Beyond Standard Model
(BSM)

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  - (SM as an) EFT
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- Lecture III : BSM Considering Hierarchy Problem
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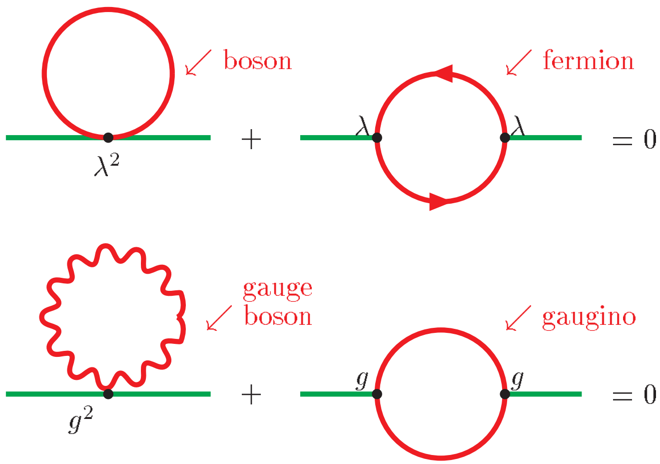
SUSY

- SUSY : FERMION $\leftrightarrow$ BOSON
  $\rightarrow$ Generators $Q, \overline{Q}$ are Fermionic
- Maximal Sym of S-matrix in 4-dim Rel Local QFT with graded Lie algebra (Haag, Lopusansky and Sohnius)
- Better High Energy Behavior with SUSY
- Essential in String Theories
  $*$ Removes tachyonic states
  $*$ Endows us with Fermions (Matter)
- Local SUSY (SUGRA) includes Gravity
  $\rightarrow$ Quantum Gravity when combined with String Theory (TOE)

SUSY

- Can solve Technical Hierarchy Problem
- Low Energy Measurements of 3 Gauge Couplings + SUSY $\rightarrow$ SUSY GUT
- Natural CDM when we impose $R-$parity conservation for proton stability
- And CDM within SUSY GUT
  cf. In many other CDM models, DM particles do not belong to a representation of grand unfied group

Quantum Corrections to a Scalar Mass



- Fermion Loop Contribution
  $$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_f^2\,\ln(\Lambda_{UV}/m_f) + ...\right]$$
- Scalar Loop Contribution
  $$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[+\Lambda_{UV}^2 - 2m_S^2\,\ln(\Lambda_{UV}/m_S) + ...\right]$$
- $\Lambda_{UV} \sim M_{pl} \sim 10^{19}$ GeV vs. $m_H \sim 10^2$ GeV
  $\rightarrow$ Technical Gauge Hierarchy Problem

SUSY helps

- Dangerous Λ_{UV}^2 terms cancel,
  if $\lambda_S = |\lambda_f|^2$, and
  if there are two dof's for each fermion
- The result will be
  $\Delta m_H^2 = m_{soft}^2 \ \left[\frac{\lambda}{16\pi^2} \ \ln(\Lambda_{UV}/m_{soft}) + ...\right]$
- m_{soft} cannot be too huge
  $*$ Otherwise, back to the hierarchy problem
  N.B. : $\Delta m_H^2 \to 0$ as $m_{soft} \to 0$
- These two relations can be realized in **SUSY** (This is why the lightest neutral Higgs in the MSSM is generically lighter than the SM Higgs.)
  $*$ f and S have the same masses in SUSY limit

How to Construct SUSY Lagrangian ?

- Supersymmetric lagrangian consists of two parts:

$$\mathcal{L}_{\mathrm{SUSY}} = [K]_D + \left[\frac{1}{4} f_{ab}(\Phi) \widehat{W^a} \widehat{W^b} + W \right]_F$$

-

$$\widetilde{\Phi^{*j}} = \phi^{*k} (e^{2T^a \hat{V}^a})_k^j$$

- K : Kähler potential is a function of both Φ and Φ^*
- W : Superpotential W is a holomorphic function of chiral superfied Φ only, and not of antichiral superfield Φ^*
- f : Gauge kinetic function is a function of Φ

- For renomalizable case (at tree level),

$$\begin{aligned} K(\Phi_i, \Phi^{j*}) &= \Phi_i \Phi^{*i} \\ W(\Phi) &= \text{holomorphic function of} \Phi([W] = 3) \\ f(\Phi) &= \delta_{ab}(1/g_a^2 - i\Theta_a/8\pi^2) \end{aligned}$$

- Scalar potential from $[W(\Phi)]_F$:

$$V_{\rm scalar} = |\frac{\delta W}{\delta \Phi_i}|^2 \equiv W_i W^{i*}$$

- Yukawa interaction from $[W(\Phi)]_F$:

$$-\frac{1}{2}\frac{\delta^2 W}{\delta\Phi_i \delta\Phi_j}\psi_i\psi_j$$

- Kinetic terms from $[K]_D$ (without gauge interaction):

$$\partial\phi^*\partial\phi + i\psi^\dagger\bar{\sigma}^\mu\partial_\mu\psi + ...$$

[See S. Martin, "SUSY Primer", http://arxiv.org/pdf/hep-ph/9709356]

Particle Contents of MSSM

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U$
squarks, quarks	Q	$(\widetilde{u}_L \quad \widetilde{d}_L)$	$(u_L \quad d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
($\times 3$ families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\ \widetilde{e}_L)$	$(\nu \quad e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
($\times 3$ families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H^+_u \quad H^0_u)$	$(\widetilde{H}^+_u \quad \widetilde{H}^0_u)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H^0_d \quad H^-_d)$	$(\widetilde{H}^0_d \quad \widetilde{H}^-_d)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

Table 1: Matter fields in the MSSM

$R-$parity

- In the MSSM, the most general gauge-invariant, renormalizable superpotential is

$$\begin{aligned}
W_{\rm ren} &= W_{\rm RPC} + W_{\rm RPV}, \\
W_{\rm RPC} &= h_l^{ij} e_i L_j H_d + h_d^{ij} Q_i d_j H_d + h_u^{ij} Q_i u_j H_u + \mu H_u H_d, \\
W_{\rm RPV} &= \lambda_{ijk} L_i L_j e_k + \lambda'_{ijk} L_i Q_j d_k + \lambda''_{ijk} u_i d_j d_k + \mu_i L_i H_d
\end{aligned}$$

- R-parity is defined as

$$R = (-1)^{3(B-L)+2S}$$

  - SM particles : $R = +1$ (even)
  - Super partners : $R = -1$ (odd)

- The origin of λ, $\lambda^{'}$ and μ_i terms is because L_i's and H_d have the same gauge quantum numbers.
- Another similar parity **Matter Parity** ($P_M \equiv (-1)^{3(B-L)}$) acts on superfields, and does the same job as $R-$parity, i.e., removes W_{RPV}.:

$$(L_i, e_i, Q_i, u_i, d_i) \to -(L_i, e_i, Q_i, u_i, d_i), \quad (H_u, H_d) \to (H_u, H_d)$$

Proton decay problem

- Strongest constraints on W_{RPV} come from proton lifetime :

$$\tau_{\mathrm{proton}}(p \to e^+\pi^0) > 10^{32}\mathrm{years}$$

- RPV interaction can induce proton decay:

$$\Gamma(p \to e^+\pi^0) \simeq \frac{\lambda_{11k}^{\prime 2}\lambda_{11k}^{\prime\prime 2}}{16\pi^2 m_{\tilde{d}_k}^4} m_{\mathrm{proton}}^5$$

- From the lower limit on proton life time ($\tau(p \to e^+\pi^0) > 10^{32}$ years), one gets

$$\left|\lambda_{112}^{\prime\prime}\lambda_{112}^{\prime}\right| \lesssim 2 \times 10^{-24} \left(\frac{m_{\tilde{d}_k}^2}{200 \text{ GeV}}\right)^2$$

- Hard to understand such a small number, unless there is some symmetry that forbids it ($\rightarrow R-$parity)
- R-parity conservation implies that
  - LSP (Lightest Superparticle) is stable
    $\rightarrow$ Good DM candidate (BONUS)
  - LSP is most likely weakly interacting (Not seen at detector)
  - Super particles are produced in pairs at colliders, and each decays into SM particles + LSP
  - There are a pair of LSP's in the final states, which lead to missing E_T signatures

MSSM

- SUSY must be (spontaneously) BROKEN in reality, since no scalar particle with electron mass has been found
- SUSY Breaking Effects can be parametrized in terms of Soft-SUSY Breaking terms ($\mathcal{L}_{soft}$) with op.'s (dim. ≤ 3) $\rightarrow$ Sparticles get masses around $O(100\ \mathrm{GeV})$ to $O(1)$ TeV.
- MSSM $\equiv$ SM + One more Higgs Doublet + SUSY + $\mathcal{L}_{soft}$

$$
\begin{aligned}
\mathcal{L}_{\mathrm{MSSM}} &= \mathcal{L}_{\mathrm{SUSY}} + \mathcal{L}_{\mathrm{soft}}, \\
\mathcal{L}_{\mathrm{soft}} &= -\frac{1}{2}\, M_\lambda \lambda^a \lambda^a - \phi^{*j} \left(\tilde{m}^2\right)^i_j \phi_i \\
&\quad - \left(\frac{1}{2}\, b^{ij} \phi_i \phi_j + \frac{1}{6}\, a^{ijk} \phi_i \phi_j \phi_k + c.c.\right)
\end{aligned}
$$

- Note that all the terms in the soft SUSY breaking terms have

$$M_\lambda \sim a^{ijk} \sim b^{ij} \sim \tilde{m} \sim m_{\rm soft}$$

- There are 105 more parameters in MSSM compared to the SM :
  $*$ more mass parameters, mixing angle and CPV phases.
  $*$ All parameters in principle calculable from underlying theory
  $*$ All parameters measurable (like quark masses and CKM parameters)

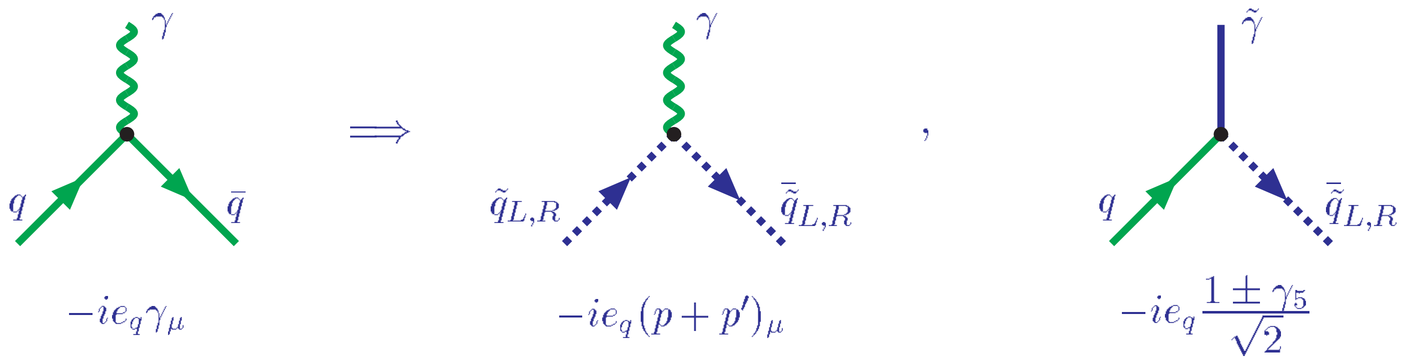


Figure 1: Gauge-matter interaction

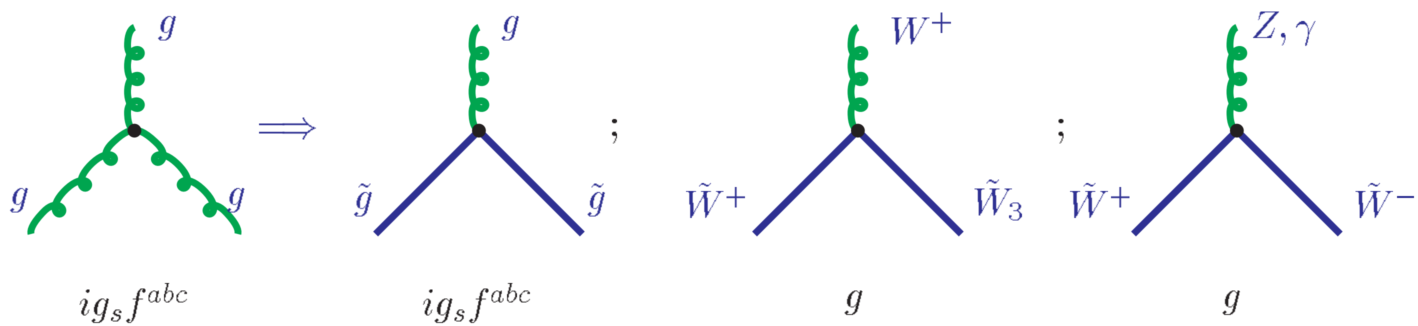


Figure 2: Gauge self-interaction

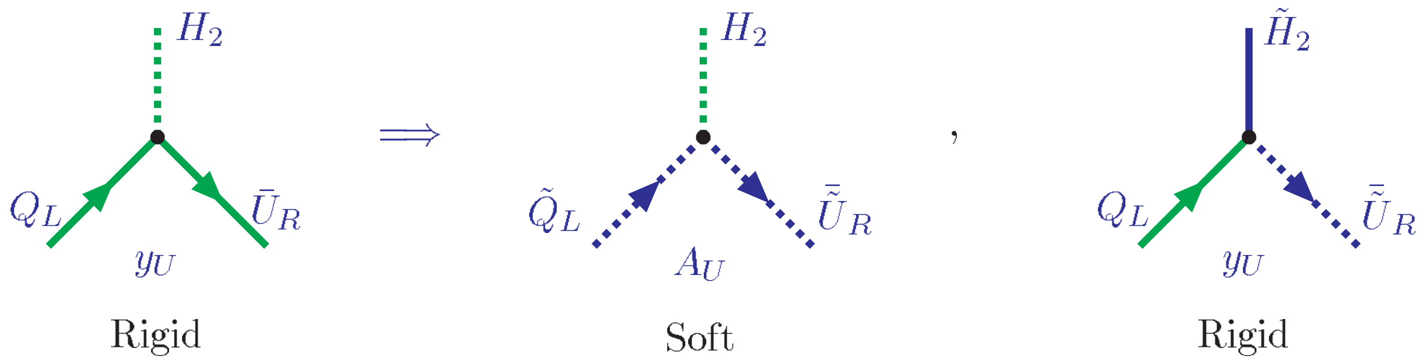


Figure 3: Yukawa-type interaction

In order to verify SUSY is realized in Nature, it is important to measure all dimensionless couplings, and check if they obey the SUSY relations shown above

$\rightarrow$ Strong Argument for a Linear Collider

- MSSM Solves Hierarchy Problem with SUSY,
- But it introduces MANY QUESTIONS to be answered, especially about μ problem, flavor and CP problems because of the Soft SUSY breaking terms with many unrelated parameters
  $*$ Why is proton stable in MSSM ? (R-parity ?)
  $*$ How is FCNC suppressed in MSSM ?
  $*$ Roles of 43 more physical CP violating phases in MSSM ?

$|\Delta F| = 2$ Diagrams

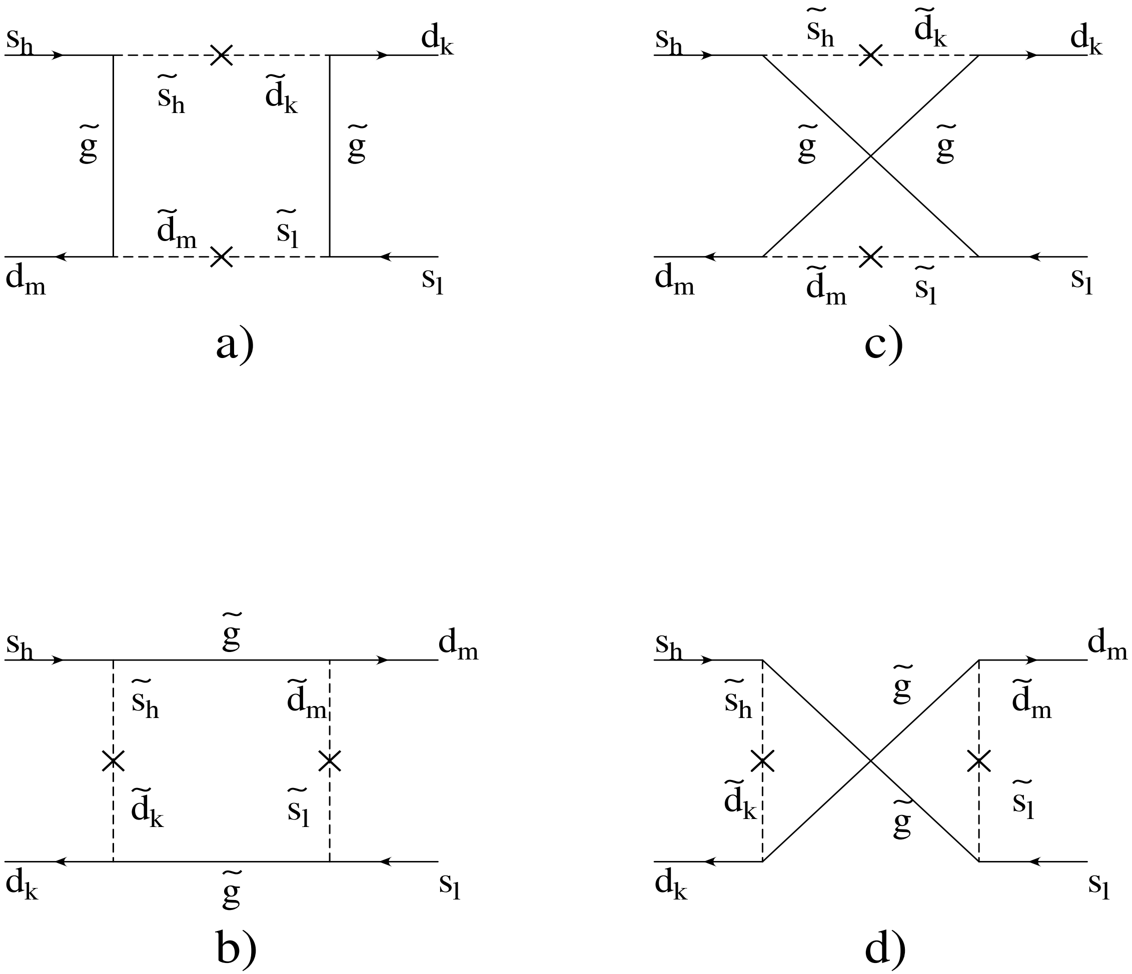


Figure 1: Feynman diagrams for $\Delta S = 2$ transitions, with $h, k, l, m = \{L, R\}$.

Possible sol's to SUSY Flavor Problem

- In the interaction basis, sfermion mass matrix is not diagonal in general $\rightarrow$ Generically Large FCNC,

$$K^0 - \overline{K^0} \text{ mixing} : \frac{A^2}{m_{\tilde{Q}}^2} \left(\frac{\delta m_{\tilde{Q}}^2}{m_{\tilde{Q}}^2} \right)^2 \leq 5 \times 10^{-9} \text{ GeV}^{-2}$$

$*$ UNLESS Sfermions with the same electric charges are almost degenerate

(i.e., $\delta m_{\tilde{Q}}^2 = 0$), OR

$*$ $U = \tilde{U}$ (for which $A^2 = 0$), OR

$*$ Decoupling of the first two generations of Sfermions (10–100 TeV)

with the third generation sferion mass below ~ 1 TeV

Why should δ's so small ?

Possible Solutions to SUSY FCNC

- Universality : mSUGRA, No scale scenario, Gauge mediation, etc. $*$ True only at some messenger scale, RG running induce some flavor violations
- Alignment : Flavor symmetry for Yukawa (SUSY) and sfermion masses (SUSY breaking) $\rightarrow$ SUSY FCNC problem is medigated, but generically larger FCNC than universality assumption
- Decoupling : 1st/2nd generation sfermions are very heavy and almost degenerate, only the third sfermion and gauginos are light (below ~ 1 TeV).
  However, cannot accommodate the muon $(g-2)_\mu$.
- Not only solutions. Can assume some nonuniversal soft terms

SUSY in the Loop: Flavor Conserving

- Usually hidden under the SM contributions (which are often tree level effects)
  $\rightarrow$ SUSY effects are usually small and decouples quickly
  N.B. : Exception : the muon $(g-2)_\mu$, because of the very accurate SM predictions and the precise measurement are available, and SUSY contribution is enhanced for large $\tan\beta$
- $\sim O(1)$ CPV phase could generate too large EDM's for e and n (SUSY CP probelm)
  $\rightarrow$ Either very small CP phase, or heavy sfermions (at least) for the 1st and 2nd generation scalar fermions

SUSY in the loop: FCNC

- SM Contributions : already loop suppressed due to GIM mechanism
- SUSY Contributions : also loop suppressed, but can compete with SM contributions, if SUSY particles are not too heavy, assuming gluino mediated FCNC is solved by some ways
- $B \to X_s \gamma$: QCD part is under control
  $\to$ Small theoretical uncertainties (Also for $B^0 - \overline{B^0}$ mixing, $B \to X_s l^+ l^-$ and $B_s \to \mu^+ \mu^-$, etc.)
- Never can be a clear evidence for SUSY.
  Only a Smoking Gun for New Physics !
- Can be complementary for direct search at colliders, especially if SUSY particles are too heavy to be produced directly at colliders

- Most phenomenological analyses were done in the context of $N = 1$ Minimal SUGRA framework with only 4 independent soft parameters :
  - Universal scalar mass : $\tilde{m}^2 \rightarrow m_0^2$
  - Triliniear Coupling : $a^{ijk} \rightarrow A$
  - Universal bilinear Coupling : $b^{ij} \rightarrow B$
    $*$ can be traded with $\tan\beta$
  - Universal Gaugino Masses : $M_\lambda \rightarrow M_{1/2}$ (independent of gauge groups)
  - Sign of μ parameter
- Huge reduction in parameter space, but much more predictive phenomenology is possible
- Tightly constrained from LHC data

How SUSY is broken ?

- SUSY breaking : better be spontaneous breaking, rather than explicit breaking
- Dynamical SUSY breaking in SUSY gauge theories
- For phenomenological purpose, we don't have to worry about the underlying mechanism of how SUSY is broken.
- One can simply parameterize the effects of SUSY breaking by some order parameters such as the scalar and auxiliary (F or D terms) components of some chiral multiplets

SUSY Breaking Mediation

- MSSM itself cannot be the Ultimate Theory of Nature, either
- 124 parameters of MSSM are arbitrary in principle. BUT!!
- Generic parameter space is already incompatible with various low energy data on FCNC and CP violations
  $\Delta M_K, \quad \Delta M_B, \quad \epsilon_K, \quad e/n$ EDM's, etc.
- The sparticle spectrum is crucially dependent on how SUSY breaking is communicated to our world $\rightarrow$ Phenomenologically very important
- We need some nice mechanisms which can solve the so-called SUSY Flavor (FCNC) and SUSY CP problems
- Many Scenarios: Gravity Mediation, GaugeMediation, Anomaly Mediation, Gaugino Mediation, etc..

Higgs potential

- Two Higgs doublets: $H_u = (H_u^+,\ H_u^0)$ and $H_d = (H_d^0,\ H_d^-)$
- Higgs potential :

$$
\begin{aligned}
V \ = \ & (|\mu|^2 + m_{H_u}^2)(|H_u^0|^2 + |H_u^+|^2) + (|\mu|^2 + m_{H_d}^2)(|H_d^0|^2 + |H_d^-|^2) \\
& +[b(H_u^+ H_d^- - H_u^0 H_d^0) + c.c.] \\
& +\frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2)^2 + \frac{1}{2}g^2|H_u^+ H_d^0
\end{aligned}
$$

- $|\mu|^2$ from F-terms
- Quartic terms proportional to g^2 and g'^2 from D-term contributions
- $m_{H_u}^2$, $m_{H_d}^2$ and b from soft SUSY breaking

EWSB from SUSY Breaking

After setting $H_u^+ = H_d^- = 0$, we are left to consider the scalar potential

$$\begin{aligned} V &= (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (b\, H_u^0 H_d^0 + c.c.) \\ &\quad + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2. \end{aligned}$$

- EWSB possible only if SUSY is broken
- Quadratic part of the scalar potential to be positive along the D-flat directions (along $|H_u^0| = |H_d^0|$)

$$2b < 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2.$$

- Requiring that one linear combination of H_u^0 and H_d^0 has a negative squared mass near $H_u^0 = H_d^0 = 0$ gives

$$b^2 > (|\mu|^2 + m_{H_u}^2)(|\mu|^2 + m_{H_d}^2).$$

EWSB

- After EWSB, one has $v_u = \langle H_u^0 \rangle, \quad v_d = \langle H_d^0 \rangle$
- Two VEVs are related to the known mass of the Z^0 boson and the electroweak gauge couplings:

$$v_u^2 + v_d^2 = v^2 = 2m_Z^2/(g^2 + g'^2) \approx (174\,\mathrm{GeV})^2$$

- The ratio of the two VEV's is free parameter:

$$\tan\beta \equiv v_u/v_d.$$

- Three neutral Higgs bosons: (h, H) (CP-even) and A (CP-odd)
- CP is conserved in the SUSY potential, but can be broken if there are CP phases in the soft SUSY breaking terms

Neutral Higgs Sector

- Masses of three neutral Higgs bosons

$$
\begin{aligned}
m_{A^0}^2 &= 2b/\sin(2\beta) = 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2 \\
m_{h^0,H^0}^2 &= \frac{1}{2}\left(m_{A^0}^2 + m_Z^2 \mp \sqrt{(m_{A^0}^2 - m_Z^2)^2 + 4m_Z^2 m_{A^0}^2 \sin^2(2\beta)}\right), \\
m_{H^\pm}^2 &= m_{A^0}^2 + m_W^2 .
\end{aligned}
$$

- The mixing angle α is determined, at tree-level, by

$$
\frac{\sin 2\alpha}{\sin 2\beta} = -\left(\frac{m_{H^0}^2 + m_{h^0}^2}{m_{H^0}^2 - m_{h^0}^2}\right), \qquad \frac{\tan 2\alpha}{\tan 2\beta} = \left(\frac{m_{A^0}^2 + m_Z^2}{m_{A^0}^2 - m_Z^2}\right),
$$

- $-\pi/2 < \alpha < 0$ (provided $m_{A^0} > m_Z$).

Upper Bound on m_h

- Tree level:

$$m_h \leq m_Z |\cos(2\beta)| \leq m_Z$$

which is already excluded

- One loop correction from can be large:

$$\Delta(m_{h^0}^2) = \frac{3}{4\pi^2}\cos^2\alpha\ y_t^2 m_t^2 \ln\left(m_{\tilde{t}_1} m_{\tilde{t}_2}/m_t^2\right)$$

- After all, one gets $m_{h^0} \lesssim 135$ GeV in the MSSM
- Can be higher in non minimal cases
- Charged Higgs Boson:

$$m_{H^\pm}^2 = m_W^2 + m_A^2$$

Charginos

- The chargino spectrum can be analyzed as folows. In the gauge-eigenstate basis $\psi^{\pm} = (\widetilde{W}^{+}, \widetilde{H}_u^{+}, \widetilde{W}^{-}, \widetilde{H}_d^{-})$, the chargino mass terms in the Lagrangian are

$$\mathcal{L}_{\text{chargino mass}} = -\frac{1}{2}(\psi^{\pm})^T \mathbf{M}_{\widetilde{C}} \psi^{\pm} + c.c.$$

where, in 2×2 block form,

$$\mathbf{M}_{\widetilde{C}} = \begin{pmatrix} \mathbf{0} & \mathbf{X}^T \\ \mathbf{X} & \mathbf{0} \end{pmatrix},$$

with

$$\mathbf{X} = \begin{pmatrix} M_2 & gv_u \\ gv_d & \mu \end{pmatrix} = \begin{pmatrix} M_2 & \sqrt{2}\sin\beta\, m_W \\ \sqrt{2}\cos\beta\, m_W & \mu \end{pmatrix}.$$

- Note that the mixing matrix for the positively charged left-handed fermions is different from that for the negatively charged left-handed fermions. They are chosen so that

$$\mathbf{U}^*\mathbf{X}\mathbf{V}^{-1} = \begin{pmatrix} m_{\widetilde{C}_1} & 0 \\ 0 & m_{\widetilde{C}_2} \end{pmatrix},$$

with positive real entries $m_{\widetilde{C}_i}$.

$$m^2_{\widetilde{C}_1}, m^2_{\widetilde{C}_2} = \frac{1}{2}\Big[|M_2|^2 + |\mu|^2 + 2m_W^2 \mp \sqrt{(|M_2|^2 + |\mu|^2 + 2m_W^2)^2 - 4|\mu M_2 - m_W^2 \sin 2\beta|^2}\Big]$$

Neutralinos

- Neutralinos are linear combinations of neutral gauginos, $\widetilde{B}$, $\widetilde{W_3^0}$, and neutral Higgsinos $\widetilde{H_u^0}$ and $\widetilde{H_d^0}$
- Mass terms are given by

$$\mathcal{L}_{\text{neutralino mass}} = -\frac{1}{2}(\psi^0)^T \mathbf{M}_{\widetilde{N}} \psi^0 + c.c.,$$

where $\mathrm{M}_{\widetilde{N}}$ is given by

$$\begin{pmatrix} M_1 & 0 & -\cos\beta\, s_W m_Z & \sin\beta\, s_W\, m_Z \\ 0 & M_2 & \cos\beta\, c_W\, m_Z & -\sin\beta\, c_W\, m_Z \\ -\cos\beta\, s_W\, m_Z & \cos\beta\, c_W\, m_Z & 0 & -\mu \\ \sin\beta\, s_W\, m_Z & -\sin\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$

- Lightest Neutralino becomes a good CDM candidate

Sfermion Sector

- Superpartners of f_L and f_R: $\widetilde{f_L}$ and $\widetilde{f_R}$
- Stop Mass matrix in the $(\widetilde{t}^*_L, \widetilde{t}^*_R)$ basis as an example:

$$\mathbf{m}^2_{\tilde{\mathbf{t}}} = \begin{pmatrix} m^2_{Q_3} + m_t^2 + \Delta_{\tilde{u}_L} & v(a_t^* \sin\beta - \mu y_t \cos\beta) \\ v(a_t \sin\beta - \mu^* y_t \cos\beta) & m^2_{\overline{u}_3} + m_t^2 + \Delta_{\tilde{u}_R} \end{pmatrix}.$$

- SImilarly for sbottom with $\sin\beta \leftrightarrow \cos\beta$..
- LR mixing significant only for the 3rd generation sfermions
- Stops can make a huge corrections to the m_h
- Stoponium might be possible (an analogue of heavy quarkonium)

Important Constraints

- Direct search bounds on masses of Higgs boson and SUSY particles
- Muon $(g-2)_\mu$ prefers large $\tan\beta$
- $B \to X_s \gamma$
- $B_s \to \mu^+ \mu^-$
- $\Omega_{CDM} h^2 \sim 0.11$
- Upper bounds on spin-indep cross section between CDM and proton
- Flavor sector is more model dependent
- Current bounds from LHC are quite tight for mSUGRA

Grand Unification Theory (GUT)

– Unanswered Questions within SM –

- Why $Q_p = -Q_e$ and $U(1)_Y$ quantum numbers ?
- Why 3 different forces ? Are they UNIFIABLE ?
  $SU(3)_c \times SU(2)_L \times U(1)_Y \to G_{\rm GUT}$
- Why proton is stable ?
  $\tau(p \to e^+\pi^0) > 1.6 \times 10^{33}$ years
- Why 3 generations ?
- Quantum Gravity ?

cf. Many other questions

$SU(5)$ GUT

- $5^* = (d_1^c, d_2^c, d_3^c, e^-, \nu_e)_L^T$ $\boxed{\text{Quark–Lepton Unification}}$

$$10 = \begin{pmatrix} 0 & u_3^c & -u_2^c & -u^1 & -d^1 \\ & 0 & u_1^c & -u^2 & -d^2 \\ & & 0 & -u^3 & -d^3 \\ & & & 0 & -e^+ \\ & & & & 0 \end{pmatrix}_L$$

$1 = N_L^c$

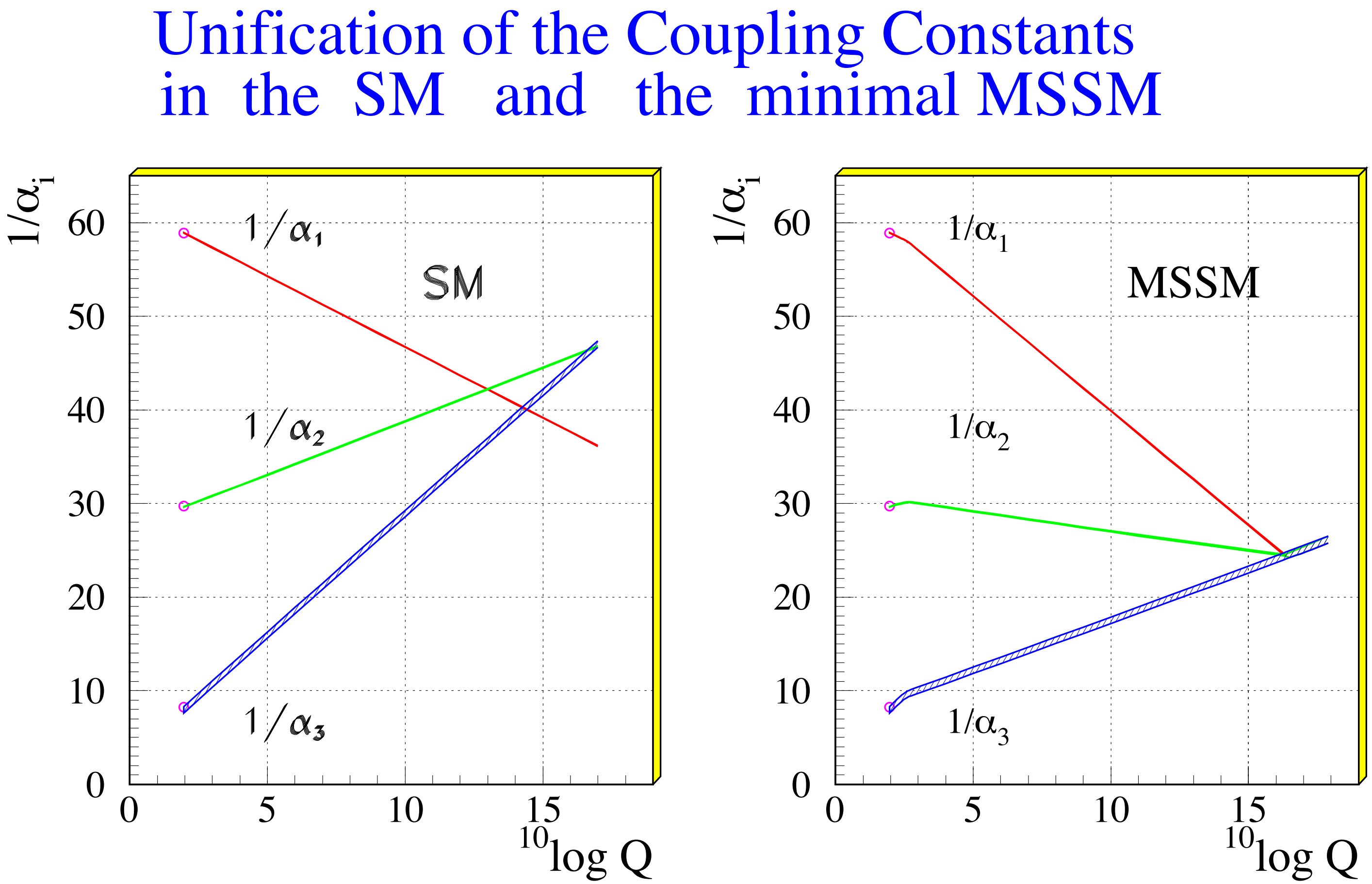
- SM particles fit into $5^* + 10 + 1$ of $SU(5)$
  $*$ Large neutrino mixing $\nu_\mu \leftrightarrow \nu_\tau \rightarrow$ large $b_L^c - s_L^c$ (or $b_R - s_R$) mixing

$SU(5)$ Gauge Bosons and Proton Decay

$$\begin{pmatrix} G^1_1 - \frac{2B}{\sqrt{30}} & G^1_2 & G^1_3 & \bar{X}^1 & \bar{Y}^1 \\ G^2_1 & G^2_2 - \frac{2B}{\sqrt{30}} & G^2_3 & \bar{X}^2 & \bar{Y}^2 \\ G^3_1 & G^3_2 & G^3_3 - \frac{2B}{\sqrt{30}} & \bar{X}^3 & \bar{Y}^3 \\ X_1 & X_2 & X_3 & \frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} & W^+ \\ Y_1 & Y_2 & Y_3 & W^- & -\frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} \end{pmatrix}$$

- Superheavy X, Y gauge boson excahnge can generate proton decay:
  $\tau^{-1} \sim \frac{\alpha^2_{\mathrm{GUT}} m^5_p}{M^4_X}$
- NonSUSY $SU(5)$: $M_X \simeq 3 \times 10^{14}$ GeV $\rightarrow \tau \simeq 10^{30\pm1}$ years EXCLUDED
- SUSY SU(5) is OK with proton decay exp. and Gauge Coupling Unification

Evidence for Gauge Coupling Unification



- Electric Charge Quantization
  - $\mathrm{Tr}(Q)_{5^*} = 3Q_{d^c} + Q_e + Q_\nu = 0$
    $\to Q_{d^c} = -\frac{1}{3}\, Q_e$
  - Likewise, $Q_u = -\frac{2}{3}\, Q_e$
  - Therefore $Q(p = uud) = -Q_e$
- Hypercharge can be embedded in SU(5): $\sin^2\theta_2 = 3/8$ at GUT scale

Supersymmetry (with MET)

Cascade ending with LSP
→ large MET

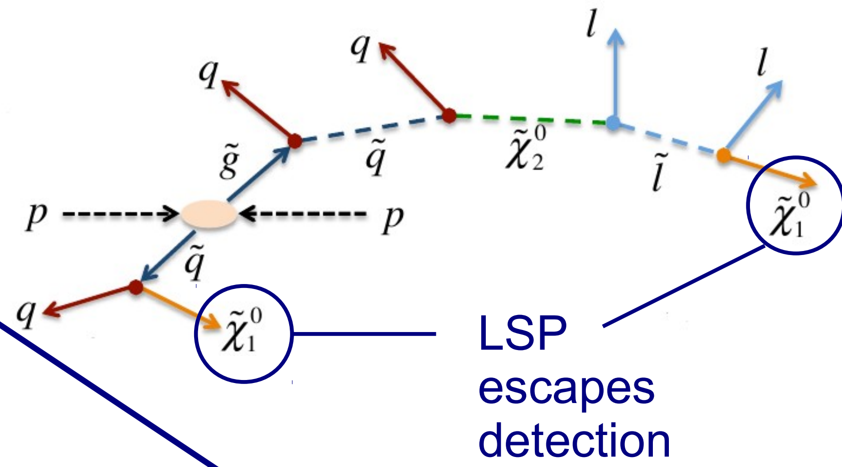
1 Jets+MET: Gluino and Squark prod. dominate

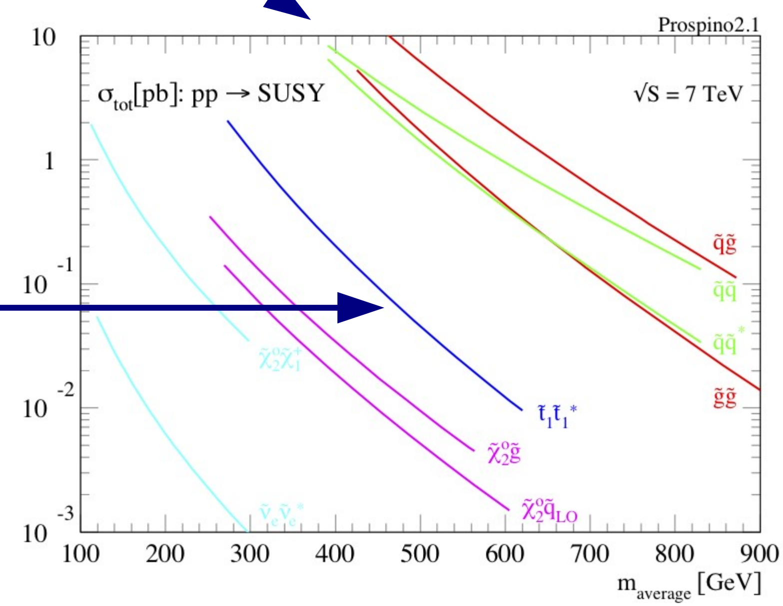
2 Leptons(+jets)+MET: lower branching ratio/cross-section but complementary

3 3rd generation (b or t):

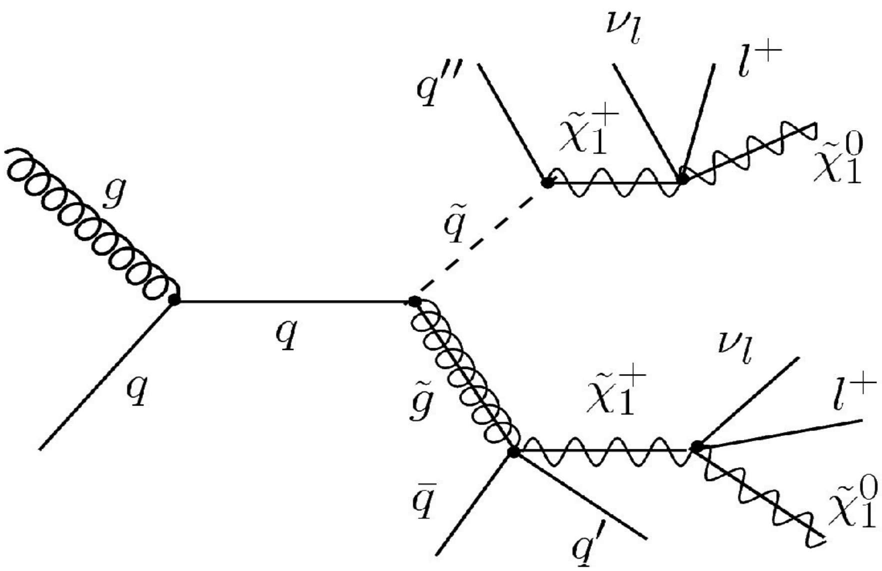
- → in cascade
- → direct production requires > 1 fb^{-1}
  → coming soon

4 Photon(s)+MET: GMSB models





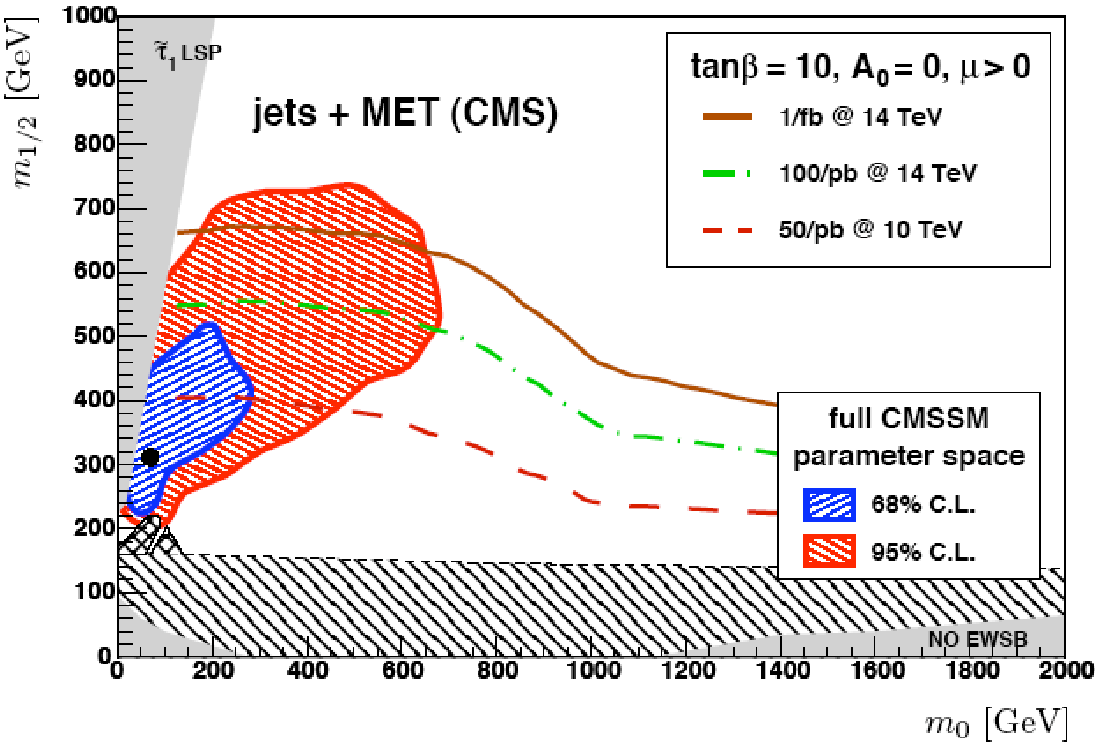
2. SUSY: Lepton(s) + Jets + Missing ET



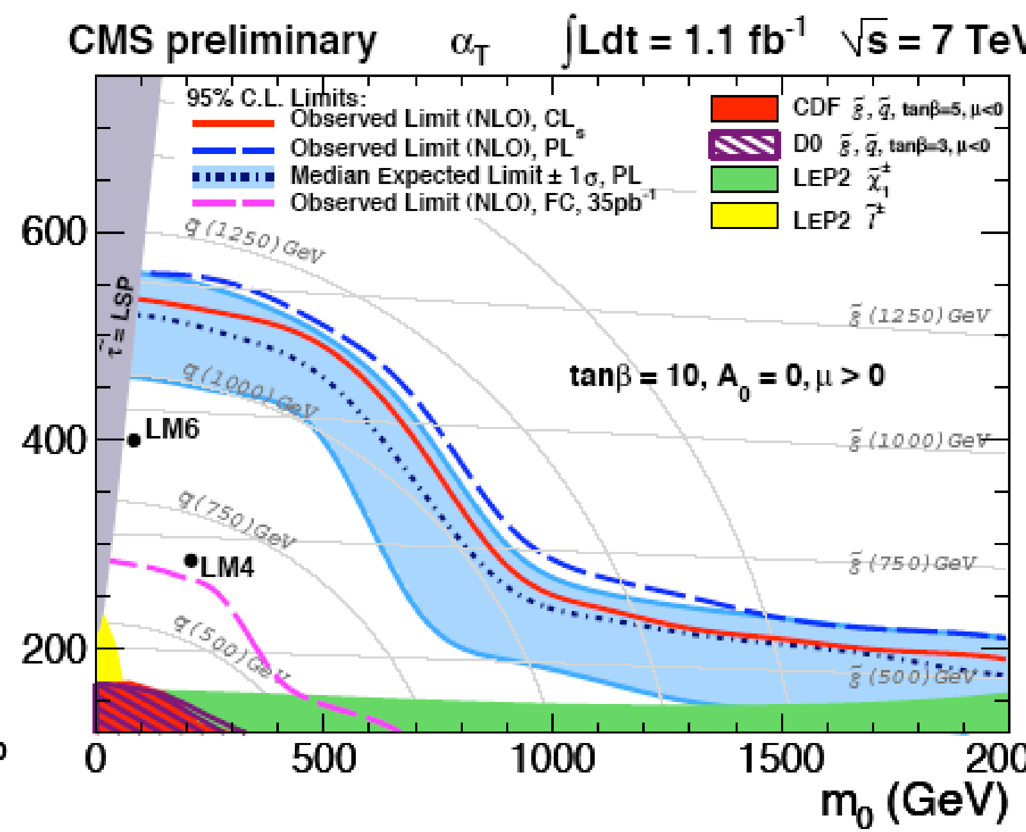
- Leptons arise from slepton or charginos or W/Z decays
- Due to smaller Branching Ratio, less stringent limits than fully hadronic but complementary
- Look for 1, 2 (same-sign or opposite sign) or more leptons
- Flavor subtraction selects flavor-correlated decays
- Can also look explicitly for heavy boson decay

Before the start of LHC, I expected early discovery of supersymmetry in the jets+MET signature. Many other theorists also had this belief. But, it was not correct.

Buchmuller, ... , DeRoeck, Ellis ... 2008



CMS LP11 α_T analysis



Supersymmetry: Summary

- SUSY in its most hoped for incarnation is starting to be in trouble
  - → Of course we will continue looking and increasing our reach
- What if SUSY were hiding? (e.g. no Missing E_T)
  - → “Split”, “low-MET”, “squashed”, “mashed?”
  - → Even if very soft cascade at tree level, Initial State Radiation still creates MET, but this needs to be studied further
- With >1 fb^{-1}, other SUSY prod. mechanisms open up → exclusive chargino/neutralino and 3rd generation production

Conclusions:

The evidence for the Higgs is tantalizing, but it is not yet in place. We need to wait until Christmas. The current signs could easily have gone away by then.

ATLAS and CMS have added a broad exclusion of the SM Higgs boson covering most of its mass range range. Either ATLAS or CMS excludes the SM Higgs at 95% conf. for all masses in the range

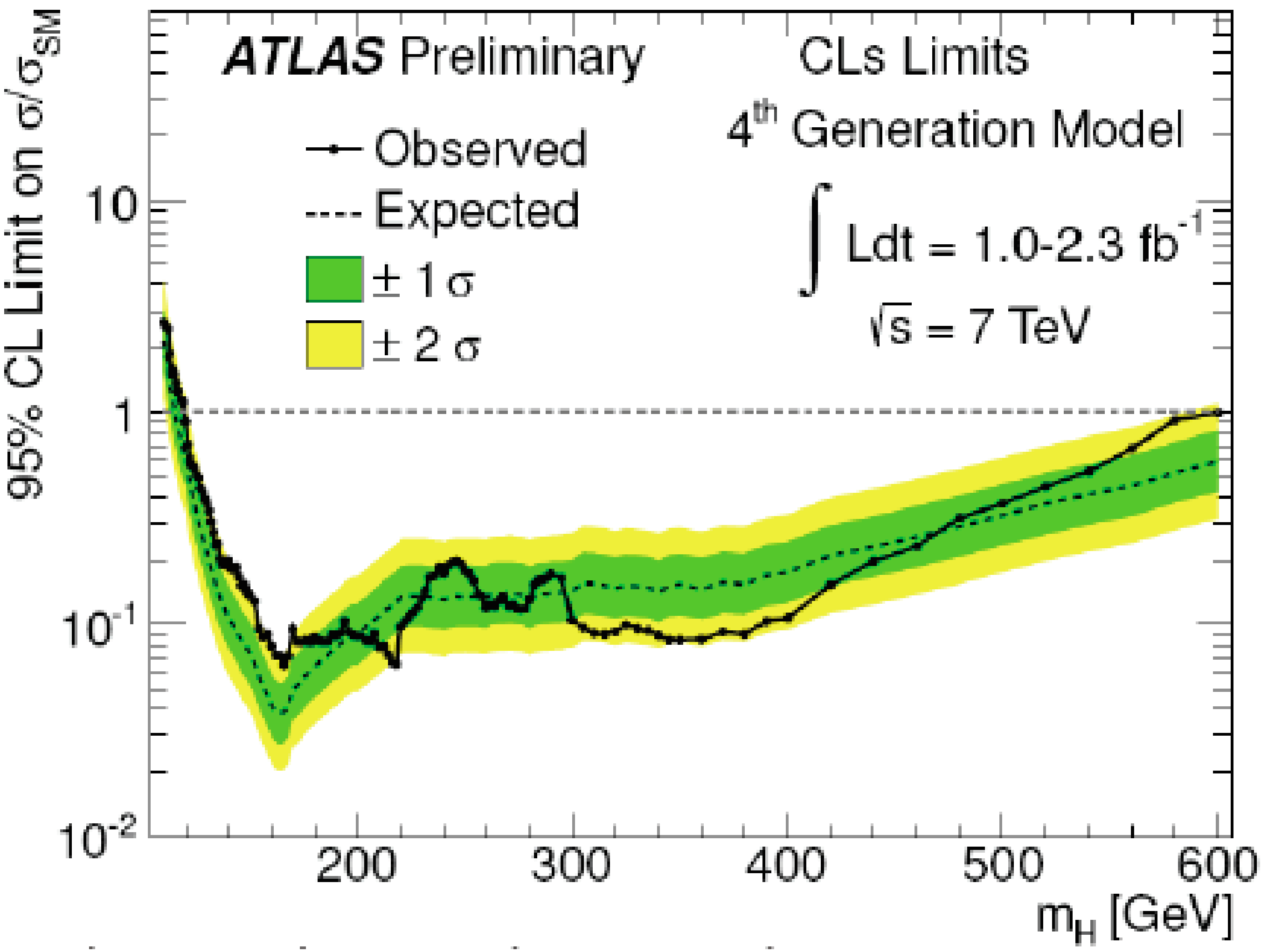
$145\ \mathrm{GeV} - 446\ \mathrm{GeV}$ except $288\ \mathrm{GeV} - 296\ \mathrm{GeV}$

Thus, there is strong evidence that either

the Higgs boson is light, consistent with precision electroweak predictions, and with theoretical prejudice

or, the Higgs boson is very heavy and strongly self-coupled

Higgs limits assuming a 4th generation of quarks and leptons:



Other exotic fermions are still alive and interesting, but the sequential 4th generation is in deep troupble!