Hide & Seek with SUSY

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Summary

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- SUSY Algebra and Representations
- MSSM
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  - Masses
  - Couplings
- Bounds: LEP, Tevatron, $\cdots$
  - Chargino, Neutralinos, $\cdots$
  - Dark Matter
- Results from LHC
- Impact of LHC on SUSY
- Conclusions

Problems with the Standard Model

We believe that, despite its enormous success the Standard Model of strong, weak and electromagnetic interactions has many problems. These are of two kinds

❒ Experimental evidence

- ◆ Neutrino masses and oscillations
- ◆ Dark Matter
- ◆ Dark Energy

❒ Theoretical questions

Here are a few:

- ◆ Why the fermions have those strange hypercharge assignments that ensure, by accident, the cancellation of anomalies?
- ◆ Why these gauge groups. Why they have so different strengths?
- ◆ Why the replication to have 3 families?
- ◆ Why is the electroweak scale much lower that the Planck scale (hierarchy problem)?

Historical Solution: go to shorter distances

Historically, many problems were solved by going to smaller distances. Here is a couple of examples

❒ Gases

- ◆ Ideal gases ⇔ Free point like molecules
- ◆ Deviation from ideal gas ⇔ size of molecules ⇒ Van der Waals equation of state

❒ Mendeleev Periodic Table

- ◆ Table explained by bound electrons + spin + Pauli principle
- ◆ Existence of nuclides explained by looking inside the nucleus at protons and neutrons ⇒ smaller distances

Idea: New Physics should appear below the typical scale of the SM

$$v \simeq \left(\sqrt{2} G_F\right)^{-1/2} \simeq 246 \text{GeV}, \quad d = \frac{\hbar c}{v c^2} \simeq 0.8 \times 10^{-16}\, \text{cm}$$

An Example: Problems with Classical Electromagnetism

❐ In classical electromagnetism we have electrons (charges) plus fields $\vec{E}$, $\vec{B}$

❐ We can calculate the Coulomb self-energy of the electron. It diverges as $1/r$ so we have to apply a cutoff, the "size" of the electron r_e

$$\Delta E_{\text{Coulomb}} = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$

❐ Therefore the mass of the electron receives a contribution

$$(m_e c^2)_{\text{observed}} = (m_e c^2)_{\text{bare}} + \Delta E_{\text{Coulomb}}$$

❐ We know experimentally that $r_e \leq 10^{-17}$ cm which implies $\Delta E \geq 10$ GeV

$$0.511\,\text{MeV} = (-9999.489 + 10000.000)\,\text{MeV}$$

❐ To avoid this fine tuned cancellation we would have to say that classical electromagnetism does not hold for distances below $d_{\text{classical}}$ such that

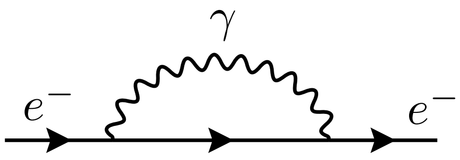
$$m_e c^2 \simeq \frac{1}{4\pi\epsilon_0}\frac{e^2}{d} \Rightarrow d_{\text{classical}} \simeq 2.8\times 10^{-13}\,\text{cm} \simeq \text{size of nucleus}$$

Positron: New degrees of freedom and a new symmetry

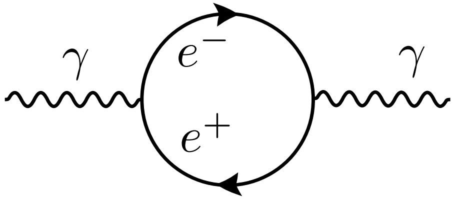
Summary
Motivation
- Problems SM
- History
- Electromagnetism
- QED
- Lessons to be taken
- Higgs & SUSY
- Other Motivations

SUSY Algebra
MSSM
LEP Results
LHC Results
Implications

The problem was solved with QED and the discovery of the positron. We have processes like



self-energy



vacuum polarization

- Vacuum fluctuations are allowed if they occur for

$$\Delta t \sim \hbar/\Delta E \sim \hbar/(2m_e c^2)$$

- This introduces a new scale

$$d_{\text{QED}} \sim c\Delta t \sim \hbar c/(2m_e c^2) \simeq 200 \times 10^{-13}\ \text{cm}$$

- Therefore classical electromagnetism should indeed break much before what we got previously, that is

$$d_{\text{QED}} \gg d_{\text{classical}}$$

New contributions to the self energy

- With the vacuum fluctuations one should also consider a process where one electron sitting in the vacuum annihilates with the positron produced by the vacuum fluctuations, remaining the other electron.

- This gives an additional contribution calculated by Weisskopf which exactly cancels the Coulomb self-energy

$$\Delta E_{\text{pair}} = -\frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e} + \frac{3\alpha}{4\pi} m_e c^2 \ln\left(\frac{\hbar}{m_e c r_e}\right)$$

So

$$\Delta E = \Delta E_{\text{Coulomb}} + \Delta E_{\text{pair}} = \frac{3\alpha}{4\pi} m_e c^2 \ln\left(\frac{\hbar}{m_e c r_e}\right)$$

and

$$(m_e c^2)_{\text{observed}} = (m_e c^2)_{\text{bare}} \left[1 + \ln\left(\frac{\hbar}{m_e c r_e}\right)\right]$$

◆ Proportional to $(m_e c^2)_{\text{bare}}$

◆ Small because of the logarithm. Even for $r_e = r_{\text{Planck}} = 1.6 \times 10^{-33}$ cm we only get a 9% correction

Lessons to be taken

- ❐ The fact that the correction is proportional to m_e is a consequence of a new (broken) symmetry with the anti-particle, chiral symmetry.
- ❐ In the limit of exact symmetry we have $m_e = 0$ and the symmetry protects the electron from getting a mass from self-energy corrections
- ❐ Doubling the degrees of freedom, and adding a new symmetry leads to the cancellation of divergences. We obtain a good theory for the electron down to very short distances.

This is the paradigm for one of the motivations for supersymmetry as we will now explain in a simple example. We do this before introducing the full structure of supersymmetry

The Higgs and Supersymmetry

- In the Standard Model the Higgs potential is

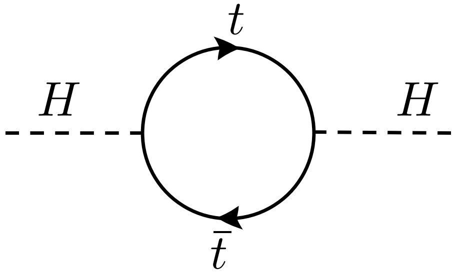
$$V = \mu^2 |H|^2 + \lambda |H|^4$$

The spontaneous breaking of the symmetry occurs when

$$v^2 = 2\left\langle H \right\rangle^2 = -\frac{\mu^2}{\lambda} = (246\,\text{GeV})^2$$

Because unitarity requires $\lambda \leq 1$ we must have $-\mu^2 = \mathcal{O}((246\,\text{GeV})^2)$

- However from the top loop



$$\Rightarrow \qquad \Delta\mu^2 = -6\,\frac{y_t^2}{4\pi^2}\,\frac{\hbar^2}{c^2 r_H^2}$$

where r_H is the "size" of the Higgs.

- An argument along the previous lines would tell us that the SM would not hold for distances below

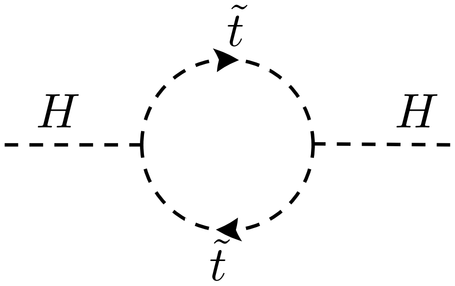
$$r_H \leq \sqrt{\frac{6\,y_t^2\,\hbar^2}{4\pi^2|\mu^2|c^2}} \simeq 10^{-18}\,\text{cm}$$

The Higgs and Supersymmetry ···

How should we make the SM consistent down to smaller distances? From the previous argument we should:

- ❐ Enlarge the number of degrees of freedom (particles)
- ❐ Enlarge the symmetry, possibly a broken one.

Suppose that we have a scalar field, call it stop, $\tilde{t}$, that couples to the Higgs in a manner related, because of some symmetry, to the coupling of the Higgs to the top. With this appropriate coupling we obtain from the diagram



$$\Delta\mu^2_{\text{stop}} = +6\frac{y_t^2}{4\pi^2}\frac{\hbar^2}{r_H^2c^2} - 6\frac{y_t^2}{4\pi^2}\left(m^2_{\tilde{t}} - m_t^2\right)\ln\left(\frac{\hbar^2}{r_H^2 m_t^2\, c^2}\right)$$

The Higgs and Supersymmetry $\cdots$

Therefore we now have

$$\Delta\mu^2 = -6\frac{y_t^2}{4\pi^2}\left(m_{\tilde{t}}^2 - m_t^2\right)\ln\left(\frac{\hbar^2}{r_H^2 m_t^2\, c^2}\right)$$

Comments:

- ❒ QFT tell us that loops of fermions and scalars have a relative minus sign, so the new particles to be partners of the top (fermion) should be bosons
- ❒ The symmetry must be responsible for the needed relation between the couplings $H\bar{t}t$ and $H\tilde{t}^*\tilde{t}$
- ❒ Like in the positron analogue, in the limit of exact symmetry, $\Delta\mu^2 = 0$
- ❒ Unlike the positron analogue we do not know $m_{\tilde{t}}$. For the argument to hold one must have

$$m_{\tilde{t}} \leq \text{Few TeV}$$

Such a symmetry exists, it is called Supersymmetry (SUSY)

Other Motivations

Historically supersymmetry appeared (around 1970) due to a different type of arguments. The most commonly invoked theoretical arguments for SUSY are:

- ❒ It evades the Coleman-Mandula theorem, showing that is it possible to enlarge the Poincaré group in a non trivial manner.
- ❒ Interrelates matter fields (leptons and quarks) with force fields (gauge and/or Higgs bosons).
- ❒ As local SUSY implies gravity (supergravity) it could provide a way to unify gravity with the other interactions.
- ❒ As SUSY and supergravity have fewer divergences than conventional field theories, the hope is that it could provide a consistent (finite) quantum gravity theory.
- ❒ SUSY can help to understand the mass problem, in particular solve the naturalness problem (and in some models even the hierarchy problem) if SUSY particles have masses $\leq \mathcal{O}(\text{FewTeV})$.

The Poincare Algebra

The Poincaré group (`PG`) is made up of the Lorentz group plus the translations. We denote by $J_{\mu\nu}$ the generators of the Lorentz group and by P_μ the generators of the translations. The algebra is defined by,

$$[J_{\mu\nu}, J_{\rho\sigma}] = i\left(g_{\nu\rho}J_{\mu\sigma} - g_{\nu\sigma}J_{\mu\rho} - g_{\mu\rho}J_{\nu\sigma} + g_{\mu\sigma}J_{\nu\rho}\right)$$

$$[P_\alpha, J_{\mu\nu}] = i\left(g_{\mu\alpha}P_\nu - g_{\nu\alpha}P_\mu\right)$$

$$[P_\mu, P_\nu] = 0$$

One can show that

$$\left[P^2, J_{\mu\nu}\right] = \left[P^2, P_\mu\right] = 0$$

$$\left[W^2, J_{\mu\nu}\right] = \left[W^2, P_\mu\right] = \left[W^2, P^2\right] = 0$$

- ❐ P^2, W^2 are the Casimir operators of `PG`
- ❐ Irreducible reps $\Rightarrow |m, s\rangle$

where

$$W_\mu = -\frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}\ J^{\nu\rho}\ P^\sigma$$

is the Pauli-Lubanski vector operator.

Rest frame:

$$W^\mu = (0, m\vec{S}) \Rightarrow W^2 = -m^2 s(s+1)$$

SUSY Algebra

The SUSY generators carry Spin 1/2 and obey the following algebra

$$\begin{aligned}
\{Q_\alpha, Q_\beta\} &= 0\\
\left\{\overline{Q}_{\dot\alpha}, \overline{Q}_{\dot\beta}\right\} &= 0\\
\left\{Q_\alpha, \overline{Q}_{\dot\beta}\right\} &= 2\,(\sigma^\mu)_{\alpha\dot\beta}\; P_\mu
\end{aligned}$$

where

$$\sigma^\mu \equiv (1, \sigma^i) \quad ; \quad \overline{\sigma}^\mu \equiv (1, -\sigma^i)$$

and $\alpha, \beta, \dot\alpha, \dot\beta = 1, 2$ (Weyl 2–component spinor notation).

SUSY Algebra and the Poincaré Group

The commutation relations with the generators of the Poincaré group

$$[P^\mu, Q_\alpha] = 0 \qquad [J^{\mu\nu}, Q_\alpha] = -i\,(\sigma^{\mu\nu})_\alpha{}^\beta\, Q_\beta$$

One can easily derive that the two invariants of the Poincaré group,

$$P^2 = P_\alpha P^\alpha \qquad W^2 = W_\alpha W^\alpha \qquad W_\mu = -\tfrac{1}{2}\epsilon_{\mu\nu\rho\sigma} J^{\nu\rho} P^\sigma$$

$$P^2\,|m,s\rangle = m^2\,|m,s\rangle \quad W^2\,|m,s\rangle = -m^2 s(s+1)\,|m,s\rangle$$

where W^μ is the Pauli–Lubanski vector operator, are no longer invariants of the Super Poincaré group:

$$[Q_\alpha, P^2] = 0 \qquad [Q_\alpha, W^2] \neq 0$$

Irreducible multiplets will have particles of the same mass but different spin.

Simple Results from the Algebra

$$\boxed{\text{Number of Bosons} = \text{Number of Fermions}}$$

$$\begin{array}{cc} Q_\alpha|B>=|F> & (-1)^{N_F}|B>=|B> \\ Q_\alpha|F>=|B> & (-1)^{N_F}|F>=-|F> \end{array}$$

where $(-1)^{N_F}$ is the fermion number of a given state. Then we obtain

$$Q_\alpha(-1)^{N_F} = -(-1)^{N_F} Q_\alpha$$

Using this relation we can show that

$$\begin{aligned} Tr\left[(-1)^{N_F}\left\{Q_\alpha,\overline{Q}_{\dot\alpha}\right\}\right] &= Tr\left[(-1)^{N_F}Q_\alpha\overline{Q}_{\dot\alpha} + (-1)^{N_F}\overline{Q}_{\dot\alpha}Q_\alpha\right] \\ &= Tr\left[-Q_\alpha(-1)^{N_F}\overline{Q}_{\dot\alpha} + Q_\alpha(-1)^{N_F}\overline{Q}_{\dot\alpha}\right] = 0 \end{aligned}$$

But we also have

$$\begin{aligned} &Tr\left[(-1)^{N_F}\left\{Q_\alpha,\overline{Q}_{\dot\alpha}\right\}\right] \\ &= Tr\left[(-1)^{N_F}2\sigma^\mu_{\alpha\dot\alpha}P_\mu\right] \end{aligned}$$

➡

$$Tr\left[(-1)^{N_F}\right] = \#\text{Bosons} - \#\text{Fermions} = 0$$

SUSY Representations: Massive case

In the rest frame

$$\boxed{\{Q_\alpha, \overline{Q}_{\dot\alpha}\} = 2\,m\;\delta_{\alpha\dot\alpha}}$$

This algebra is similar to the algebra of the spin 1/2 creation and annihilation operators. Choose $|\Omega\rangle$ such that

$$\boxed{Q_1\,|\Omega\rangle = Q_2\,|\Omega\rangle = 0}$$

Then we have 4 states

$$\boxed{|\Omega\rangle\ ;\ \overline{Q}_1\,|\Omega\rangle\ ;\ \overline{Q}_2\,|\Omega\rangle\ ;\ \overline{Q}_1\overline{Q}_2\,|\Omega\rangle}$$

If $J_3\,|\Omega\rangle = j_3\,|\Omega\rangle$

State	J_3 Eigenvalue
$\|\Omega\rangle$	j_3
$\overline{Q}_1\,\|\Omega\rangle$	$j_3 + \frac{1}{2}$
$\overline{Q}_2\,\|\Omega\rangle$	$j_3 - \frac{1}{2}$
$\overline{Q}_1\overline{Q}_2\,\|\Omega\rangle$	j_3

Two bosons and two fermions
states separated by
one half unit of spin

SUSY Representations: Massless case

If $m = 0$ then we can choose $P^\mu = (E, 0, 0, E)$. In this frame

$$\boxed{\{Q_\alpha, \overline{Q}_{\dot\alpha}\} = M_{\alpha\dot\alpha}}$$

where the matrix M takes the form

$$\boxed{M = \begin{pmatrix} 0 & 0 \\ 0 & 4E \end{pmatrix}}$$

Then $\boxed{\{Q_2, \overline{Q}_2\} = 4E}$ all others vanish.

We have then just **two** states $\boxed{|\Omega\rangle \ ; \ \overline{Q}_2 |\Omega\rangle}$

If $J_3 |\Omega\rangle = \lambda |\Omega\rangle$

State	J_3 Eigenvalue
$\|\Omega\rangle$ $\overline{Q}_2 \|\Omega\rangle$	λ $\lambda - \frac{1}{2}$

Two states, one fermion one boson separated by one half unit of spin

Superfields for Massless Particles

- Chiral Superfields: Spin 0 + Spin $\frac{1}{2}$

$\Phi = \Phi(\phi, \chi_L)$ ➡

ϕ Complex Scalar: $2\,\mathrm{d.o.f}$
χ_L Chiral Fermion: $2\,\mathrm{d.o.f}$ (on-shell)

- Vector Superfields: Spin $\frac{1}{2}$ + Spin 1

$V = V(\lambda, W^\mu)$ ➡

λ Chiral Fermion: $2\,\mathrm{d.o.f}$
W^μ Massless Vector: $2\,\mathrm{d.o.f}$ (on-shell)

$\boxed{\phi}$ ➡ superpartner of the fermion: sfermion
$\boxed{\lambda}$ ➡ superpartner of gauge field: gaugino

MSSM Particle Content: Gauge Fields

❐ Gauge Fields

We want to have gauge fields for the gauge group $G = SU_c(3) \otimes SU_L(2) \otimes U_Y(1)$. Therefore we will need three vector superfields (or vector supermultiplets) $\widehat{V}_i$ with the following components:

$$\boxed{\begin{array}{lclcl} \widehat{V}_1 \equiv (\lambda', W_1^{\mu}) & \to & U_Y(1) & & \\ \widehat{V}_2 \equiv (\lambda^a, W_2^{\mu a}) & \to & SU_L(2) & , & a = 1, 2, 3 \\ \widehat{V}_3 \equiv (\widetilde{g}^b, W_3^{\mu b}) & \to & SU_c(3) & , & b = 1, \ldots, 8 \end{array}}$$

where W_i^{μ} are the gauge fields and λ', λ and $\widetilde{g}$ are the $U_Y(1)$ and $SU_L(2)$ gauginos and the gluino, respectively.

Particle Content: Leptons

❐ Leptons

As each chiral multiplet only describes one helicity state, we will need two chiral multiplets for each charged lepton (We will assume that the neutrinos do not have mass).

Supermultiplet	$SU_c(3) \otimes SU_L(2) \otimes U_Y(1)$ Quantum Numbers
$\widehat{L}_i \equiv (\widetilde{L}, L)_i$	$(1, 2, -\frac{1}{2})$
$\widehat{R}_i \equiv (\widetilde{\ell}_R, \ell^c_L)_i$	$(1, 1, 1)$

Each helicity state corresponds to a complex scalar and we have that $\hat{L}_i$ is a doublet of $SU_L(2)$

$$\widetilde{L}_i = \begin{pmatrix} \widetilde{\nu}_{Li} \\ \widetilde{\ell}_{Li} \end{pmatrix} \quad ; \quad L_i = \begin{pmatrix} \nu_{Li} \\ \ell_{Li} \end{pmatrix}$$

Particle Content: Quarks

❐ Quarks

The quark supermultiplets are given in the Table. The supermultiplet $\widehat{Q}_i$ is also a doublet of $SU_L(2)$, that is

Supermultiplet	$SU_c(3) \otimes SU_L(2) \otimes U_Y(1)$ Quantum Numbers
$\widehat{Q}_i \equiv (\widetilde{Q}, Q)_i$	$(3, 2, \frac{1}{6})$
$\widehat{D}_i \equiv (\widetilde{d}_R, d^c_L)_i$	$(3, 1, \frac{1}{3})$
$\widehat{U}_i \equiv (\widetilde{u}_R, u^c_L)_i$	$(3, 1, -\frac{2}{3})$

$$\widetilde{Q}_i = \begin{pmatrix} \widetilde{u}_{Li} \\ \widetilde{d}_{Li} \end{pmatrix} \quad ; \quad Q_i = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix}$$

Particle Content: Higgs Bosons

Higgs Bosons

Finally the Higgs sector. In the MSSM we need at least two Higgs doublets. This is in contrast with the SM where only one Higgs doublet is enough to give masses to all the particles. The reason can be explained in two ways. Either the need to cancel the anomalies, or the fact that, due to the analyticity of the superpotential, we have to have two Higgs doublets of opposite hypercharges to give masses to the up and down type of quarks.

Supermultiplet	$SU_c(3) \otimes SU_L(2) \otimes U_Y(1)$ Quantum Numbers
$\widehat{H}_1 \equiv (H_1, \widetilde{H}_1)$	$(1, 2, -\frac{1}{2})$
$\widehat{H}_2 \equiv (H_2, \widetilde{H}_2)$	$(1, 2, +\frac{1}{2})$

R-Parity

Summary
Motivation
SUSY Algebra
MSSM
Building MSSM· · ·
● R-Parity
● Superpotential
● Self Matter Int
● Soft breaking
● CMSSM
LEP Results
LHC Results
Implications

Most discussions of SUSY phenomenology assume R-Parity conservation where,

$$\boxed{R_P = (-1)^{2J+3B+L}}$$

This is the case of the MSSM. It implies:

- SUSY particles are pair produced.
- Every SUSY particle decays into another SUSY particle.
- There is a LSP that it is stable ($\not\!\!E$ signature).

- This is just an *ad hoc* assumption without a deep justification
- However, if it is required we have a candidate for dark matter, the LSP that is stable
- This has been a big motivation for the MSSM

The Superpotential and SUSY Breaking Lagrangian

The MSSM Lagrangian is specified by the R–parity conserving superpotential W

$$\boxed{W = \varepsilon_{ab}\left[h_U^{ij}\widehat{Q}_i^a\widehat{U}_j\widehat{H}_2^b + h_D^{ij}\widehat{Q}_i^b\widehat{D}_j\widehat{H}_1^a + h_E^{ij}\widehat{L}_i^b\widehat{R}_j\widehat{H}_1^a - \mu\widehat{H}_1^a\widehat{H}_2^b\right]}$$

where $i,j=1,2,3$ are generation indices, $a,b=1,2$ are $SU(2)$ indices, and ε is a completely antisymmetric 2×2 matrix, with $\varepsilon_{12}=1$. The coupling matrices h_U, h_D and h_E will give rise to the usual Yukawa interactions needed to give masses to the leptons and quarks.

If it were not for the need to break SUSY
the number of parameters involved
would be less than in the SM.

Self Interactions of the Matter Multiplet

These correspond in non supersymmetric gauge theories both to the Yukawa interactions and to the scalar potential. In supersymmetric gauge theories we have less freedom to construct these terms. The first step is to construct the superpotential W. This must be a gauge invariant polynomial function of the *scalar* components of the chiral multiplet Φ_i, that is ϕ_i. It *does not* depend on ϕ_i^*. In order to have renormalizable theories the degree of the polynomial must be at most three.

The Yukawa interactions are

$$\boxed{\mathcal{L}_{Yukawa} = -\frac{1}{2}\left[\frac{\partial^2 W}{\partial\phi_i\partial\phi_j}\,\chi_i\chi_j + \left(\frac{\partial^2 W}{\partial\phi_i\partial\phi_j}\right)^*\,\overline{\chi}_i\overline{\chi}_j\right]}$$

and the scalar potential is

$$\boxed{V_{scalar} = \tfrac{1}{2}D^a D^a + F_i F_i^*}$$

where

$$\boxed{F_i = \frac{\partial W}{\partial\phi_i}, \qquad D^a = g\,\phi_i^* T^a_{ij}\phi_j}$$

❐ In $V_{\rm Higgs}$ we have $\lambda|\phi|^4 \Rightarrow g^2|\phi|^4$

❐ The Higgs mass is not completely free!

SUSY Soft Breaking

The most general SUSY soft breaking is

$$
\begin{aligned}
-\mathcal{L}_{SB} \;=\; & M_Q^{ij2}\widetilde{Q}_i^{a*}\widetilde{Q}_j^a + M_U^{ij2}\widetilde{U}_i\widetilde{U}_j^* + M_D^{ij2}\widetilde{D}_i\widetilde{D}_j^* + M_L^{ij2}\widetilde{L}_i^{a*}\widetilde{L}_j^a + M_R^{ij2}\widetilde{R}_i\widetilde{R}_j^* \\
& + m_{H_1}^2 H_1^{a*}H_1^a + m_{H_2}^2 H_2^{a*}H_2^a - \left[\frac{1}{2}M_s\lambda_s\lambda_s + \frac{1}{2}M\lambda\lambda + \frac{1}{2}M'\lambda'\lambda' + h.c.\right] \\
& + \varepsilon_{ab}\left[A_U^{ij}h_U^{ij}\widetilde{Q}_i^a\widetilde{U}_jH_2^b + A_D^{ij}h_D^{ij}\widetilde{Q}_i^b\widetilde{D}_jH_1^a + A_E^{ij}h_E^{ij}\widetilde{L}_i^b\widetilde{R}_jH_1^a - B\mu H_1^aH_2^b\right]
\end{aligned}
$$

Parameter Counting

Theory	Gauge Sector	Fermion Sector	Higgs Sector
SM	e, g, α_s	h_U, h_D, h_E	μ^2, λ
MSSM	e, g, α_s	h_U, h_D, h_E	μ
Broken MSSM	e, g, α_s	h_U, h_D, h_E	$\mu, M_1, M_2, M_3, A_U, A_D, A_E, B$ $m_{H_2}^2, m_{H_1}^2, m_Q^2, m_U^2, m_D^2, m_L^2, m_R^2$

The Constrained MSSM

The number of independent parameters can be reduced if we impose some further constraints. The most popular is the MSSM coupled to $N = 1$ Supergravity (`mSUGRA`).

$$A_t = A_b = A_\tau \equiv A\,,$$

$$m^2_{H_1} = m^2_{H_2} = M^2_{\tilde{L}} = M^2_{\tilde{R}} = m^2_0\,, M^2_{\tilde{Q}} = M^2_{\tilde{U}} = M^2_{\tilde{D}} = m^2_0\,,$$

$$M_3 = M_2 = M_1 = M_{1/2}$$

Parameter Counting

Parameters	Conditions	Free Parameters
$y_t,\ h_b,\ h_\tau,\ v_1,\ v_2$	$m_W,\ m_t,\ m_b,\ m_\tau$	$\tan\beta = v_2/v_1$
$A,\ B,\ m_0,\ M_{1/2},\ \mu$	$t_i = 0,\ i = 1, 2$	$A,\ m_0,\ M_{1/2},\ \mathrm{sign}(\mu)$
Total $= 10$	Total $= 6$	Total $= 4+$"1"

It is remarkable that with so few parameters we can get the correct values for the parameters, in particular $m^2_{H_2} < 0$. For this to happen the top Yukawa coupling has to be large which we know to be true.

Neutral Higgs Mass Matrices

$$\boldsymbol{M}^2_{S^0} = \begin{pmatrix} \tan\beta & -1 \\ -1 & \cot\beta \end{pmatrix} B\mu + \begin{pmatrix} \cot\beta & -1 \\ -1 & \tan\beta \end{pmatrix} \tfrac{1}{2} m_Z^2 \sin^2\beta$$

with masses

$$m^2_{h,H} = \frac{1}{2}\left[m_A^2 + m_Z^2 \mp \sqrt{(m_A^2+m_Z^2)^2 - 4 m_A^2 m_Z^2 \cos 2\beta}\right]$$

$$\boldsymbol{M}^2_{P^0} = \begin{pmatrix} \tan\beta & -1 \\ -1 & \cot\beta \end{pmatrix} B\mu$$ with mass $$m_A^2 = \frac{B\mu}{\sin 2\beta}$$

Sum Rule

$$m_h^2 + m_H^2 = m_A^2 + m_Z^2$$

$\Rightarrow$

$$m_h < m_A < m_H$$
$$m_h < m_Z < m_H$$

Higgs Boson Mass: Standard Model

In the Standard Model

$$\mathcal{L}_{\text{Higgs}} = \left(D_\mu \Phi\right)^\dagger D^\mu \Phi - \frac{\lambda}{4}\left(\Phi^\dagger \Phi - \frac{v^2}{2}\right)^2$$

where

$$\Phi = \begin{pmatrix} \varphi^+ \\ \frac{v+H+i\varphi_Z}{\sqrt{2}} \end{pmatrix}$$

Therefore

$$\mathcal{L}_{\text{Higgs}} = \partial_\mu H \partial^\mu H - \frac{\lambda v^2}{4} H^2 + \cdots$$

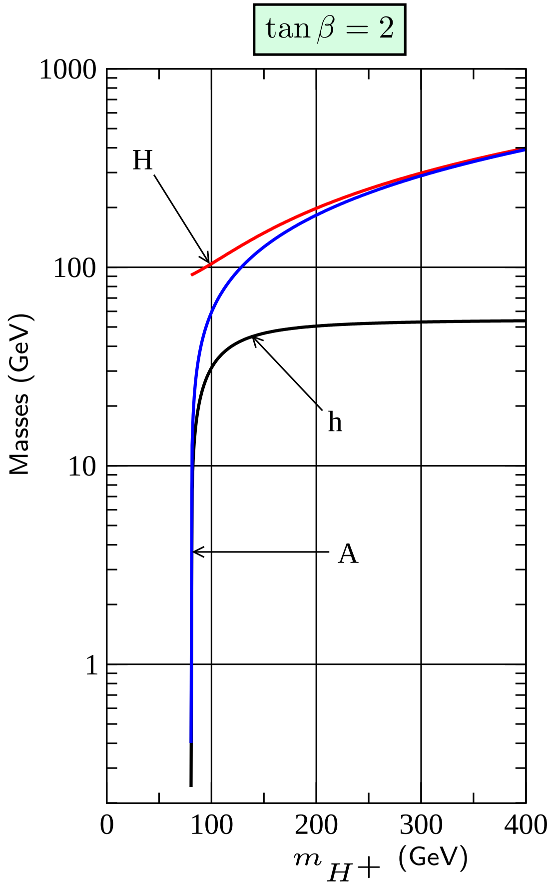
or

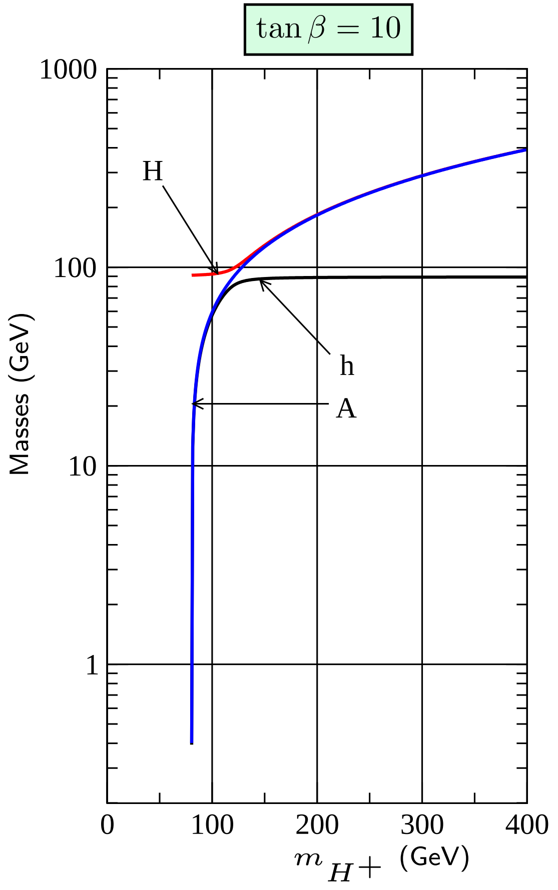
$$M_H = \sqrt{\frac{\lambda}{2}}\, v \quad \Rightarrow \quad \boxed{v = 246 \text{ GeV fixed but } \lambda \text{ free.}} \quad \Rightarrow \quad \boxed{M_H \text{ free.}}$$

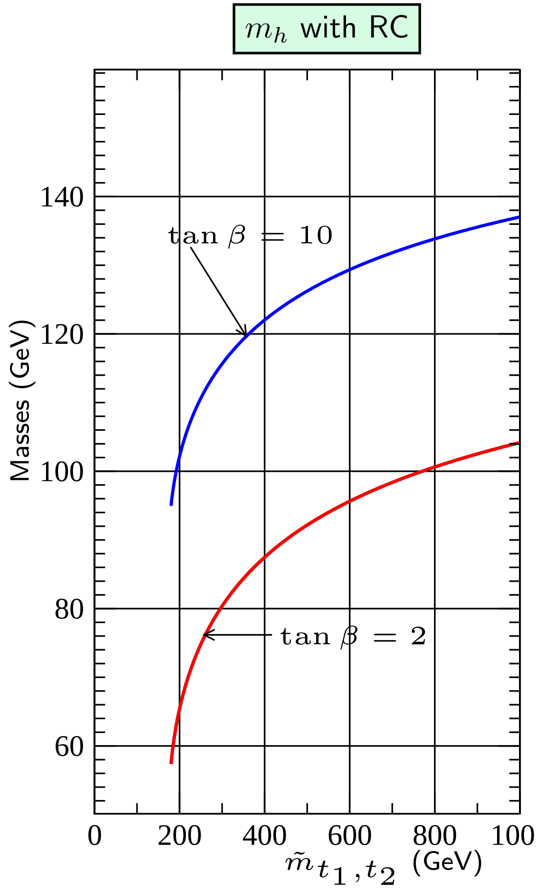
Higgs Boson Mass: Radiative corrections

As the top mass is very large there are important radiative corrections to the Higgs boson mass. The most important are:

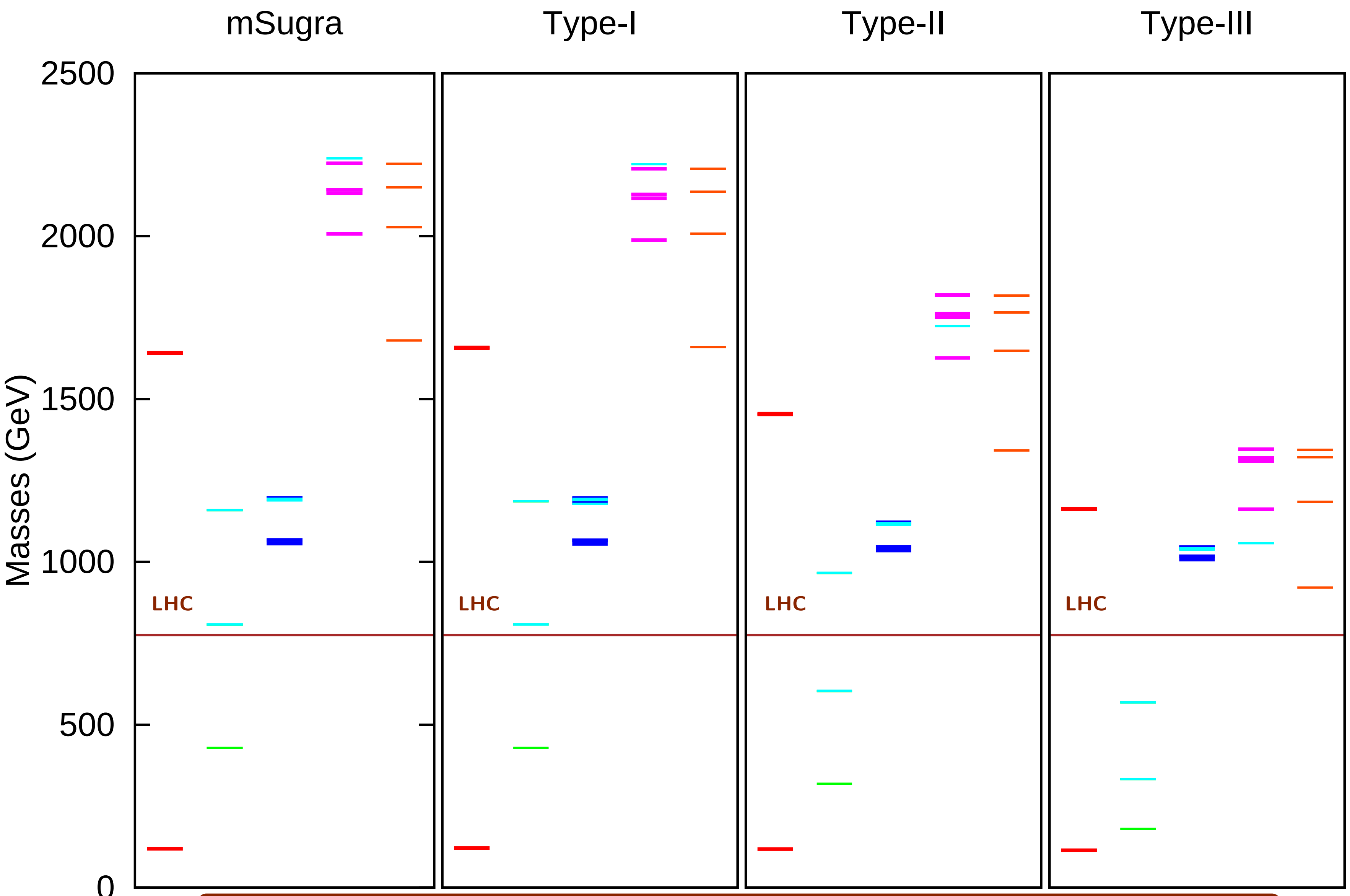
$$\boxed{m_h^2 = m_h^{(0)\,2} + \frac{3g^2}{16\pi^2 m_W^2}\,\frac{m_t^4}{\sin^2\beta}\,\ln\left(\frac{\tilde{m}_{t_1}^2\,\tilde{m}_{t_2}^2}{m_t^4}\right)}$$







Example of Spectra: $M_{1/2}=m_0=1$ TeV ($M_{SS}=10^{14}$ GeV)



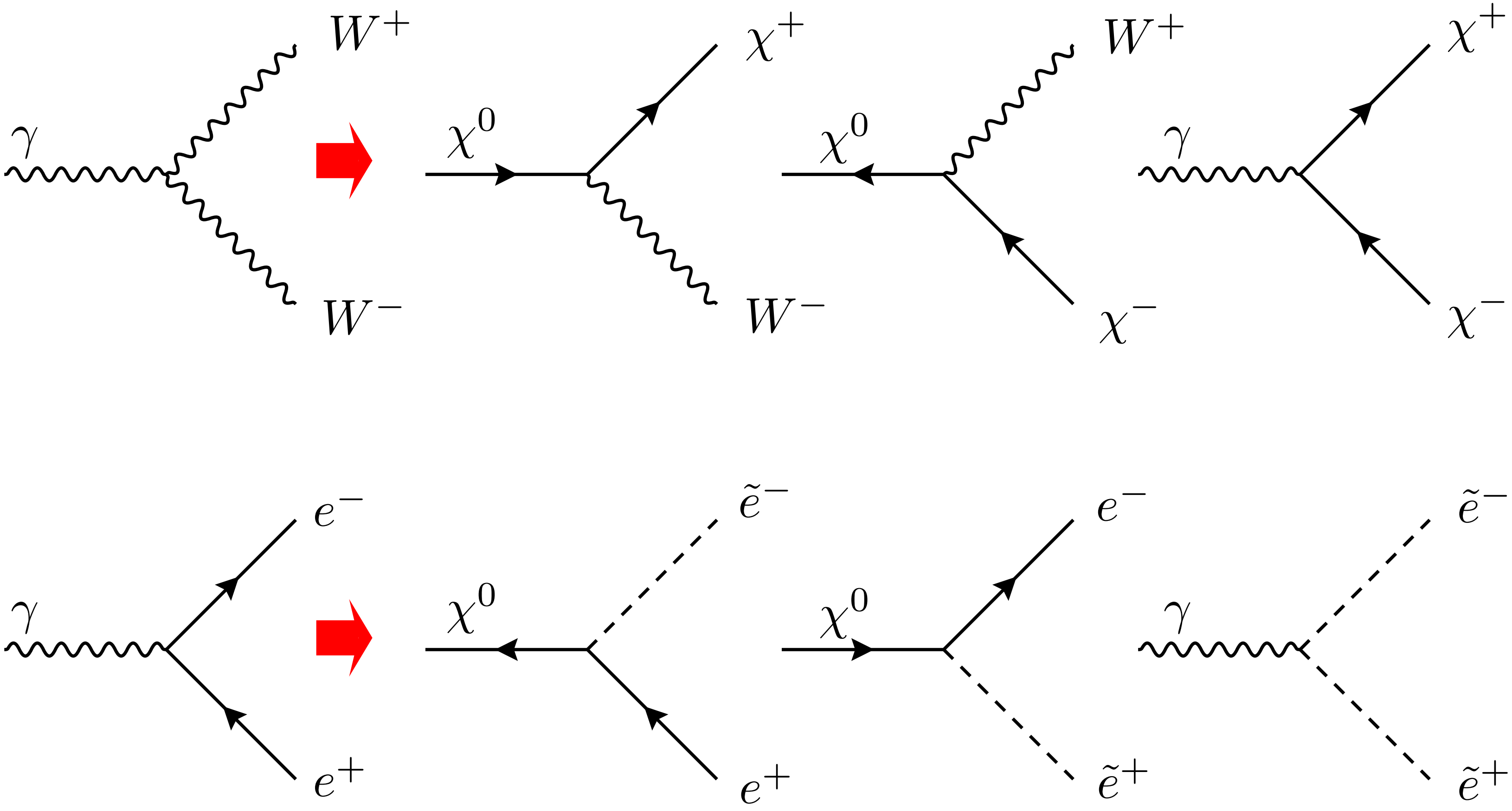
$m_0 = 1$ TeV, $M_{1/2} = 1$ TeV, $\tan\beta = 10$, $A_0 = 0$ GeV, $\mu > 0$

Couplings in the MSSM

Name	Type
Gauge Self-Interaction	VVV VVVV
3-Point Gauge Coupling	Vff $V\tilde{f}\tilde{f}$ $V\tilde{\chi}\tilde{\chi}$ VHH VGH VGG
3-Point Higgs Coupling	Hff $H\tilde{f}\tilde{f}$ $H\tilde{\chi}\tilde{\chi}$ HVV
3-Point Goldstone Coupling	Gff $G\tilde{f}\tilde{f}$ $G\tilde{\chi}\tilde{\chi}$ GVV
Other 3-Point	$\tilde{f}f\tilde{\chi}$

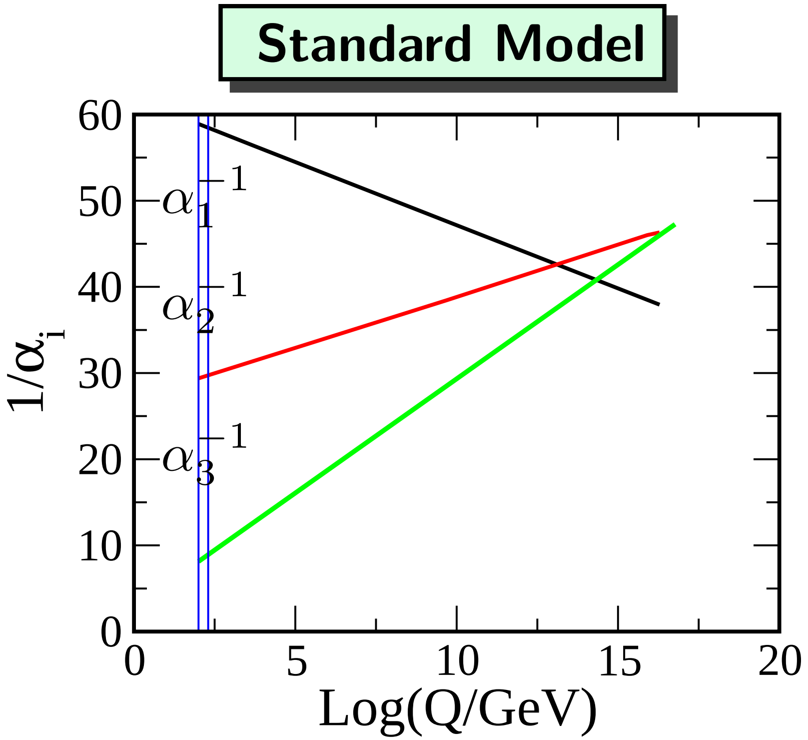
Name	Type
4-Point Coupling	$VVff$ $HHVV$ $HGVV$ $GGVV$ $\tilde{f}\tilde{f}HH$ $\tilde{f}\tilde{f}GH$ $\tilde{f}\tilde{f}GG$ $\tilde{f}\tilde{f}\tilde{f}\tilde{f}$
Goldstone-Higgs Interaction	HHG HGG $HHHG$ $HHGG$ $HGGG$ $GGGG$
Ghost	$\overline{\omega}\omega$ V $\overline{\omega}\omega$ H $\overline{\omega}\omega$ G

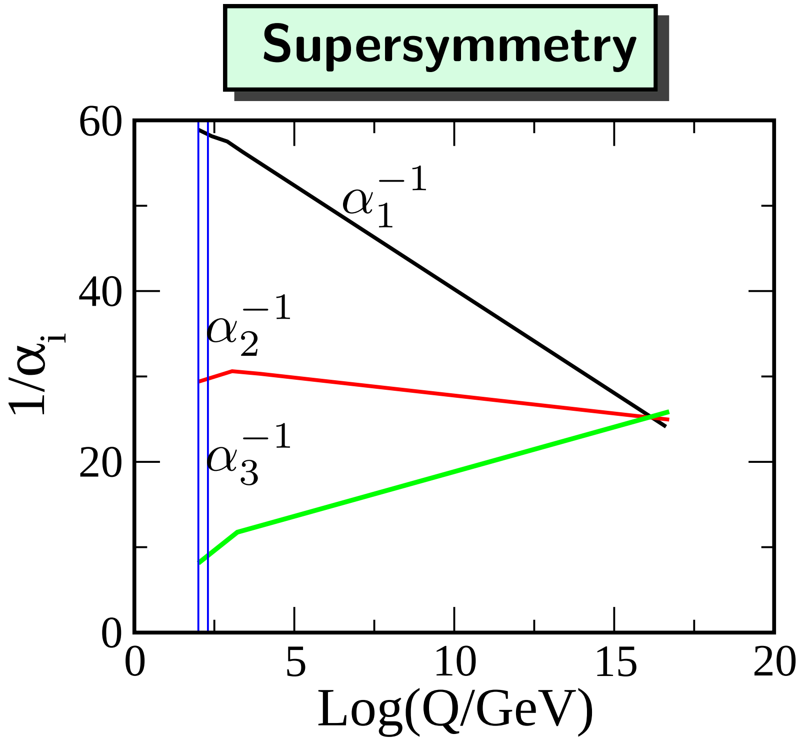
Examples of New Couplings: Conserving R-Parity

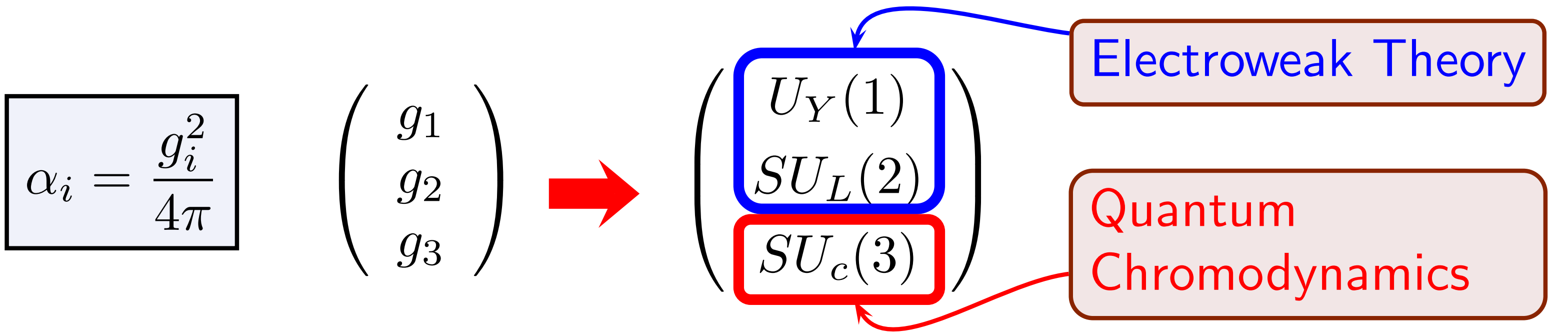


Rule: Change any two lines into the superpartners.

Gauge Couplings Unification







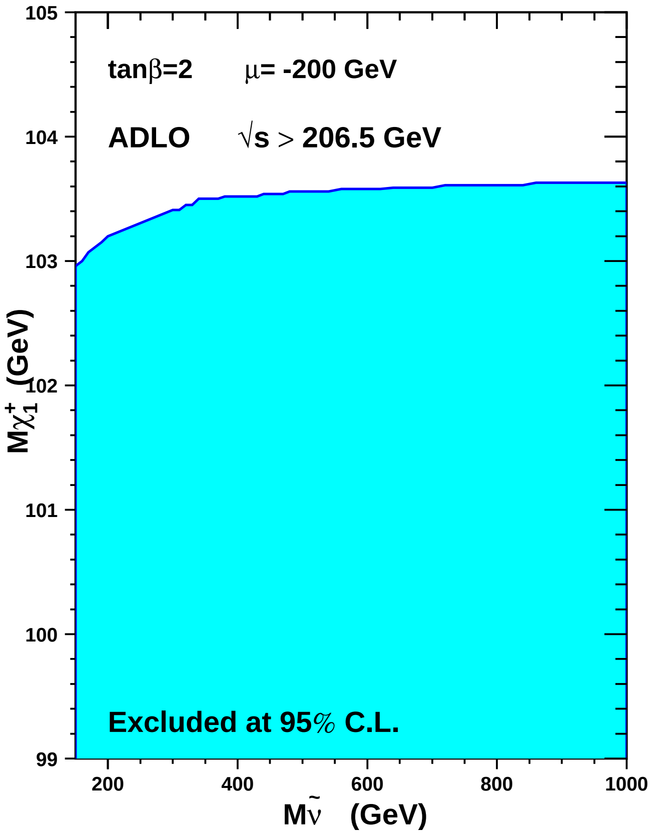
$$\boxed{\alpha_i = \frac{g_i^2}{4\pi}}$$

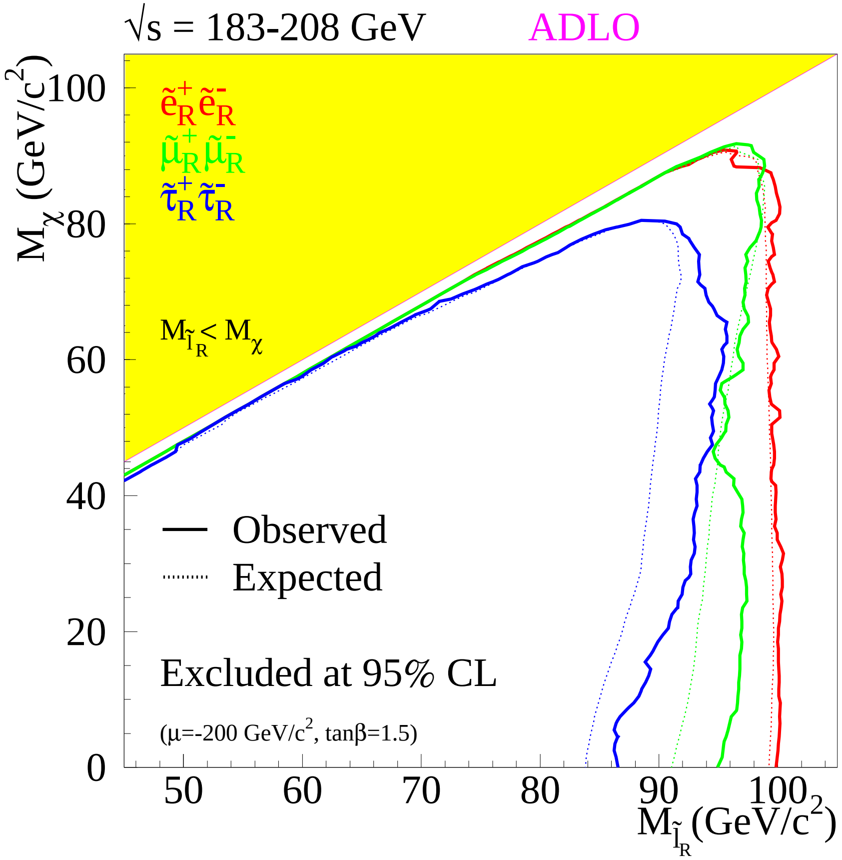
$$\begin{pmatrix} g_1 \\ g_2 \\ g_3 \end{pmatrix} \Rightarrow \begin{pmatrix} U_Y(1) \\ SU_L(2) \\ SU_c(3) \end{pmatrix}$$

Electroweak Theory

Quantum Chromodynamics

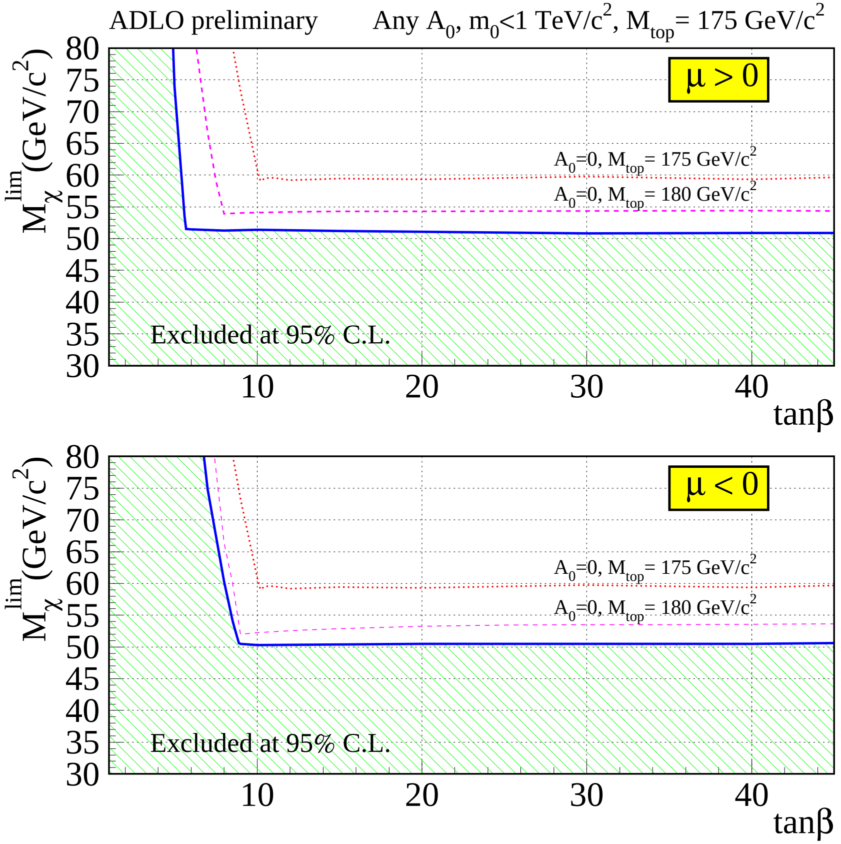
LEP Limits on Charginos, Sneutrinos & Sleptons

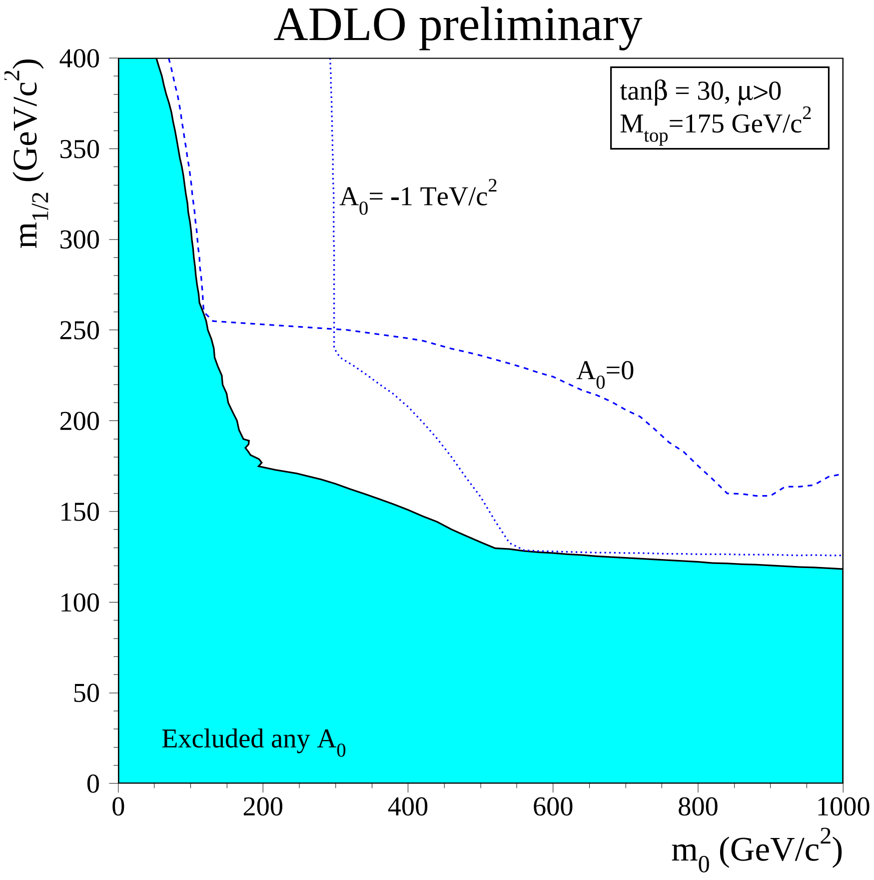




Limits on $\chi^\pm$, $\tilde{l}^\pm \simeq 100$ GeV.

LEP Limits on Neutralinos





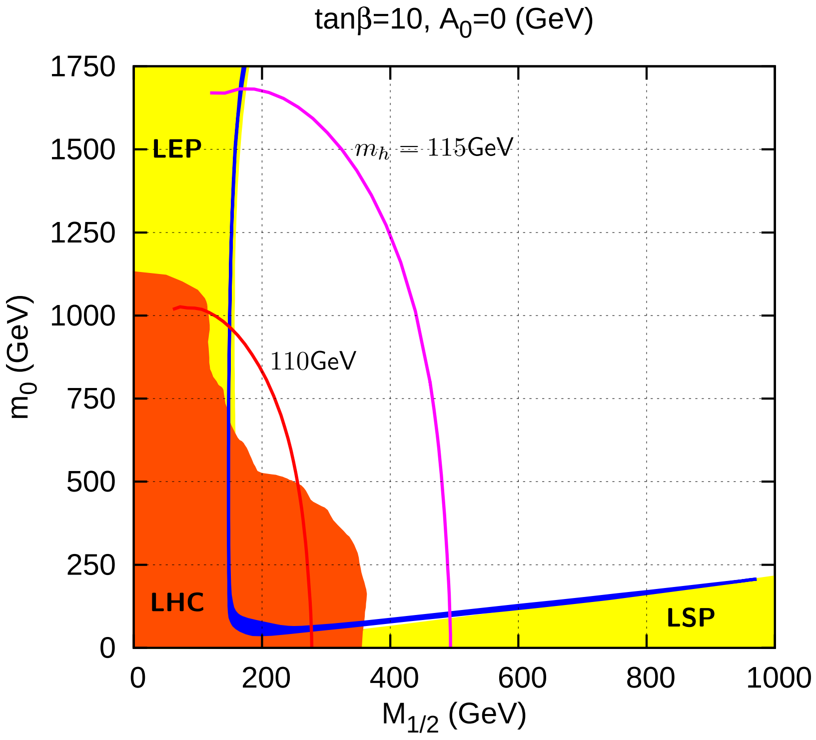
Limits on $\chi^0 \geq 50\ \mathrm{GeV}$. More model dependent.

Neutralino Dark Matter

In mSugra only four (three) very specific regions can explain the `WMAP` data (3σ)

$$0.081 \leq \Omega h^2 \leq 0.129$$

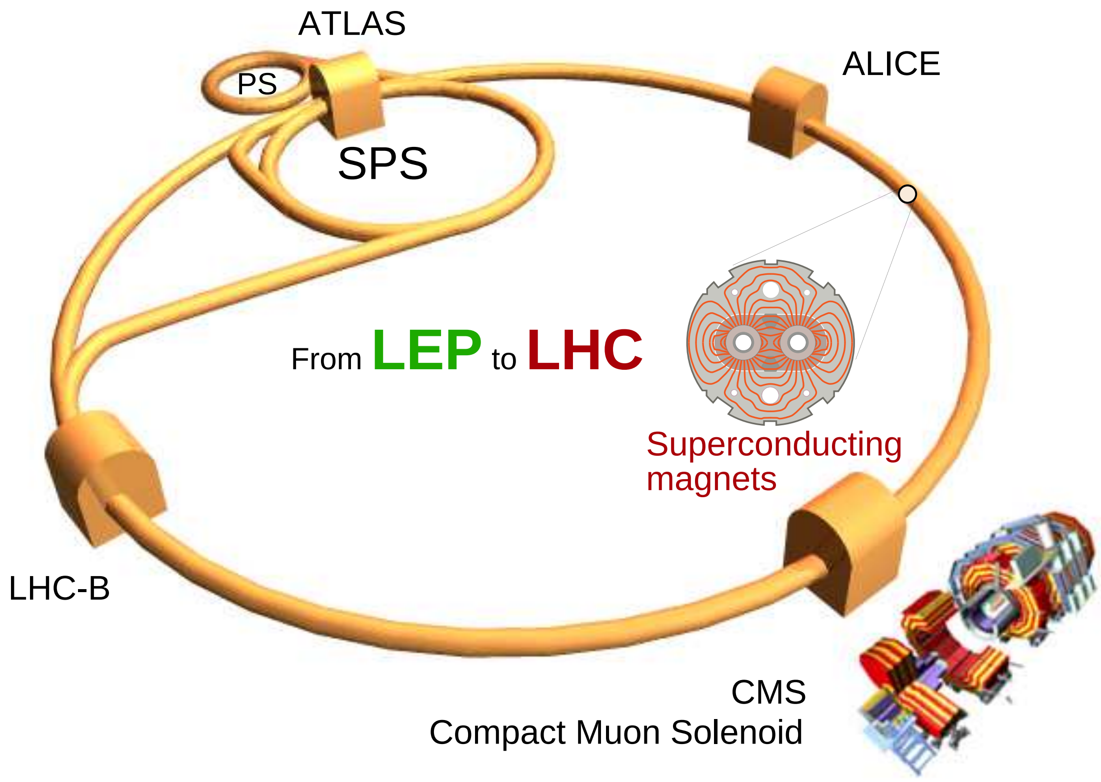
- (The bulk region)
- The co-annihilation line
- The "focus point" line
- The "higgs funnel" region (large $\tan\beta$)



Pre-LHC Plot
$m_h = 125$GeV outside plot!

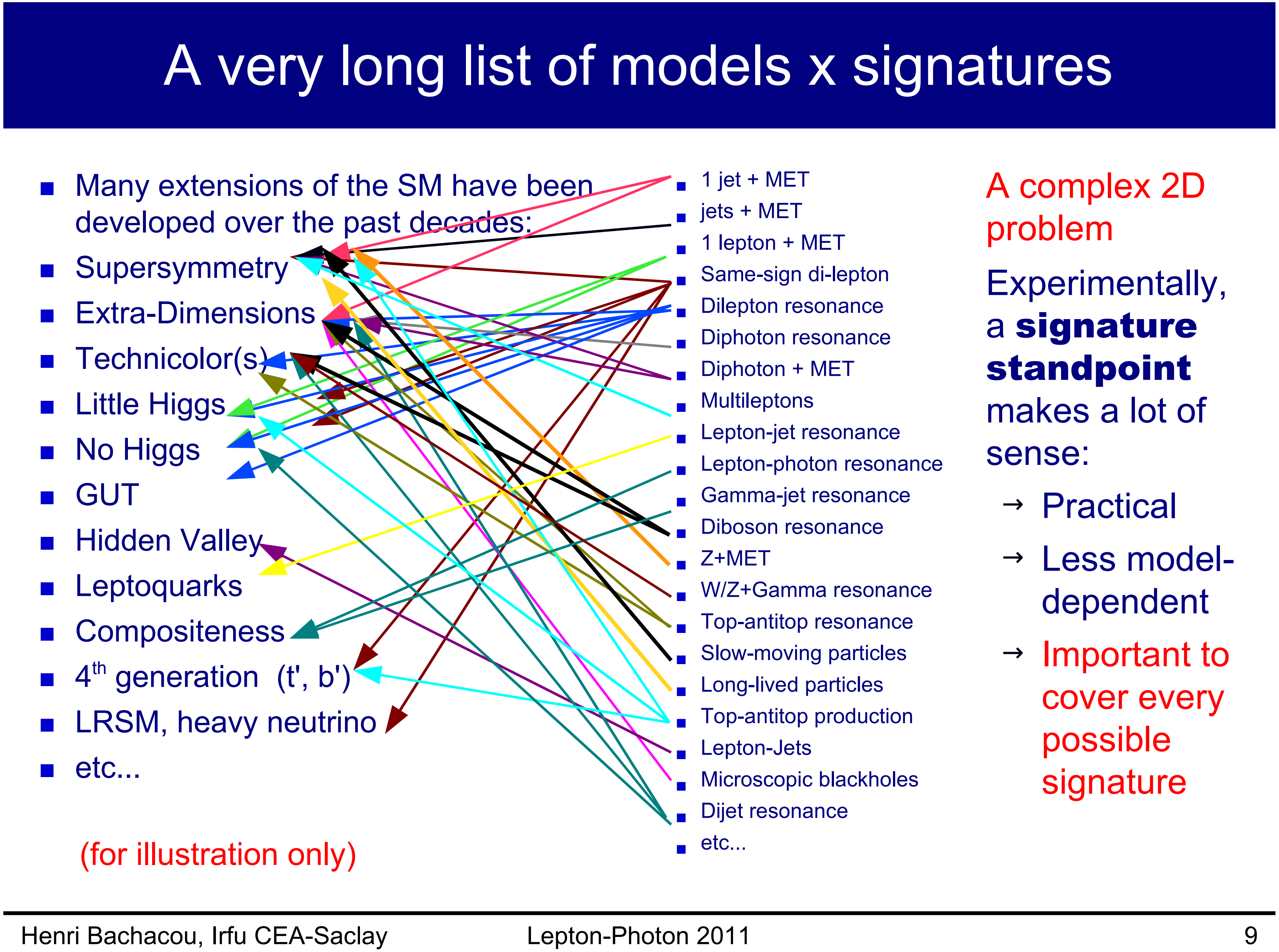
LHC Overview

The Large Hadron Collider (LHC)



	Beams	Energy		Luminosity
LEP	e+ e-	200	GeV	10^{32} cm^{-2}s^{-1}
LHC	p p	14	TeV	10^{34}
	Pb Pb	1312	TeV	10^{27}

Results from the LHC (LP2011)



A very long list of models x signatures

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4^{th} generation (t', b')
- LRSM, heavy neutrino
- etc...

(for illustration only)

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

A complex 2D problem

Experimentally, a **signature standpoint** makes a lot of sense:

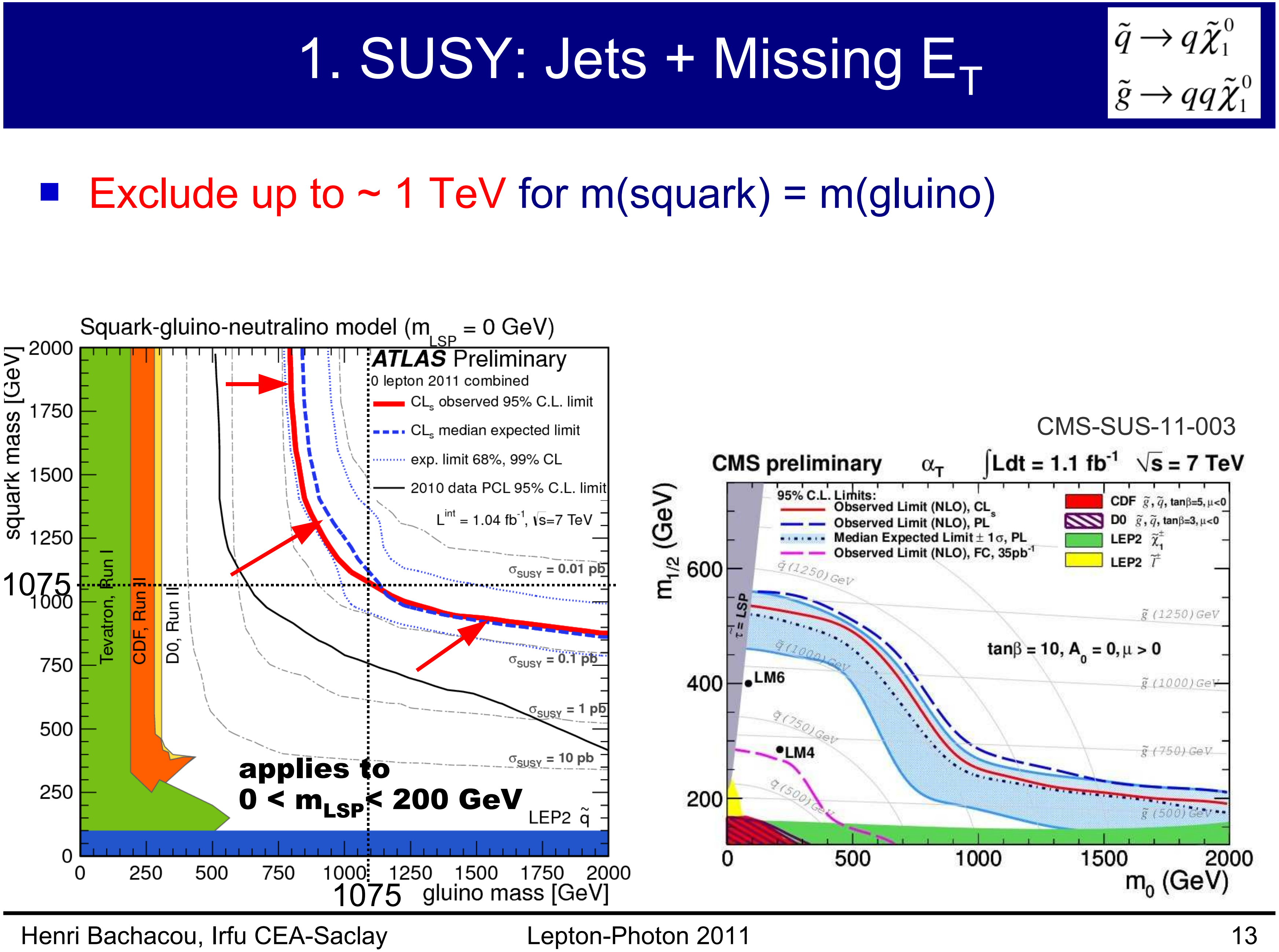
→ Practical

→ Less model-dependent

→ Important to cover every possible signature

Henri Bachacou, Irfu CEA-Saclay Lepton-Photon 2011 9

First Results from the LHC in 2011



1. SUSY: Jets + Missing E_T

$\tilde{q} \to q\tilde{\chi}_1^0$

$\tilde{g} \to qq\tilde{\chi}_1^0$

- Exclude up to ~ 1 TeV for m(squark) = m(gluino)

Squark-gluino-neutralino model (m_{LSP} = 0 GeV)

applies to
$0 < m_{LSP} < 200$ GeV

CMS-SUS-11-003

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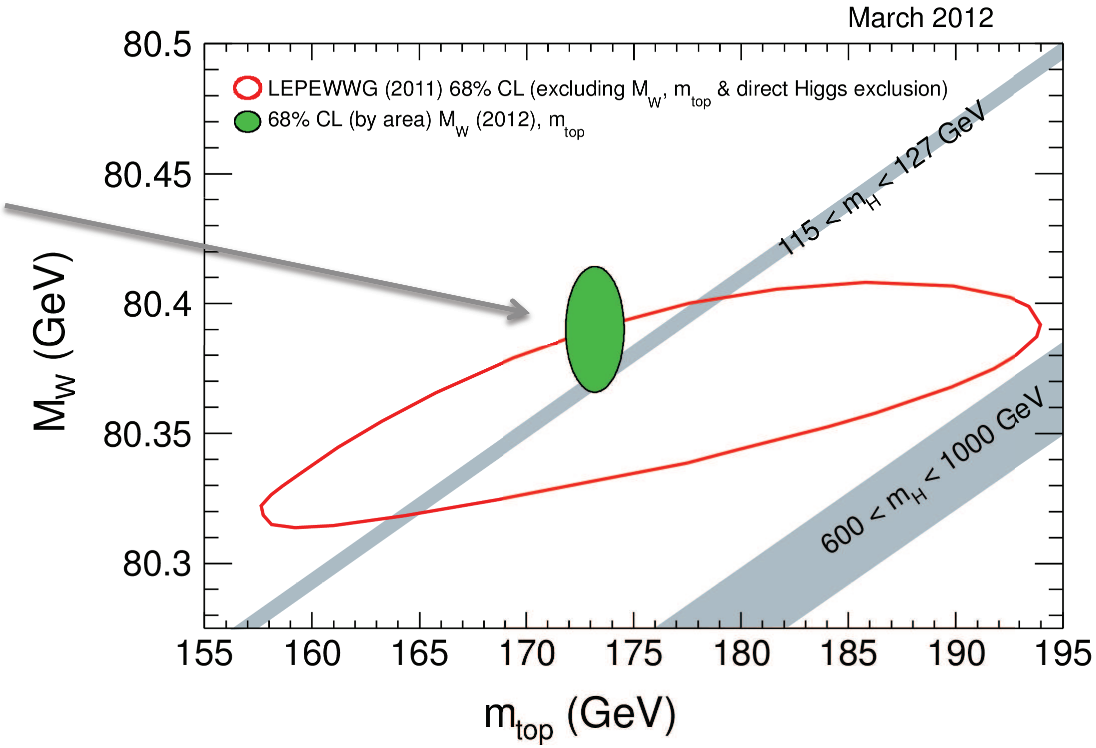
Results from the LHC in 2012

Situation in early 2012

Very precise measurement of $M_W = 80.390 \pm 0.016$ GeV, driven mainly by the Tevatron.

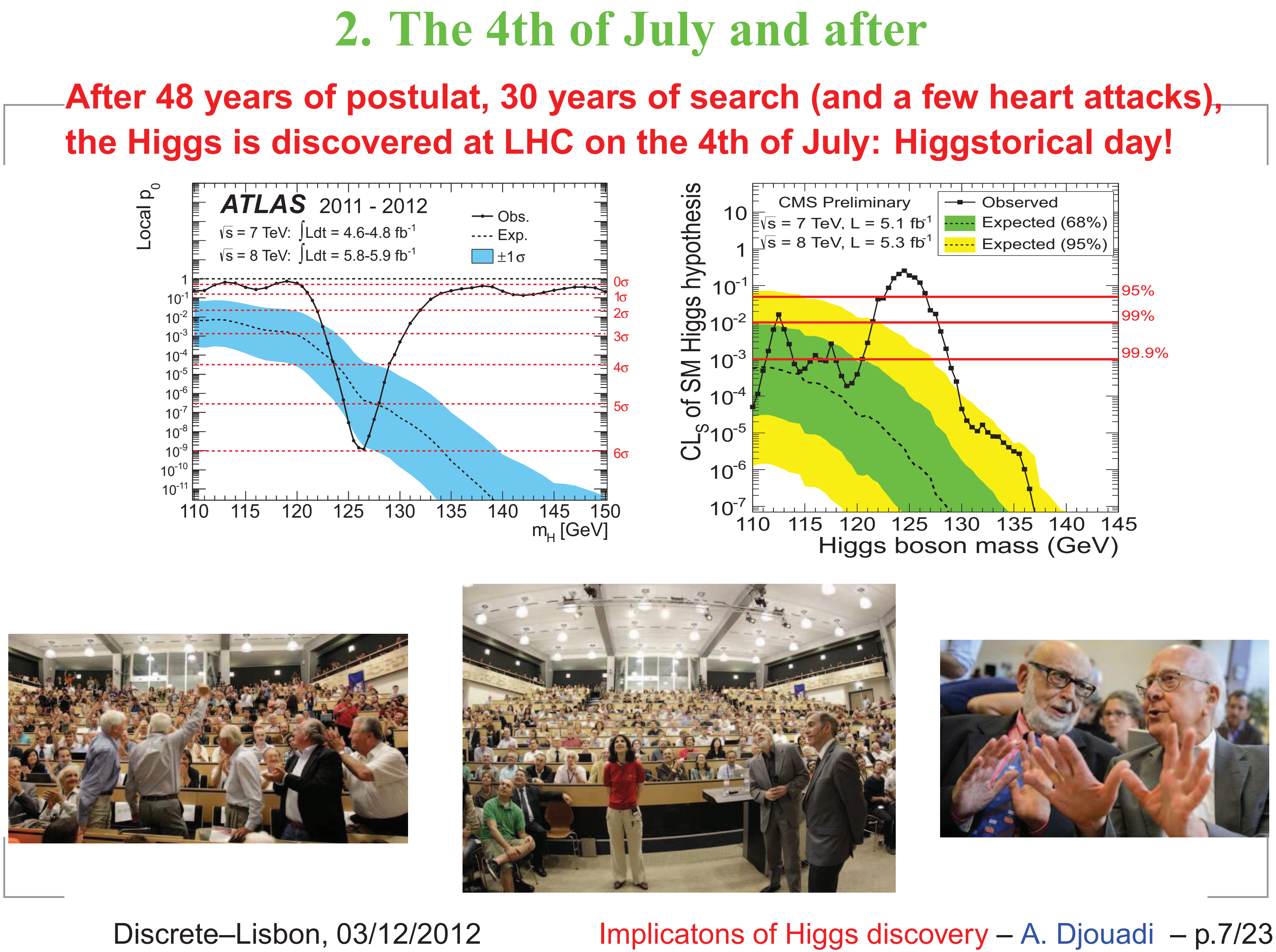


Much of the SM Higgs range had been ruled out by 2011 LHC running.

Excess of events in the low mass region seen in ATLAS and CMS

Exclusions of M_H:
- LEP < 114 GeV (arXiv:0602042v1)
- Tevatron [156,177] GeV (arXiv:1107.5518)
- LHC [~127, 600] GeV arXiv:1202.1408 (ATLAS) arXiv:1202.1488 (CMS)

Results from the LHC in 2012: Higgs

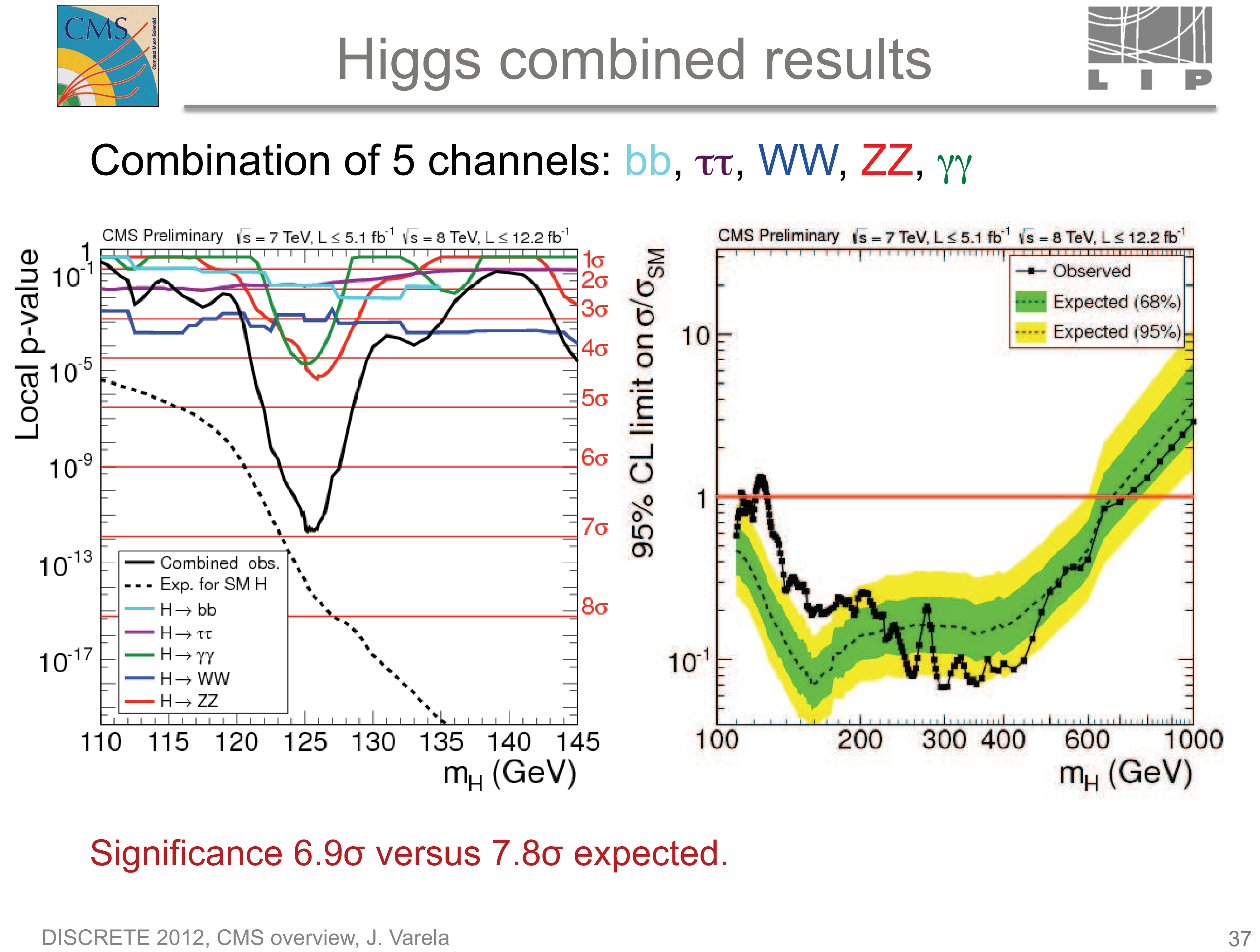


2. The 4th of July and after

After 48 years of postulat, 30 years of search (and a few heart attacks), the Higgs is discovered at LHC on the 4th of July: Higgstorical day!

Discrete–Lisbon, 03/12/2012 Implicatons of Higgs discovery – A. Djouadi – p.7/23

Results from the LHC in 2012: Higgs



Higgs combined results

Combination of 5 channels: bb, ττ, WW, ZZ, γγ

Significance 6.9σ versus 7.8σ expected.

DISCRETE 2012, CMS overview, J. Varela

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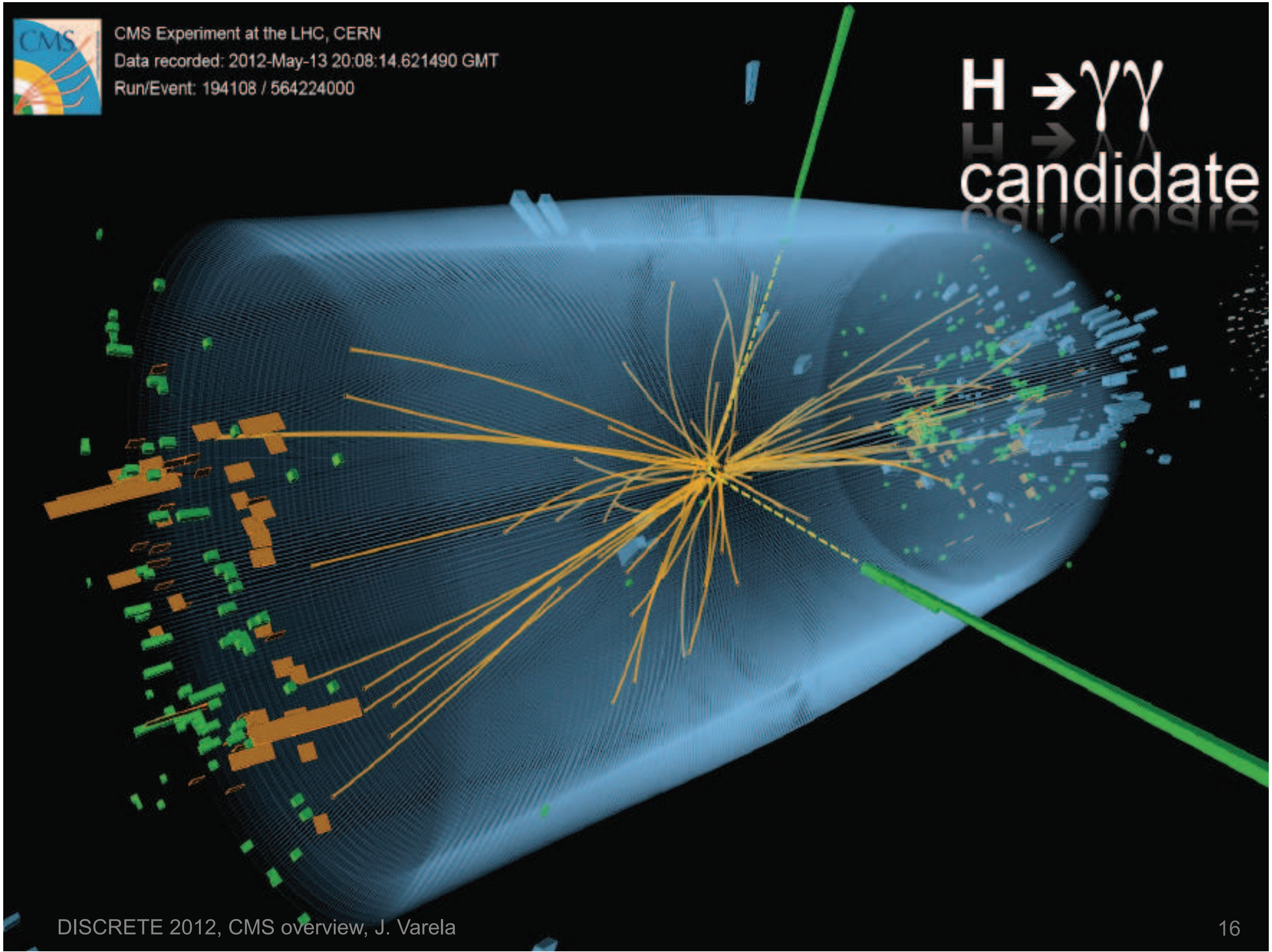
Results from the LHC in 2012

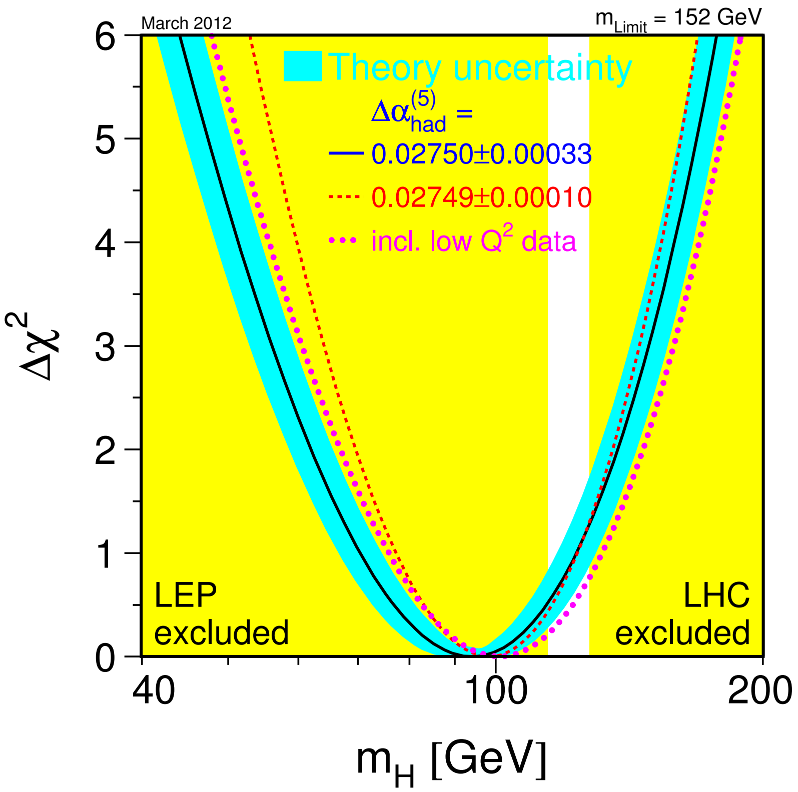


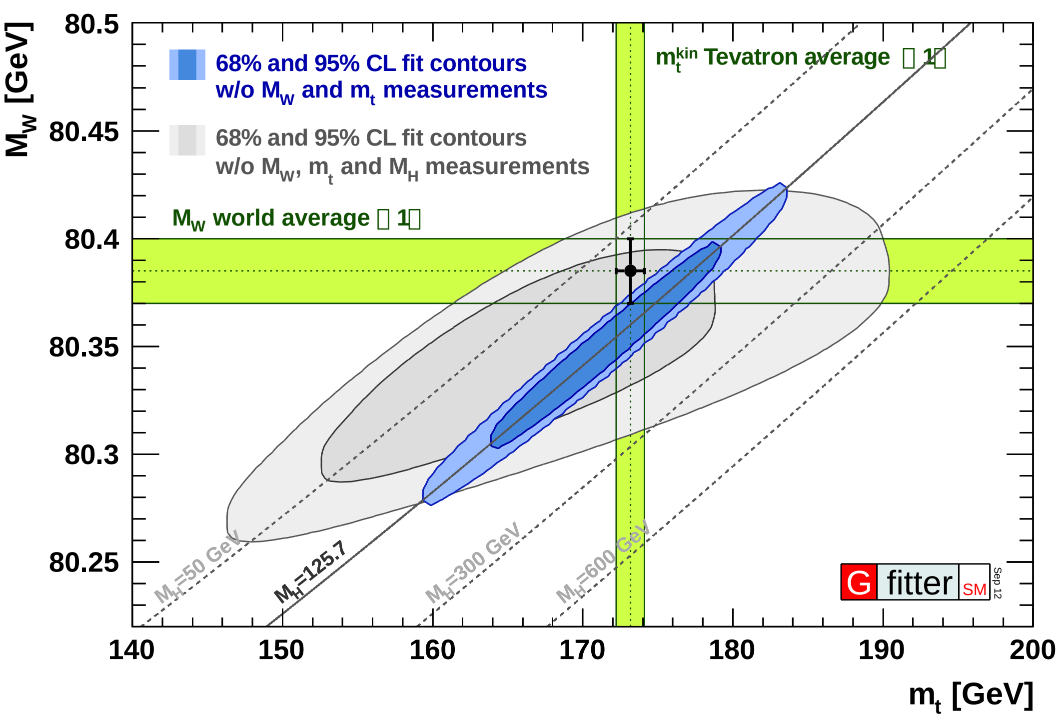
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

DISCRETE 2012, CMS overview, J. Varela

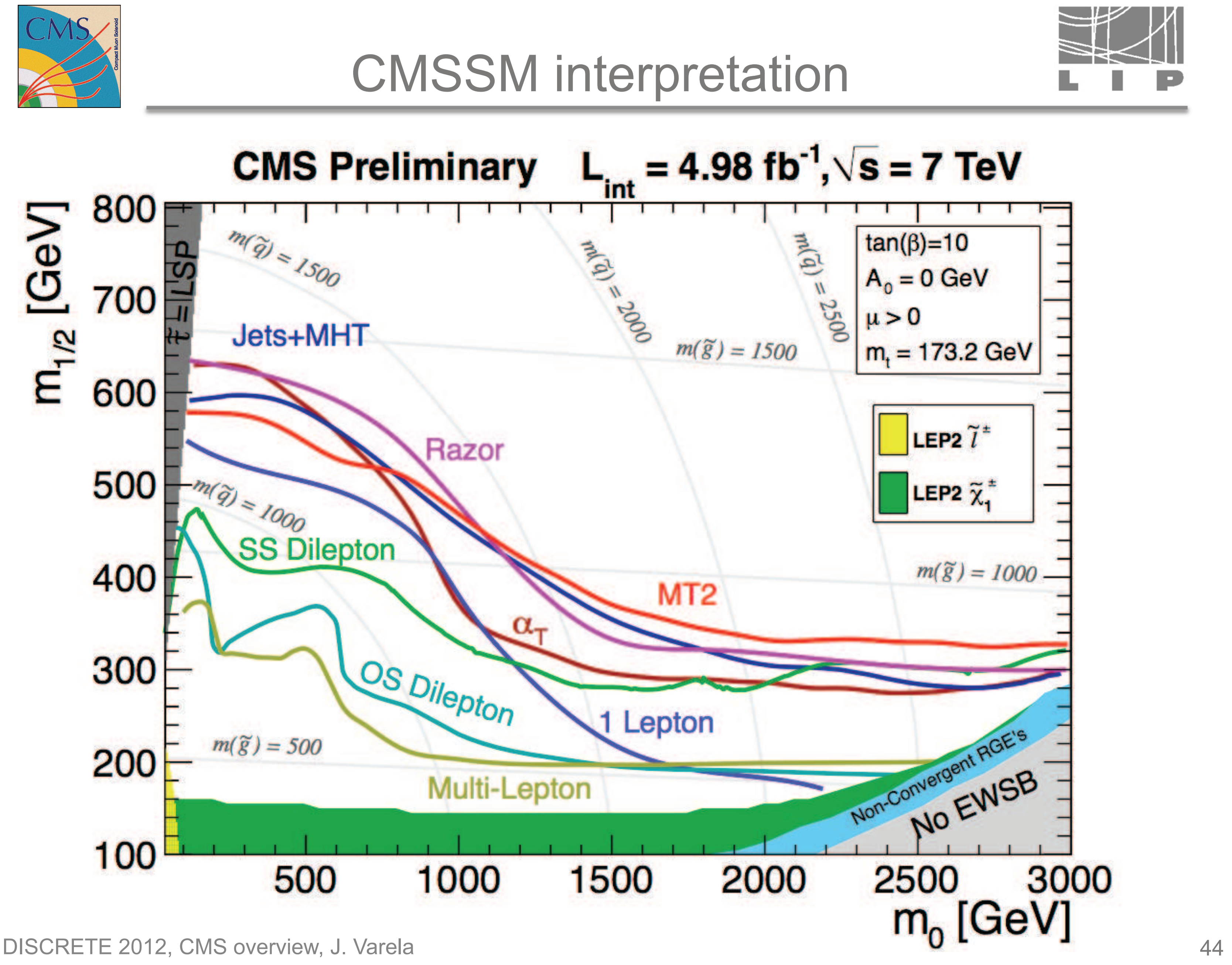
Results from the LHC in 2012: Higgs

- Results from direct searches in good agreement width indirect evidence
- The Higgs boson is light!





Results from the LHC in 2012: SUSY



CMSSM interpretation

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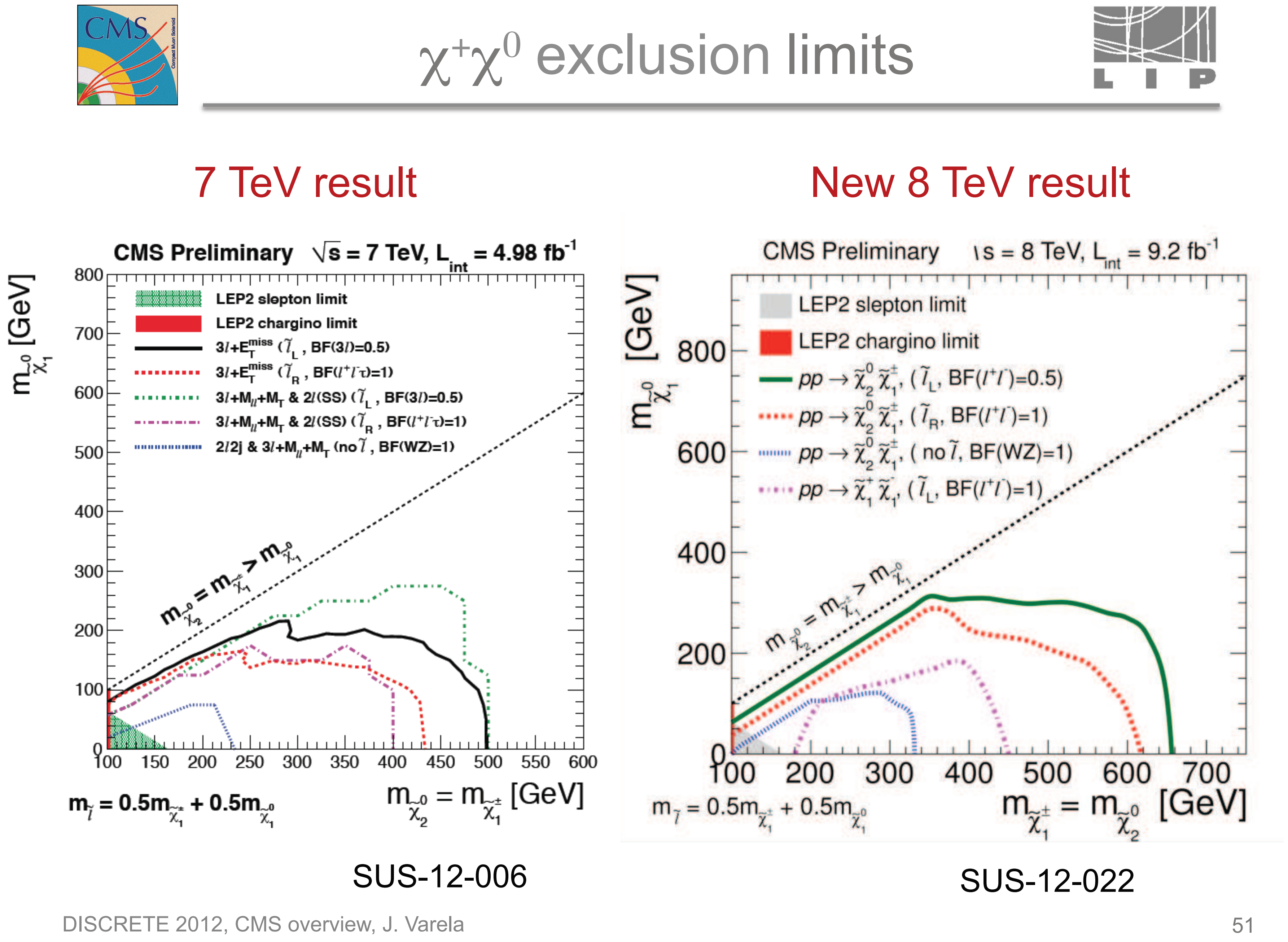
Results from the LHC in 2012:SUSY



$\chi^+\chi^0$ exclusion limits

7 TeV result

New 8 TeV result

SUS-12-006

SUS-12-022

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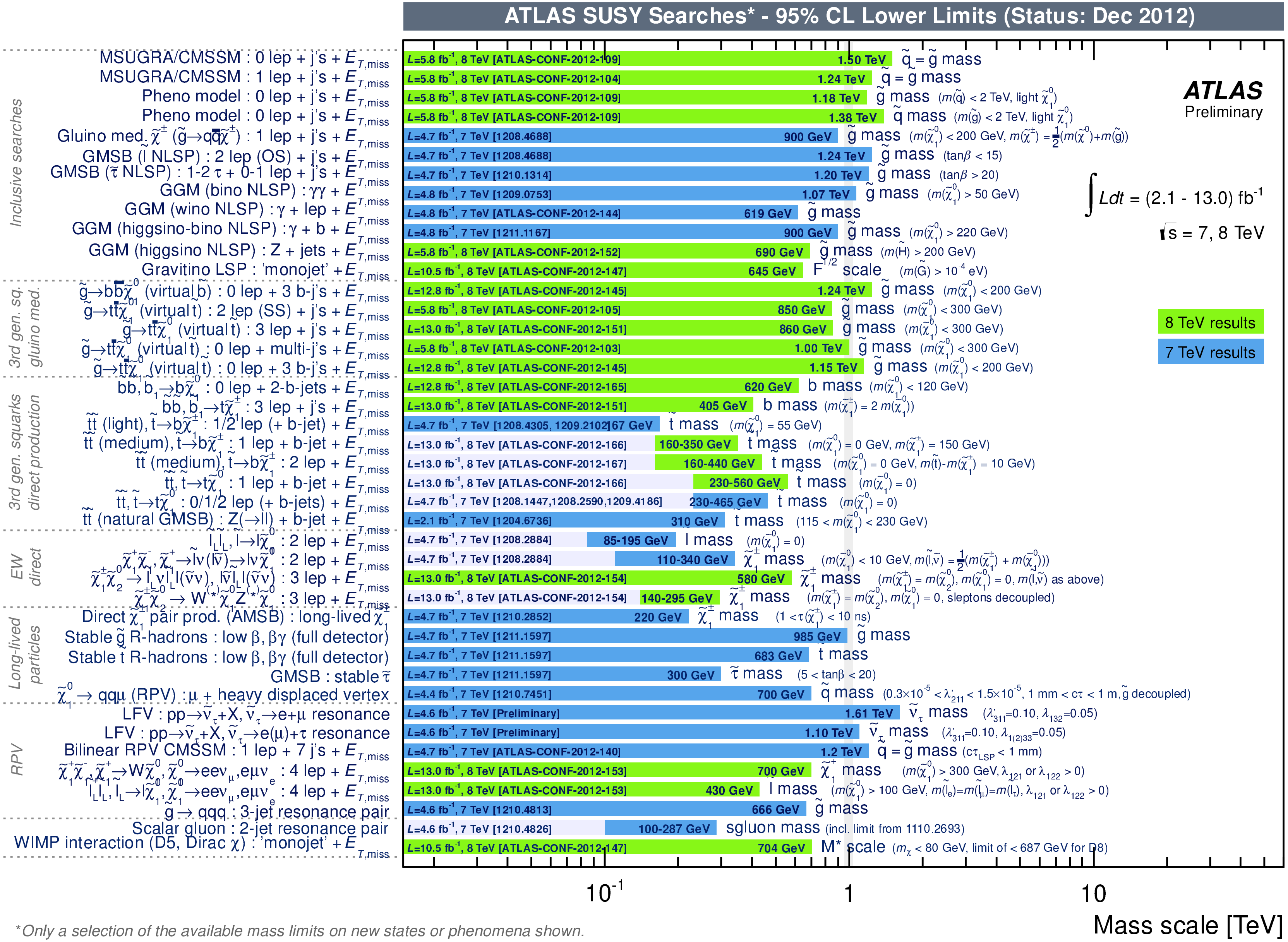
Results from the LHC in 2012: SUSY

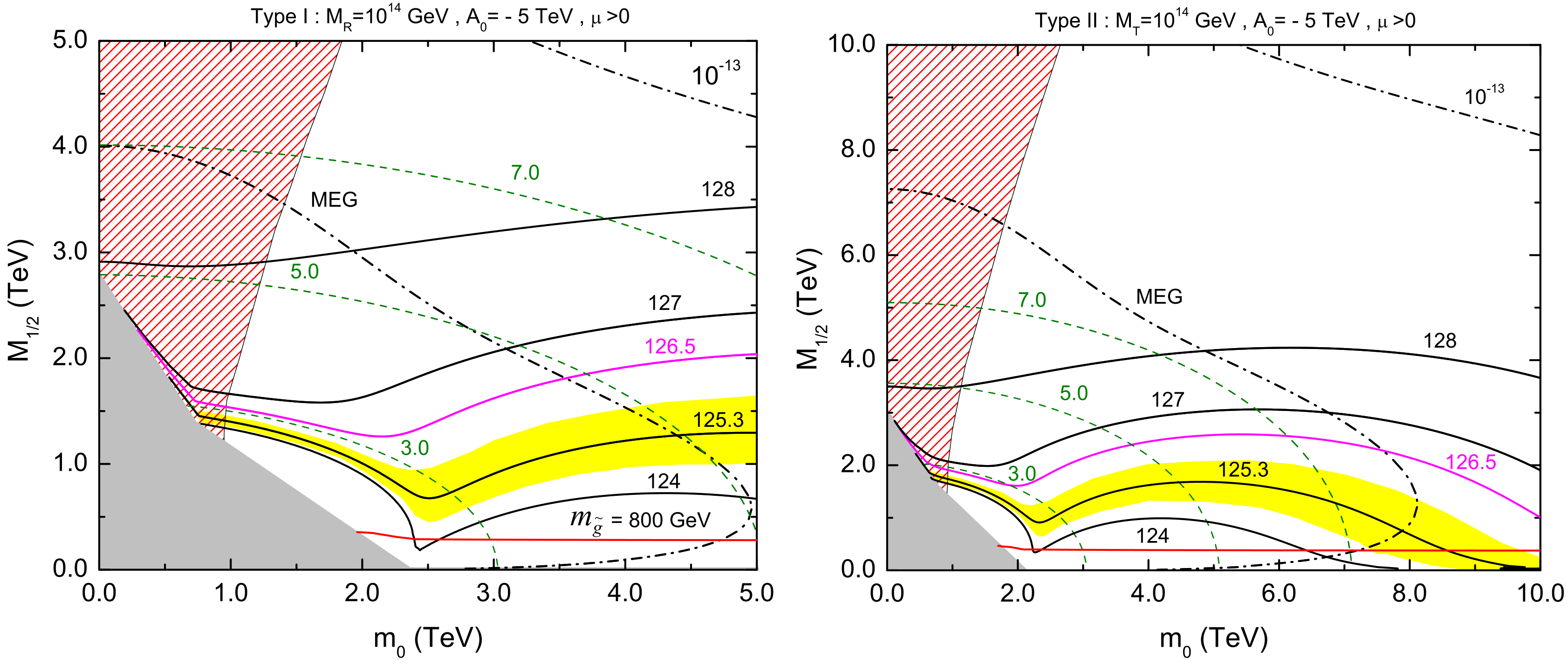


*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Implications for SUSY: 1

- ❐ From the experimental evidence
- ❐ From internal consistency of SUSY

Spectra is Heavy $\mathcal{O}$(few TeV)



Hirsch, Joaquim and Vicente, JHEP11(2012)109

Implications for SUSY: 2

Two possible views:

❒ **The Pessimist**

- Spectra is too heavy
- Too much fine tuning
- Even if true, LHC will not see it. It will be hiding forever!

❒ **The Optimist**

- After all, the Higgs boson is light in agreement with indirect searches and with the SUSY predictions
- Given the Higgs mass around 125 GeV, the spectra is where it should be!
- With a bit of luck LHC will see it and the seeking will be successful

Conclusion: While SUSY is still hiding we should continue seeking for it at LHC

Bibliography

Summary
Motivation
SUSY Algebra
MSSM
LEP Results
LHC Results
Implications

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Other Texts

- *The search for supersymmetry: Probing physics beyond the standard model*, H. E. Haber and G. L. Kane, Phys. Rep. 117 (1985) 75. $(+,-,-,-)$
- *A Supersymmetry primer*, Stephen Martin, hep-ph/9709356. $(-,+,+,+)$
- *BUSSTEPP Lectures on Supersymmetry*, José M. Figueroa-O'Farrill, hep-ph/0109172. $(-,+,+,+)$
- *The Minimal Supersymmetric Standard Model*, Jorge C. Romão, (see my homepage). $(+,-,-,-)$