        # AU3
        12      -2500.D0        # AD3
        13      -2500.D0        # AE3
#       16      -2500.D0        # AE2 = AE1 (If =/= AE3)
        33      200.D0          # ML3
#       32      200.D0          # ML2 = ML1 (If =/= ML3)
        36      200.D0          # ME3
#       35      200.D0          # ME2 = ME1 (If =/= ME3)
        43      1000.D0         # MQ3
#       42      1000.D0         # MQ2 = MQ1 (If =/= MQ3)
        46      1000.D0         # MU3
#       45      1000.D0         # MU2 = MU1 (If =/= MU3)
        49      1000.D0         # MD3
#       48      1000.D0         # MD2 = MD1 (If =/= MD3)
        61      .7D0            # LAMBDA
        62      .05D0           # KAPPA
        63      1280.           # ALAMBDA (If MA is not an input)
        64      0.D0            # AKAPPA
        65      530.D0          # MUEFF
#       124     1321.D0         # MA (If ALAMBDA is not an input)
```

randinpsp.dat

```
# Input file for NMSSMTools
# Based on SUSY LES HOUCHES ACCORD II

BLOCK MODSEL
        3       1               # NMSSM particle content
        1       1               # IMOD (0=general NMSSM, 1=mSUGRA, 2=GMSB)
        10      2               # ISCAN (0=no scan, 1=grid scan, 2=random scan)
        9       0               # Call micrOmegas (default 0=no, 1=relic density only,
#                                 2=dir. det. rate, 3=indir. det. rate, 4=both det. rates)
        8       0               # Precision for Higgs masses (default 0: as before,
#                                 1: full 1 loop + full 2 loop from top/bot Yukawas
#                                 2: as 1 + pole masses - 1&2 by courtesy of P. Slavich)
BLOCK SMINPUTS
        1       127.92D0        # ALPHA_EM^-1(MZ)
        2       1.16639D-5      # GF
        3       .1172D0         # ALPHA_S(MZ)
        4       91.187D0        # MZ
        5       4.214D0         # MB(MB) (running mass)
        6       171.4D0         # MTOP (pole mass)
        7       1.777D0         # MTAU

BLOCK MINPAR
#       0       1000.D0         # MSUSY (If =/= SQRT(2*MQ1+MU1+MD1)/2)
        17      0.D0            # M0_min
        18      1000.D0         # M0_max (If =/= min)
        27      100.D0          # M12_min
        28      1000.D0         # M12_max (If =/= min)
        37      1.D0            # TANB_min at MSUSY
        38      50.D0           # TANB_max at MSUSY (If =/= min)
        4       1.D0            # SIGMU
        57      -1000.D0        # A0_min
        58      1000.D0         # A0_max (If =/= min)

BLOCK EXTPAR
#       107     0.D0            # M1_min at MGUT (If =/= M12)
#       108     0.D0            # M1_max at MGUT (If =/= min)
#       207     0.D0            # M2_min at MGUT (If =/= M12)
#       208     0.D0            # M2_max at MGUT (If =/= min)
#       307     0.D0            # M3_min at MGUT (If =/= M12)
#       308     0.D0            # M3_max at MGUT (If =/= min)
#       217     0.D0            # MHD^2_min at MGUT (If =/= M0)
#       218     0.D0            # MHD^2_max at MGUT (If =/= min)
#       227     0.D0            # MHU^2_min at MGUT (If =/= M0)
#       228     0.D0            # MHU^2_max at MGUT (If =/= min)
        617     1.D-2           # LAMBDA_min at MSUSY
        618     7.D-1           # LAMBDA_max at MSUSY (If =/= min)
#       637     0.D0            # ALAMBDA_min at MGUT (If =/= A0)
#       638     0.D0            # ALAMBDA_max at MGUT (If =/= min)
        647     -1000.D0        # AKAPPA_min at MGUT (If =/= A0)
        648     1000.D0         # AKAPPA_max at MGUT (If =/= min)

BLOCK STEPS
        0       100             # NTOT
        1       1               # ISEED
```

Radiative corrections to the Higgs mass

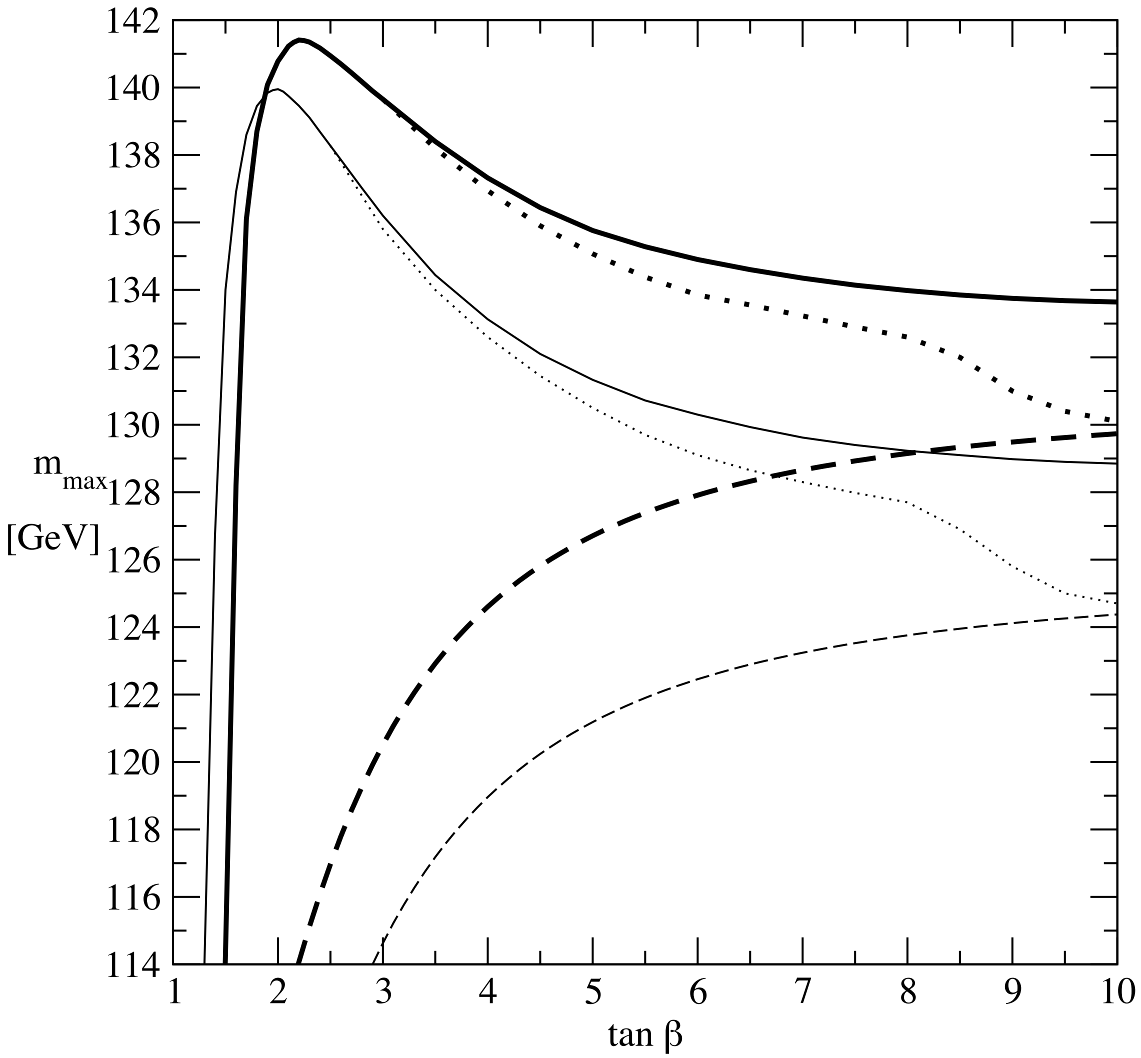
- At tree level: $m_h^2 = M_Z^2 \left(\cos^2 2\beta + \frac{\lambda^2}{g^2} \sin^2 2\beta\right) \sim (g^2 + \lambda^2) v^2$
- Radiative corrections considered:
  - Full one loop top/stop, bottom/sbottom: $h_{t/b}^4 v^2 \left(\log\left(\frac{M_{\rm susy}^2}{m_{\rm top}^2}\right) + \text{finite}\right)$

    \+ stop/sbottom D-term couplings: $g^2 h_{t/b}^2 v^2 \left(\log\left(\frac{M_{\rm susy}^2}{m_{\rm top}^2}\right) + \text{finite}\right)$

    \+ leading logs at two loops: $(h_{t/b}^6 + h_{t/b}^4 \alpha_s) v^2 \log^2\left(\frac{M_{\rm susy}^2}{m_{\rm top}^2}\right)$
  - EW leading logs at one loop: $(g^2 + \lambda^2 + \kappa^2)^2 v^2 \log\left(\frac{M_{\rm susy}^2}{m_{\rm top}^2}\right)$
  - Higgs pole mass corrections: $g^2 h_{t/b}^2 \left(\log\left(\frac{M_{\rm susy}^2}{m_{\rm top}^2}\right) + \text{finite}\right)$
- Terms *à la* Slavich:
  - full two loop stop/sbottom: $h_{t/b}^4 \alpha_s v^2 \left(\log\left(\frac{M_{\rm susy}^2}{m_{\rm top}^2}\right) + \text{finite}\right)$
  - full one loop EW: $(g^2 + \lambda^2 + \kappa^2)^2 v^2 \times \text{finite}$
- Still missing: $h_{t/b}^6 v^2 \left(\log\left(\frac{M_{\rm susy}^2}{m_{\rm top}^2}\right) + \text{finite}\right)$

Interlude: how to cook a 125 GeV Higgs

- The large λ small $\tan\beta$ solution



➡ Requires heavy singlet sector disfavoured in $\tilde{S}$ LSP scenario

- Large $M_{\rm susy}$ (as in the MSSM)

  ⇒ large fine-tuning, defined as

$$\Delta = \max\left(\left|\frac{\partial \ln(M_Z)}{\partial \ln(p_i)}\right|\right)$$

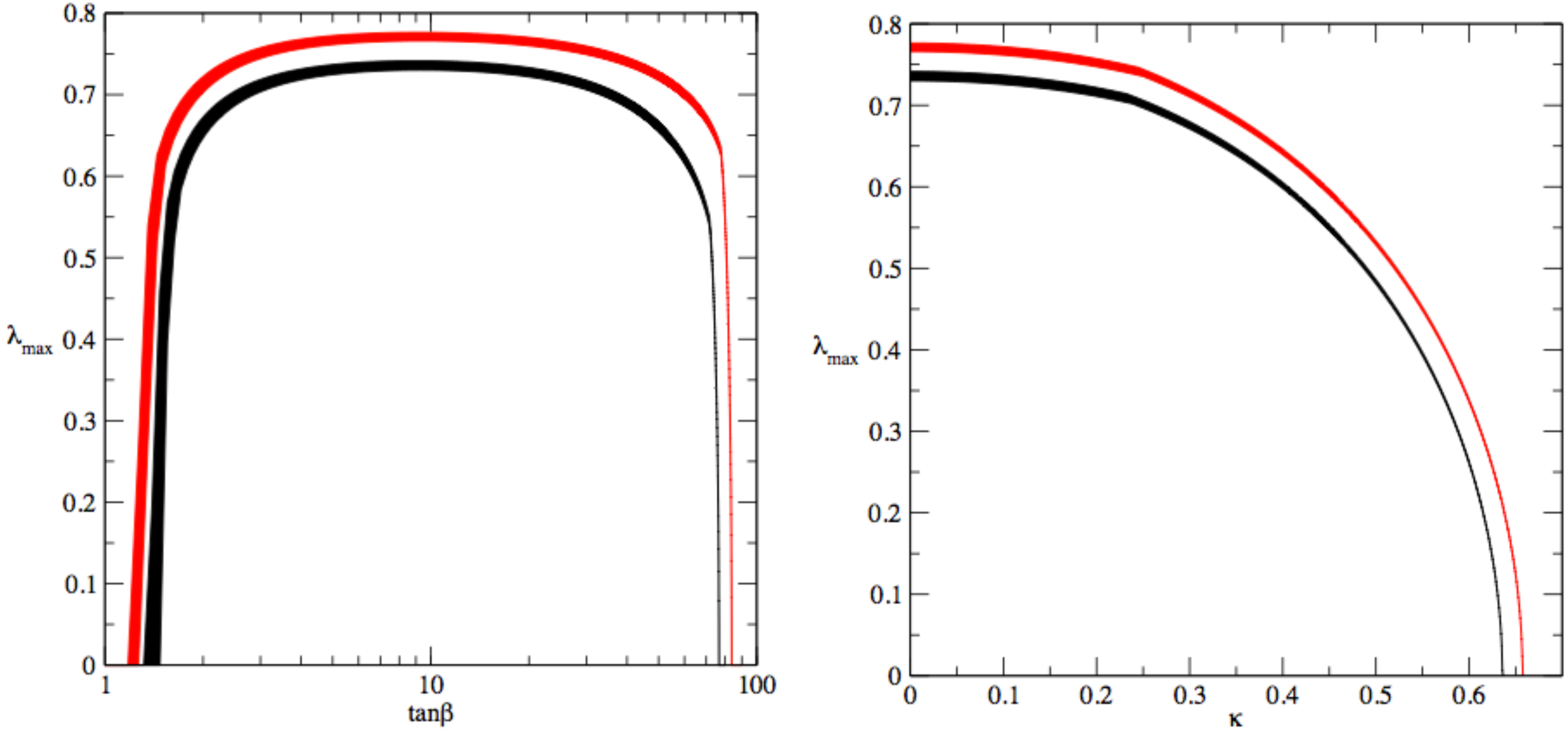
- The push-up mechanism

$$\mathcal{M}_H^2 = \begin{bmatrix} m_S^2 & \lambda(\ldots) & \ldots \\ \lambda(\ldots) & m_h^2 & \ldots \\ \ldots & \ldots & m_A^2 \end{bmatrix}$$

➡ Requires $\lambda \sim .1$

Theoretical constraints

- No unphysical minimum of the scalar potential:
  - $\langle H_u^0\rangle, \langle H_d^0\rangle, \langle S\rangle \neq 0 \Rightarrow \kappa \leq \lambda$
  - $\langle H_u^+\rangle, \langle H_d^-\rangle = 0 \Rightarrow \lambda \leq g$
- No Landau pole for λ, κ, h_t below the GUT scale:



Left panel: upper bound on λ (λ_{max}) as a function of tanβ for fixed $\kappa = 0.01$. Right panel: λ_{max} as a function of κ for fixed tan$\beta = 10$. Black (lower) bands: light spectrum, red (upper) bands: heavy spectrum. Inside the bands the top quark mass is 171.2 ± 2.1 GeV.

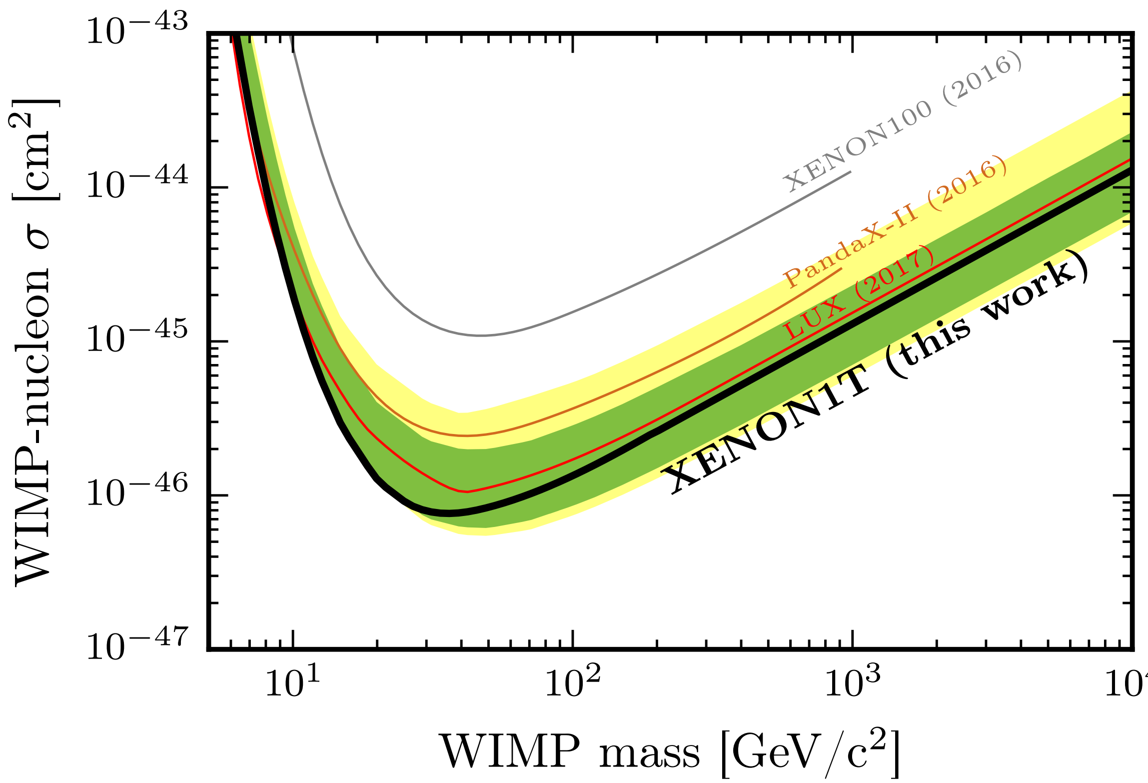
Experimental constraints

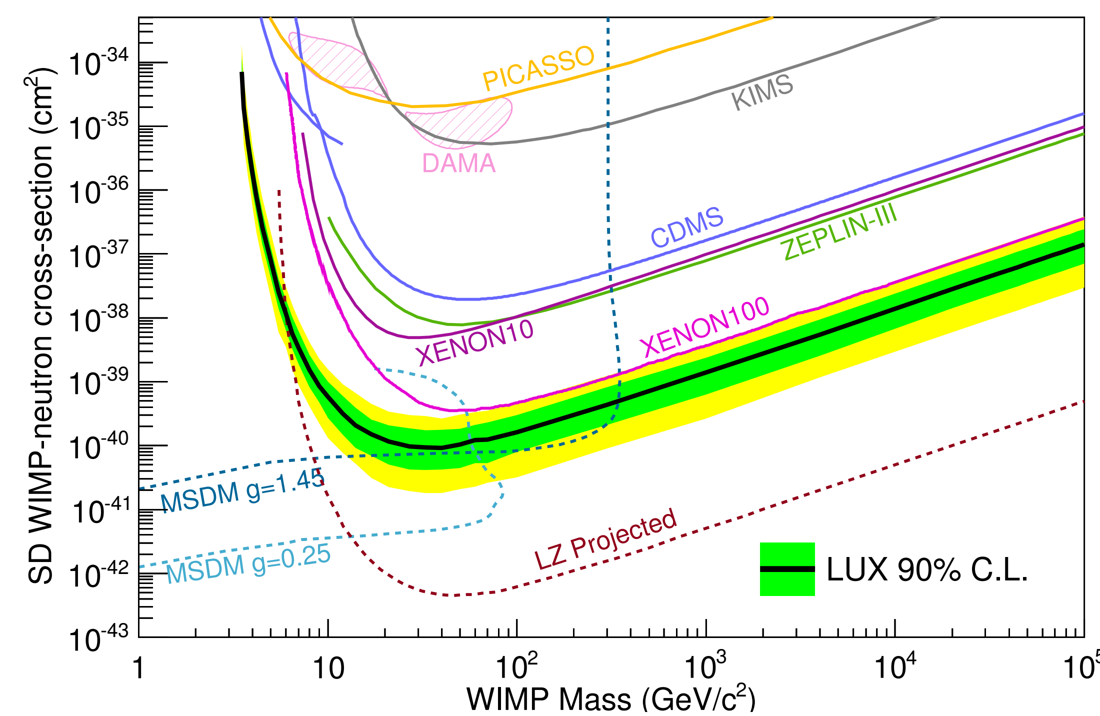
After computing all observables, NMSSMTools checks:

- $\tilde{\chi}_1^0$ (or gravitino) is the LSP
- LEP limits on $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^0$ (direct search + $\Gamma_{\mathrm{inv}}(Z)$)
- Tevatron + LEP constraints on gluinos/sfermions
- LEP limit on the charged Higgs mass $m_{h^\pm}$
- LEP constraints from neutral Higgs searches:
  - $e^+e^- \to hZ$ with $h \to bb$, $\tau\tau$, jj, $\gamma\gamma$, invisible, "any" (Z recoil mass)
  - $e^+e^- \to hZ$ with $h \to aa$ and $a \to bb$ or $\tau\tau$
  - $e^+e^- \to ha$ with $h \to aa$ and $a \to bb$ or $\tau\tau$
  - $e^+e^- \to ha$ with $h/a \to bb$ or $\tau\tau$
- Constraints on very light Higgs states/mixing with light mesons
- CDF/D0, BABAR, BELLE, CLEO and LHCb limits on B-physics
- BNL constraint on $(g\text{-}2)_\mu$ from e^+e^- data (**3σ away from SM**)

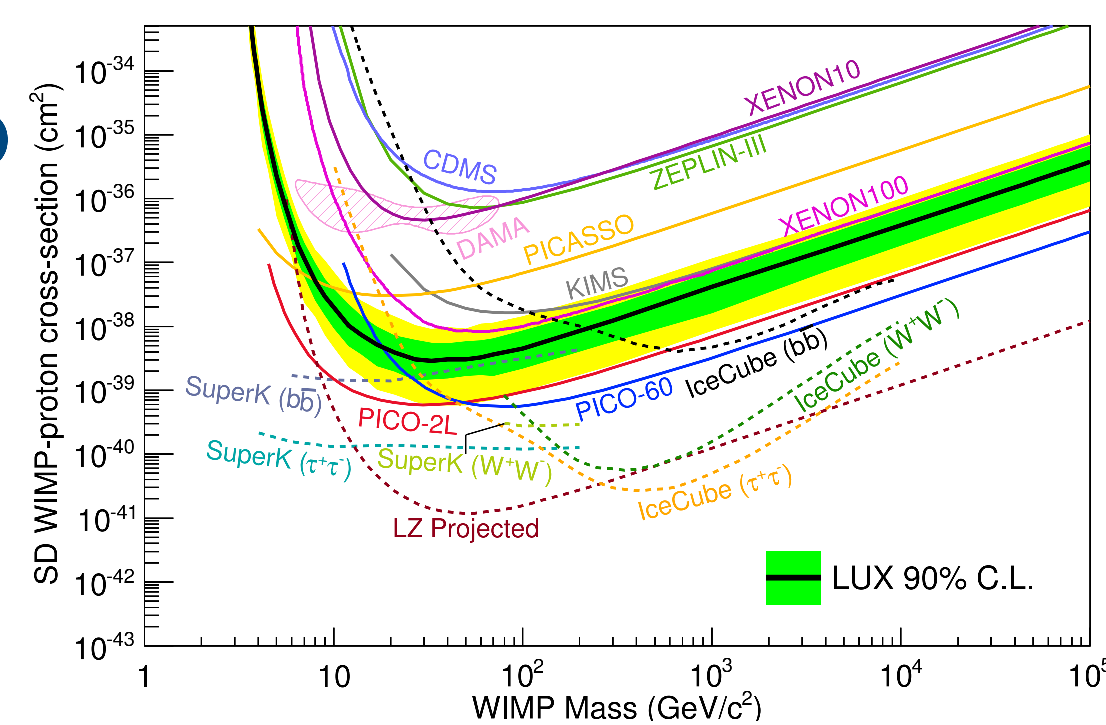
Dark Matter constraints

- Planck constraints: $\Omega h^2 = 0.1187$ +/- 10% (or just upper bound)
- SI limits from LUX, PandaX, XENON-1T





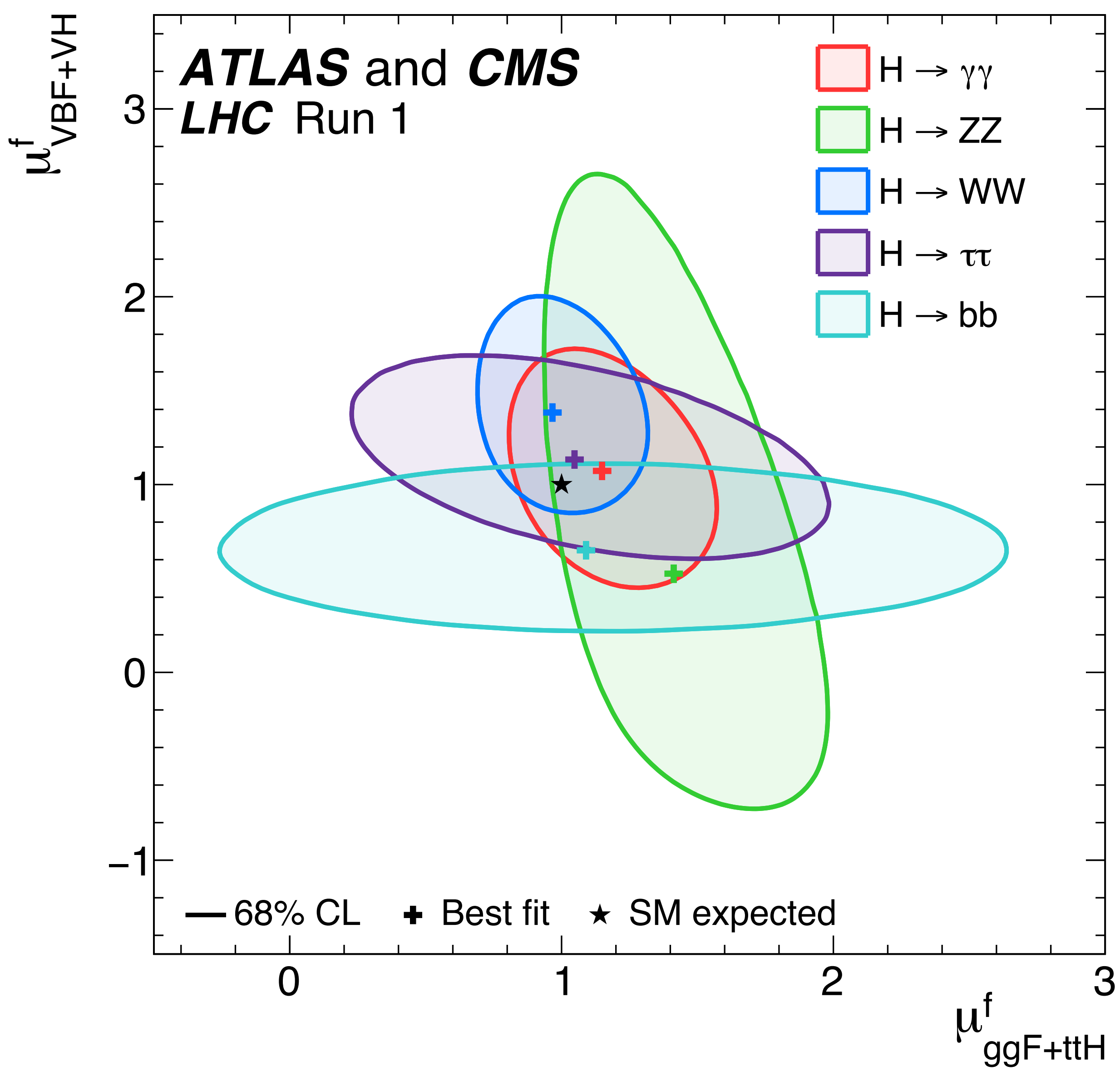
- SD limits from LUX, PandaX, PICO (from neutron and proton Xsections)



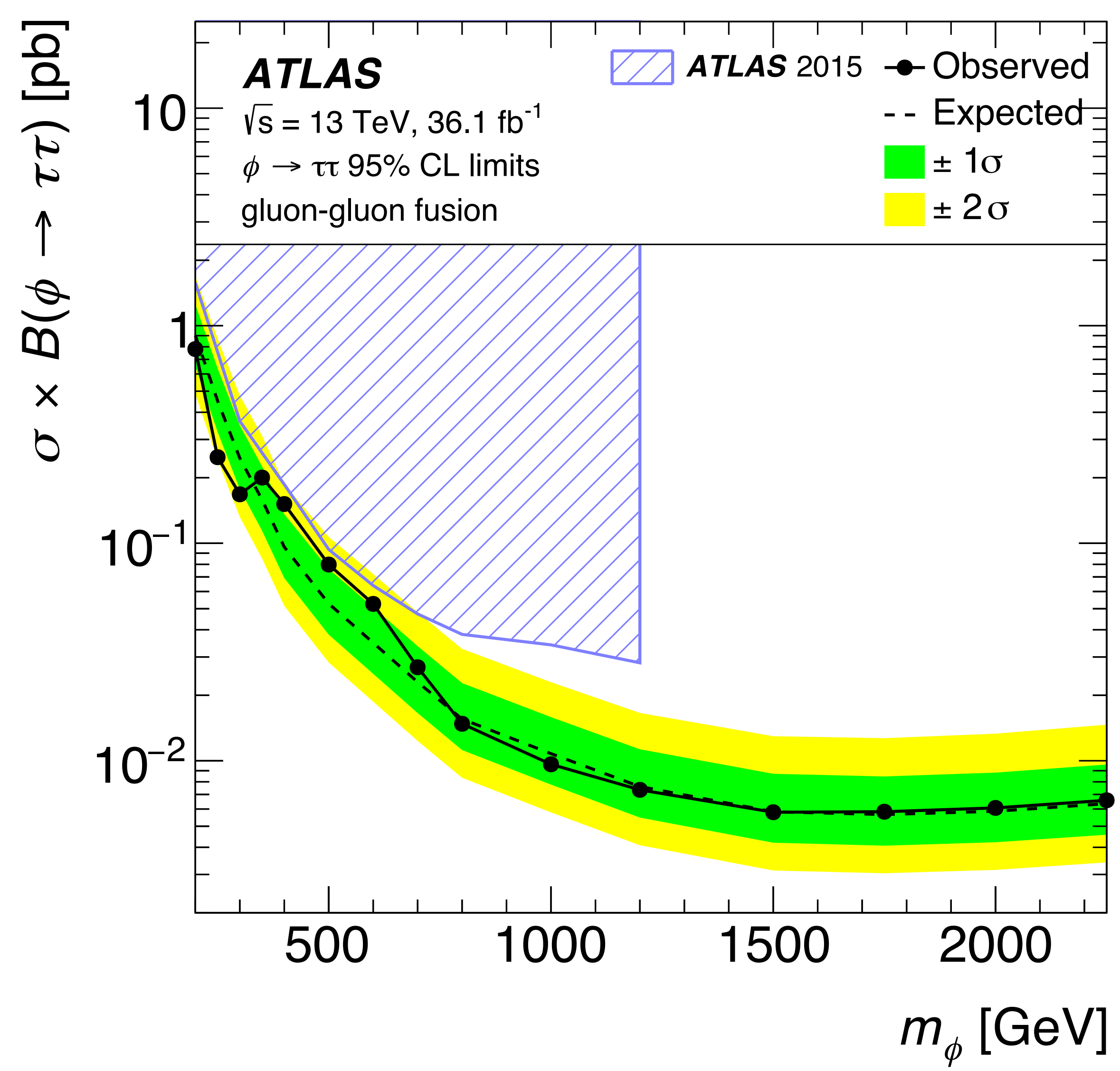
- Relic density and direct detection cross sections from **`micrOMEGAs`**

LHC constraints

- Limit on the gluino mass: $m_g > 1.6$ TeV
- Mass of the observed (SM-like) Higgs state: $m_h = 125.1$ +/- 3 GeV
- Couplings of the observed Higgs:



- Constraints on heavy Higgs states $H/A \longrightarrow bb$ or $\tau\tau$



Light singlino/higgsino scenario

- Light higgsinos are natural:
  - Mass given by μ (MSSM) or $\mu_{\rm eff}$ (NMSSM)
  - EWSB requires fine-tuning if $\mu_{\rm eff} \gg M_Z$
- But are not good dark matter candidates:
  - Relic density too small unless $|\mu_{\rm eff}| > 1$ TeV
  - Large Direct Detection rates (SD via Z-exchange)
- In the MSSM:
  - bino LSP: relic density too large
  - bino-higgsino mixing: DD rates too large unless $m_{\rm LSP} > 1$ TeV
- In the NMSSM: singlino LSP!
- Mass relation in singlet sector: $m_{\tilde{S}}^2 = m_S^2 + \frac{1}{3} m_P^2 - \frac{4}{3}\left(\lambda^2 \frac{A_\lambda}{\mu_{\rm eff}} + \kappa\right) v_u v_d$

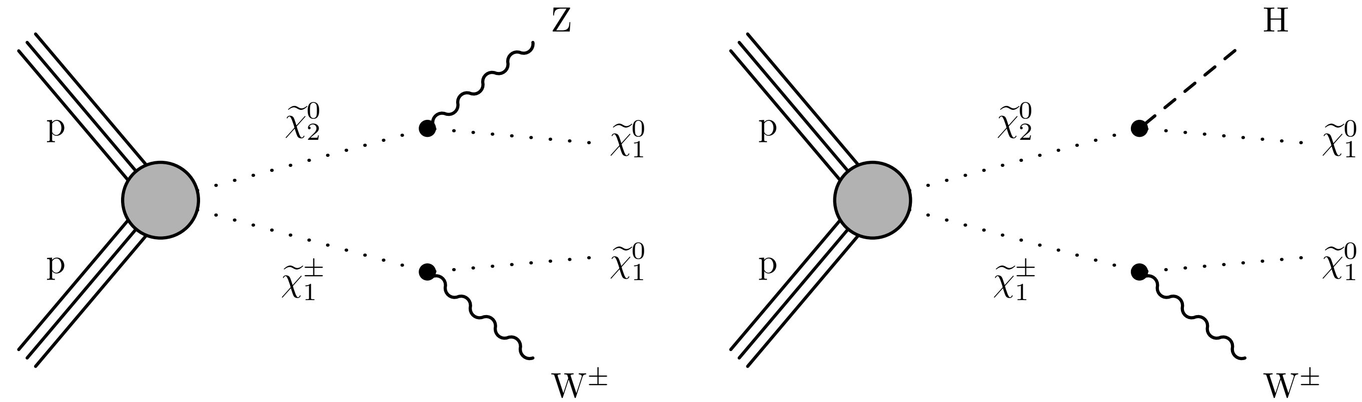
  Last term negligible in decoupling limit ($\lambda, \kappa \sim 0$) or large $\tan\beta$

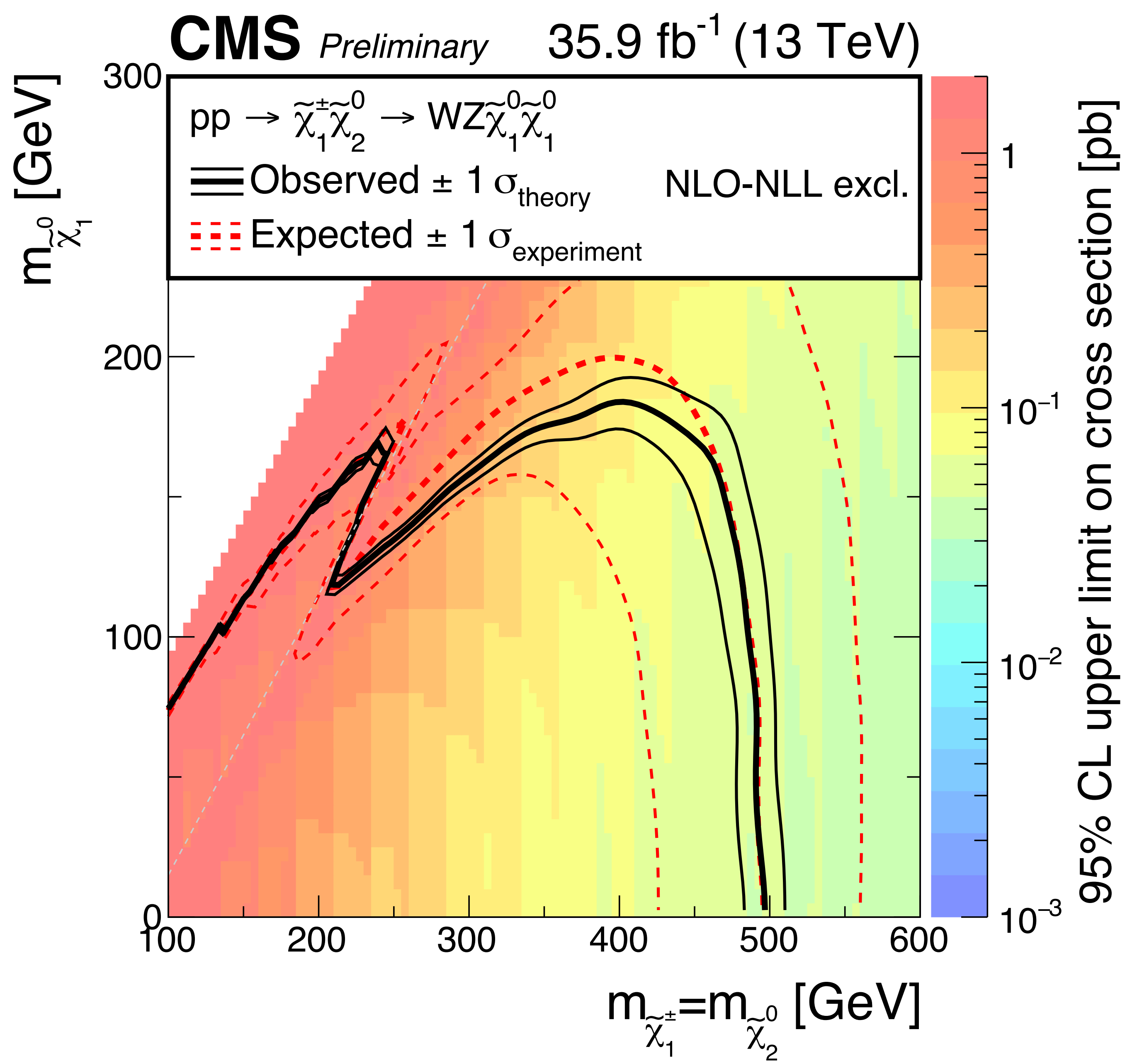
Singlino dark matter

- Efficient processes to get correct relic density:
  - annihilation via the pseudo-scalar singlet P in the s-channel requires $m_P \simeq 2m_{\widetilde{S}} \;\Rightarrow\; 3m_{\widetilde{S}}^2 + m_S^2 = 4\left(\lambda^2 \frac{A_\lambda}{\mu_{\text{eff}}} + \kappa\right) v_u v_d$ hence $\lambda \gtrsim .2$ and $\tan\beta$ not too large unless $m_{\widetilde{S}} \lesssim 20$ GeV
  - h or Z exchange in the s-channel if $m_h \simeq 2m_{\widetilde{S}}$ or $M_Z \simeq 2m_{\widetilde{S}}$
  - co-annihilation with higgsinos if $m_{\widetilde{S}} \simeq |\mu_{\text{eff}}|$
- Note: singlino/singlet coupling ~ κ ➠ no higgsino mixing needed
- Still: LSP acquires higgsino component unless mass splitting large
- Direct Detection limits affect the present scenario if $m_{\widetilde{S}} \gtrsim 5$ GeV
  - SI: singlet Higgs exchange in the t-channel, negative interference with the SM-like Higgs ➠ cross section possibly below ν floor
  - SD: weaker constraint but t-channel Z exchange more efficient Z/LSP coupling from higgsino component ➠ upper bound on λ For light LSP: similar upper bound on λ from Z invisible width

LHC constraints on light higgsinos

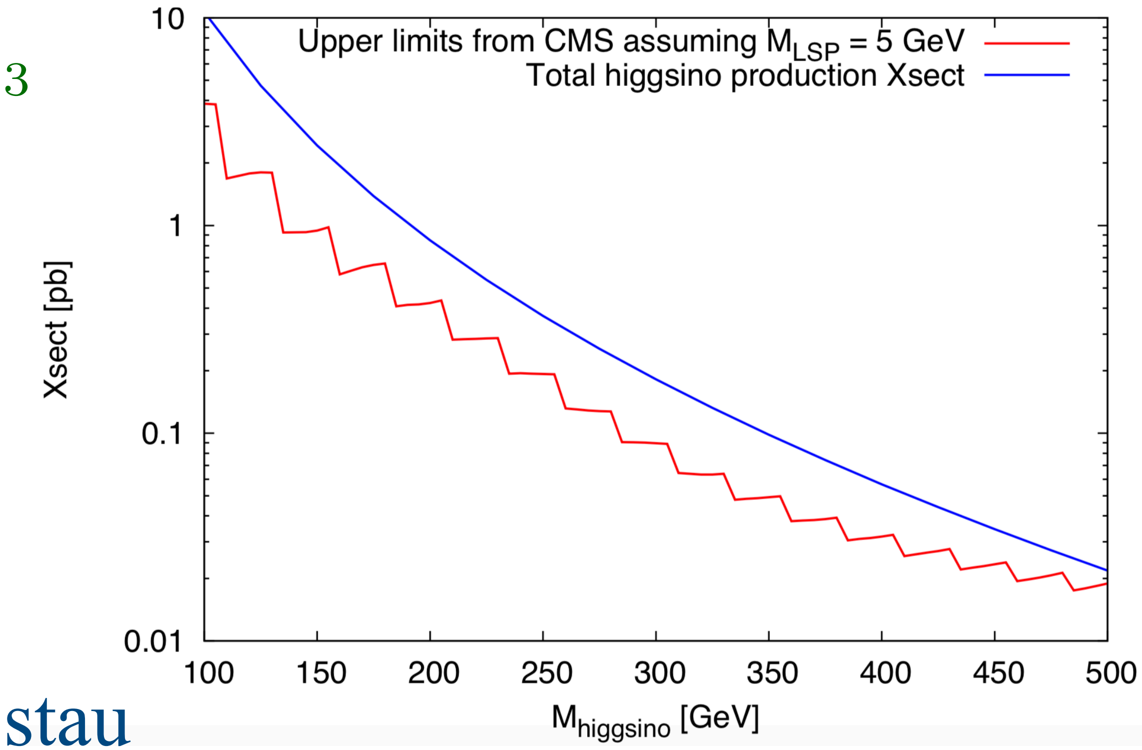
- Search for $W^* \to \tilde{\chi}_1^\pm + \tilde{\chi}_2^0$, with $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$ (winos) and $\tilde{\chi}_1^0$ = bino LSP
- H is the ~125 GeV Higgs
  Best sensitivity in $3l$ (W,Z)
- Result: limit on cross section times branching ratios in the plane $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$, $m_{\tilde{\chi}_1^0}$
- Line: assuming pure winos and 100% branching ratios
- How does this translate for light singlino/higgsinos?





And how to avoid them

- 1 charged higgsino $\chi_1^\pm$, 2 neutrals $\chi_{2,3}^0$
  Assuming mass degenerate states
  total cross section ~ half of winos
  For $m_{\rm LSP}$ = 5 GeV: not excluded if
  branching ratios to W, Z < 100%



- $\chi_1^\pm \to W^{\pm(*)} + \chi_1^0$ unless light bino or stau
- $\chi_{2,3}^0 \to Z^{(*)} + \chi_1^0$ and $\chi_{2,3}^0 \to h^{(*)} + \chi_1^0$ are of order λ^2: comparable BRs
  $\chi_{2,3}^0 \to h^{(*)} + \chi_1^0$ limits much weaker ➠ consider only $\chi_{2,3}^0 \to Z^{(*)} + \chi_1^0$
  Alleviates constraints, notably for $M_1 \sim |\mu_{\rm eff}|$ (bino component of $\chi_{2,3}^0$)
- $\chi_{2,3}^0 \to S/P + \chi_1^0$ (if kinematically allowed) suppressed compared to Z/h
  However if the latter are kinematically forbidden, BRs to S/P = 100%
- Other loophole: light bino (still singlino LSP) then higgsinos $\chi_{3,4}^0 \to \chi_2^0$
  considered (conservatively) not to contribute to the signal

Recasting procedure and results

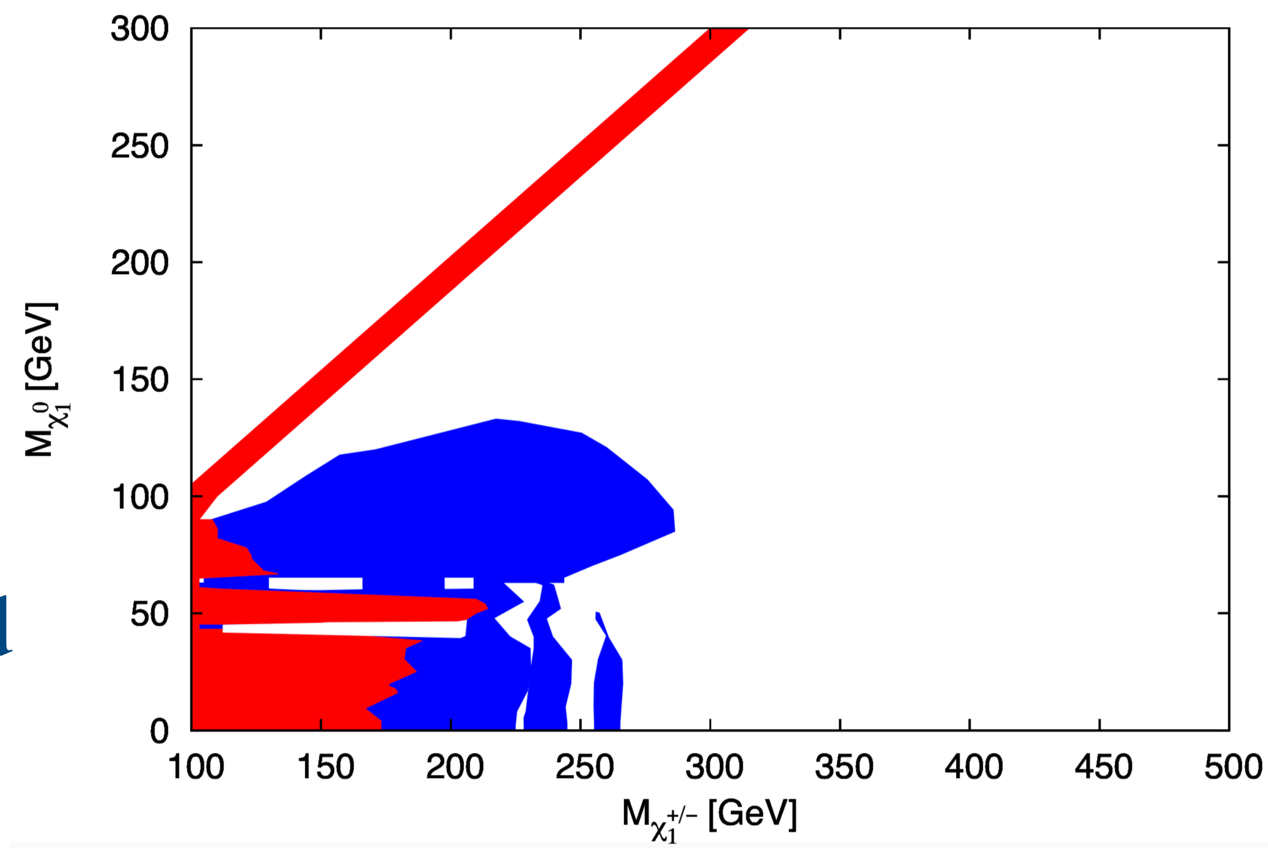
- $\chi_1^\pm$ and $\chi_{2,3}^0$ not mass degenerate ($m_{\chi_3^0} - m_{\chi_1^\pm} \simeq m_{\chi_1^\pm} - m_{\chi_2^0} \lesssim 20$ GeV)
  - ➥ find the $\chi_1^\pm \chi_i^0$ production cross sections (from an array)
  - ➥ weigh by $X_i/(X_1+X_2)$ where $X_i = \chi_1^\pm \chi_i^0 W$ reduced coupling squared (production) times branching ratios to W, Z (decay)
  - ➥ Find a degenerate triplet (mass m_T) with same cross section
  - ➥ Compare to the cross section excluded by CMS at $m_T, m_{\chi_1^0}$

- Results in the pNMSSM
  - ➥red: excluded for arbitrary M_1
  - ➥blue: for $M_1 > 300$ GeV

  Diagonal band: coannihilation

  Near *Z/h* funnel: *S/P* not needed

  for annihilation: $\chi_{2,3}^0 \to S/P + \chi_1^0$

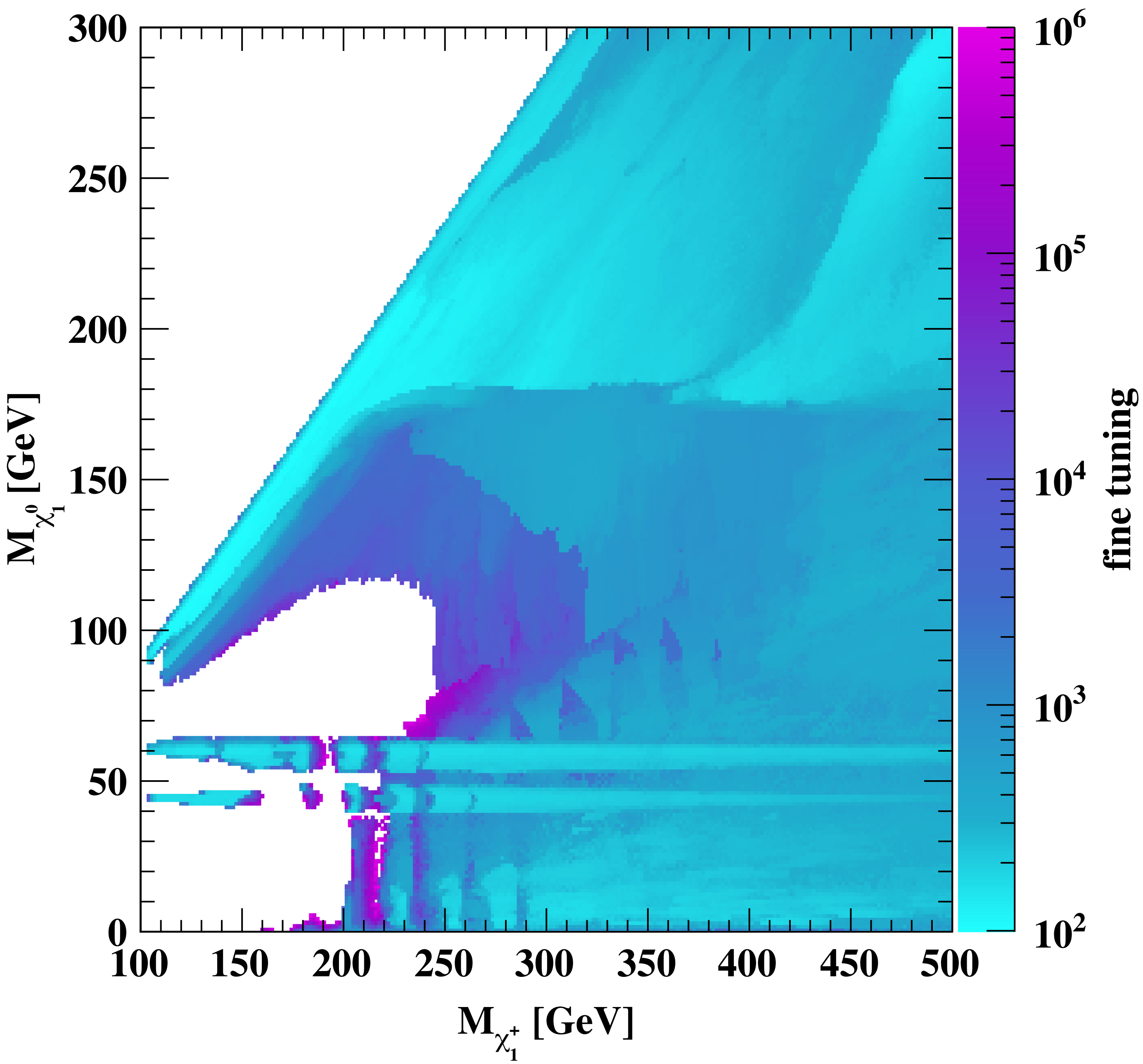


Results in the NUH-NMSSM

- Large MCMC scans of NUH-NMSSM parameter space (~ 10^{12} pts)

➥Fine-tuning map in the $m_{\chi_1^\pm}, m_{\chi_1^0}$ plane divided in a 2D histogram

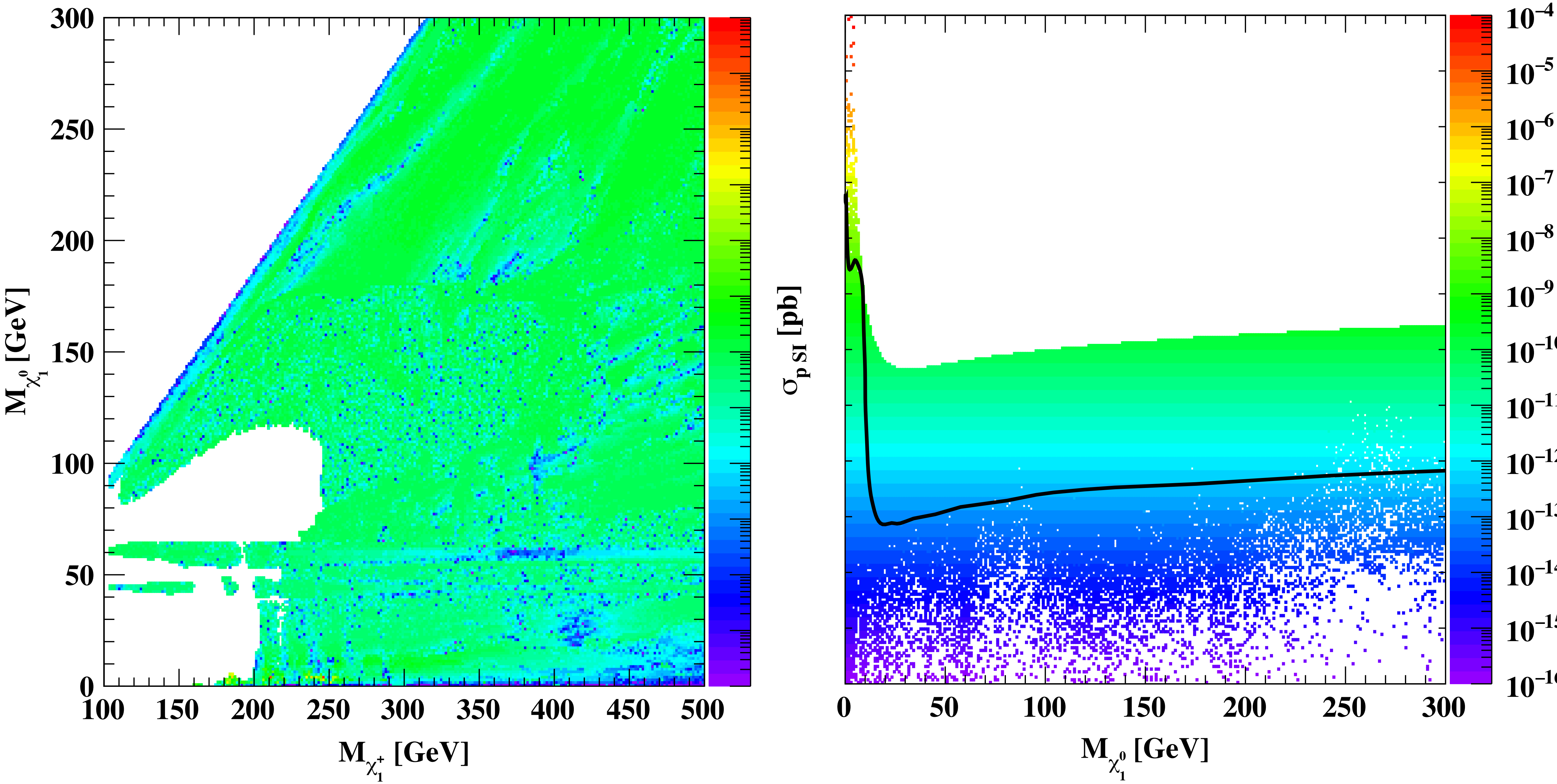
➥In each bin: keep the point with the lowest fine-tuning



- Excluded (white) region = red+part of blue in pNMSSM
- Low FT regions (light blue):
  - close to Z/h funnels
  - coannihilation region
  - light singlino ($m_{\chi_1^\pm} > 20$ GeV)
  - P + off-shell Z ($m_{\chi_1^\pm} > m_{top}$)
- Large FT in regions where CMS constraints are strong

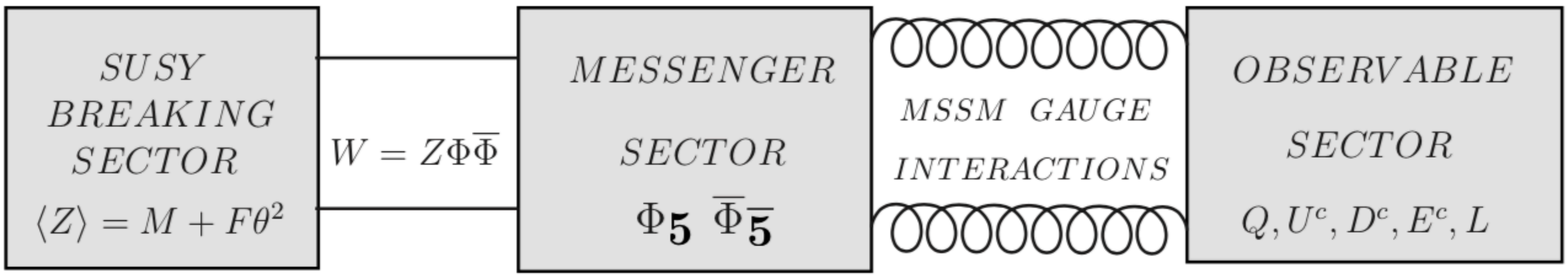
Direct detection rates

- SI Direct Detection rates can fall below the ν floor
  - in regions where LSP is very singlino-like
  - elsewhere due to *S/h* negative interference



Gauge mediated SUSY breaking

- SUSY has too many free parameters ⇒ predictive scenarios?



- Minimal GMSB is a very predictive setup
- It solves easily the SUSY flavour problem
- Problem: it is hard to obtain a 125 GeV Higgs
- Solutions:

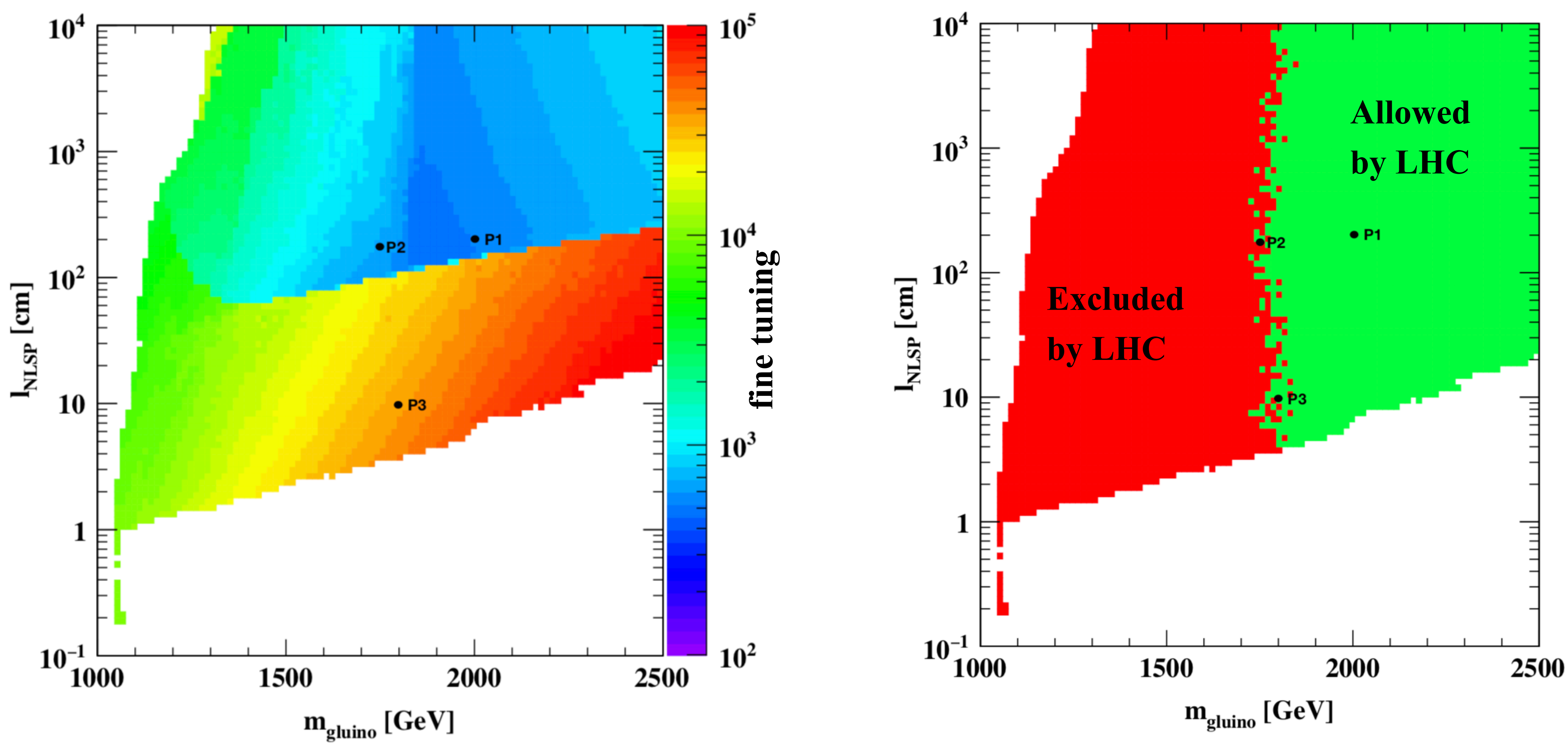
1. New tree level Δm_h at messenger scale, possible in the **NMSSM** with extra Higgs singlet + singlet/messenger coupling
2. Large A_t at messenger scale from matter/messenger coupling

Solution 1: the DGS model

- 2 messengers Φ_u, Φ_d coupled to the singlet [Delgado, Guidice, Slavich '07]
- Only 4 parameters (all other fixed by correct EWSB):
  - λ: Higgs singlet/doublet coupling H_uH_dS
  - ξ: singlet/messenger coupling $\Phi_u\Phi_dS$
  - M: messenger scale
  - Λ: SUSY scale
- **The push-up scenario** [Allanach, Badziak, Hugonie, Ziegler '15]:
  - $m_{h1} \sim 90$ GeV (singlet-like), $m_{h2} \sim 125$ GeV (SM-like) $\Rightarrow$ $\lambda, \xi \sim 10^{-2}$
  - Additional light pseudoscalar Higgs with $m_a \sim 25$ GeV
  - Gluino/squarks as light as ~ 1.5 TeV (depending on Λ)
  - Singlino NLSP ~ 100 GeV decaying to gravitino + pseudoscalar
- Possibly displaced singlino to gravitino decay (depending on M)
  - First studied in [Allanach, Badziak, Cottin, Desai, Hugonie, Ziegler '16]
  - Updated in [Badziak, Desai, Hugonie, Ziegler '18]: new constraints on the Heavy Higgs sector push the gluino mass beyond the LHC reach…

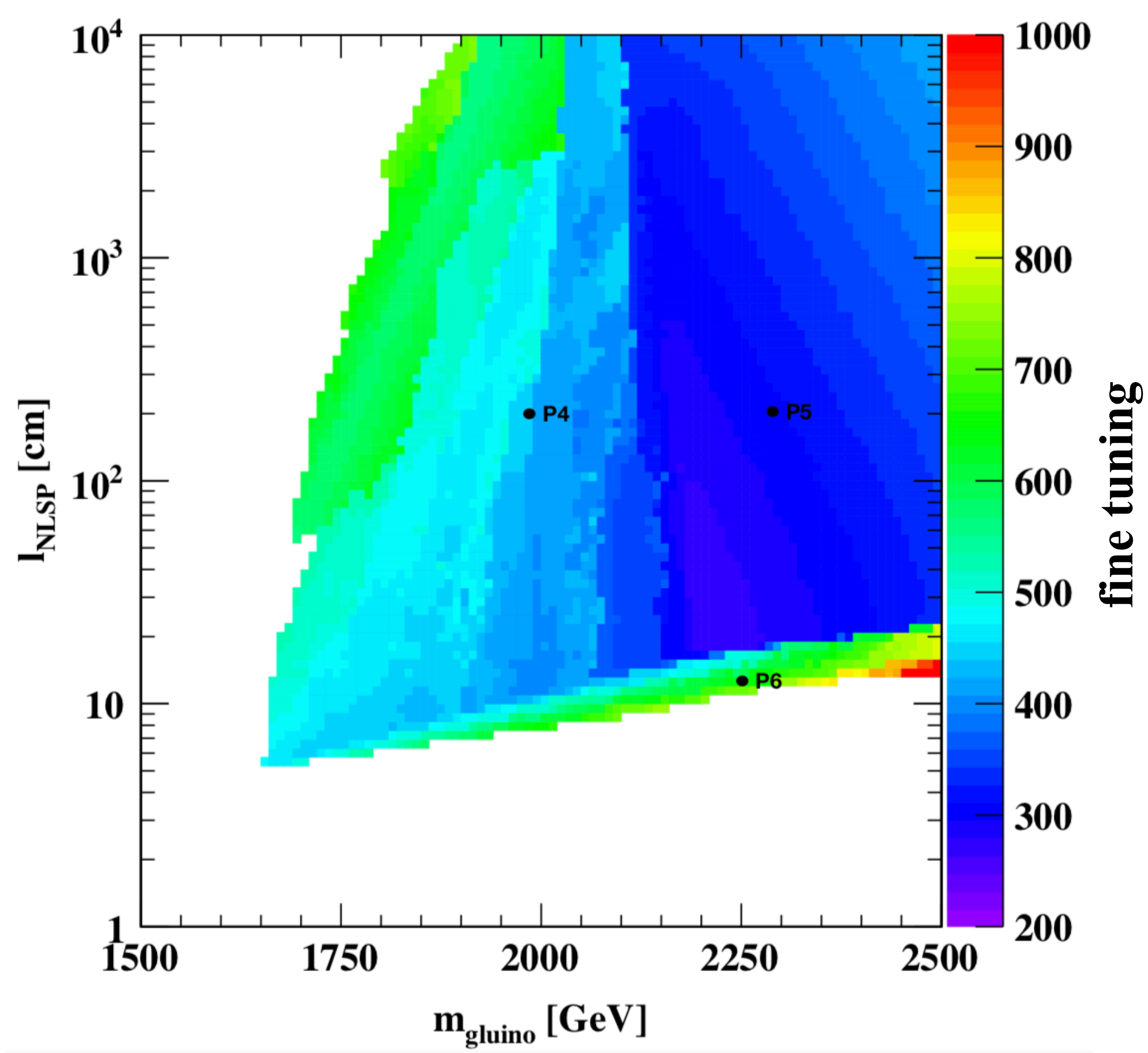
Solution 2: the U model

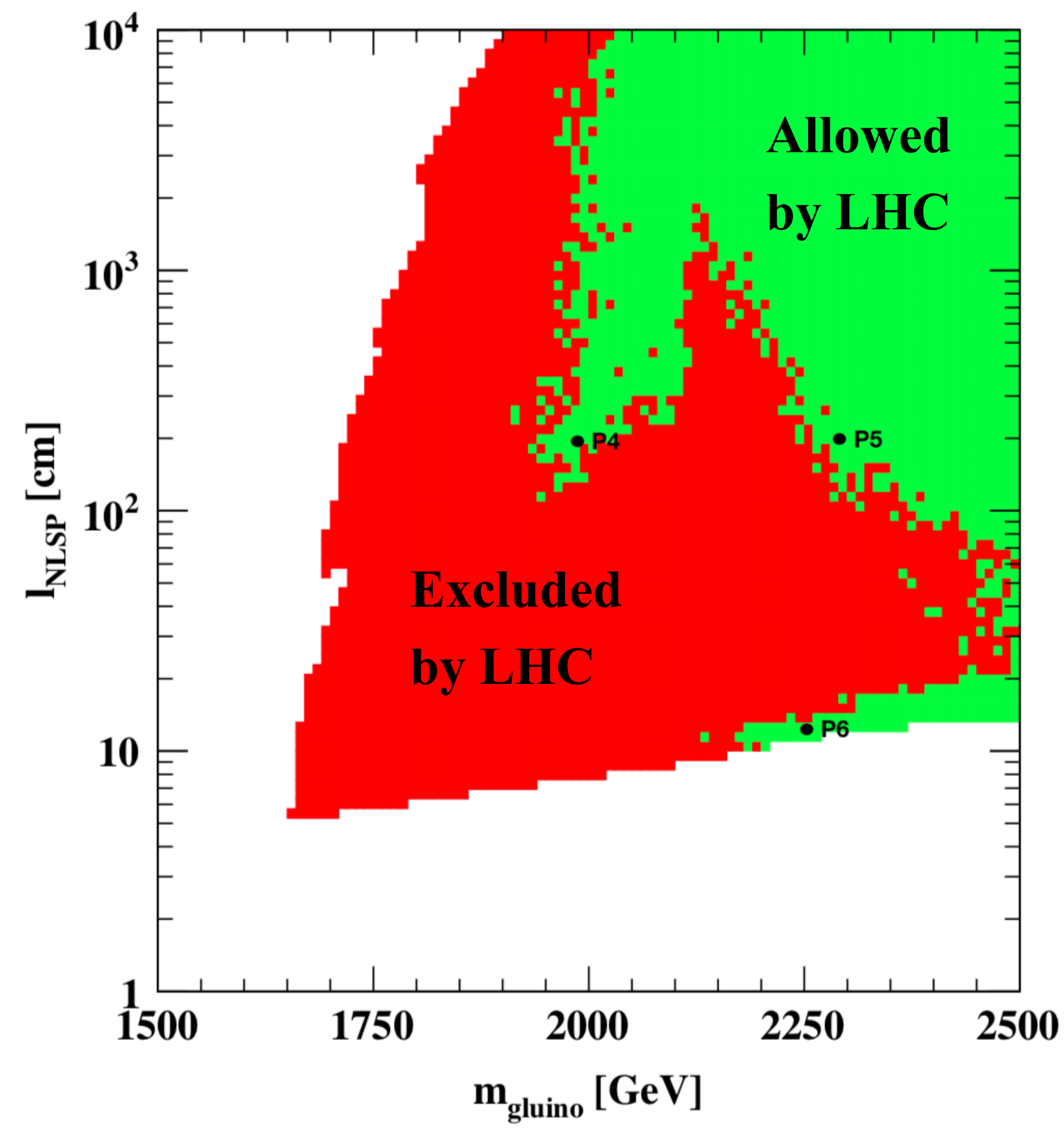
- 1 messenger Φ_u coupled to matter and Higgs sector
- Now 5 free parameters:
  - λ_t: $\Phi_u QU$ coupling
  - M: messenger scale
  - λ: $H_u H_d S$ coupling
  - λ_S: $\Phi_u H_d S$ coupling
  - Λ: SUSY scale
- Possibly light gluino with displaced singlino NLSP to gravitino LSP decay!



Solutions 1 & 2: the DGSU model

- Mixture of the 2 previous models with 2 messengers Φ_u, Φ_d
- Still 5 free parameters:
  - ξ: $\Phi_u \Phi_d S$ coupling
  - M: messenger scale
  - λ: $H_u H_d S$ coupling
  - λ_t: $\Phi_u QU + \Phi_u S H_d$
  - Λ: SUSY scale
- Again light gluino with displaced singlino NLSP to gravitino LSP decay





Conclusions

- Light singlino/higgsino scenario still alive and kicking
- Could be challenging to test
  - Small DD rates (possibly below the ν floor)
  - $\chi^0_{2,3} \to S/P + \chi^0_1$ difficult channel at the LHC
- Benchmark points given in [arXiv:1806.09478]

  ➥ Test ATLAS sensitivity to non degenerate higgsinos
- Displaced singlino NLSP to gravitino LSP vertices in GMSB models could also be challenging signals [arXiv:1810.05618]