Introduction to Supersymmetry

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Motivation

Although there is not yet direct experimental evidence for supersymmetry (SUSY), there are many theoretical arguments indicating that SUSY might be of relevance for physics below the 1 TeV scale.

The most commonly invoked theoretical arguments for SUSY are:

- 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 $\leq \mathcal{O}(1\text{TeV})$.

The Naturalness Problem: I

- As the SM is not asymptotically free, at some energy scale Λ, the interactions must become strong indicating the existence of new physics. Candidates for this scale: $M_X \simeq \mathcal{O}(10^{16}$ GeV) in GUT's or the Planck scale $M_P \simeq \mathcal{O}(10^{19}\text{GeV})$.
- The only consistent way to give masses to the gauge bosons and fermions is through the Higgs mechanism involving at least one spin zero Higgs boson.
- Although the Higgs boson mass is not fixed by the theory, a value much bigger than $< H^0 > \simeq G_F^{-1/2} \simeq 250$ GeV would imply that the Higgs sector would be strongly coupled making it difficult to understand why we are seeing an apparently successful perturbation theory at low energies.
- The one loop radiative corrections to the Higgs boson mass

$$\boxed{\delta m_H^2 = \mathcal{O}\left(\frac{\alpha}{4\pi}\right)\ \Lambda^2}$$

would be too large if Λ is identified with Λ_{GUT} or Λ_{Planck}.

The Naturalness Problem: II

- SUSY cures this problem in the following way. If SUSY were exact, radiative corrections to the scalar masses squared would be absent because the contribution of fermion loops exactly cancels against the boson loops.
- Therefore if SUSY is broken, as it must, we should have

$$\boxed{\delta m_H^2 = \mathcal{O}\left(\frac{\alpha}{4\pi}\right) \; |m_B^2 - m_F^2|}$$

- We conclude that

SUSY provides a solution for the the naturalness problem if the masses of the superpartners are below $\mathcal{O}(1\ \text{TeV})$. This is the main reason behind all the phenomenological interest in SUSY.

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

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

where

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

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

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

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

$$\boxed{\begin{array}{c} P^2 = P_\alpha P^\alpha \qquad W^2 = W_\alpha W^\alpha \qquad W_\mu = -\frac{i}{2}\epsilon_{\mu\nu\rho\sigma} J^{\nu\rho} P^\sigma \\ P^2 \left|m, s\right\rangle = m^2 \left|m, s\right\rangle \quad W^2 \left|m, s\right\rangle = -m^2 s(s+1) \left|m, s\right\rangle \end{array}}$$

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

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

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

Simple Results from the Algebra

Number of Bosons = Number of Fermions

$$Q_\alpha|B>=|F> \qquad (-1)^{N_F}|B>=|B>$$
$$Q_\alpha|F>=|B> \qquad (-1)^{N_F}|F>=-|F>$$

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

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

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

Energy of the Vacuum State

$$\boxed{\langle 0|H|0\rangle \geq 0}$$

From the algebra we get

$$\left\{Q_1, \overline{Q}_{\dot{1}}\right\} + \left\{Q_2, \overline{Q}_{\dot{2}}\right\} = 2Tr\left(\sigma^\mu\right) P_\mu = 4H$$

Then

$$H = \frac{1}{4}\left(Q_1\overline{Q}_1 + Q_2\overline{Q}_{\dot{2}} + \overline{Q}_{\dot{1}}Q_1 + \overline{Q}_{\dot{2}}Q_2\right)$$

and

$$\begin{aligned}\langle 0|H|0\rangle &= \left(||Q_1\,|0\rangle\,||^2 + ||Q_1\,|0\rangle\,||^2 + ||\overline{Q}_{\dot{1}}\,|0\rangle\,||^2 + ||\overline{Q}_{\dot{2}}\,|0\rangle\,||^2\right)\\ &\geq 0\end{aligned}$$

$\Downarrow$

The vacuum state is always positive definite.

SUSY Representations: Massive case

In the rest frame $$\boxed{\left\{Q_\alpha, \overline{Q}_{\dot\alpha}\right\} = 2\,m\,\delta_{\alpha\dot\alpha}}$$

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

$\Downarrow$

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

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

where the matrix M takes the form

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

Then $\boxed{\left\{Q_2, \overline{Q}_2\right\} = 4E}$ 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
$\vert\Omega\rangle$	λ
$\overline{Q}_2\,\vert\Omega\rangle$	$\lambda - \frac{1}{2}$

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

Superfields for Massless Particles

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

$$\boxed{\phi = \phi(A, \psi_L)} \Rightarrow \boxed{\begin{array}{l} A \text{ Complex Scalar: } 2\,\text{d.o.f} \\ \psi_L \text{ Chiral Fermion: } 2\,\text{d.o.f} \end{array}}$$

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

$$\boxed{V = V(\lambda, W^\mu)} \Rightarrow \boxed{\begin{array}{l} \lambda \text{ Chiral Fermion: } 2\,\text{d.o.f} \\ W^\mu \text{ Massless Vector: } 2\,\text{d.o.f} \end{array}}$$

$\boxed{A}$ ➡ superpartner of the fermion: sfermion

$\boxed{\lambda}$ ➡ superpartner of gauge field: gaugino

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:

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

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.

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 $SU_L(2)$

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

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
$\widehat{Q}_i \equiv (\widetilde{Q}, Q)_i$	$(3, 2, \frac{1}{6})$
$\widehat{D}_i \equiv (\widetilde{d}_R, d_L^c)_i$	$(3, 1, \frac{1}{3})$
$\widehat{U}_i \equiv (\widetilde{u}_R, u_L^c)_i$	$(3, 1, -\frac{2}{3})$

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

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

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).

But this is just an ad hoc assumption without a deep justification. We will see later what are the consequences of non conservation of R-Parity.

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.

The most general SUSY soft breaking is

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

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 (SUGRA).

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

$$m^2_{H_1} = m^2_{H_2} = M^2_L = M^2_R = m^2_0 \,, M^2_Q = M^2_U = M^2_D = m^2_0 \,,$$

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

Parameter Counting

Parameters	Conditions	Free Parameters
$h_t,\ h_b,\ h_\tau,\ v_1,\ v_2$	$m_W,\ m_t,\ m_b,\ m_\tau$	$\tan\beta = v_2/v_1$
$A,\ B,\ m_0,\ M_{1/2},\ \mu$	$t_i = 0,\ i=1,2$	$A,\ m_0,\ M_{1/2},\ \text{sign}(\mu)$
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.

The Chargino Mass Matrices

The charged gauginos mix with the charged higgsinos giving the so–called charginos. In a basis where $\psi^{+T} = (-i\lambda^+, \widetilde{H}_2^+)$ and $\psi^{-T} = (-i\lambda^-, \widetilde{H}_1^-)$, the chargino mass terms in the Lagrangian are

$$\boxed{\mathcal{L}_m = -\frac{1}{2}(\psi^{+T}, \psi^{-T}) \begin{pmatrix} \mathbf{0} & \boldsymbol{M}_C^T \\ \boldsymbol{M}_C & \mathbf{0} \end{pmatrix} \begin{pmatrix} \psi^+ \\ \psi^- \end{pmatrix} + h.c.}$$

where the chargino mass matrix is given by

$$\boxed{\boldsymbol{M}_C = \begin{bmatrix} M_2 & \frac{1}{\sqrt{2}} g v_2 \\ \frac{1}{\sqrt{2}} g v_1 & \mu \end{bmatrix}}$$

and M_2 is the $SU(2)$ gaugino soft mass. We can write this as

$$\boxed{\boldsymbol{M}_C = \begin{bmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{bmatrix}}$$

Neutral Higgs Mass Matrices

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

with masses

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

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

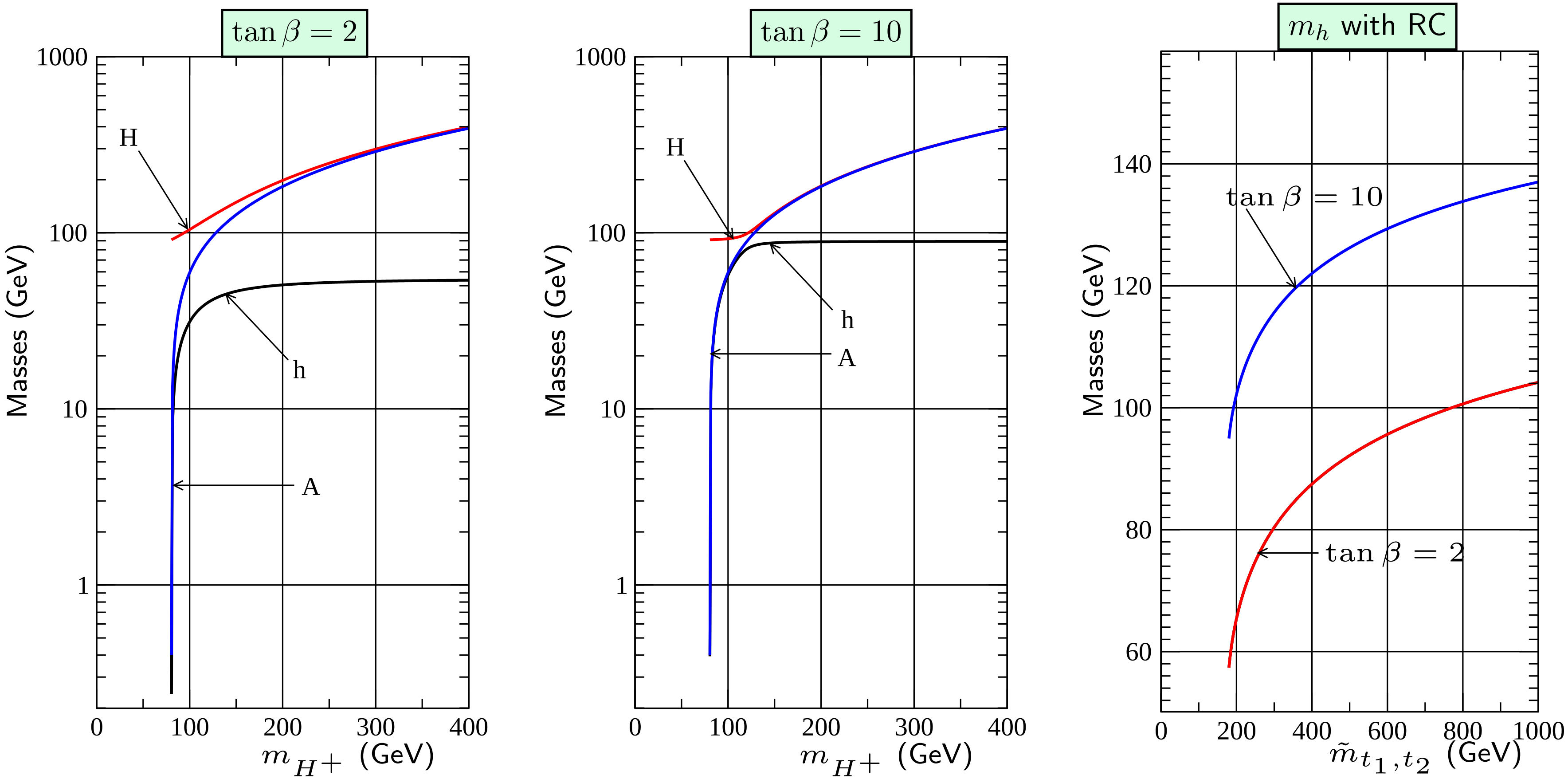
Sum Rule

$$\boxed{m_h^2 + m_H^2 = m_A^2 + m_Z^2} \Rightarrow \boxed{\begin{array}{c} m_h < m_A < m_H \\ m_h < m_Z < m_H \end{array}}$$

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:

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



Sfermion Mass Matrices: Sleptons

As an example of the sfermion mass matrices we have

$$M_{\tilde{\ell}}^2 = \begin{pmatrix} \boldsymbol{M^2_{LL}} & \boldsymbol{M^2_{LR}} \\ \boldsymbol{M^2_{RL}} & \boldsymbol{M^2_{RR}} \end{pmatrix}$$

$6 \times 6 = 4$ Blocks 3×3

where

$$\boldsymbol{M^2_{LL}} = \frac{1}{2}\, v_1^2\, h_E^* h_E^T + M_L^2 - \frac{1}{2}\,(2m_W^2 - m_Z^2)\cos 2\beta$$

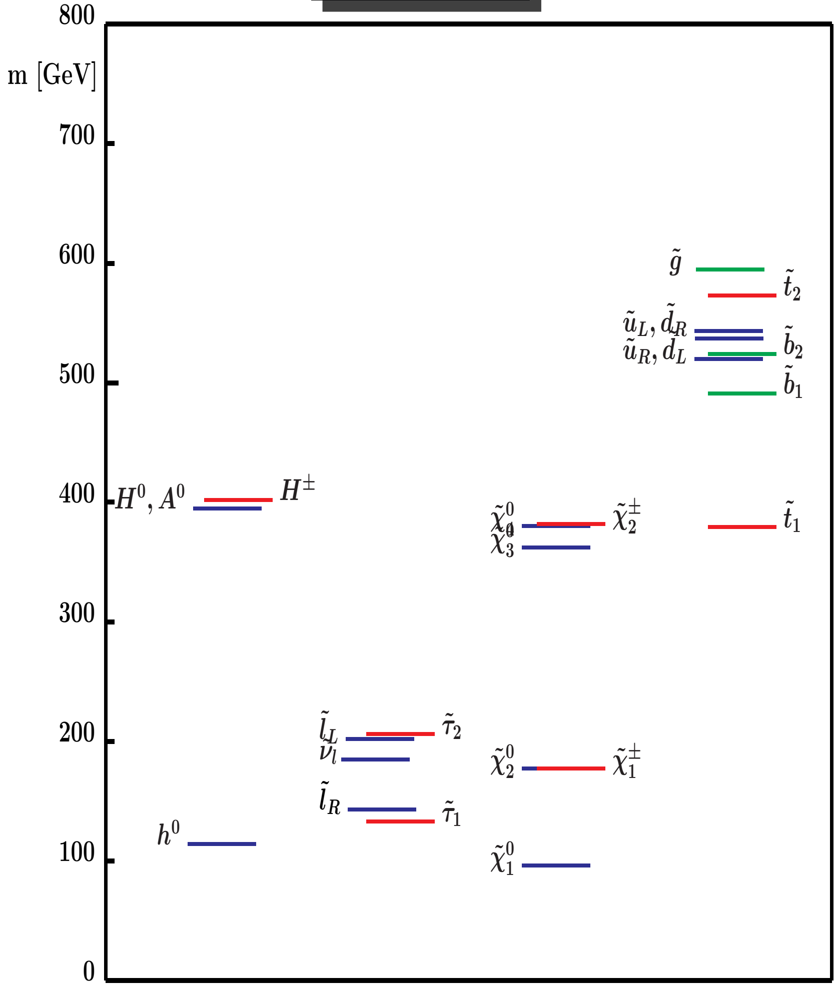
$$\boldsymbol{M^2_{RR}} = \frac{1}{2}\, v_1^2\, h_E^T h_E^* + M_R^2 - (m_Z^2 - m_W^2)\cos 2\beta$$

$$\boldsymbol{M^2_{LR}} = \frac{v_1}{\sqrt{2}}\, A_E^* - \mu \frac{v_2}{\sqrt{2}}\, h_E^*$$

$$\boldsymbol{M^2_{RL}} = \boldsymbol{M^2_{LR}}^{\dagger}$$

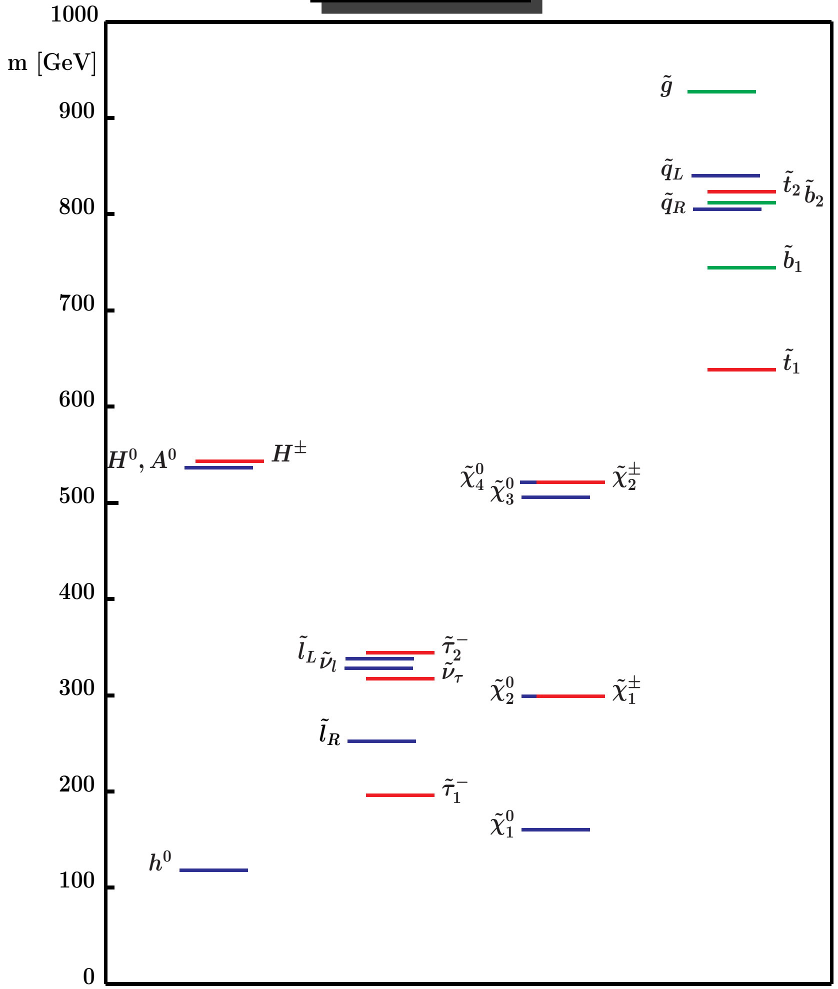
Example of Spectra

SPS1a



$$m_0 = 100\text{GeV},\ m_{1/2} = 250\text{GeV}$$
$$A_0 = -100\text{GeV},\ \tan\beta = 10,\ \mu > 0$$

SPS1b



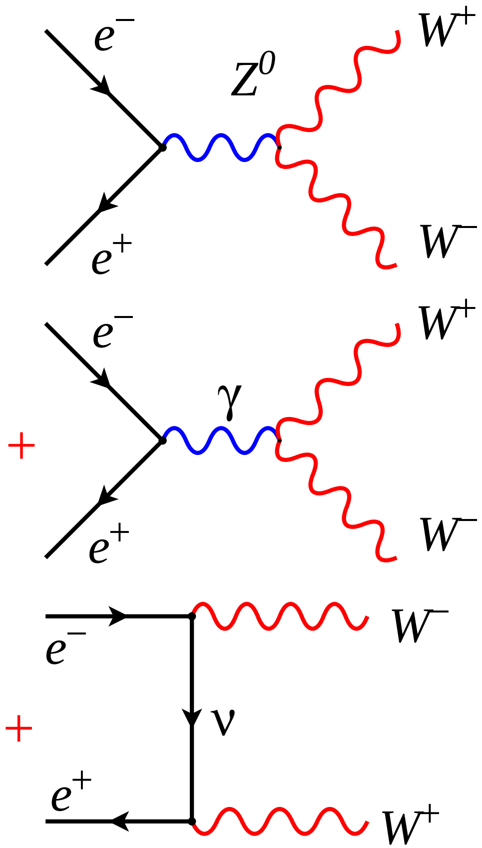
$$m_0 = 200\text{GeV},\ m_{1/2} = 400\text{GeV}$$
$$A_0 = 0,\ \tan\beta = 30,\ \mu > 0$$

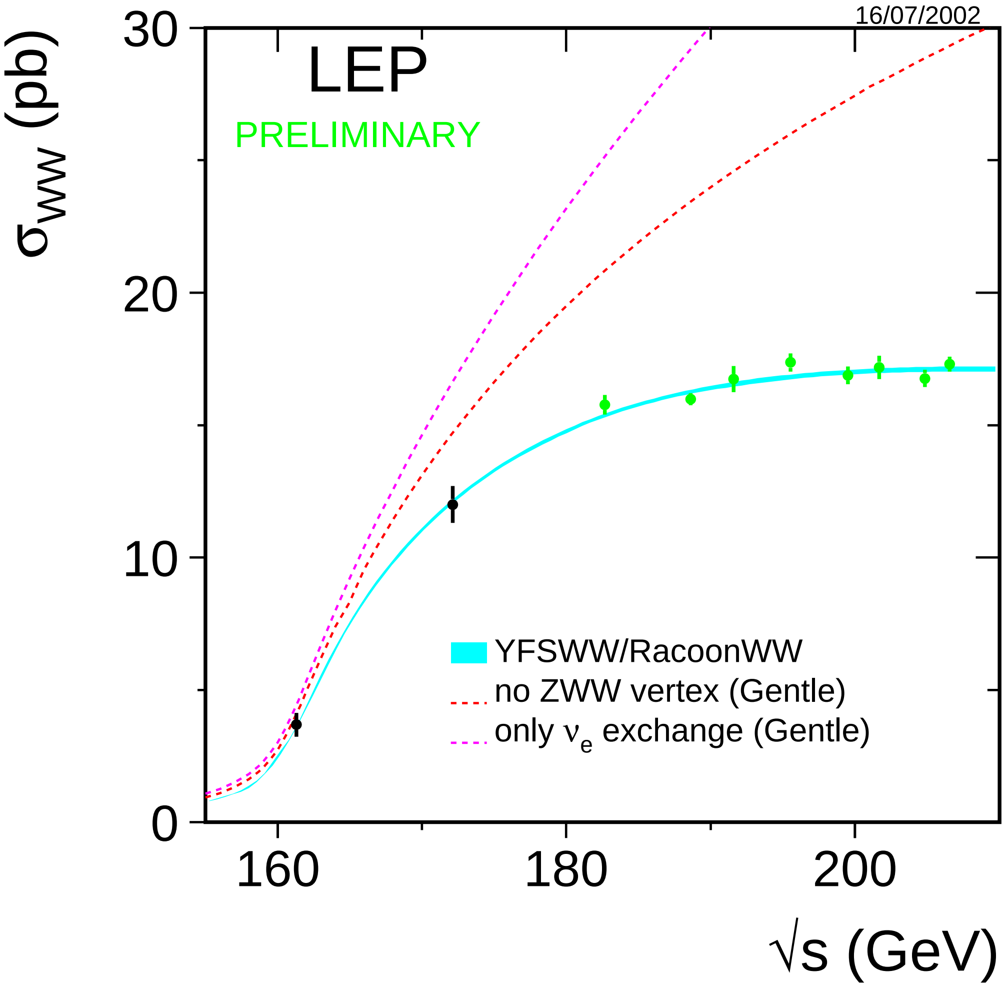
Couplings in the MSSM

Name	Type
Gauge Self-Interaction	VVV VVVV
3-Point Gauge Coupling	$V f f$ $V \tilde{f} \tilde{f}$ $V \tilde{\chi} \tilde{\chi}$ $V H H$ $V G H$ $V G G$
3-Point Higgs Coupling	$H f f$ $H \tilde{f} \tilde{f}$ $H \tilde{\chi} \tilde{\chi}$ $H V V$
3-Point Goldstone Coupling	$G f f$ $G \tilde{f} \tilde{f}$ $G \tilde{\chi} \tilde{\chi}$ $G V V$
Other 3-Point	$\tilde{f} f \tilde{\chi}$

Name	Type
4-Point Coupling	$V V f f$ $H H V V$ $H G V V$ $G G V V$ $\tilde{f} \tilde{f} H H$ $\tilde{f} \tilde{f} G H$ $\tilde{f} \tilde{f} G G$ $\tilde{f} \tilde{f} \tilde{f} \tilde{f}$
Goldstone-Higgs Interaction	$H H G$ $H G G$ $H H H G$ $H H G G$ $H G G G$ $G G G G$
Ghost	$\overline{\omega}\omega$ V $\overline{\omega}\omega$ H $\overline{\omega}\omega$ G

Test of the Triple Vertices



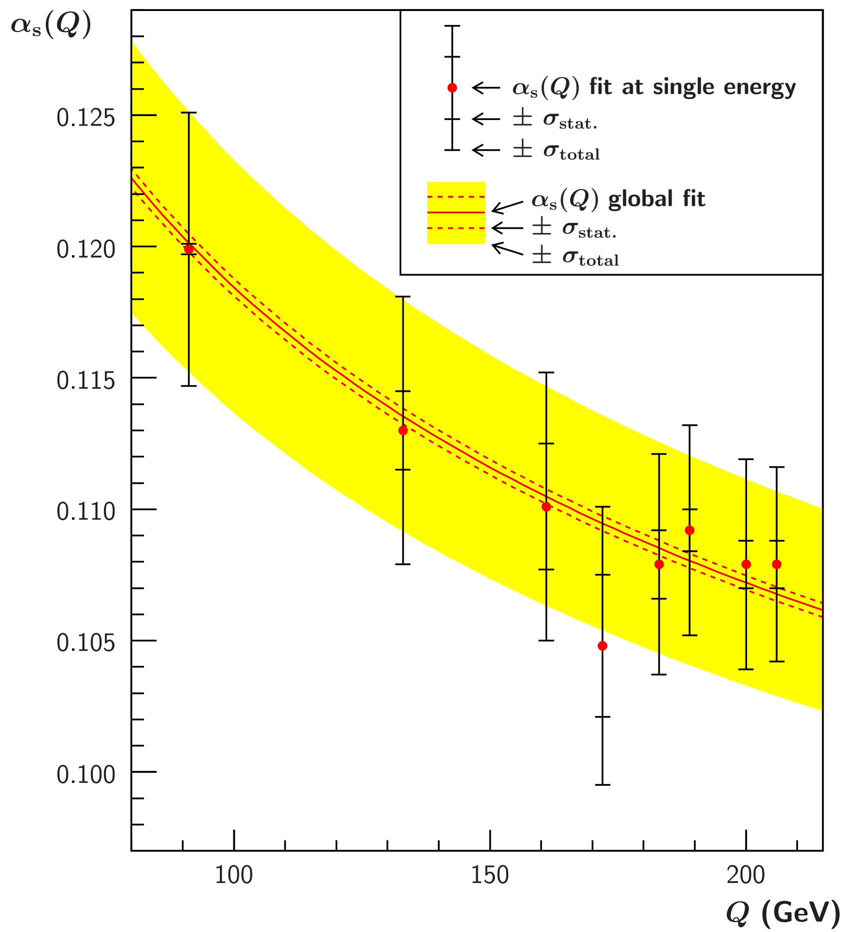


Gauge Self-Interactions: Asymptotic Freedom

Asymptotic Freedom: Gross, Wilczek & Politzer showed that for high energies the strong interactions become weak (Nobel Prize 2004)

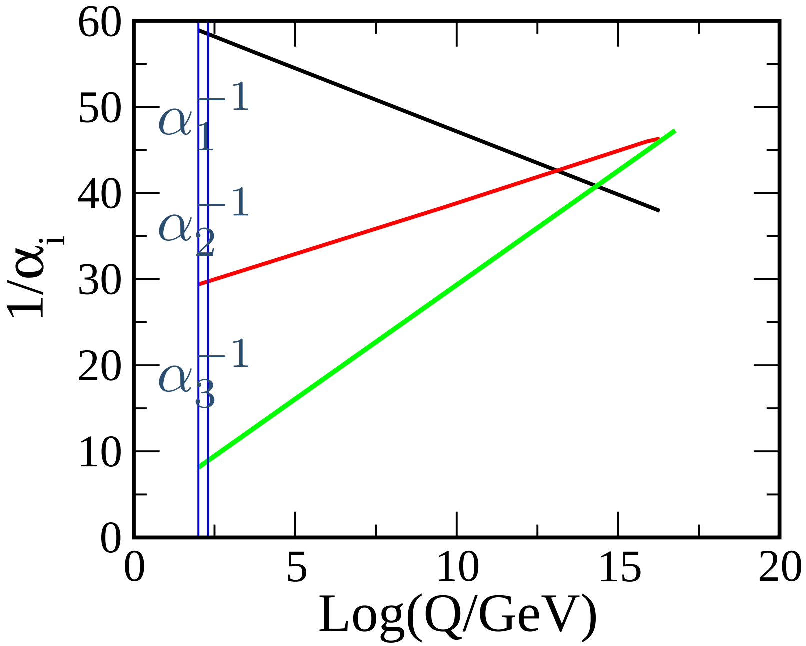
Test of $VVV + VVVV$ Interactions

LEP QCD Working Group

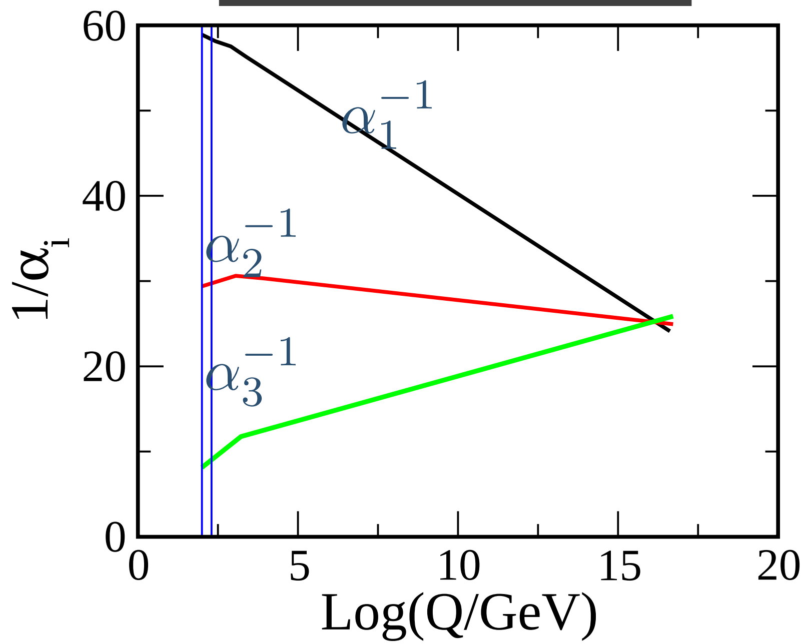


Gauge Couplings Unification

Standard Model



Supersymmetry



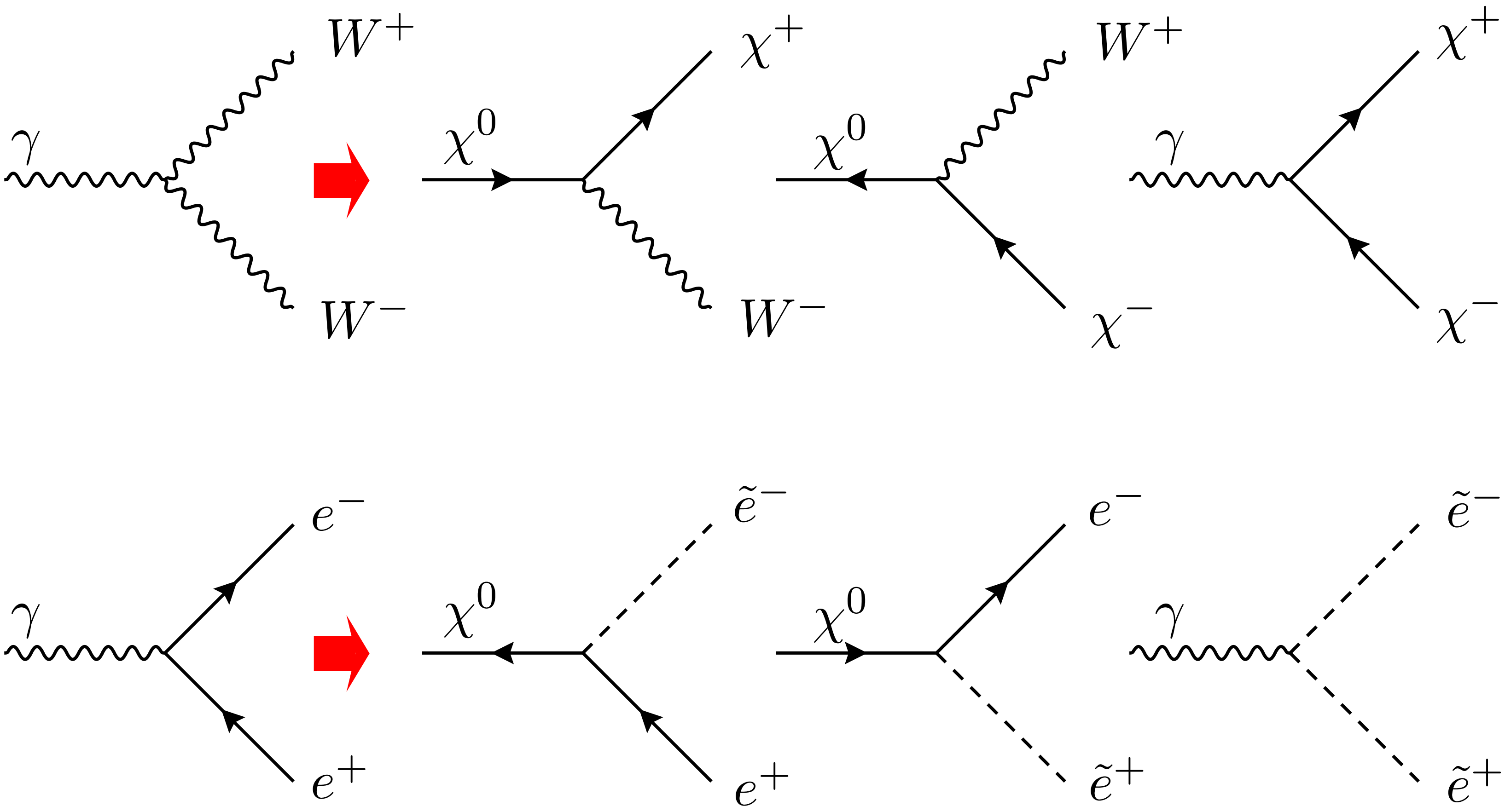
$$\boxed{\alpha_i = \frac{g_i^2}{4\pi}}$$

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

Electroweak Theory

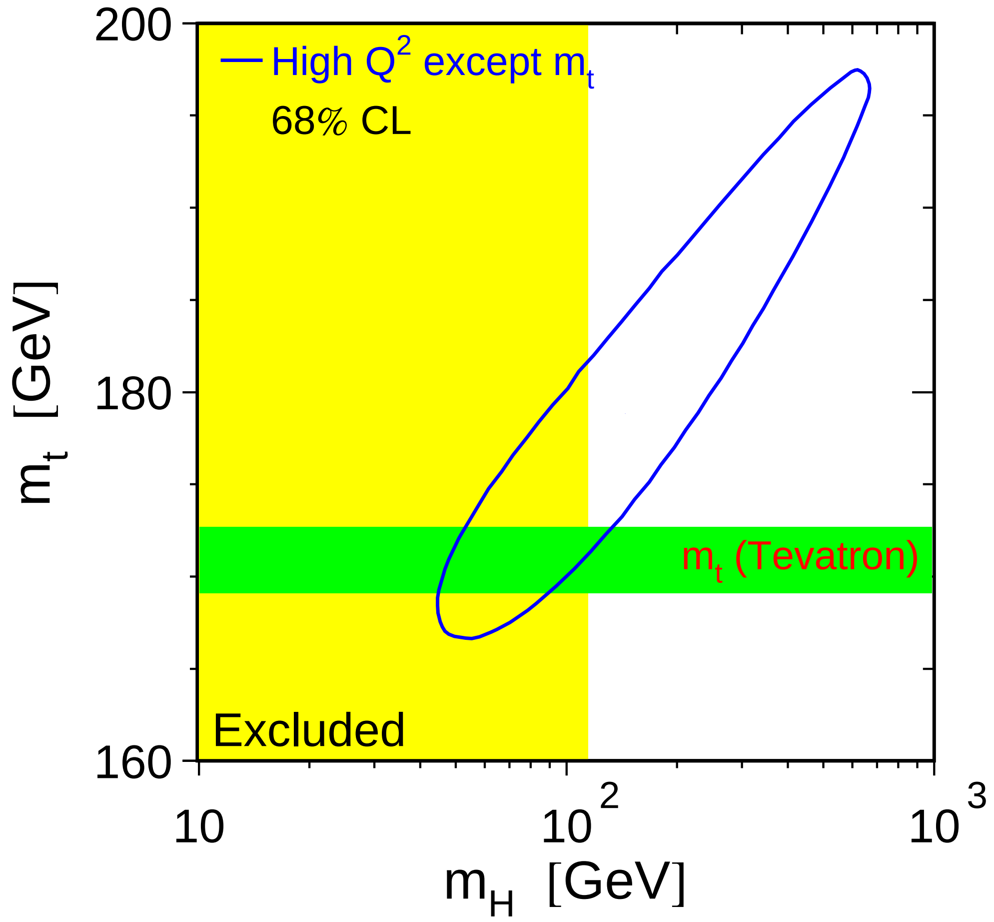
Quantum Chromodynamics

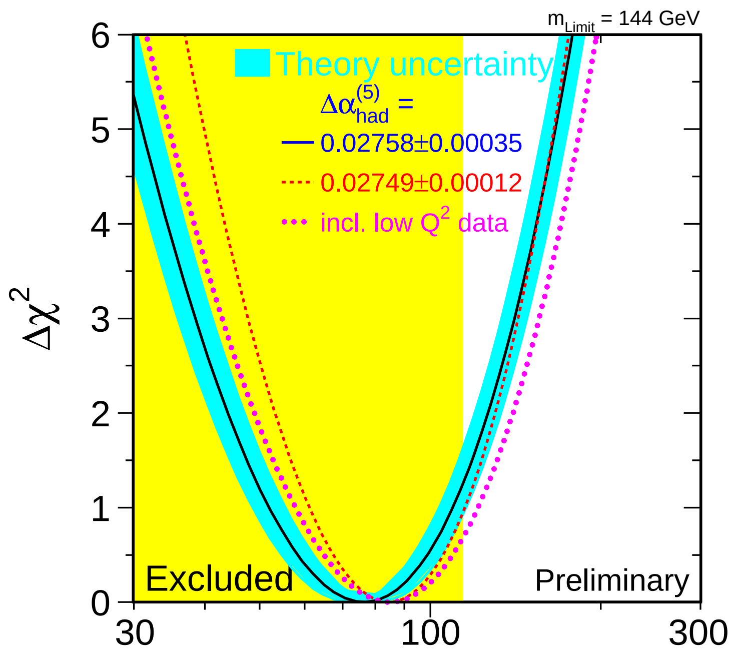
Examples of New Couplings: Conserving R-Parity



Rule: Change any two lines into the superpartners.

Higgs Boson



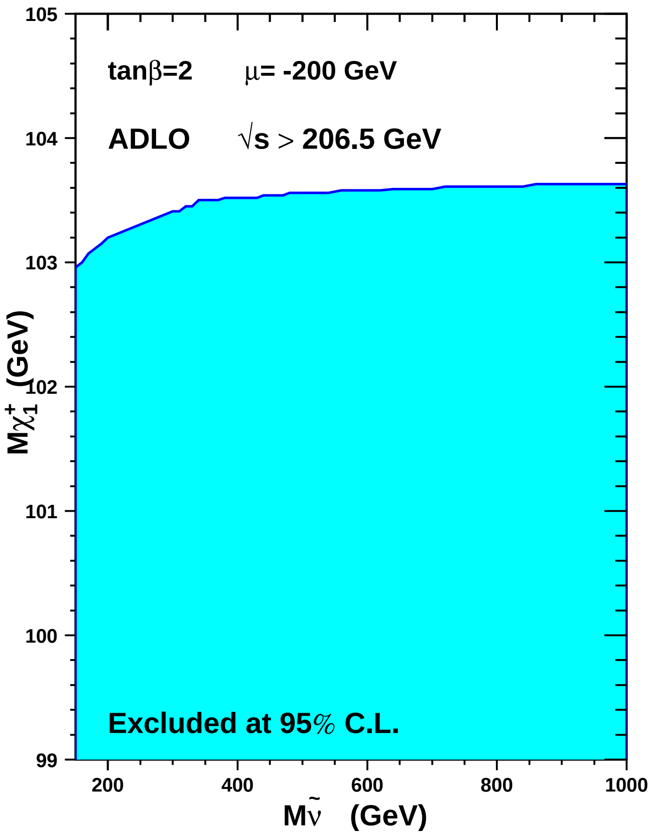


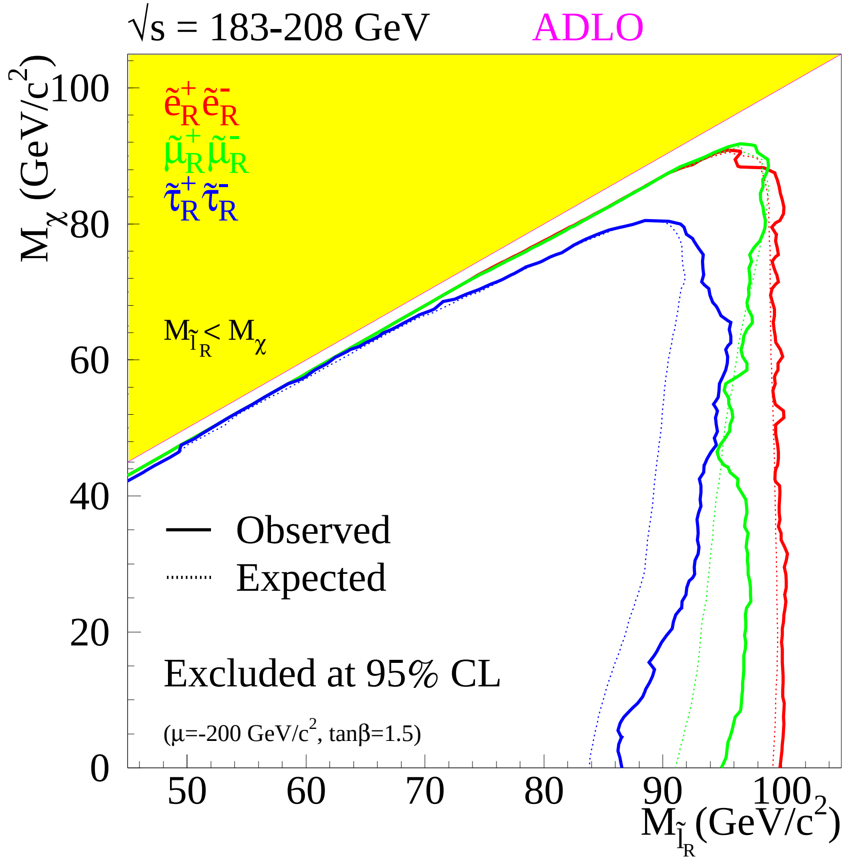
$M_H = 114^{+69}_{-45}$ **GeV**

$M_H < 260$ **GeV @** $95\% CL$

$M_H > 114.4$ **GeV**

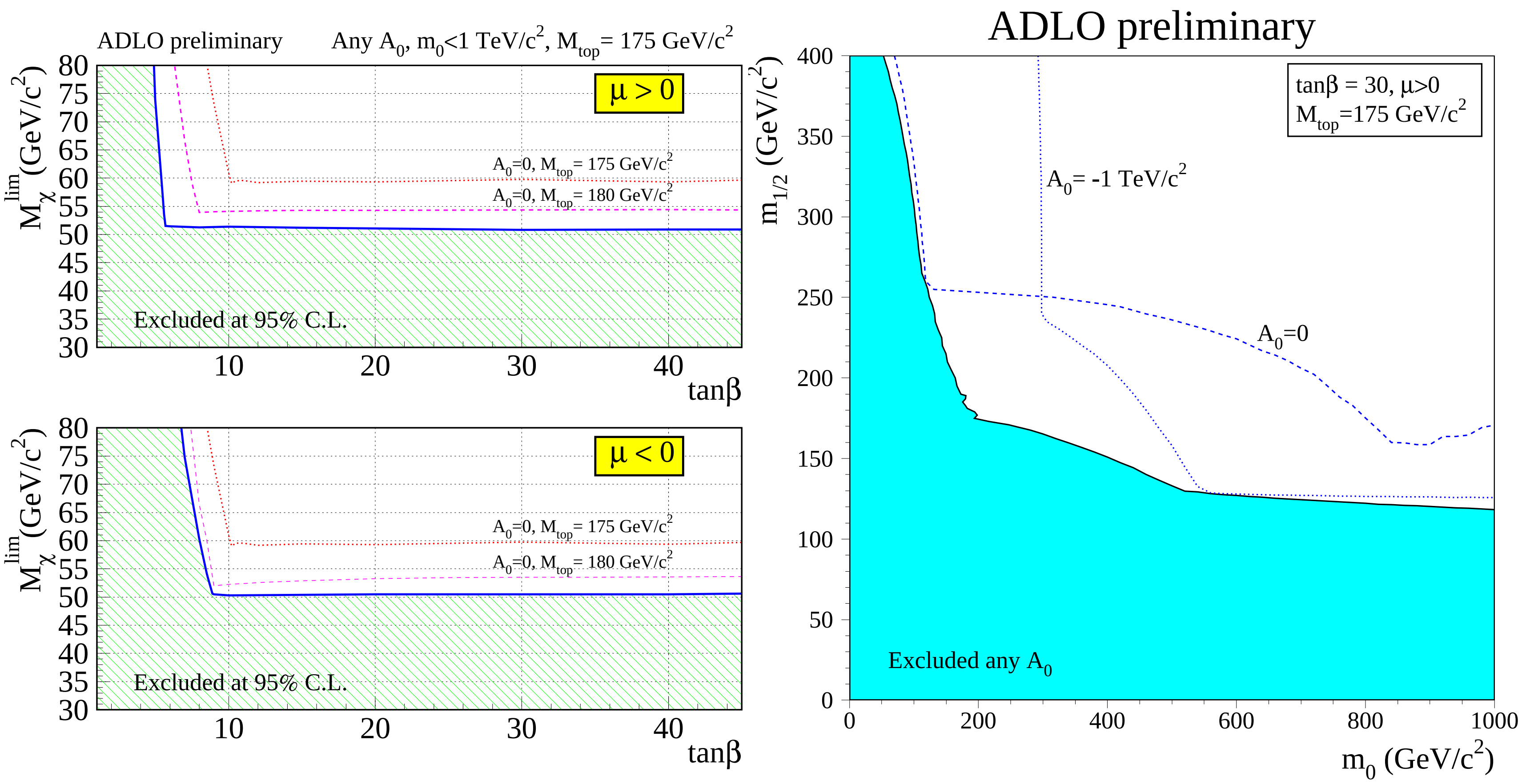
Limits on Charginos, Sneutrinos & Sleptons





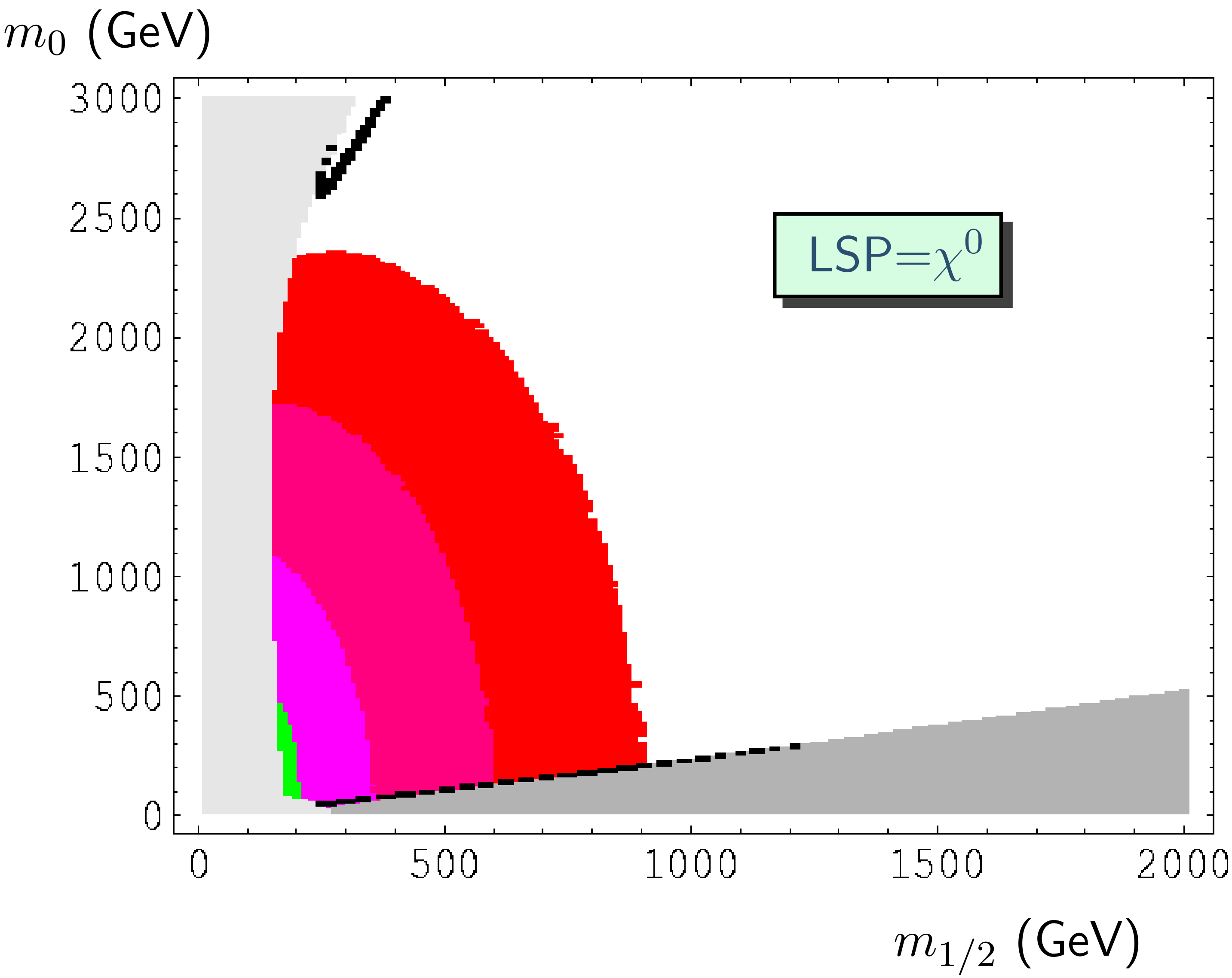
Limits on $\chi^{\pm}$, $\tilde{l}^{\pm} \simeq 100$ GeV.

Limits on Neutralinos



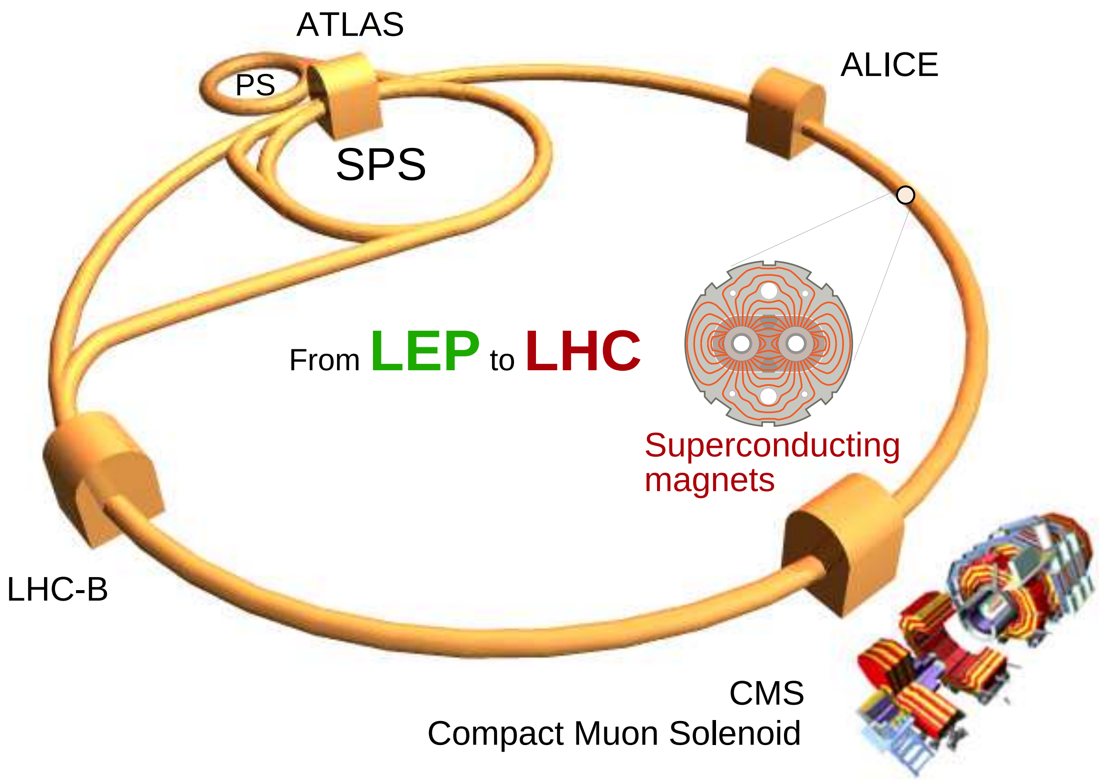
Limits on $\chi^0 \geq 50$ GeV. More model dependent.

Neutralino as Dark Matter



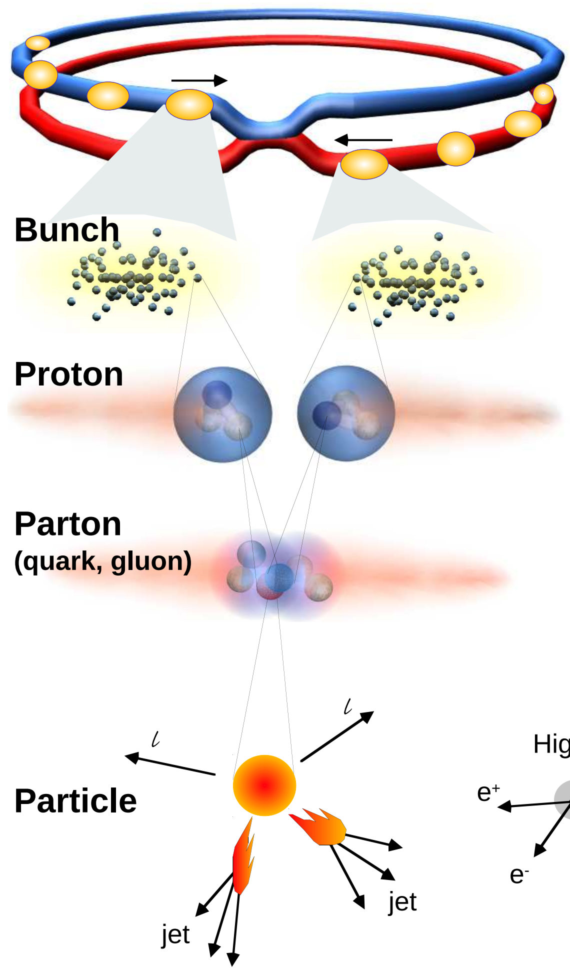
Black lines: Neutralino consistent with dark matter.

The Large Hadron Collider (LHC)

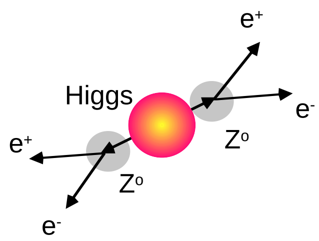


	Beams	Energy		Luminosity
LEP	e+ e-	200	GeV	10^{32} cm^{-2}s^{-1}
LHC	p p	14	TeV	10^{34}
	Pb Pb	1312	TeV	10^{27}

Collisions at LHC



Proton-Proton	(2835 x 2835 bunches)
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions $\approx$	10^{7} - 10^{9} Hz

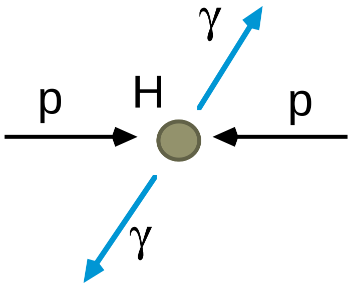


Higgs

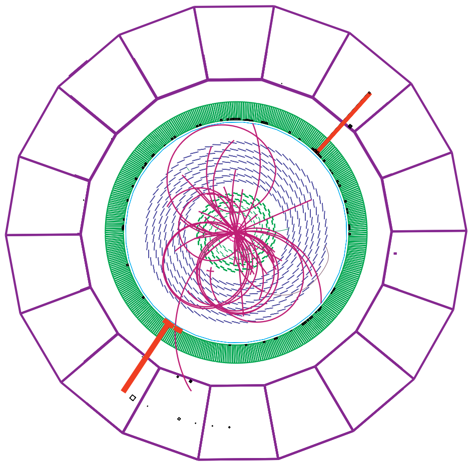
SUSY.....

Selection of 1 in 10,000,000,000,000

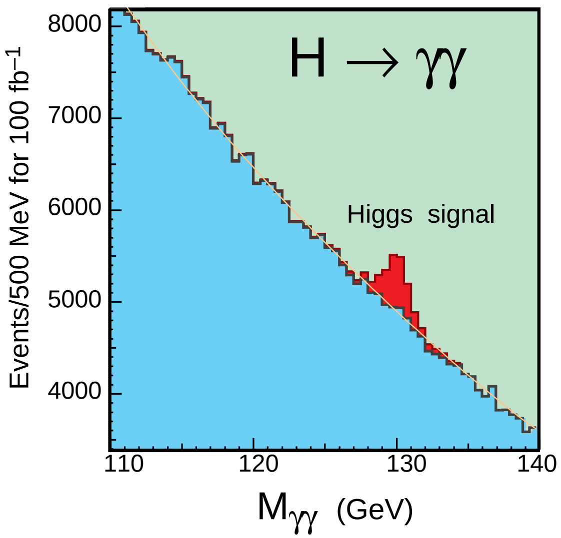
Higgs to 2 photons ($M_H < 140$ GeV)



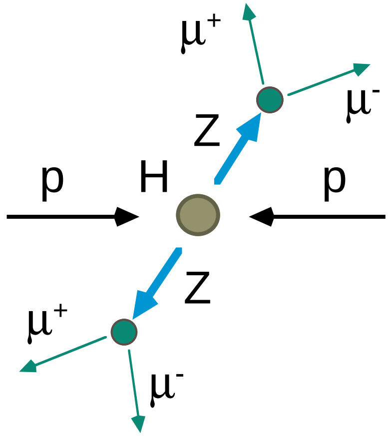
$H^0 \to \gamma\gamma$ is the most promising channel if M_H is in the range 80 – 140 GeV. The high performance $PbWO_4$ crystal electromagnetic calorimeter in CMS has been optimized for this search. The $\gamma\gamma$ mass resolution at $M_{\gamma\gamma} \sim 100$ GeV is better than 1%, resulting in a S/B of ≈1/20



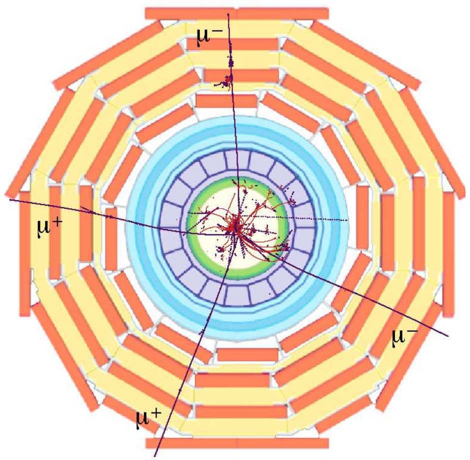
$M_{Higgs} = 100$ GeV



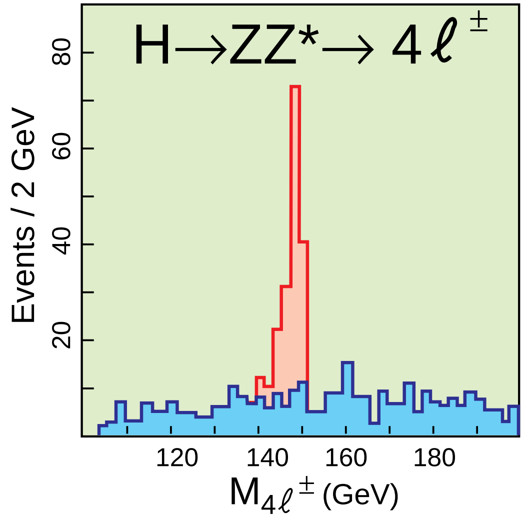
Higgs to 4 leptons ($140 < M_H < 700$ GeV)



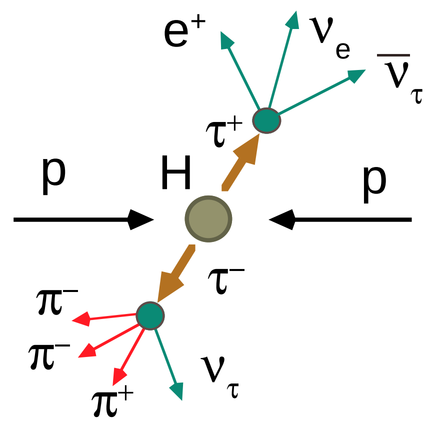
In the M_H range 130 - 700 GeV the most promising channel is $H^0 \to ZZ^* \to 2\ell^+ 2\ell^-$ or $H^0 \to ZZ \to 2\ell^+ 2\ell^-$. The detection relies on the excellent performance of the muon chambers, the tracker and the electromagnetic calorimeter.
For $M_H \leq 170$ GeV a mass resolution of ~1 GeV should be achieved with the combination of the 4 Tesla magnetic field and the high resolution of the crystal calorimeter



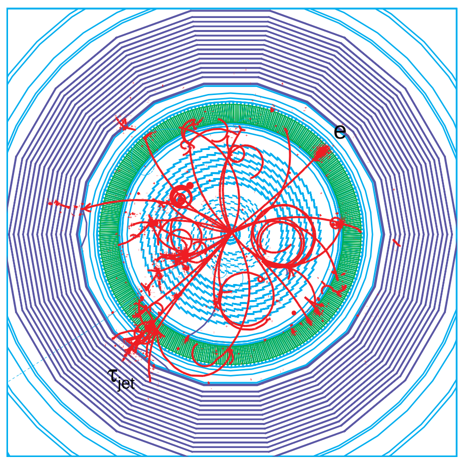
M_{Higgs} = 150 GeV



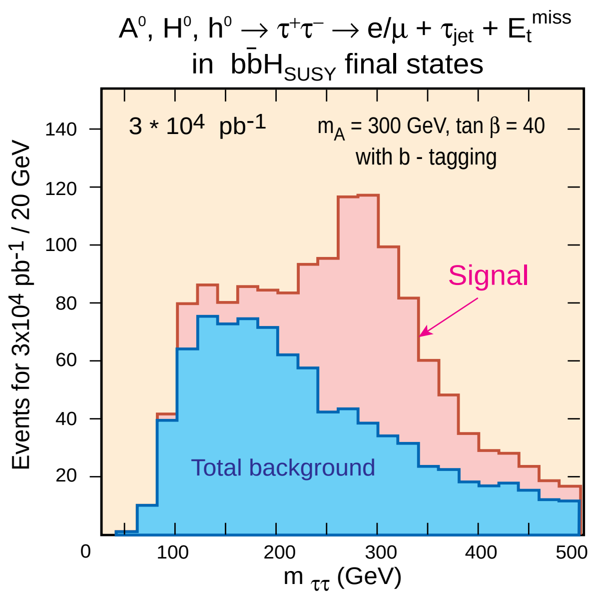
SUSY Higgs bosons



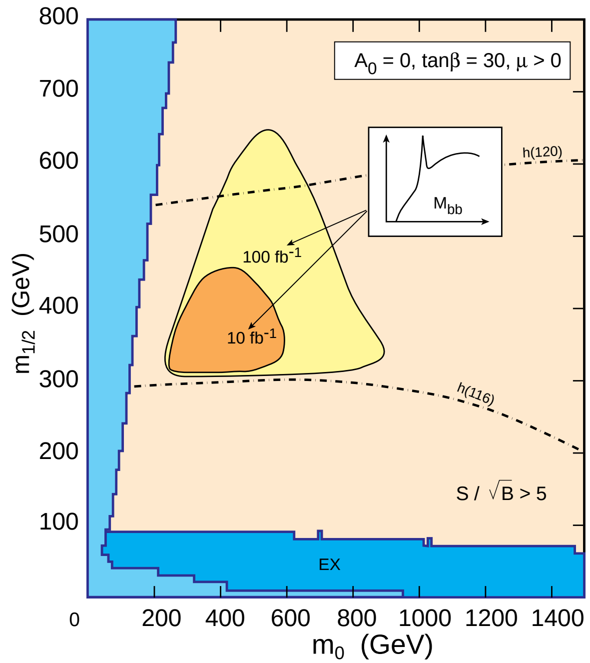
In the MSSM there are 5 Higgs bosons: h^0, H^0, A^0 and $H^\pm$ decaying through a variety of decay modes to γ, $e^\pm$, $\mu^\pm$, $\tau^\pm$ and jets in final states. Below left: an example of a SUSY Higgs decay to $\tau\,\tau$ in CMS. On the right is the reconstructed $\tau\tau$ mass spectrum



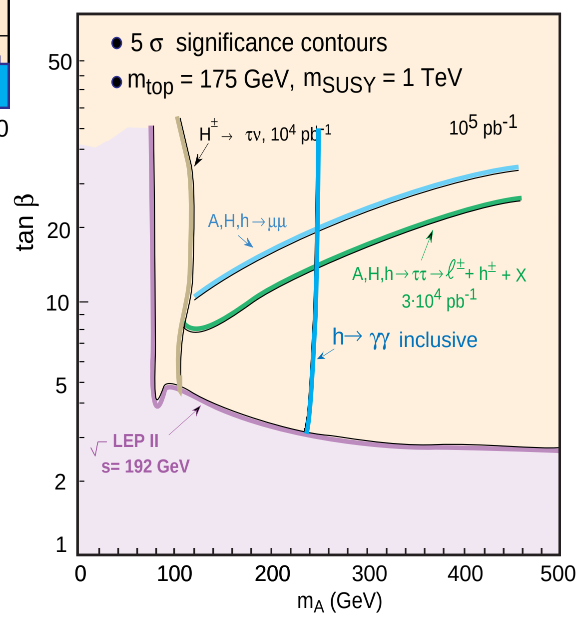
$H \to \tau\tau \to e + \tau_{jet}$("3-prong")



SUSY Higgs: discovery ranges

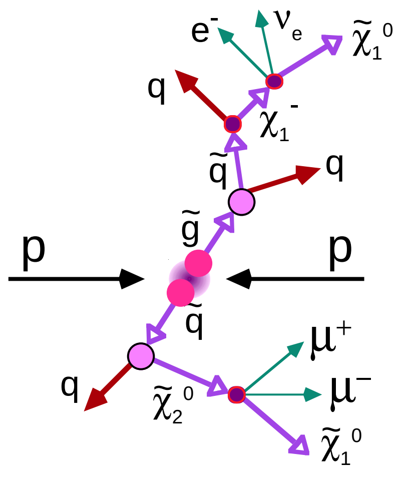


Example of the domain of parameter space of mSUGRA-MSSM where the h^0 can be discovered via its decay in $b\bar{b}$

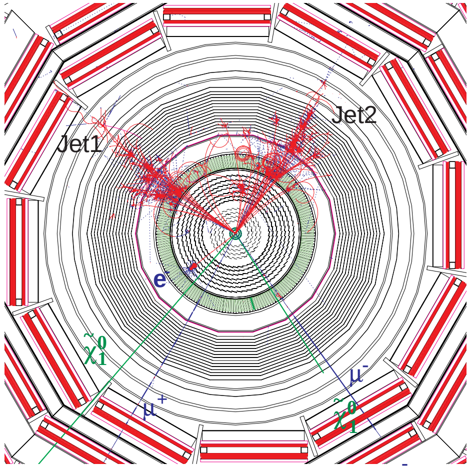


The search for the various MSSM Higgs bosons in different decay modes allows the exploration of most of the parameter region ($\tan\beta, m_A$)

Sparticles

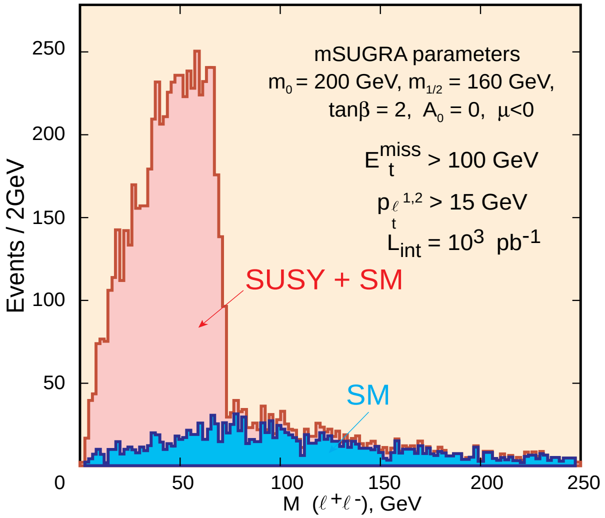


Production of sparticles may reveal itself though some spectacular kinematical spectra, with a pronounced "edge" in the $\ell^+\ell^-$ mass spectrum reflecting $\chi_2^0 \rightarrow \ell^+\ell^-\chi_1^0$ production and decay.
An example of such a spectrum in inclusive $\ell^+\ell^- + E_t^{miss}$ and of a 3 $\ell^\pm$ production event are shown below



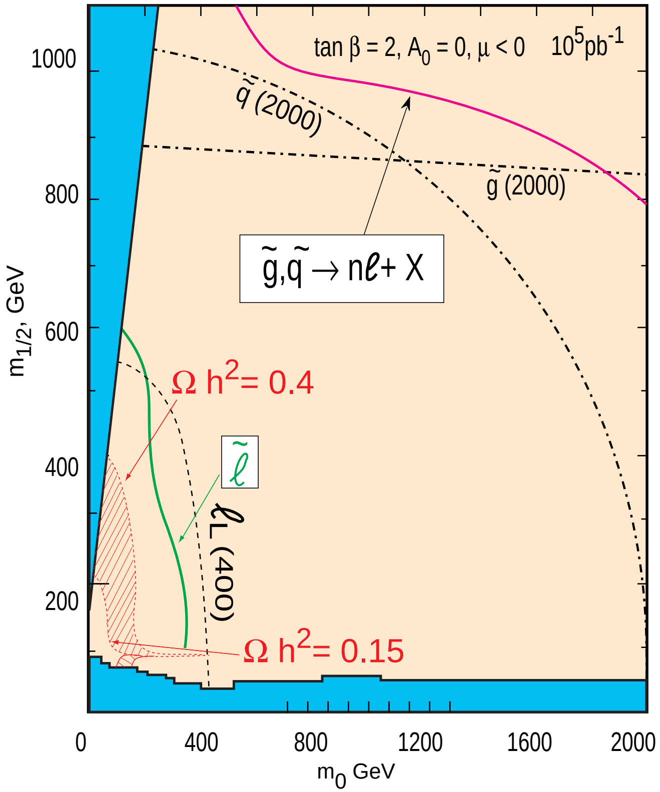
SUSY event with
3 leptons + 2 Jets signature

Inclusive $\ell^+\ell^-$ + E_t^{miss} final states



Sparticles: discovery ranges

Domains of mSUGRA parameter space (m_0,$m_{1/2}$) where various sparticles can be identified



Gluinos and squarks can be searched for in various channels with leptons + E_t^{miss} + jets and discovered for masses up to ~ 2.2 TeV. Sleptons can be discovered for masses up to ~ 350 GeV. The region of parameter space 0.15 < Ω h² < 0.4 — where LSP would be the Cold Dark Matter particle — is contained well within the explorable region

Sparticles cannot escape discovery at the LHC

Same particle content as the MSSM

- The superpotential W is

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

where $i,j=1,2,3$ are generation indices, $a,b=1,2$ are $SU(2)$ indices.

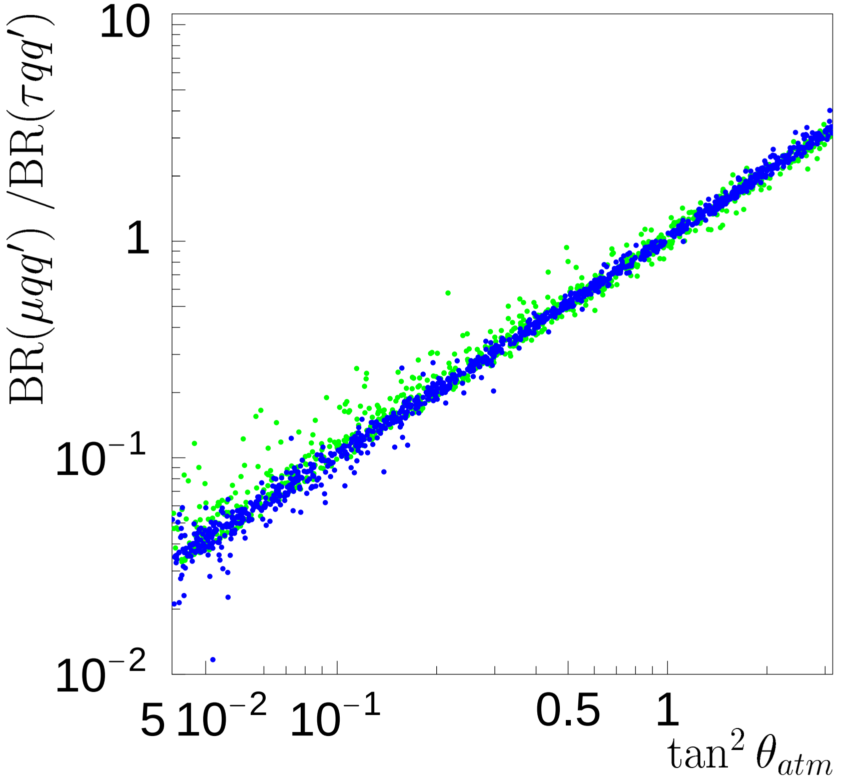
- The set of soft supersymmetry breaking terms are

$$V_{soft} = V_{soft}^{\text{MSSM}} + \varepsilon_{ab}\ B_i\epsilon_i\widetilde{L}_i^a H_u^b$$

M.A. Diaz, JCR, J.W.F. Valle, Nucl.Phys.B524:23-40,1998

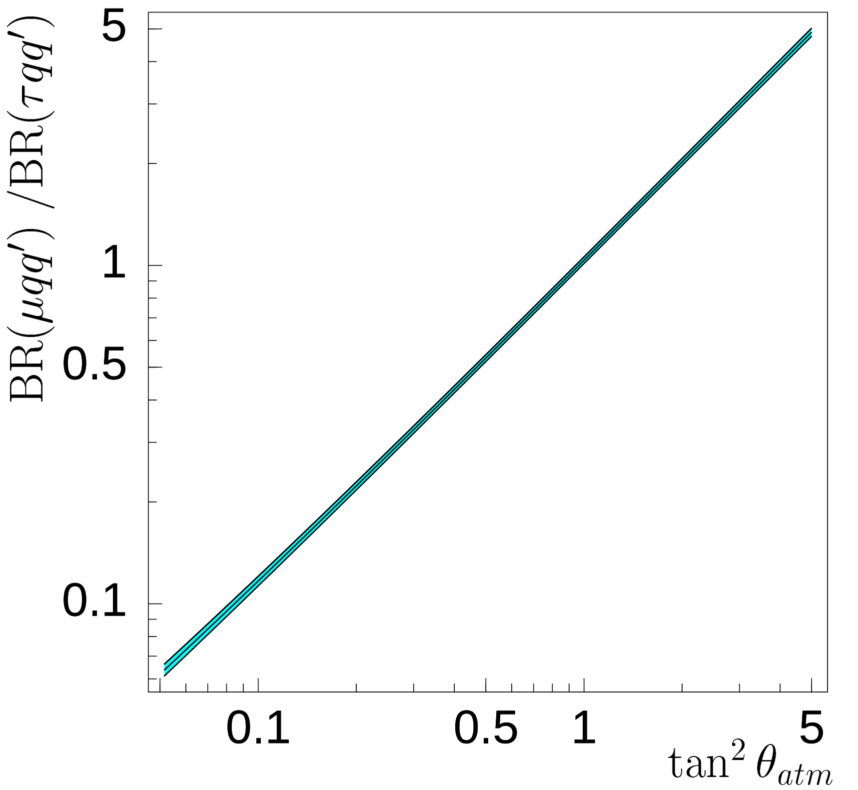
Probing the Atmospheric Angle

Before SUSY



W. Porod, M. Hirsch, JCR, J.W.F. Valle
Phys.Rev.D63:115004,2001

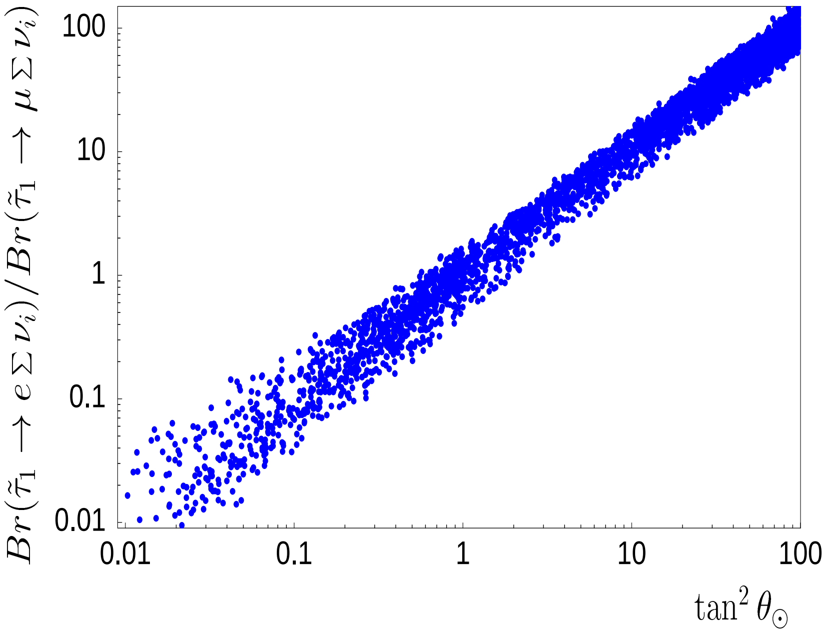
After SUSY



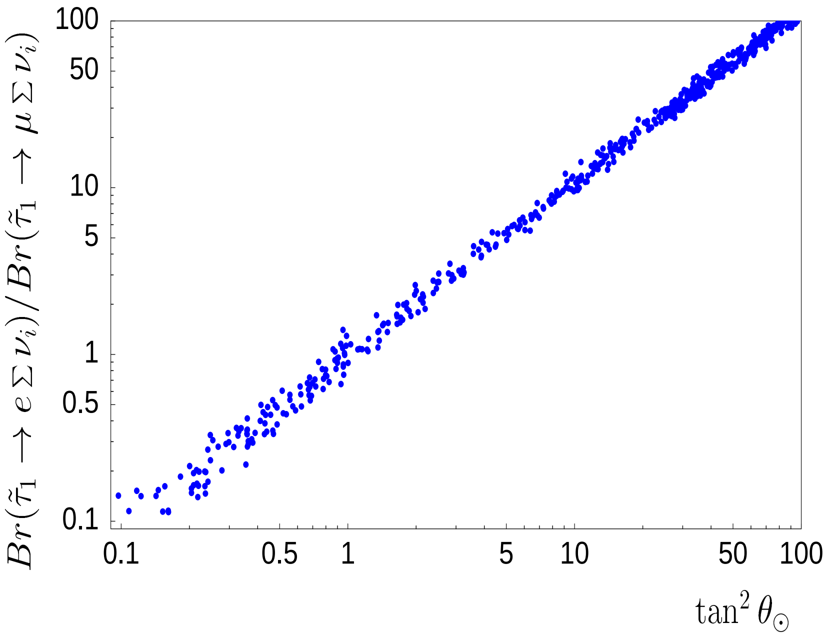
$M_2 = 120$ GeV, $\mu = 500$ GeV, $\tan\beta = 5$
$m_0 = 500$ GeV, $A = -500$ GeV.

Stau Decays and the Solar Angle

All points



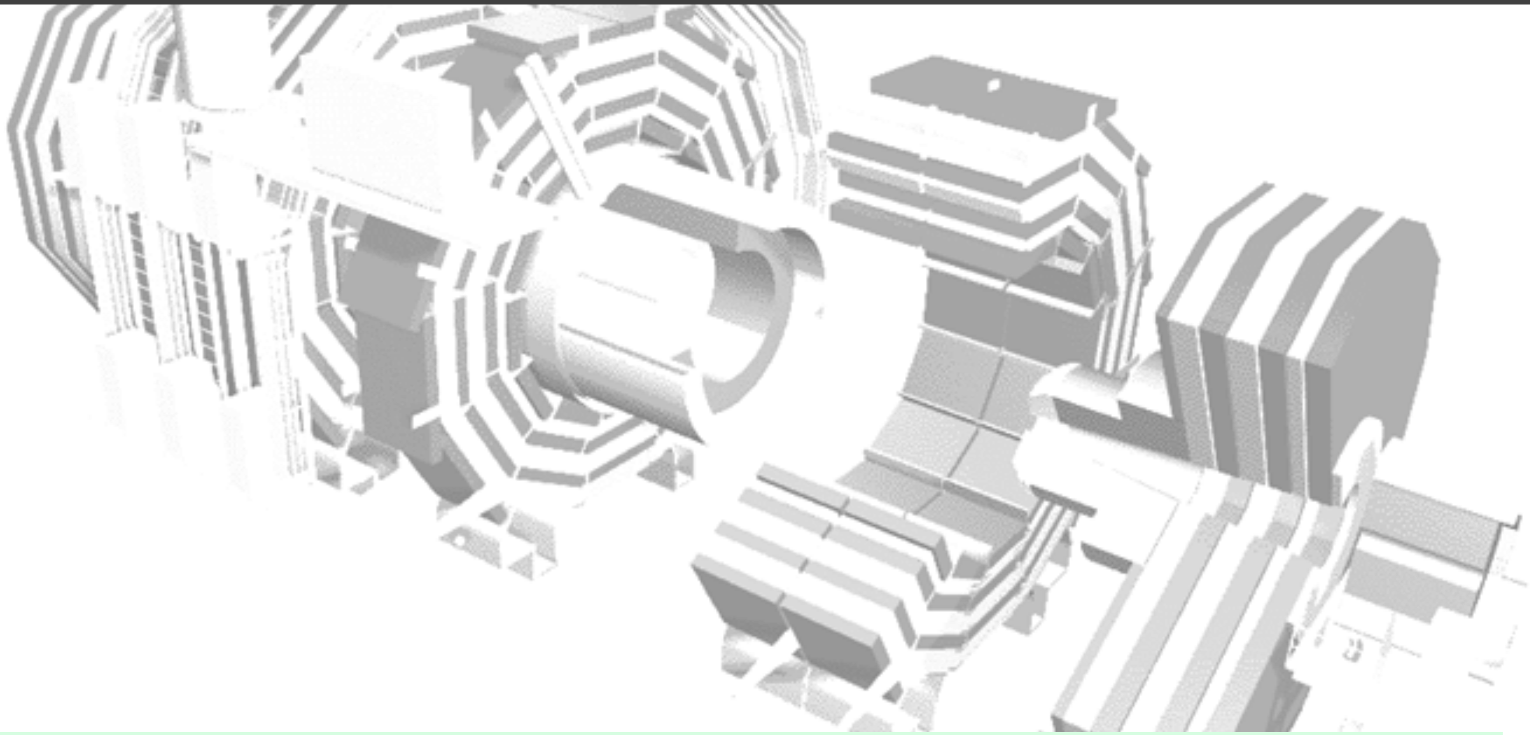
$0.9 < \epsilon_2/\epsilon_3 < 1.1$



M. Hirsch, W. Porod, JCR, J.W.F. Valle, Phys.Rev.D66:095006,2002

Conclusions

Although there is not yet direct experimental evidence for supersymmetry (SUSY), there are many theoretical arguments indicating that SUSY might be of relevance for physics below the 1 TeV scale.



We will be waiting for the LHC verdict!

Lots of things to be done by Experimentalists and Theoreticians