Supersymmetry after LHC run I

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Outline

LHC results

LHC results at center-of mass $\sqrt{s} = 8$ TeV and $\mathcal{L} = 20$ fb^{-1}, if available; If not, results at $\sqrt{s} = 7$ TeV and $\mathcal{L} = 5$ fb^{-1}

- LHC confirms SM by the discovery of the Higgs boson;
- And puts in jeopardy any BSM predicting new particles with mass close to the EW scale. [Not just SUSY, any model which explains the naturalness of the weak scale]
- Run I is complete: but intriguing hints could still appear in data not yet released/analyzed.
- Even if nothing is found, still hope for LHC @13 TeV or 14 TeV.
- And are we looking in the right region/searching for right signals?

What we know so far of SUSY

Advantages of SUSY

- It resolves the hierarchy problem without UV sensitivity;
- Predicts that EW symmetry broken by elementary scalar particle;
- It predicts the Higgs mass to lie below 135 GeV;
- It provides a dark matter candidate;
- Decoupling properties excellent, agreement with precision limits on EW observables.

Disadvantages of SUSY: where is everybody?

What did we expect: I. Naturalness

1. Introduce a symmetry to control radiative corrections to elementary scalar masses to Planck scale. [SUSY, no quadratic dependence]
   - high scales for logarithmic dependence on the cutoff; and
   - quadratic dependence on lighter particle masses.
2. Introduce a cutoff of the effective theory containing the elementary scalar. [extra-dimensional theories]

Important parameters

- Soft mass, Higgs coupling from tree level $M_Z^2 = -2(m_{H_U}^2 + \mu^2)...$ $\Longrightarrow \mu \lesssim 200$ GeV.
- Stop masses from loop corrections $\delta m_{H_u}^2 = -\frac{3Y_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln(\frac{\Lambda}{m_{\tilde{t}}})$, $\Longrightarrow m_{\tilde{t}} \lesssim 400$ GeV, $\Lambda \sim 10$ TeV.
- Wino masses from loop corrections $\delta m_{H_u}^2 = -\frac{3g^2}{8\pi^2}(m_{\tilde{W}}^2 + m_{\tilde{h}}^2)\ln(\frac{\Lambda}{m_{\tilde{W}}})$, $\Longrightarrow m_{\tilde{W}} \lesssim$ TeV.
- Gluino masses $\delta m_{\tilde{t}}^2 = \frac{2g_s^2}{3\pi^2} m_{\tilde{g}}^2 \ln(\frac{\Lambda}{m_{\tilde{g}}})$, $\Longrightarrow m_{\tilde{g}} \lesssim 2m_{\tilde{t}}$.

What did we expect II: MSSM

Standard Model

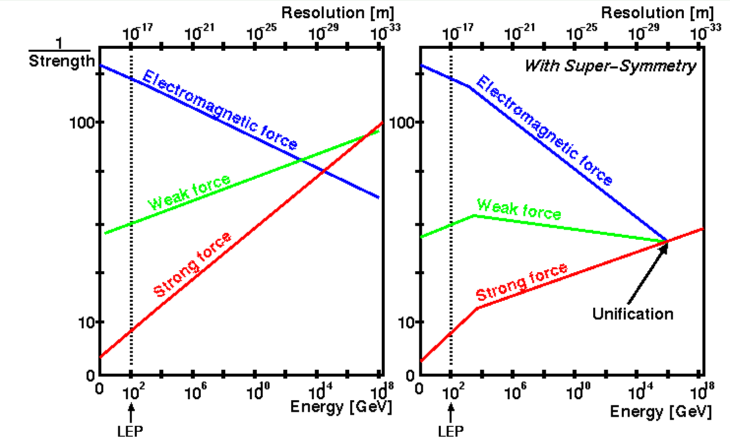
- $\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} \nu \\ e \end{pmatrix}_L, u_R, d_R, e_R$
  quarks, leptons
- $W^\pm, Z, \gamma, g$
  W, Z bosons, photon, gluon
- $\begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix}, \begin{pmatrix} H_2^0 \\ H_2^- \end{pmatrix}$
  Higgs bosons

MSSM: minimal extension

- $\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_L, \begin{pmatrix} \tilde{\nu} \\ \tilde{e} \end{pmatrix}_L, \tilde{u}_R, \tilde{d}_R, \tilde{e}_R$
  squarks, sleptons
- $\widetilde{W}^\pm, \tilde{Z}, \tilde{\gamma}, \tilde{g}$
  Wino,Zino,photino, gluino
- $\begin{pmatrix} \tilde{H}_1^+ \\ \tilde{H}_1^0 \end{pmatrix}, \begin{pmatrix} \tilde{H}_2^0 \\ \tilde{H}_2^- \end{pmatrix}$ Higgsino
- $\left(\widetilde{W}^\pm, \tilde{H}_{1,2}^\pm\right) \Rightarrow (\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)$
  $\left(\tilde{Z}^\pm, \tilde{\gamma}, \tilde{H}_1^0, \tilde{H}_2^0\right) \Rightarrow \tilde{\chi}_{1,2,3,4}^0$

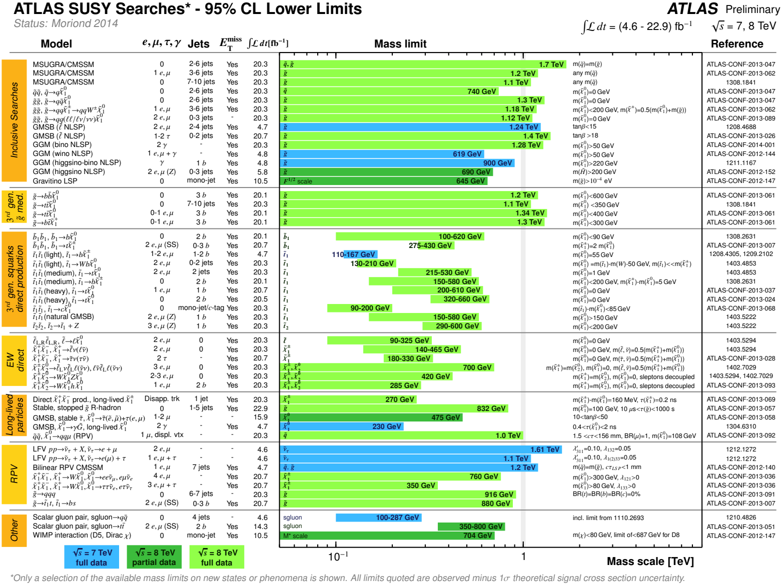
- minimal fields for $N = 1$ anomaly-free SUSY;
- SUSY breaking scale high;
- number of fundamental breaking parameters small;
- colored particles heavier than uncolored ones.

MSSM Bonus: Gauge couplings unification at $M_{\mathrm{GUT}} = 2 \times 10^{16}$ GeV

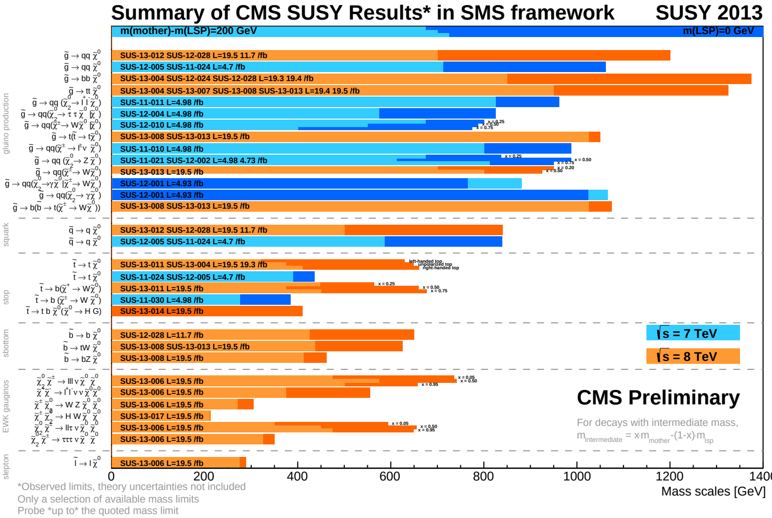


- Baryon and lepton number violating operators allowed $\Longrightarrow$ impose R-parity, lightest R-odd particle is the LSP.
- MSSM provides a natural DM candidate with mass $\sim$ GeV.
- Expect SUSY decay chains with pairs of LSP, *i.e.*, significant $\not{E}_T$.

Summary of searches for SUSY–ATLAS

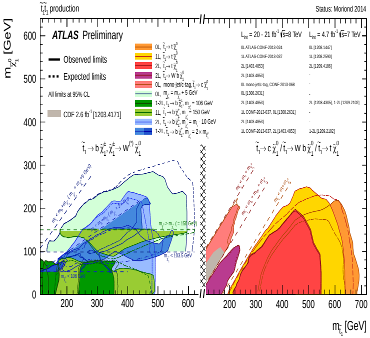


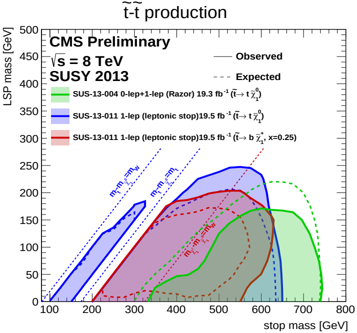
Summary of searches for SUSY–CMS



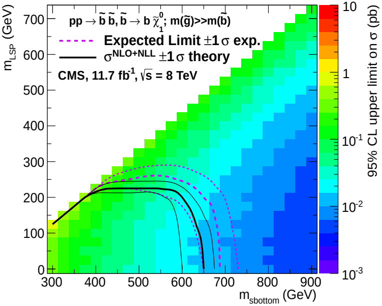
Summary of searches for SUSY–stop

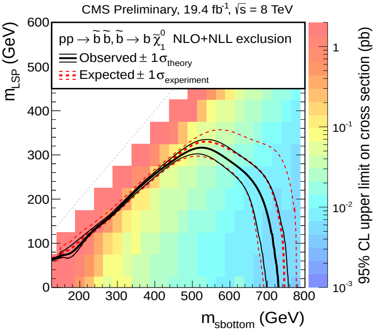
- Essential particle for SUSY naturalness
- Suppressed production rates vs. other coloured particles at LHC
  - s-channel gluon and t-channel $\tilde{t}$ exchange
  - p-wave suppressed as final state need angular momentum
  - direct production $\sigma \sim 10$ pb –1 fb for $m_{\tilde{t}} \sim 200$ - 900 GeV.
- Final states difficult to disentangle from $t\bar{t}$ backgrounds; current reach $\sim$ 650 GeV at 10 fb.





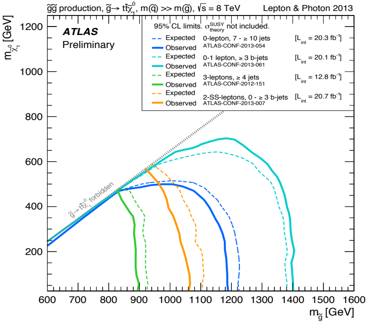
- Complimentary to stop searches
- Though is not as important as stop in naturalness, expect that as part of same doublet, same soft masses
    - production and decay rates are similar, slight relative enhancement due to electroweak corrections
    - complementary decay modes
    - direct production $\sigma \sim 10$ pb -1 fb for $m_{\tilde{b}} \sim$ 200-900 GeV.
- Final states also difficult to disentangle from $t\bar{t}$ backgrounds; current reach $\sim$ 600 GeV at 10 fb.

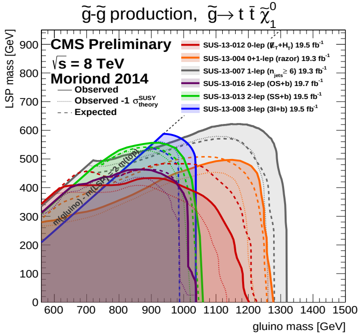




Summary of searches for SUSY–gluino

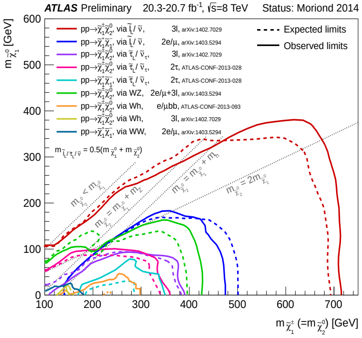
- Driving forces of SUSY signals at the LHC
- Considerable production rates vs. other coloured particles at LHC
  - pair production cross section $\sim \times 2$ that for stops
  - direct production from $\sigma \sim 10$ pb – 1 fb for $m_{\tilde{t}} \sim$ 400-1300 GeV
  - if squarks are heavier ("pure gluino") decay into 3-bodies $\tilde{g} \to q\bar{q}\chi_1^0$, into final states with high jet multiplicity $\gtrsim 4j$
  - limits reach ~1.2 TeV from leptonic, or b-quark final states.

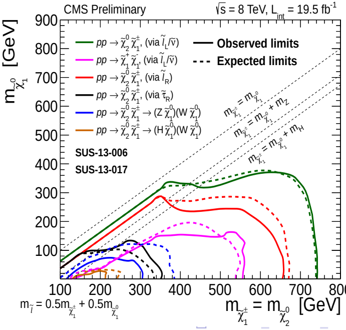




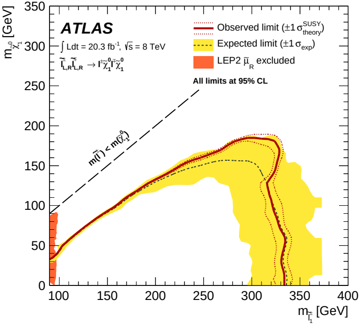
Summary of Searches–electroweakinos

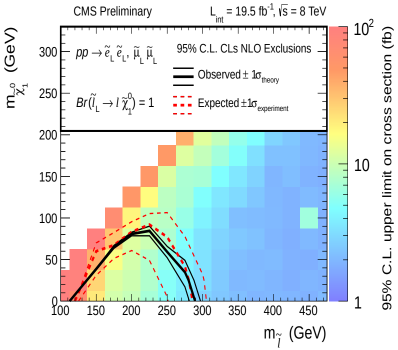
- Expected to be the lightest SUSY particles in most scenarios.
- Challenging searches, substantial background from SM di-boson production:
  - most effective channels are trileptons including one OSSF pair (sensitivity $\sim$ few fb)
  - also $2\ell + 2j$ final states;
  - sensitivity to cross section BR ~ 10 fb;
  - limits reach $m_{\chi_2^0,\chi_1^\pm} \gtrsim 325$ GeV for LSP masses lower than 70 GeV.





- Direct limits on pair production through EW processes better than LEP
- Cross sections of $\sim$ few fb
- Current reach $\sim$ 275 GeV for left-handed leptons only; $\sim$ 300 GeV for degenerate $\tilde{l}_L$ and $\tilde{l}_R$.





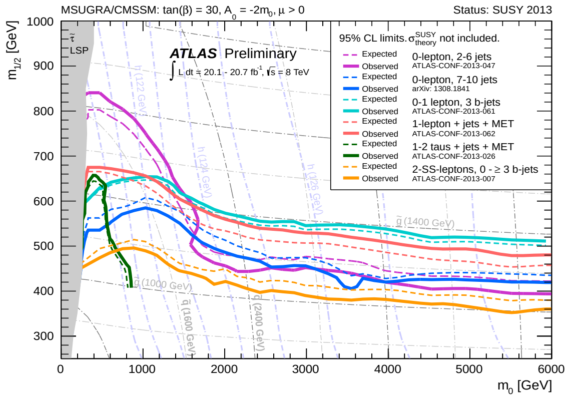
Restrictions from the Higgs data

$$m_h^2 = m_Z^2 \cos^2(2\beta) + \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \frac{(A_t - \mu\cot\beta)^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}}\left(1 - \frac{(A_t - \mu\cot\beta)^2}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right)\right]$$

- Higgs mass has difficulties with respect to minimal predictions, requiring a correction of the same size as minimal tree-level contribution.
  - If radiative effects are unimportant $m_h < m_Z$. [But $m_h^2 = m_Z^2$, problems with Veltman Condition].
  - If the ln is large, without stop mixing, $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \gtrsim 4$ TeV.
  - With stop mixing, one must close-tune $A_t - \mu\cot\beta \approx \pm\sqrt{6 m_{\tilde{t}_1} m_{\tilde{t}_2}}$.
  - Enhancing tree-level contributions to m_h from F and D terms yields $\tan\beta = 1$.
  - Enhance loop level m_h from additional matter multiplets.
- Explaining the Higgs mass in MSSM involves tuning the log enhanced and finite corrections.
- Coupling measurements impose useful constraints for light sparticles only.

MSUGRA/CMSSM

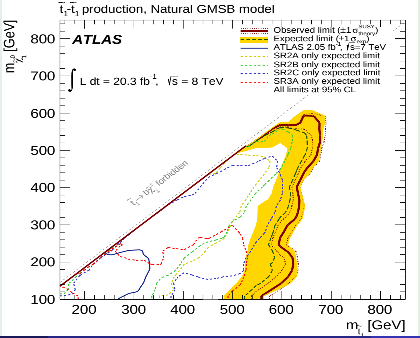
- Supersymmetry is broken *universally* by the gravity sector in the model.
- LSP χ_1^0 is generally bino-like $\tilde{B}$.
- Only 5 parameters $m_{1/2}$, $m_0, \tan\beta, A_0$ and $sign(\mu)$.
- Mass difference between the LSP and squarks and gluinos is large.



Summary of searches for GMSB

GMSB

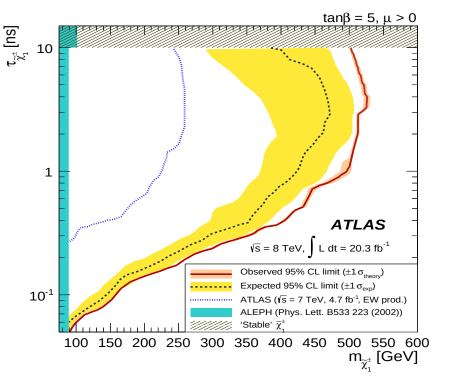
- Supersymmetry is broken by the gauge sector in the model, which being flavour blind, avoids SUSY flavour violation.
  - Has an observable sector, usual quarks, leptons, and superpartners.
  - Has a secluded sector, responsible for symmetry breaking (X, goldstino).
  - Has a messenger sector, new fields which couple to X
- LSP χ_1^0 is always the gravitino $\tilde{G}$, with the NLSP a slepton, chargino or neutralino.



Summary of searches for AMSB

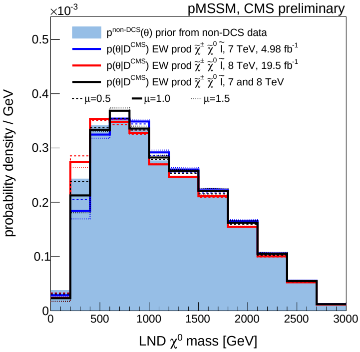
AMSB

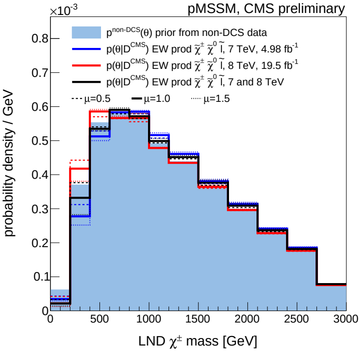
- Soft SUSY broken by loop effects, all soft SUSY breaking parameters are determined by the $m_{3/2}$ and anomalous dimensions at EW scale.
- LSP χ_1^0 in general neutral wino $\tilde{W}^0$, mass degenerate with $\tilde{W}^{\pm}$.
- $\chi_1^{\pm}$ only slightly heavier than χ_1^0, $\chi_1^{\pm}$ long lived, and $\chi_1^{\pm} \to \chi_1^0 \pi^{\pm}$.



pMSSM

- Assumes absence of FCNC, CP violation and universality of the first and second generation;
- Reduces the number of MSSM parameters to 19;
- Sensitivity of searches to configurations of SUSY masses and branching ratios can be assessed.





Could SUSY still be hiding somewhere?

The Signal is not what we expect

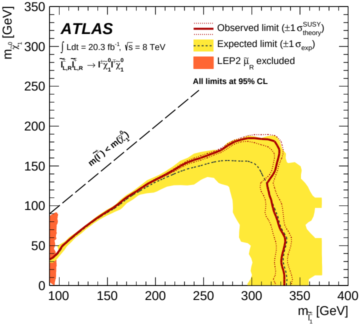
- No large missing transverse energy associated with decays of heavy states into the LSP;
- Suppress large hadronic activity associated with heavier mass scales.
  - Compressed SUSY (no significant separation between colored and uncolored particles);
  - RPV SUSY [$R = (-1)^{3B+L+2s}$]

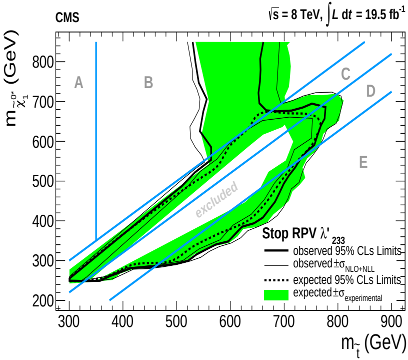
R-parity violation

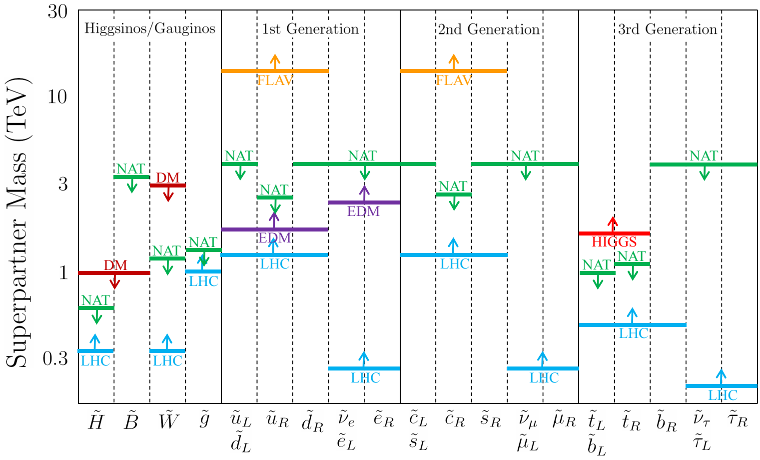
$$W_{\rm RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k .$$

- Models accommodate neutrino masses and oscillations.
- Assume either λ_{ijk}, λ'_{ijk} or λ''_{ijk} are 0, so no proton decay.
- Pair production of superpartners no longer necessary, thus typical signal does not show missing energy.
- LSP unstable, can have colour and electric charge.

R-parity violation







Superpartner Mass (TeV)
30
10
3
1
0.3
Higgsinos/Gauginos
1st Generation
2nd Generation
3rd Generation
NAT
DM
LHC
FLAV
EDM
HIGGS
$\tilde{H}$ $\tilde{B}$ $\tilde{W}$ $\tilde{g}$ $\tilde{u}_L$ $\tilde{d}_L$ $\tilde{u}_R$ $\tilde{d}_R$ $\tilde{\nu}_e$ $\tilde{e}_L$ $\tilde{e}_R$ $\tilde{c}_L$ $\tilde{s}_L$ $\tilde{c}_R$ $\tilde{s}_R$ $\tilde{\nu}_\mu$ $\tilde{\mu}_L$ $\tilde{\mu}_R$ $\tilde{t}_L$ $\tilde{b}_L$ $\tilde{t}_R$ $\tilde{b}_R$ $\tilde{\nu}_\tau$ $\tilde{\tau}_L$ $\tilde{\tau}_R$

[1302.6587]

Could SUSY still be hiding somewhere?

The Spectrum is not what we expect

Non-minimal models which live in parameter spaces less contained by LHC limits.

- Single Sector SUSY breaking (flavour and soft-spectrum arising from the same source, strong dynamics, with light fermion generations identified with bound states of the strong dynamics);
- Split families (first two generations are charged under a different set of SM gauge groups at high energies);
- Flavor mediation (supersymmetry breaking through spontaneously broken through a gauged flavour symmetry yielding the observed pattern of fermion masses and mixings);
- Colourless SUSY (top partners do not carry QCD charges at low energies–no strong production modes, eroding limits on stop masses);
- Focus Point SUSY (eliminate radiatively the sensitivity of EW scales to soft masses by allowing large soft masses but small radiative effects).

Conclusion

- Physicists very successful at discovering good/correct models:
  - Standard Model (electroweak and strong);
  - Higgs Mechanism;
  - neutrino seesaw;
- But bad track guessing the correct parameters
  - top Mass;
  - neutrino masses and mixing;
  - V_{cb}.

- Supersymmetry remains the most promising BSM scenario:
  - consistent and completely formulated models working to GUT scales;
  - computable framework up to M_{Planck};
  - consistent with coupling unification and proton decay bounds;
  - provide a DM candidate;
  - and eminently testable at the LHC,
- but we may be not looking in the right region, that is we were wrong about how SUSY would be detected at the LHC.

SUSY already seen?

- $W^{\pm}W^{\mp}$ cross section ~ 20 % higher than theoretical predictions $(1-2\sigma$ excess);
- SUSY searches for 3 leptons show $1.6-2.1\sigma$ excess;
- SUSY searches for squarks and gluinos show $\sim 2.5\sigma$ excess.

A SUSY Model with a light stop $(m_{\tilde{t}_1} \sim 212$ GeV), light winos and light binos $(m_{\chi^0_1} \sim 150$ GeV) can match the data .

[1406.0858]