ICTP SAIFR International Centre for Theoretical Physics South American Institute for Fundamental Research

IFT unesp UNIVERSIDADE ESTADUAL PAULISTA "JÚLIO DE MESQUITA FILHO"

# Physics Beyond the Standard Model

Eduardo Pontón

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School on "New Trends on High-Energy Physics and QCD"

- Lecture 1: The Standard Model
  Why the SM cannot be a complete description of Nature?
  Why do we think we could find new physics at the TeV scale?
- Lecture 2: Supersymmetry as an example for new Physics at the TeV scale.
  Motivations and virtues.
  Assessment of the present status.
- Lecture 3: Elementary or composite Higgs?
  Strong dynamics as the origin of EWSB.
  The connection to extra spatial dimensions.

# Table of contents: Lecture 2

# Summary of Lecture 1

What have we learned from the SM edifice?

# The Hierarchy Problem: Power-Law Divergences

- We saw in the first lecture that the Higgs sector of the SM suffers from a *Naturalness* problem: suggests there should be new physics near the weak scale.
  Comment: in the following, whenever we talk about "UV divergences", we mean that certain observables exhibit "sensitivity to the UV". As we will emphasize, a power-law sensitivity is qualitatively different from the much milder logarithmic sensitivity.
- One may note that the quantum corrections to the Higgs mass parameter due to fermions and bosons come with an opposite sign. Could the effects cancel in the SM? (c.f. Veltman's condition, see Marc's lecture)

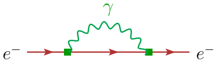
$$\Delta m_H^2\big|_{\rm top} = -\frac{3}{8\pi^2}\, y_t^2 \Lambda^2 \,, \qquad \Delta m_H^2\big|_{\rm gauge} = \frac{9}{64\pi^2}\, g^2 \Lambda^2 \,, \qquad \Delta m_H^2\big|_{\rm Higgs} = -\frac{1}{16\pi^2}\, \lambda\, \Lambda^2 \,,$$

- Unfortunately, the SM does not suggest the presence of special cancellations in the Higgs sector.
- But it does offer inspiring guidance in other sectors...

# We have seen this before

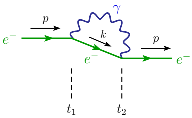
As emphasized recently by H. Murayama

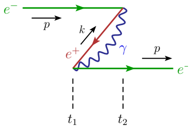
The electron self-energy, in QED, is logarithmically sensitive to the UV:




$$\sim \frac{\alpha}{4\pi} m_e \log(\Lambda/m_e) \quad \Rightarrow \quad \frac{\Delta m_e}{m_e} \sim \frac{\alpha}{4\pi} \log(\Lambda/m_e) \overset{\Lambda \approx M_P}{\sim} 0.03$$

Hence, we do not talk about a "hierarchy problem" for the electron. However, there is something non-trivial going on in this result, which can be appreciated by doing it in "old-fashioned perturbation theory":




- The first diagram, involving electrons only, gives a linearly divergent result!

$$\Delta E_e \sim \frac{e^2}{4\pi}\,\frac{1}{a} \qquad \text{where} \qquad a \sim 1/\Lambda$$

- This is nothing but the classical electric potential contribution, cutoff at a distance of order $a$.

# We have seen this before

- The classical result becomes unreliable either when
  - $a \sim 1/m_e$ (de Broglie wavelength, where QM becomes important), or
  - $\Delta E_e \sim m_e$ (where relativity becomes important).
- However, the existence of the positron (required by QM + relativity) leads to the second diagram, which cancels the linearly divergent piece, leaving behind the much milder logarithmic sensitivity!

## Lessons

- The cancellation of power-law divergences can be seen as motivation for the existence of new particles
- Deeper *symmetry principles* can be behind the existence of new particles with the right properties! [the $e^+$ and $e^-$ have the same mass and the same charge (albeit with opposite sign), as required by QM and relativity]

# Naturalness

Ready to dive into some computations?

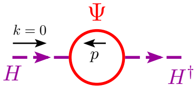
# Thinking about Conspiracies

Consider a "toy model" consisting of a Dirac fermion and a complex scalar:

$$\Delta\mathcal{L}_\Psi = i\bar{\Psi}\not{\partial}\Psi - M_\psi \bar{\Psi}\Psi + \left(y H \bar{\Psi} P_L \Psi + \text{h.c.}\right)$$

We can think of these as "the top" and "the Higgs", except we will not need to put in the SM quantum numbers (because they would only be distracting in the following)

The "Higgs" self-energy at 1-loop is then: ($\epsilon$ prescription is implicit)




$$= -(iy)^2 \int \frac{d^4p}{(2\pi)^4} \text{Tr}\left\{P_L \frac{i}{\not{p}-M_\psi} P_R \frac{i}{\not{p}-M_\psi}\right\}$$

$$= -\frac{y^2}{16\pi^2}\int p^2 dp^2 \frac{2p^2}{(p^2-M_\psi^2)^2}$$

(Using $\text{Tr}\left[P_L(\not{p}+M_\psi)P_R(\not{p}+M_\psi)\right] = 2p^2$)

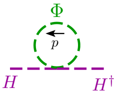
[Although straightforward to evaluate, we won't need to perform the momentum integration]

# Thinking about Conspiracies

Add now a second complex scalar interacting with the Higgs as follows:

$$\Delta\mathcal{L}_\Phi = \partial_\mu \Phi^\dagger \partial^\mu \Phi - M_\phi^2 \Phi^\dagger \Phi - \lambda\, H^\dagger H \Phi^\dagger \Phi$$

The "Higgs" self-energy from $\Phi$ at 1-loop is then:




$$= \frac{1}{2}\,(-i\lambda) \int \frac{d^4p}{(2\pi)^4}\, \frac{i}{p^2 - M_\phi^2} \overset{\text{high p region}}{\sim} \frac{1}{2}\lambda \int \frac{d^4p}{(2\pi)^4}\, \frac{1}{p^2}$$

which also exhibits a quadratic UV dependence, but with the opposite sign to the fermion one!

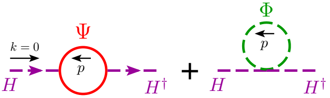
**Observation 1**

The leading (quadratic) divergence cancels between the fermion and scalar 1-loop diagrams if

$$\lambda = (2y)^2$$

# Thinking about Conspiracies

If this is the case, we have




$$= \frac{\lambda}{2}\int \frac{d^4p}{(2\pi)^4}\left\{-\frac{p^2}{(p^2-M_\psi^2)^2}+\frac{1}{p^2-M_\phi^2}\right\}$$

$$= \frac{\lambda}{2}\int \frac{d^4p}{(2\pi)^4}\,\frac{(M_\phi^2-2M_\psi^2)p^2+M_\psi^4}{(p^2-M_\phi^2)(p^2-M_\psi^2)^2}$$

$$\overset{\text{high p region}}{\sim} \frac{1}{2}\lambda(M_\phi^2-2M_\psi^2)\int\frac{d^4p}{(2\pi)^4}\,\frac{1}{p^4}$$

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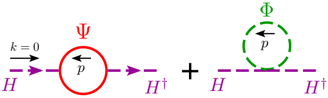


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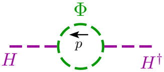
It is tempting to require a relation between the fermion and scalar masses that makes the result finite. However, before doing so, we should note that there is another interaction among scalars we could have considered:

$$\Delta\mathcal{L}_{\text{trilineal}} = m\,\Phi^\dagger\Phi\left(H+H^\dagger\right)$$

which leads to:




$$= \frac{1}{2}\,(im)^2\int\frac{d^4p}{(2\pi)^4}\left[\frac{i}{p^2-M_\phi^2}\right]^2$$

# Thinking about Conspiracies

Then the logarithmically divergent pieces are:

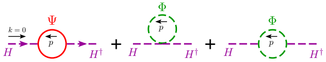
$$\frac{1}{2}\lambda \int \frac{d^4p}{(2\pi)^4} \left[ \frac{M_\phi^2 - 2M_\psi^2}{p^4} + \frac{m^2}{\lambda}\frac{1}{p^4} \right]$$

## Observation 2

The subleading (logarithmic) divergence cancels between the fermion and scalar 1-loop diagrams if

$$\frac{m^2}{\lambda} = 2M_\psi^2 - M_\phi^2$$

Imposing the two relations, we find a finite and well-defined result:




$$= \frac{\lambda}{2}\left(M_\phi^2 - M_\psi^2\right) \int \frac{d^4p}{(2\pi)^4} \frac{(3M_\psi^2 - M_\phi^2)p^2 - 2M_\psi^4}{(p^2 - M_\phi^2)^2 (p^2 - M_\psi^2)^2}$$

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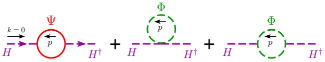


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But having come this far, why not take it to the end?

## Observation 3

Even the finite correction vanishes if $M_\psi = M_\phi$!

# The Importance of Symmetries

Putting it all together, we have identified a (toy) theory with interesting UV properties:

$$\Delta\mathcal{L} = \bar{\Psi}(i\partial\!\!\!/ - M)\Psi + \partial_\mu\Phi^\dagger\partial^\mu\Phi - M^2\Phi^\dagger\Phi$$
$$- \left(\tfrac{\lambda}{2}H\bar{\Psi}P_L\Psi + \text{h.c.}\right) - \lambda^2\, H^\dagger H\Phi^\dagger\Phi - \lambda M\,\Phi^\dagger\Phi\left(H + H^\dagger\right)$$

where the three "SUSY" relations, i.e. *observations 1, 2 and 3*, have been imposed (and I relabeled some parameters, and chose some inconsequential signs)

- We checked explicitly the soft UV properties of the above theory (treating $H$ as an external field), when the properties of the fermion $\Psi$ and scalar $\Phi$ are related. *We will be able to draw additional useful lessons from our example!*
- Worry: In QFT, parameters are scale dependent. Are the imposed relations invariant under RG evolution?
- Turns out that the above relations are enforced by a symmetry transformation that interchanges fermionic and bosonic d.o.f. This is a *spacetime* symmetry! It is called **SUPERSYMMETRY** (See Marc's lectures for a detailed formulation)

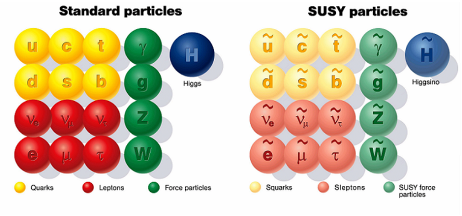
# The Supersymmetric Standard Model

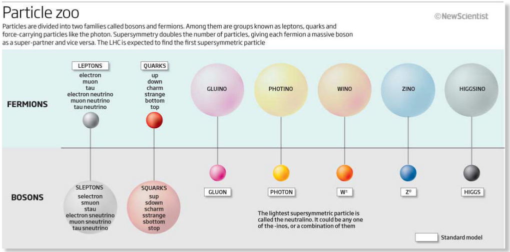
- The idea then is to implement the above magic in the context of a realistic theory, e.g. to supersymmetrize the SM.
- Although it is in principle possible to get the answer following the "pedestrian" approach used in our toy example, this would be quite a complex endeavor! (recall that the SM has over 300 d.o.f.)
- Fortunately, there are powerful tools that allow writing field theories that automatically enjoy the soft UV properties illustrated above. Furthermore, they allow for a complete classification (given the field content and the gauge symmetries). These are called **Superfield Methods**.
- It is outside the scope of (a single) lecture to describe the machinery of *Superfields and Superspace*, but if you are at all interested in SUSY it will be worth to spend some time mastering them. Just to illustrate, using those rules, the Minimal Supersymmetric Standard Model is specified simply by

$$W_{\rm MSSM} = QH_u\lambda_u U^c + QH_d\lambda_d D^c + LH_d\lambda_e E^c + \mu H_u H_d$$

# The Supersymmetric Particle Zoo

- The Minimal Supersymmetric Standard Model (MSSM) contains slightly more than twice the number of d.o.f. in the SM
- Interactions (approximately) dictated by those of the SM.
- Some of the new particles are strongly interacting. Others interact only weakly.
- Thera are two Higgs doublets, hence 5 physical Higgs bosons.



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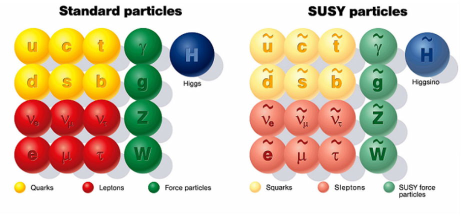
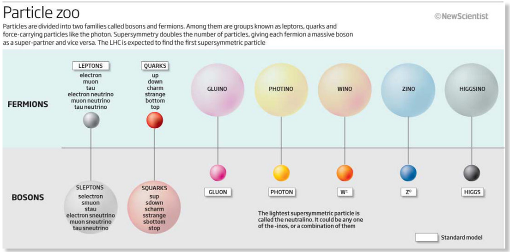
- Interactions (approximately) dictated by those of the SM.
- Some of the new particles are strongly interacting. Others interact only weakly.
- Thera are two Higgs doublets, hence 5 physical Higgs bosons.
- **We have not seen any of the superpartners.**



# Supersymmetry Breaking

- We saw in our toy example that to protect the Higgs mass from a quadratic sensitivity to unknown UV physics it is sufficient to require an appropriate relation between the dimensionless couplings: the Yukawa and the quartic scalar interactions (our *Observation 1*)
- Even if the masses of the fermion and boson inside a SUSY multiplet are not identical, or if the trilinear terms do not satisfy the SUSY relations, the Higgs mass would display only a mild logarithmic sensitivity to the UV.
- Hence, it is possible for the superpartners to be heavier than their SM counterparts, thus escaping detection so far, while providing a solution to the Hierarchy Problem! However, naturalness still suggest they should not be much heavier than the weak scale, and therefore the LHC may very well have the necessary reach to discover them!
- What is important is that the SUSY breaking terms be of the soft type (do not introduce quadratic divergences) as opposed to the hard type (which would). The first kind is associated with dimensional parameters, the second one with dimensionless ones.

# Supersymmetry Breaking

- Soft SUSY breaking is what one would expect if supersymmetry is *spontaneously* broken.
- If we simply parametrize the soft breaking parameters allowed in the MSSM, one finds on the order of 100 (the ugly!). However, not all of them are relevant for given observables. In addition, most are already strongly constrained by flavor and CP-violation measurements.
- Recall that SSB is typically reflected in relations between different parameters. Indeed, in specific models of SUSY breaking [1] one finds a much smaller set of "fundamental" parameters. Some buzz words are:
  - Supergravity Mediation
  - Anomaly Mediation
  - Gauge Mediation
  - Gaugino Mediation
- Given that there are several SUSY breaking mechanisms, we should keep an open mind from our low-energy point of view. If we were to discover SUSY particles and measure their properties (a tough task!), we could start dreaming about inferring the possible SUSY breaking mechanism at work...

[1] Most importantly, of SUSY mediation, but this is another story that lies beyond the scope of these short lecture

# Supersymmetry: A Love Affair

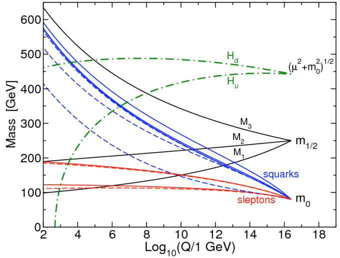
So why have we been in love with SUSY for more than three decades?

(both theorists and experimentalists)

# Radiative EW Symmetry Breaking

- Besides being an elegant solution to the Hierarchy Prb, SUSY has other virtues!
- It is useful to think about what can happen well above the weak scale:

from S. Martin, "A Supersymmetry Primer"




$m_2^2$ is driven to negative values, radiatively!

MSSM Higgs potential:

$$V_{\rm tree} = m_2^2 H_u^\dagger H_u + m_1^2 H_d^\dagger H_d - [b\, H_u H_d + h.c.]$$
$$+ \tfrac{1}{2}\lambda_1 (H_d^\dagger H_d)^2 + \tfrac{1}{2}\lambda_2 (H_u^\dagger H_u)^2$$
$$+ \lambda_3 (H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4 |H_u H_d)|^2$$

where

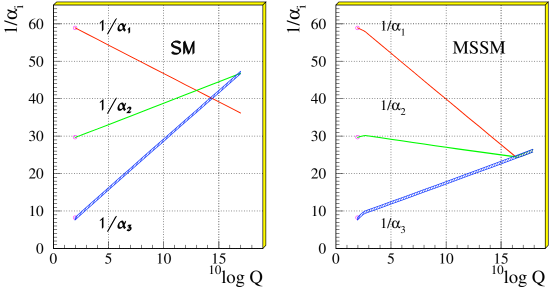
$$\lambda_1 = \lambda_2 = \tfrac{1}{4}\left(g'^2 + g^2\right),$$
$$\lambda_3 = \tfrac{1}{4}\left(g^2 - g'^2\right), \ \lambda_4 = -\tfrac{g^2}{2}$$

RG equation for $m_{H_u}^2$:

$$\frac{d}{dt} m_{H_u}^2 = \frac{6|y_t|^2}{16\pi^2}(m_{H_u}^2 + m_Q^2 + m_u^2) - \mathcal{O}\left(\frac{g^2}{16\pi^2}\right)$$

# Gauge Coupling Unification

The difference in field content between the SM and the MSSM implies that the gauge $\beta$-functions differ. As a result, in the MSSM the three gauge couplings unify at a single scale $M_{\rm GUT} \approx 2\times 10^{16}$ GeV. Not so in the SM! Is there a deeper meaning?

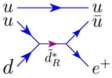



$$\frac{d}{dt}g_a = \frac{1}{16\pi^2} b_a g_a^3 \,, \qquad (b_1,b_2,b_3) = \begin{cases} (\frac{41}{10}, -\frac{19}{6}, -7) & \text{Standard Model} \\ (\frac{33}{5}, 1, -3) & \text{MSSM} \end{cases}$$

# Dark Matter

- First, a drawback w.r.t to the SM: baryon/lepton number are no longer accidental symmetries.
- Indeed, there are (gauge invariant) Yukawa interactions not involving the Higgs(es), but rather the squarks or sleptons. For instance,

$$(\bar{u}d^c)\,\tilde{d}_R^* \quad \text{or} \quad (\bar{e}u^c)\,\tilde{d}_R$$




  The baryon/lepton number violation (at dimension-4) would lead to extremely rapid proton decay!
- The dangerous operators can be forbidden by imposing a discrete symmetry (R-parity), under which all new particles are odd, while all SM particles are even.
- There are two important consequences. The first one is that the lightest R-parity odd particle must be absolutely stable. If it was produced in the early universe, it must still be around!

# Dark Matter

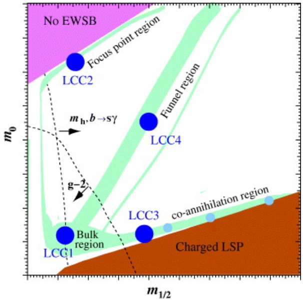
The Lightest Supersymmetric Particle (LSP) can naturally be a (neutral) weakly interacting state: an ideal candidate for DM.

- **The WIMP Miracle**: for a thermally produced relic $\chi$:

$$\Omega_\chi \approx \frac{0.8 \text{ pb}}{\langle \sigma v \rangle}$$

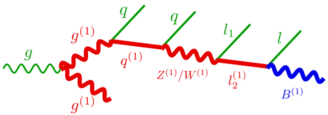
- A neutralino LSP is an attractive possibility. The annihilation cross section depends on its composition, and on other nearby states.
- The fact that SUSY with R-parity conservation can accommodate the DM density remains a selling point!

from M. Battaglia (2009)



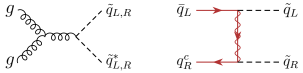
# Supersymmetry: Expectations at the LHC

- The second important consequence of R-parity is that sparticles must be pair produced. This has two types of implications:
  - The new physics can affect low-energy observables only at 1-loop order, not tree-level, so that the corrections are expected to be small. We count this as an important success of SUSY, as an extension of the SM.
  - Sparticles must be pair produced (e.g. at colliders). This is more difficult than single production, and leads to distinct signatures.
- The fact that the lightest R-parity odd particle is stable means that once a pair of new particles is produced, their decay products will involve two LSP's. This leads to the well-known $\not{E}_T$ signal.

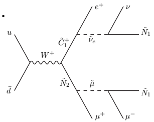


# Supersymmetry: Expectations at the LHC

- Strongly interacting particles heavier than weakly interacting ones.
- However, stops lighter than other squarks due to top Yukawa coupling.
- Gluino and squark pair production from (SUSY) QCD, e.g.

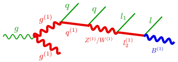



- Weak production with clean ("spectacular") signals, e.g.

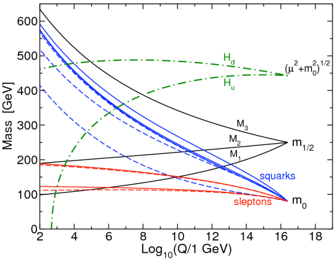


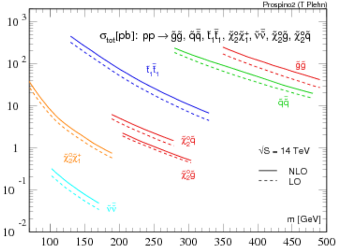

$(\mu^+\mu^-e^+ + \not{E}_T)$

- Long Cascade Decays, e.g.



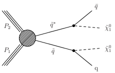

from S. Martin, "A Supersymmetry Primer"

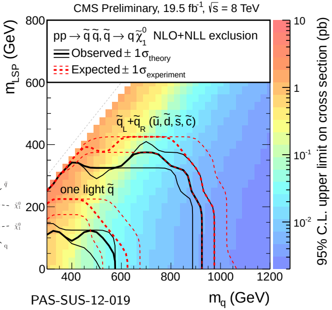


# Current constraints: squarks and gluinos

- Bounds presented in terms of Simplified Models (a positive development)
- Squarks and gluinos heavier than $\sim 1$ TeV or more. (interpretation within "full models" may give different bounds)



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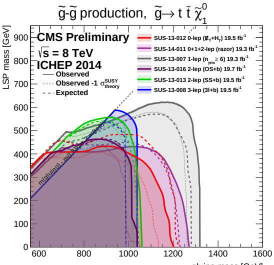
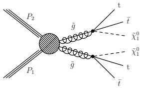
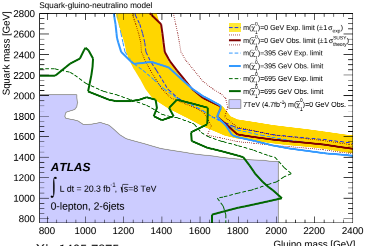



CMS-SUS-12-028

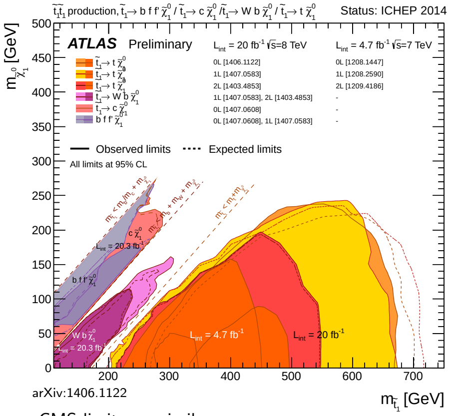





arXiv:1405.7875

# Current constraints: Direct stop searches

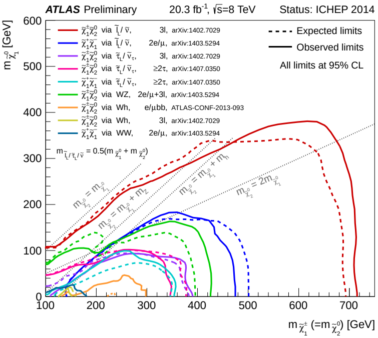
- Stop sector: most closely connected to naturalness.
- Significant effort to constrain the direct production of stops.
- Bounds dependent on decay mode:
    - Can reach $\sim 700$ GeV for a "light" neutralino.
    - Bounds disappear for $m_{\tilde{\chi}_1^0} \gtrsim 250$ GeV.
    - Difficult degenerate regions, where decay products are soft.
- Sbottoms do not impact naturalness directly, but $\tilde{b}_L$ typically connected to $\tilde{t}_L$. Direct production bounds also around $700$ GeV (not shown).

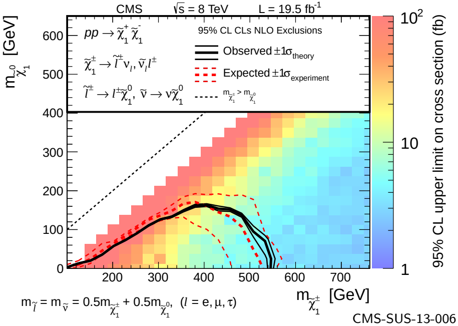


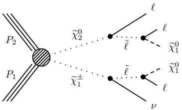

CMS limits are similar

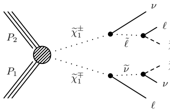
# Current constraints: electroweakinos

Interesting new bounds that start improving on previous LEP limits!



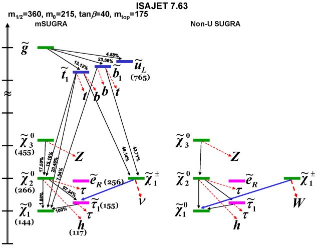



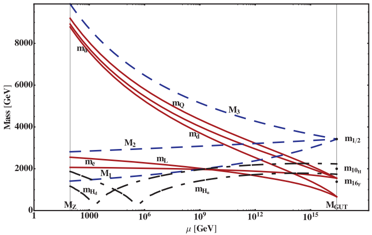





# Beyond Minimality

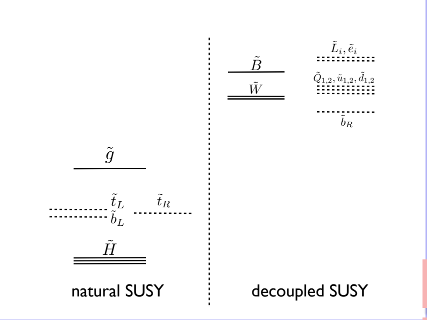
- In the context of SUSY, the Higgs mass $m_h \approx 125$ GeV already suggests a non-minimal framework (e.g. existence of a singlet or other possibilities).
- Could SUSY be hiding in some of the difficult regions?



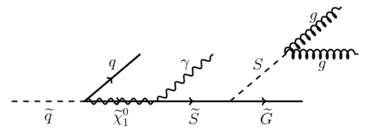



# Beyond Minimality

**Unexpected spectra, perhaps motivated by naturalness?**




**Stealth SUSY?**




**Suppressed production, e.g. Dirac gauginos?**

**R-Parity violation (RPV) or even full $U(1)_R$**

# Conclusions

SUSY is a very elegant solution to the hierarchy problem and can easily be consistent (perhaps help) with other solutions to the open questions in the SM, in particular providing a rational for EWSB. It may also be an integral part of incorporating a quantum description of gravity, as suggested by String Theory (see Gary's lectures)

It is important that we check to the fullest extent possible if it plays a role at the weak scale. The philosophy must be to "leave no stone unturned"...

# End of Second Lecture

Thank you!