Collider Physics for String Theorists: #2

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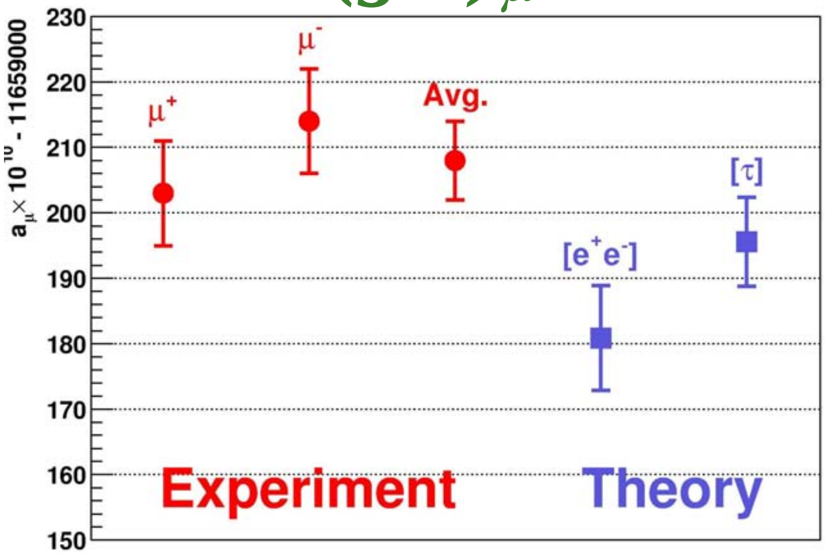
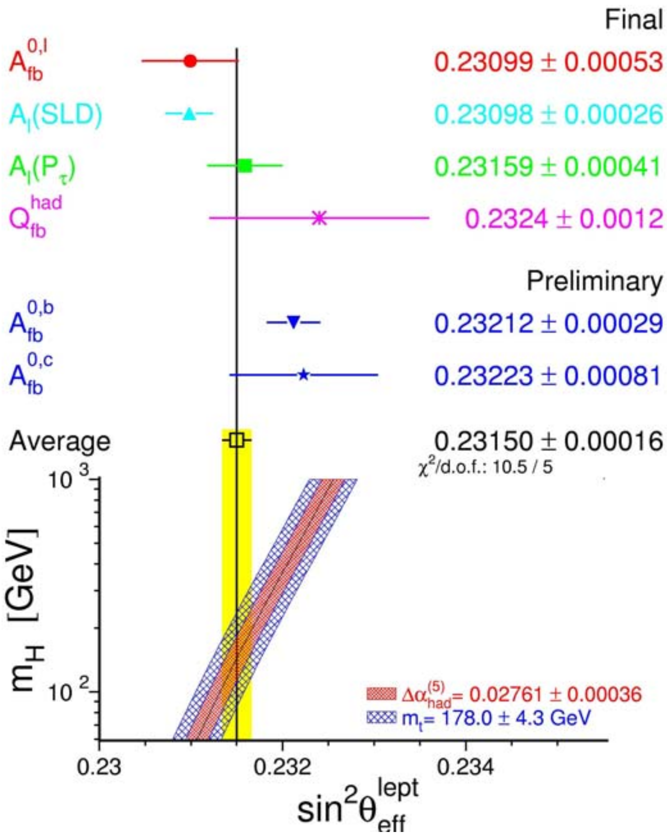
Basics of the MSSM

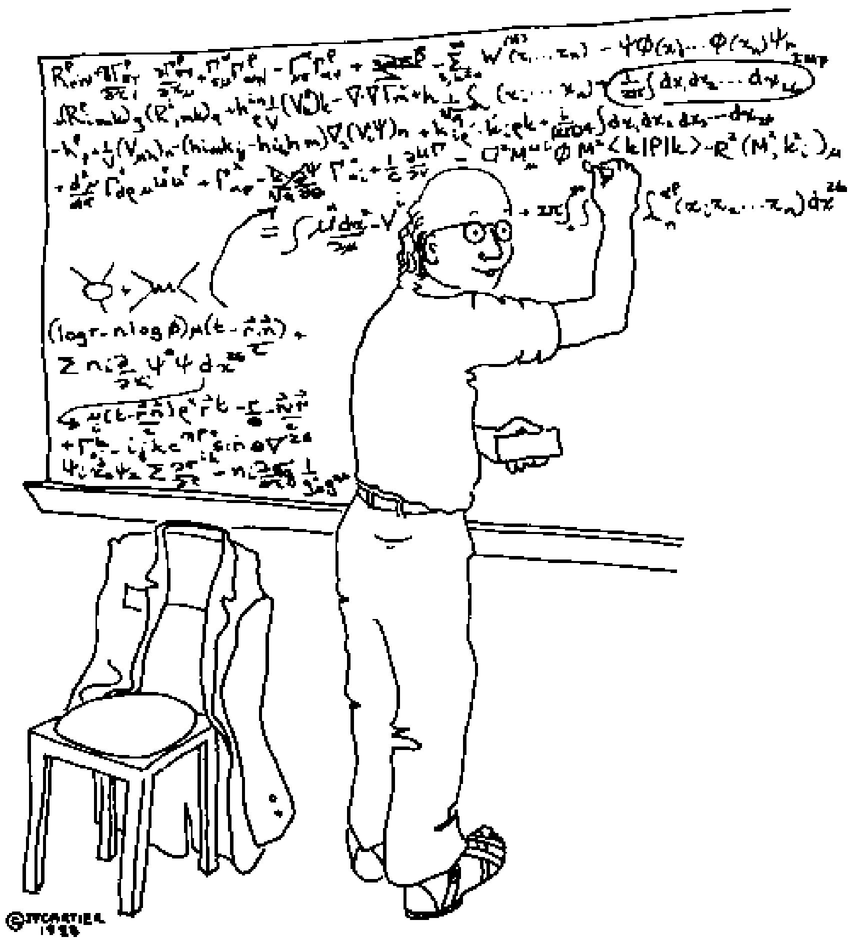
The SM isn't perfect

(g-2)$_\mu$



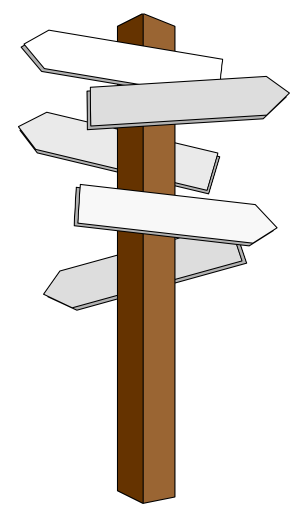


How do we know where to go?



"At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions."

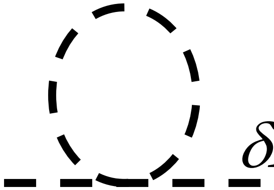
Precision measurements versus direct observation of new particles



Much easier if we see new particles

Standard Model isn't Completely Satisfactory

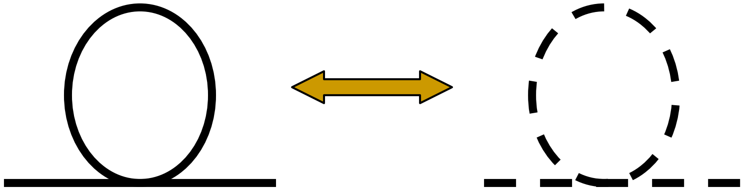
Quantum corrections drag weak scale to Planck scale



$$\delta M_H^2 \approx M_{Pl}^2$$

Quantum Corrections and Supersymmetry

$$\delta M_H^2 \approx -M_{Pl}^2$$



$$\delta M_H^2 \approx M_{Pl}^2$$

Quantum corrections cancel order by order in perturbation theory

What about fermion masses?

- Fermion mass term:

$$L = m\overline{\Psi}\Psi = m\left(\overline{\Psi}_L \Psi_R + \overline{\Psi}_R \Psi_L\right)$$ ←

Forbidden by SU(2)xU(1) gauge invariance

- Left-handed fermions are SU(2) doublets

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

- Scalar couplings to fermions:

$$L_d = -\lambda_d \overline{Q}_L \Phi d_R + h.c.$$

- Effective Higgs-fermion coupling

$$L_d = -\lambda_d \frac{1}{\sqrt{2}} (\overline{u}_L, \overline{d}_L) \begin{pmatrix} 0 \\ v+h \end{pmatrix} d_R + h.c.$$

- Mass term for down quark:

$$\boxed{\lambda_d = -\frac{M_d \sqrt{2}}{v}}$$

Fermion Masses, 2

- M_u from $\Phi_c = i\sigma_2\Phi^*$ (not allowed in SUSY): $L = -\lambda_u \overline{Q}_L \Phi_c u_R + hc$

$$\Phi_c = \begin{pmatrix} \overline{\phi}^0 \\ -\phi^- \end{pmatrix}$$

$$\boxed{\lambda_u = -\frac{M_u\sqrt{2}}{v}}$$

- Supersymmetric models always have at least two Higgs doublets
  - General 2 Higgs doublet potential has 6 couplings + phase
  - 5 physical Higgs particles: h, H, A, $H^\pm$
  - VEVS described by $\tan\beta = v_2/v_1$
  - M_W gives $v_{SM}^2 = v_1^2 + v_2^2$
  - Supersymmetry restricts form of scalar potential: 2 parameters (Usually taken to be $\tan\beta$ and M_A)

Particle Content

- Supersymmetric theories constructed from supermultiplets
- Chiral superfield, Φ_i, has:
  - Complex scalar field, ϕ_i
  - 2-component Weyl fermion field, ψ_i
  - Auxiliary Field, F_i (no kinetic energy term)
- Interactions described in terms of chiral superfields

$$\Phi_i(x) \equiv \phi_i(x) + \sqrt{2}\theta\psi_i(x) + \theta\theta F_i(x)$$

[Taylor series stops at θ^2 since
θ is anti-commuting Grassman variable, $\theta^3 = \frac{\theta}{2}\{\theta, \theta\}$]

- Components of Φ have identical quantum numbers (except spin) and masses
- Construct model with supermultiplets corresponding to known particles
- More than doubles spectrum

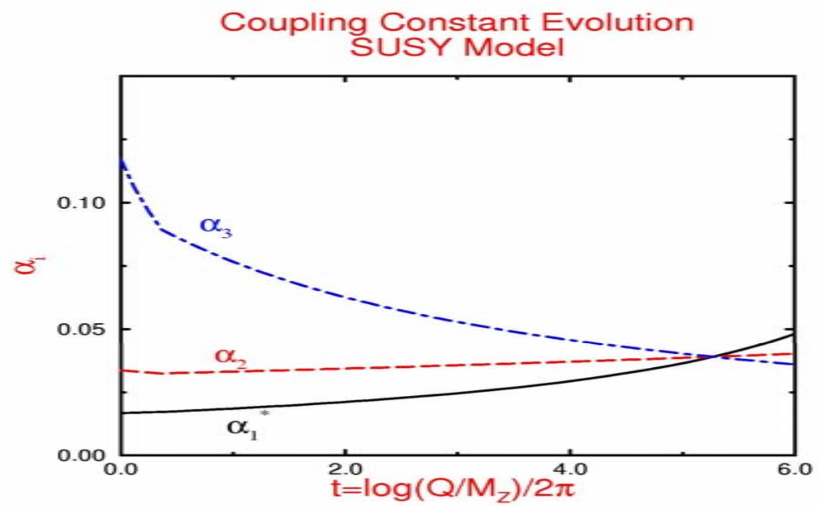
Chiral Superfields

Superfield	SU(3)	$SU(2)_L$	$U(1)_Y$	Particle Content
$\hat{Q}$	3	2	$\frac{1}{6}$	(u_L, d_L), $(\tilde{u}_L, \tilde{d}_L)$
$\hat{U}^c$	$\overline{3}$	1	$-\frac{2}{3}$	$\overline{u}_R$, $\tilde{u}_R^*$
$\hat{D}^c$	$\overline{3}$	1	$\frac{1}{3}$	$\overline{d}_R$, $\tilde{d}_R^*$
$\hat{L}$	1	2	$-\frac{1}{2}$	(ν_L, e_L), $(\tilde{\nu}_L, \tilde{e}_L)$
$\hat{E}^c$	1	1	1	$\overline{e}_R$, $\tilde{e}_R^*$
$\hat{H}_1$	1	2	$-\frac{1}{2}$	$(H_1, \tilde{h}_1)$
$\hat{H}_2$	1	2	$\frac{1}{2}$	$(H_2, \tilde{h}_2)$

Unification

- Gauge couplings evolve differently in SUSY models
- Running is slower than SM

$$b_1 = 2N_g + \frac{3N_h}{10}$$
$$b_2 = -6 + 2N_g + \frac{N_h}{2}$$
$$b_3 = -9 + 2N_g$$



The Cynic

- Assume supersymmetric at some scale, Λ_{SUSY} (say 1 TeV)
- Input 2 couplings, say g_1, g_2, at M_Z
- Evolve couplings until they meet at scale M_{GUT}
- Assume unification at M_{GUT}, $g_i(M_{GUT}) = g_{GUT}$
- Evolve $3rd$ coupling, say g_3, down to M_Z
- If $g_3(M_Z)$ disagrees with measured number, change Λ_{SUSY}
- Keep going until it works!

Amazing fact: consistency occurs for
$\Lambda_{SUSY} \sim 1\ TeV$

(Actually, $\alpha_s(M_z)$ typically a little large)

Scalar Interactions

Define superpotential:

$$W = \frac{1}{2} M^{ij} \phi_i \phi_j + \frac{g^{ijk}}{6} \phi_i \phi_j \phi_k$$

- Most general $SU(3) \times SU(2)_L \times U(1)_Y$ invariant superpotential:

(Hats denote scalar component of supermultiplet)

$$W = -\epsilon_{ij} \mu \hat{H}_1^i \hat{H}_2^j + \epsilon_{ij} \left[\lambda_L \hat{H}_1^i \hat{L}^{cj} \hat{E}^c + \lambda_D \hat{H}_1^i \hat{Q}^j \hat{D}^c + \lambda_U \hat{H}_2^j \hat{Q}^i \hat{U}^c \right]$$
$$+ \epsilon_{ij} \left[\lambda_1 \hat{L}^i \hat{L}^j \hat{E}^c + \lambda_2 \hat{L}^i \hat{Q}^j \hat{D}^c \right] + \lambda_3 \hat{U}^c \hat{D}^c \hat{D}^c$$

i, j $SU(2)$ indices

- Superpotential has Yukawa interactions of fermions with scalars and quartic interactions of potential:

$$\mathcal{L}_W = -\sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2 - \frac{1}{2} \sum_{ij} \left[\frac{\partial^2 W}{\partial \phi_i \partial \phi_j} \psi_i \psi_j + \text{c.c.} \right]$$

Aside on R Parity

Allowed terms in superpotential:

$$W_{RP} = \lambda_1^{ijk} \hat{L}^i \hat{L}^j \hat{E}^c + \lambda_2^{ijk} \hat{L}^i \hat{Q}^j \hat{D}^c + \lambda_3^{ijk} \hat{U}^c \hat{D}^c \hat{D}^c$$

- W_{RP} gives lepton/baryon number violating interactions

$$\mathcal{L} \sim \lambda_2 u_L e_L \tilde{d}_R^* + \lambda_3 \overline{u}_R \overline{d}_R \tilde{d}_R^*$$

- Could just make coefficients small
- Limits on proton decay require:

$$| \lambda_2^{11i} \lambda_3^{11i} | < 10^{-27} \left(\frac{M_{\tilde{d}_i}}{100 \ GeV} \right)^2$$

Impose *symmetry* which forbids W_{RP}

- R parity is multiplicative quantum number: Discrete Z_2 symmetry
- Imposed by hand

$$R \equiv (-1)^{3(B-L)+2s}$$

Consequences of R Parity

- SM particles have $R = 1$, SUSY partners have $R = -1$
- $\theta \to -\theta$ does same thing

$$\Phi_i(x) \equiv \phi_i(x) + \sqrt{2}\theta\psi_i(x) + \theta\theta F_i(x)$$

- SM dimension- 4 baryon/lepton number violating interactions forbidden by the gauge symmetries

Consequences of R parity:

- SUSY partners are pair produced
- Lightest SUSY particle (LSP) is stable

Add Gauge Fields

Add:

- Massless gauge boson, A_μ^a
- 2-component Weyl fermion gaugino, λ^a (adjoint representation of group)
- Auxilliary Field, D^a (adjoint representation of group; $[mass]^2$)

Gauge invariant interactions are:

$$\mathcal{L}_{gauge} = -\frac{1}{4}F_{\mu\nu}^a F^{\mu\nu a} - i\lambda^{\dagger a}\overline{\sigma}^\mu D_\mu \lambda^a + \frac{1}{2}D^a D^a$$

As usual:

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g f^{abc} A_\mu^b A_\nu^c$$
$$D_\mu \lambda^a = \partial_\mu \lambda^a - g f^{abc} A_\mu^b \lambda^c$$

Gauge Multiplets of MSSM

Superfield	SU(3)	$SU(2)_L$	$U(1)_Y$	Particle Content
$\hat{G}^a$	8	1	0	$g, \tilde{g}$
$\hat{W}^i$	1	3	0	$W_i, \tilde{\omega}_i$
$\hat{B}$	1	1	0	$B, \tilde{b}$

Construct Gauge-Scalar Interactions

$$\begin{aligned}\mathcal{L} =& \mathcal{L}_{gauge} + \mathcal{L}_{chiral} \\ & - \sqrt{2}g\left[\left(\phi^* T^a \psi\right)\lambda^a + \lambda^{\dagger a}\left(\psi^\dagger T^a \phi\right)\right] \\ & + g\left(\phi^* T^a \phi\right) D^a\end{aligned}$$

What about terms involving D^a?

$$\mathcal{L} \sim \frac{1}{2} D^a D^a + g\left(\phi^* T^a \phi\right) D^a$$

Use equation of motion:

$$D^a = -g\left(\phi^* T^a \phi\right)$$

Complete scalar potential:

$$V\left(\phi, \phi^*\right) = F^{*i} F_i + \frac{1}{2} D^a D^a = W_i^* W^i + \frac{1}{2}\Sigma_a g_a^2 \left(\phi^* T^a \phi\right)^2$$

Construct Scalar Potential

$$W \sim -\epsilon_{ij}\mu \hat{H}_1^i \hat{H}_2^j + \ldots$$

"F-Term":

$$V_F = \sum_i \mid \frac{\partial W}{\partial \phi_i} \mid^2$$
$$= \mid \mu \mid^2 \left(\mid H_1 \mid^2 + \mid H_2 \mid^2 \right)$$

"D Terms"

$$V_D = \frac{1}{2} D^a D^a$$
$$D^a = - g_a \phi_i^* T^a \phi_i$$

H_1 has $Y = -\frac{1}{2}$
H_2 has $Y = +\frac{1}{2}$

$$U(1): \quad D' = \frac{g}{2} \left(\mid H_2 \mid^2 - \mid H_1 \mid^2 \right)$$
$$SU(2): \quad D^a = \frac{g}{2} \left(H_1^{i*} \sigma_{ij}^a H_1^j + H_2^{i*} \sigma_{ij}^a H_2^j \right)$$

(Normalization $T^a = \frac{\sigma^a}{2}$)

$SU(2)$ identity: $\sigma_{ij}^a \sigma_{kl}^a = 2\delta_{il}\delta_{jk} - \delta_{ij}\delta_{kl}$

$$V_D = \frac{g^2}{8} \left(4 \mid H_1^* \cdot H_2 \mid^2 - 2 \left(H_1^* \cdot H_1 \right) \left(H_2^* \cdot H_2 \right) + \left(\mid H_1 \mid^2 \right)^2 + \left(\mid H_2 \mid^2 \right) \right.$$
$$\left. + \frac{g'^2}{8} \left(\mid H_2 \mid^2 - \mid H_1 \mid^2 \right)^2 \right.$$

Scalar Potential, #2

$$V = |\mu|^2 \left(|H_1|^2 + |H_2|^2\right) + \frac{g^2 + g'^2}{8} \left(|H_2|^2 - |H_1|^2\right)^2 + \frac{g^2}{2} |H_1^* \cdot H_2|^2$$

Minimum at $\langle V \rangle = \langle H_1 \rangle = \langle H_2 \rangle = 0$

No EWSB, No SUSY breaking....

SUSY Breaking

- Spontaneous SUSY doesn't work

Scalar potential:

$$V(\phi, \phi^*) = F^{*i} F_i + \frac{1}{2} D^a D^a = W_i^* W^i + \frac{1}{2} \Sigma_a g_a^2 (\phi^* T^a \phi)^2$$

[W is superpotential, $W^i = \frac{\partial W}{\partial \phi_i} = M^{ij}\phi_j + \frac{g^{ijk}}{2}\phi_j \phi_k$]

SUSY spontaneously broken if either:

$\langle 0 \mid F_i \mid 0 \rangle \neq 0$ O'Raifeartaigh

$\langle 0 \mid D^a \mid 0 \rangle \neq 0$ Fayet-Iliopoulos

- Generates bad mass relations

Spontaneously Broken SUSY = BAD

Define supertrace:

$$STr\left(M^2\right) \equiv \sum (-1)^{2s}(2s+1)\,Tr\left(M^2\right)$$
$$= 3Tr\left(M_V^2\right) + Tr\left(M_\phi^2\right) - 2Tr M_F^2$$
$$= 0$$

- Holds for arbitrary values of scalar fields
- Holds separately for gauge and matter sector

$$\tilde{m}^2_{e_L} + \tilde{m}^2_{e_R} = 2m_e^2$$

Softly Broken SUSY

Consider low scale SUSY ($\sim 1\ TeV$) as effective theory

- Break SUSY "softly" (terms of dimension ≤ 3)
- Add all possible terms which introduce $\log(\Lambda)$ divergences, but not Λ^2

Allowed terms:

- Scalar Masses ($\phi^* \phi, \phi\phi$)
- Gaugino masses ($\lambda^a \lambda^a$)
- Cubic scalar couplings ($\phi_i \phi_j \phi_k$)

Theorem: Introduction of soft terms doesn't reintroduce Λ^2 divergences to all orders of PT in SUSY

Parameters of the MSSM

- 5 3×3 Hermitian mass matrices for squarks and sleptons:

$$M^2_{\tilde{Q}} \tilde{Q}^* \tilde{Q} + M^2_{\tilde{u}} \tilde{u}^*_R \tilde{u}_R + M^2_{\tilde{d}} \tilde{d}^*_R \tilde{d}_R + M^2_{\tilde{L}} \tilde{L}^* \tilde{L} + M^2_{\tilde{e}} \tilde{e}^*_R \tilde{e}_R$$

(45 new parameters)

- 2 (complex) Higgs scalar masses

$$m_1^2 H_1^2 + m_2^2 H_2^2$$

(4 new parameters)

- 3 gaugino masses (complex)

$$\Sigma_{a=1,2,3} M^a_{1/2} \lambda^a \lambda^a$$

(6 new parameters)

- 1 complex Higgs mixing parameter

$$m_{12}^2 H_1 H_2$$

(2 new parameters)

- 27 trilinear couplings for scalar fields (complex)

$$H_2 \tilde{Q} A_u \tilde{u}_R + H_1 \tilde{Q} A_d \tilde{d}_R + H_1 \tilde{L} A_l \tilde{e}_R$$

(54 new parameters)

111 new parameters

SM has 17 parameters $\longrightarrow$ 128 parameters

Soft SUSY Breaking Terms Allow SSB

$$V = \left(m_1^2 + |\mu|^2\right) |H_1|^2 + \left(m_2^2 + |\mu|^2\right) |H_2|^2 - m_{12}^2 \left(\epsilon_{ij} H_1^i H_2^j + h.c.\right) + \frac{g^2 + g'^2}{8} \left(|H_2|^2 - |H_1|^2\right)^2 + \frac{g^2}{2} |H_1^* \cdot H_2|^2$$

$$H_1 = \begin{pmatrix} \phi_1^{0*} \\ -\phi_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

$$\langle H_1^1 \rangle = v_1 \qquad \langle H_2^2 \rangle = v_2$$

Potential has 3 parameters. Trade 1 for $\tan\beta = \frac{v_2}{v_1}$

Conditions for EWSB:

$\longrightarrow$ if $m_{12}^2 = 0$ potential positive definite

"D-flat" direction: $|H_1^0| = |H_2^0|$
$\longrightarrow$ quartic contributions vanish

Quadratic term in this direction must be positive:

$$m_1^2 + m_2^2 + 2|\mu|^2 > 2m_{12}^2$$

Broken $SU(2) \times U(1)$:

$$\left(m_1^2 + |\mu^2|\right)\left(m_2^2 + |\mu|^2\right) < |m_{12}|^2$$

Constrained Potential in MSSM

- Tree level scalar potential has 2 free parameters

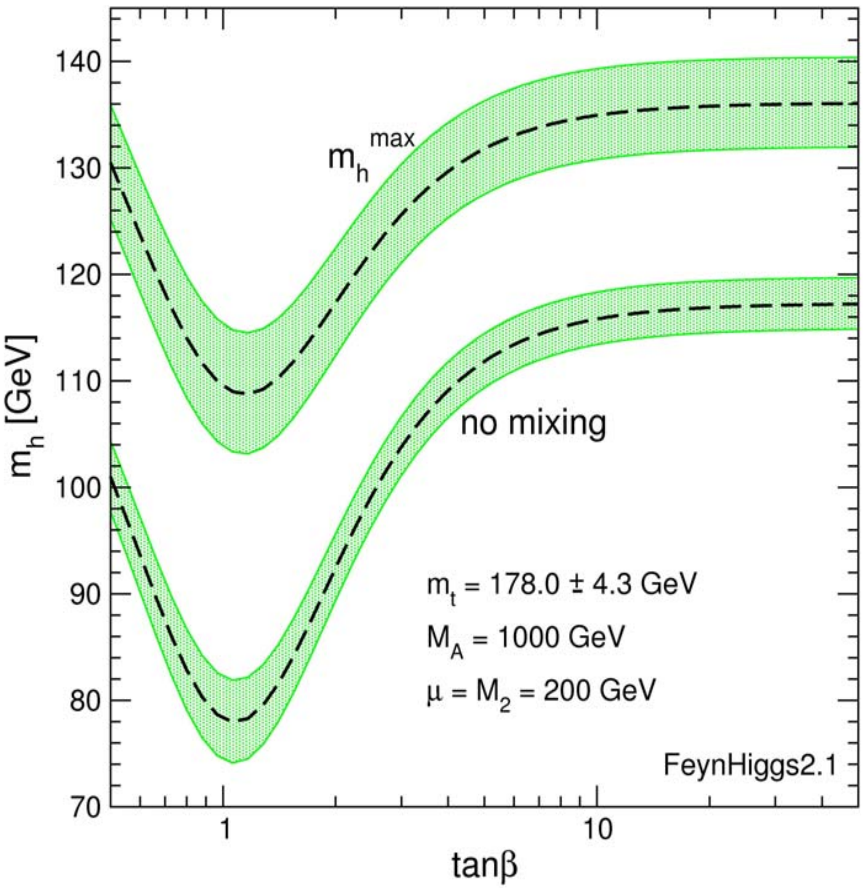
$$V = m_1^2 H_1 H_1^+ + m_2^2 H_2 H_2^+ - m_{12}^2(\varepsilon_{ab} H_1^a H_2^b + h.c.) + \left(\frac{g'^2 + g^2}{8}\right)\left(H_1 H_1^+ - H_2 H_2^+\right)^2 + \frac{g^2}{2}\left|H_1 H_2^+\right|^2$$

Gauge Couplings

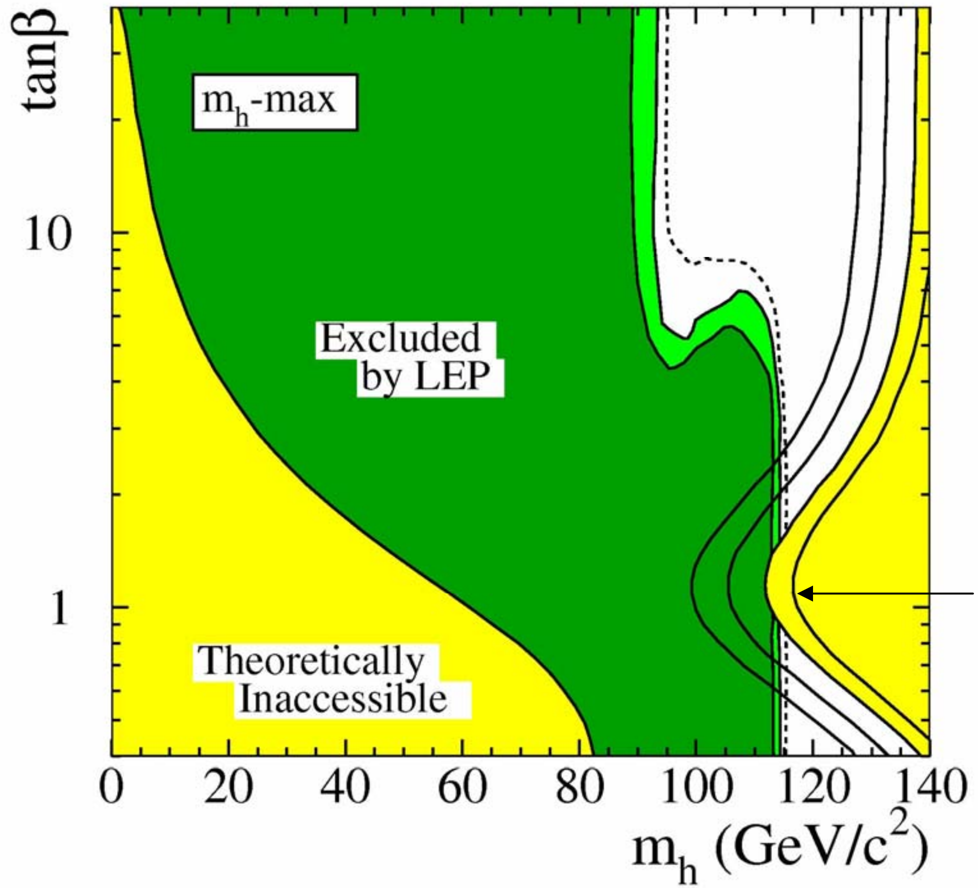
- Typically pick M_A, tan β as parameters
- Predict M_h, M_H, $M_{H\pm}$, all couplings (at tree level)
- At tree level, $M_h < M_Z$
- Large corrections $O(G_F m_t^2)$ to predictions
  - Predominantly from stop squark loop

$$M_h^2 \leq M_Z^2 \cos^2 2\beta + \frac{3 G_F m_t^4}{\sqrt{2}\pi^2 \sin^2\beta} \ln\left[\frac{\tilde{m}_t^2}{m_t^2}\right] + \ldots$$

Theoretical Upper bound on M_h



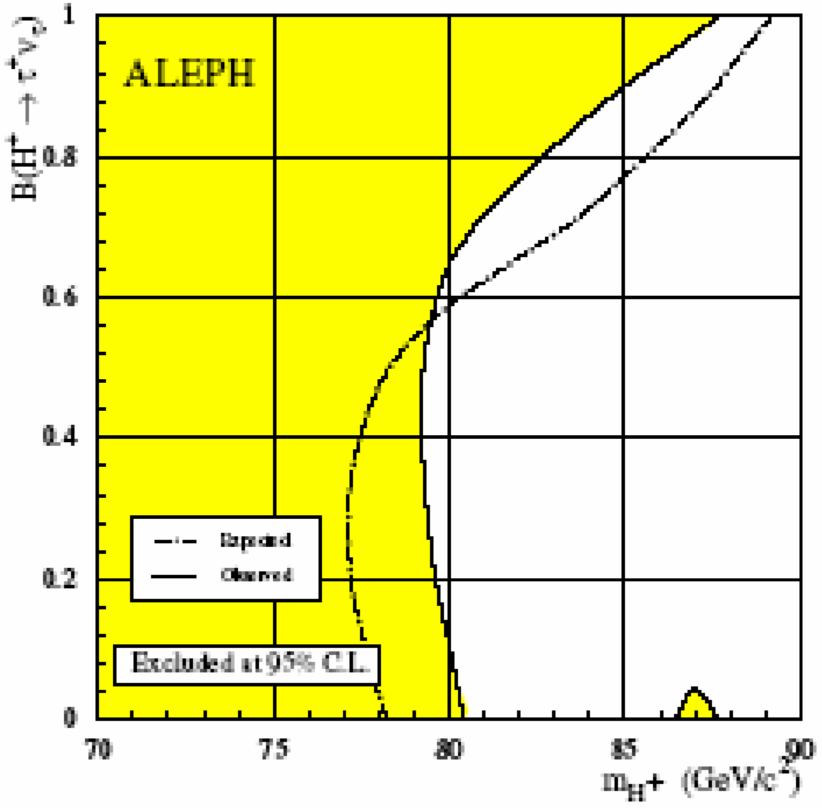
Limits on SUSY Higgs from LEP



M_t=169.3,174.3, 179.3, 183 GeV

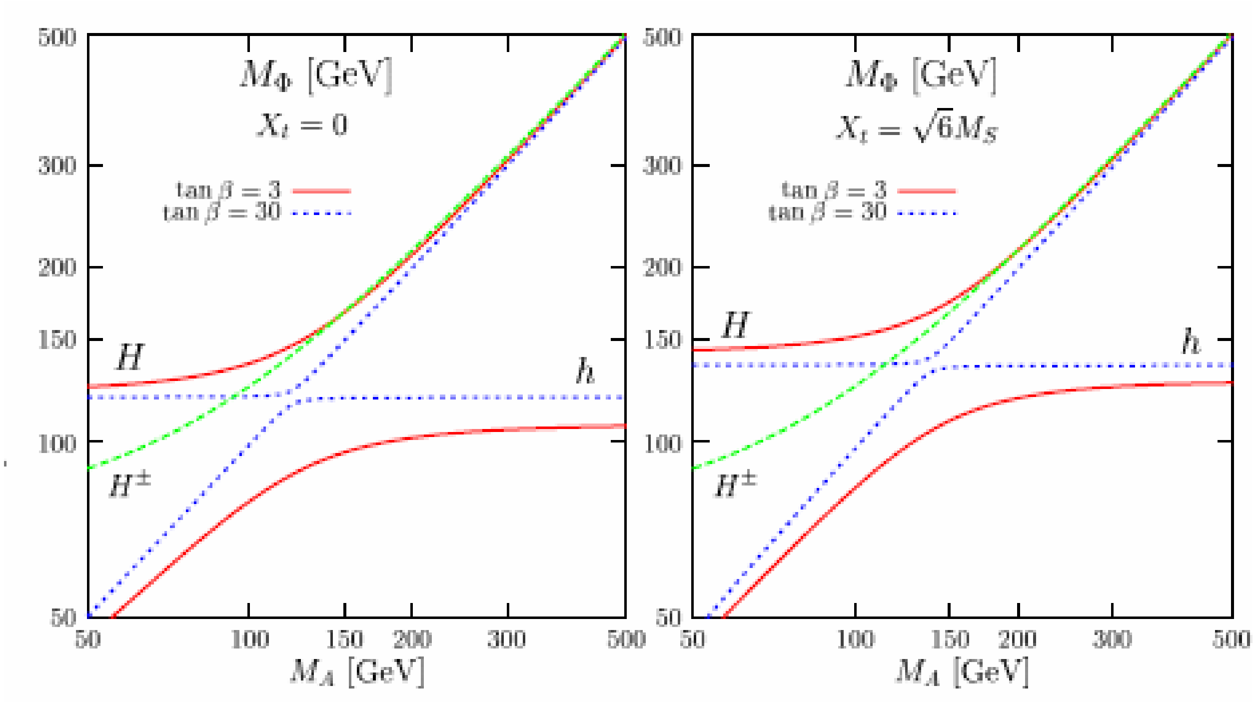
Bound on Charged Higgs

- Fairly model independent



Higgs Masses in MSSM

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$



Find Higgs Couplings

Find Higgs couplings:

$$\mathcal{L}_W = \frac{\partial^2 W}{\partial\phi_i \partial\phi_j}\psi_i\psi_j + \text{c.c.}$$

$$W \sim \epsilon_{ij}\left[\lambda_L \hat{H}_1^i \hat{L}^{cj} \hat{E}^c + \lambda_D \hat{H}_1^i \hat{Q}^j \hat{D}^c + \lambda_U \hat{H}_2^j \hat{Q}^i \hat{U}^c\right]$$

Yukawa interactions give mass matrices:

$$m_d = \lambda_D v_1 \qquad \lambda_D = \frac{g m_d}{\sqrt{2}\sin\beta M_W}$$

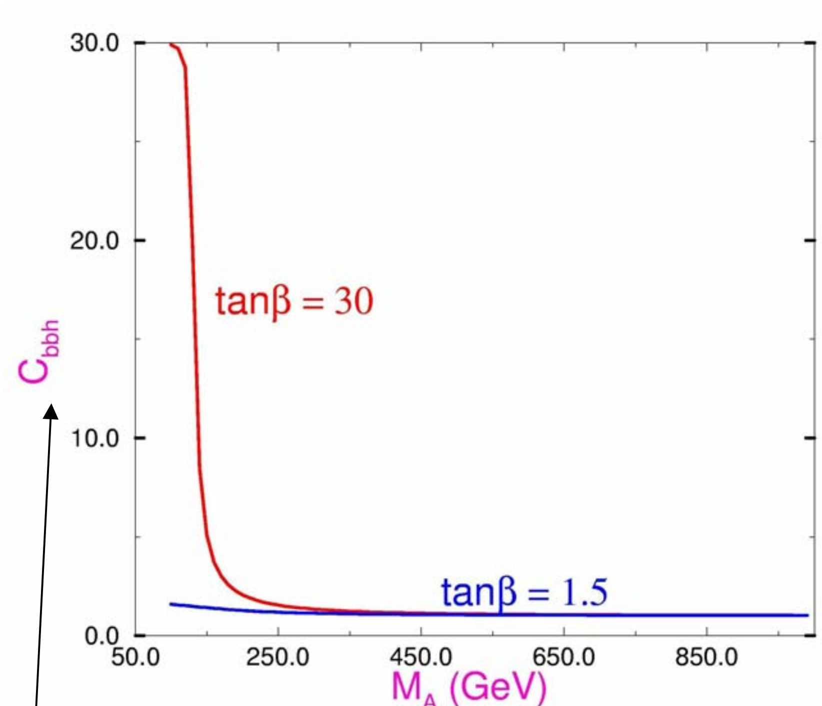
$$m_u = \lambda_U v_2 \qquad \lambda_U = \frac{g m_u}{\sqrt{2}\cos\beta M_W}$$

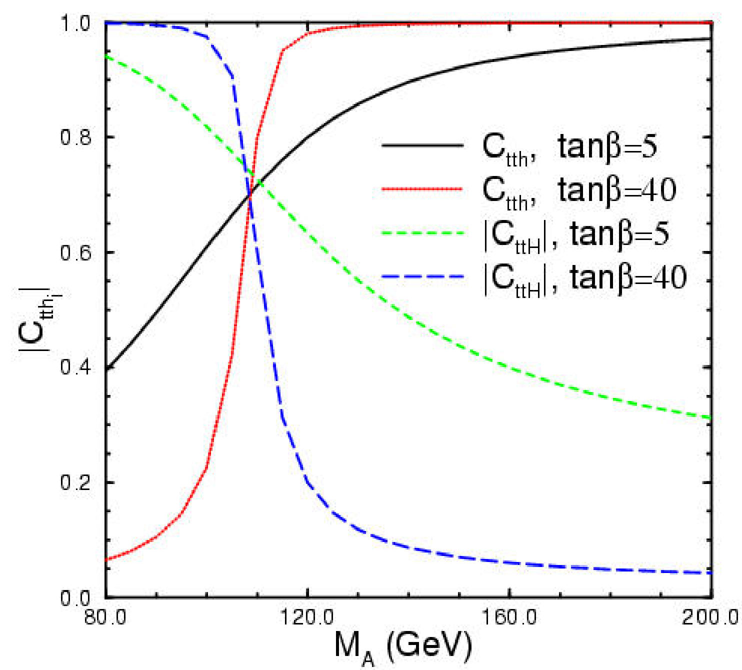
MSSM Couplings

Φ	$g_{\Phi uu}$	$g_{\Phi dd}$	$g_{\Phi VV}$	$g_{\Phi ZA}$
h	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\sin(\beta-\alpha)$	$\frac{1}{2}\cos(\beta-\alpha)$
H	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\cos(\beta-\alpha)$	$\frac{1}{2}\sin(\beta-\alpha)$
A	$i\gamma_5\cot\beta$	$-i\gamma_5\cot\beta$	0	0

- Couplings given in terms of α, β
- Can be very different from SM

Higgs Couplings very different from SM in SUSY Models

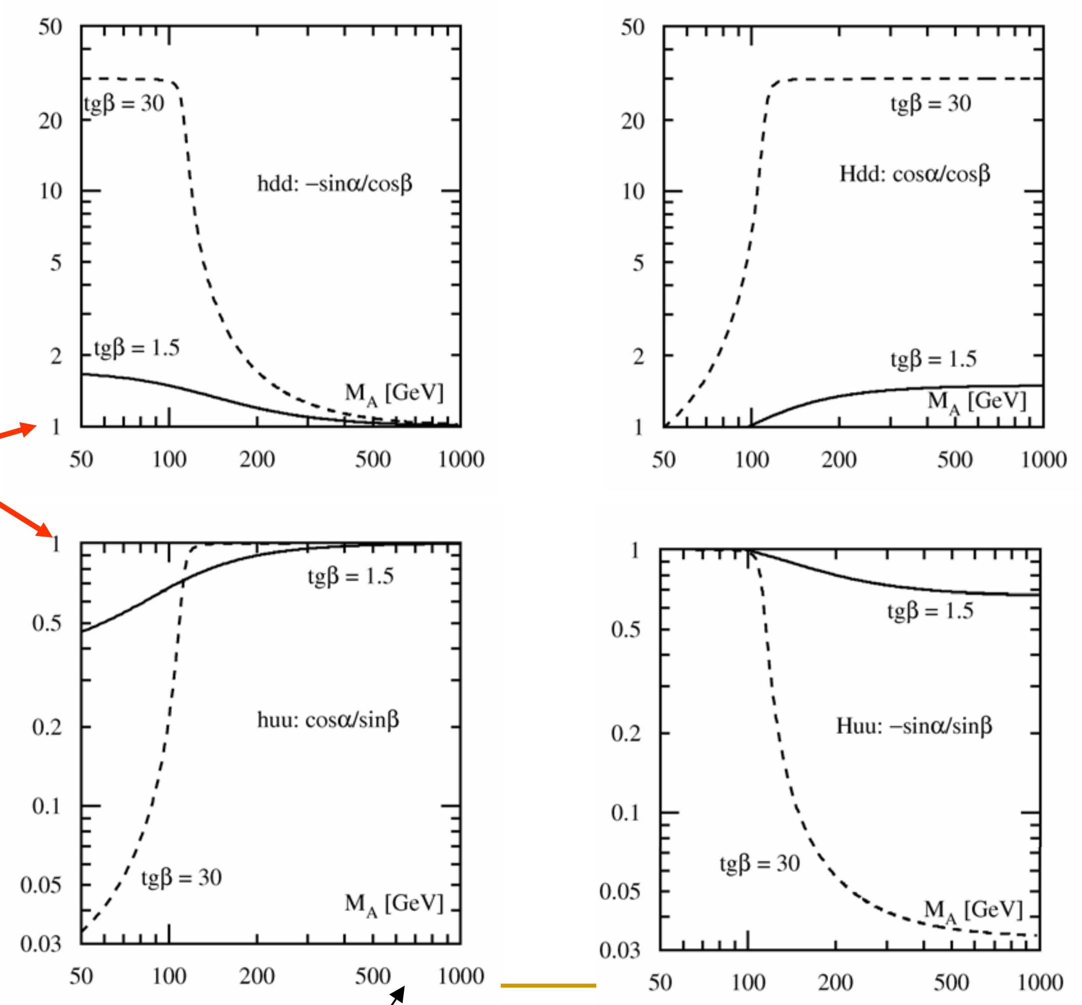




Ratio of h coupling to b's in SUSY model to that of SM

Higgs Couplings different in MSSM

Lightest Neutral Higgs | **Heavier Neutral Higgs**



SM

Decoupling limit

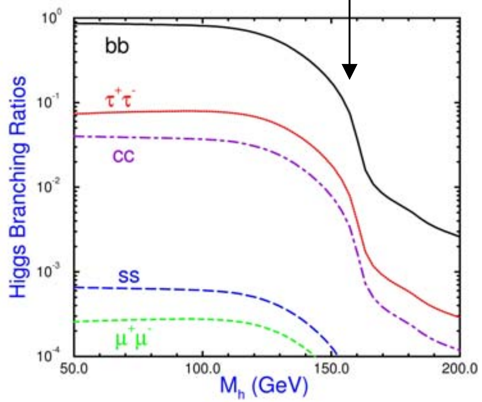
- Couplings to d, s, b enhanced at large tan β

- Couplings to u, c, t suppressed at large tan β

Higgs Decays affected at large tan β

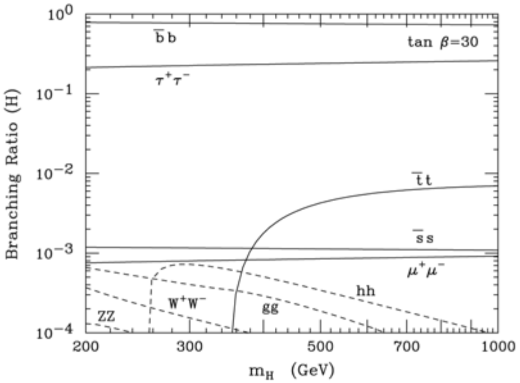
- SM: Higgs branching rates to bb and $\tau^+\tau^-$ turn off as rate to W^+W^- turns on (M_h > 160 GeV)

•MSSM: At large tan β, rates to bb and $\tau^+\tau^-$ stay large

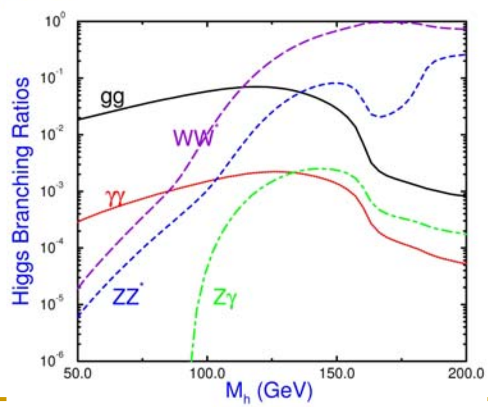


Rate to bb and $\tau^+\tau^-$ almost constant in MSSM

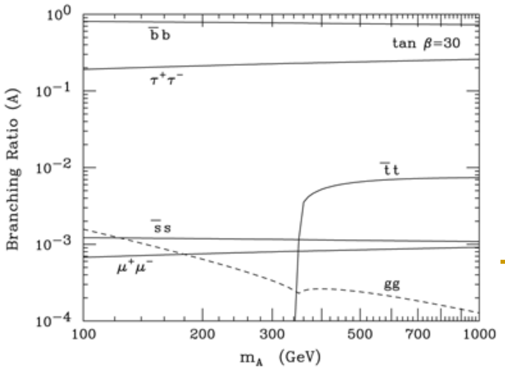
Heavy H^0 MSSM BRs



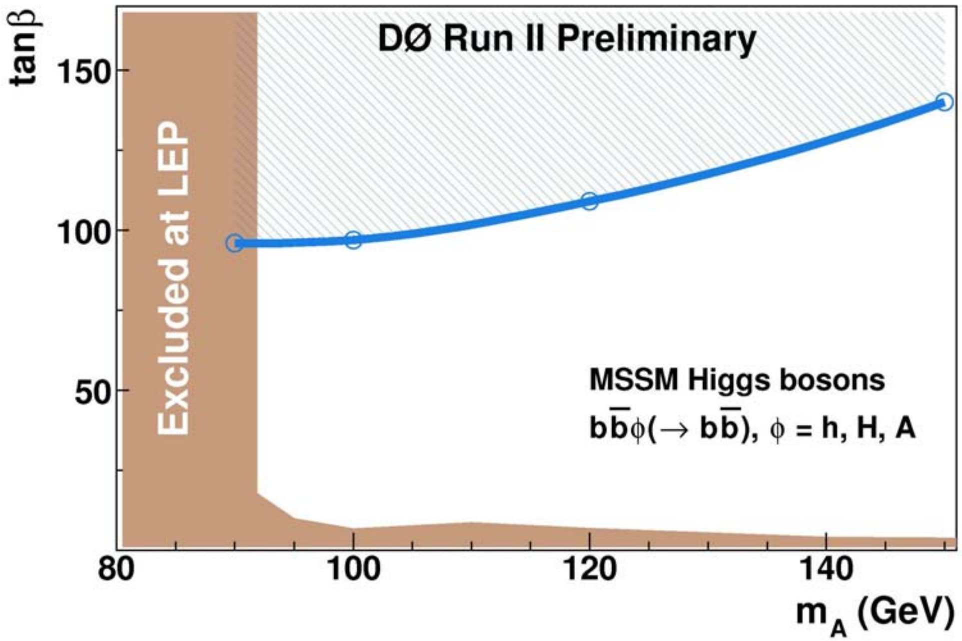
SM



A^0 MSSM BRs

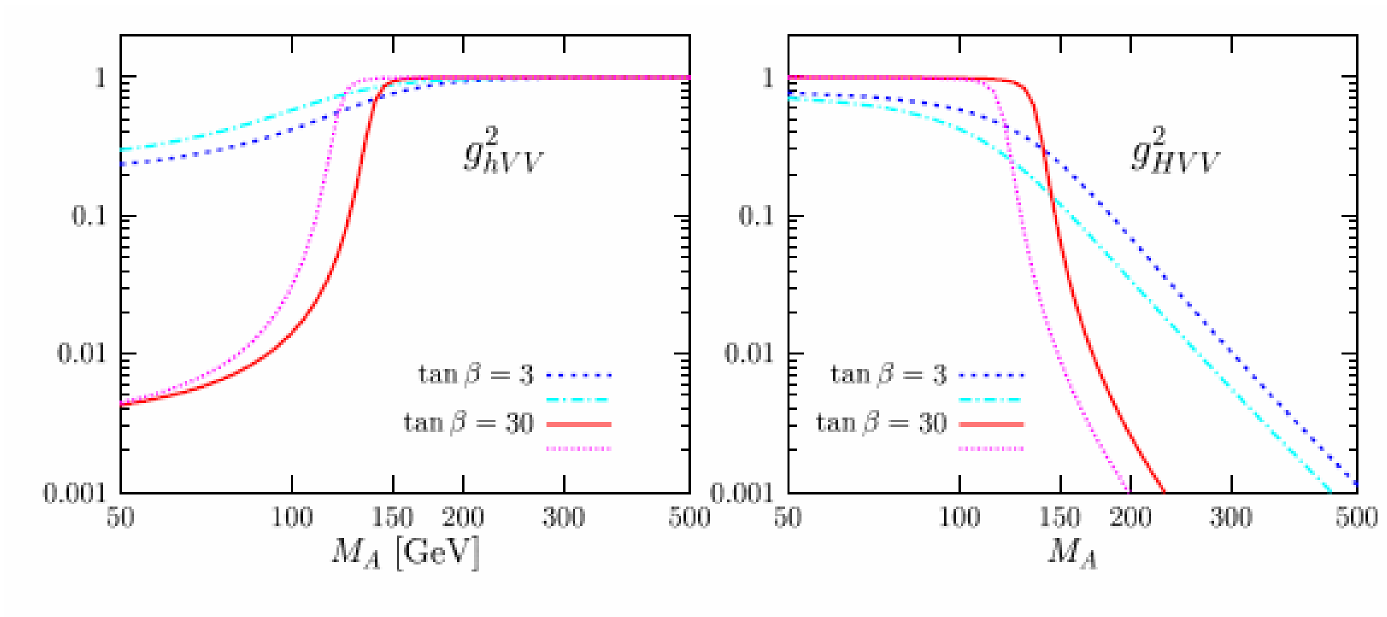


New Discovery Channels in SUSY

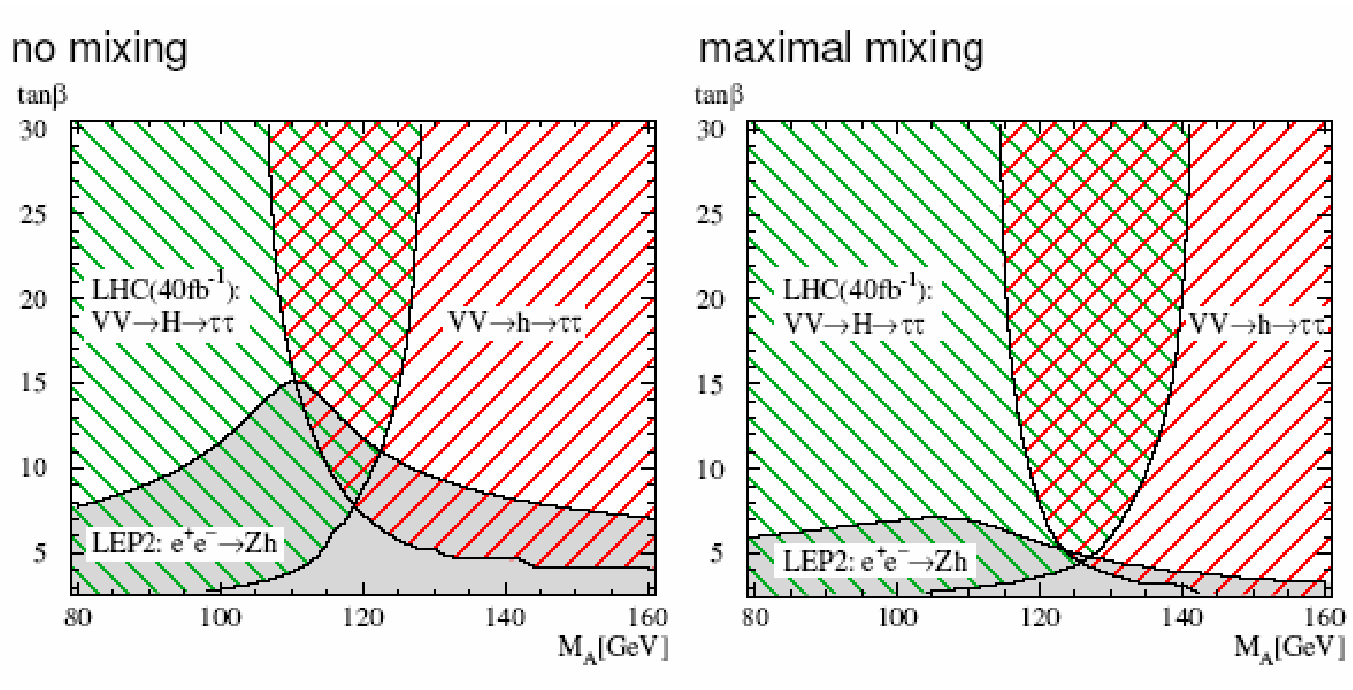


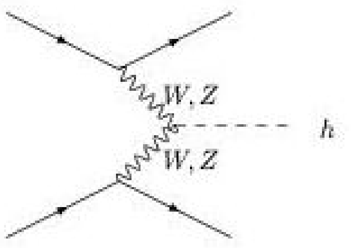
Gauge Coupling Constants

- $g_{hVV}^2 + g_{HVV}^2 = g_{hVV}^2(\mathrm{SM})$
- Vector boson fusion and Wh production always suppressed in MSSM



LHC can find h or H in weak boson fusion



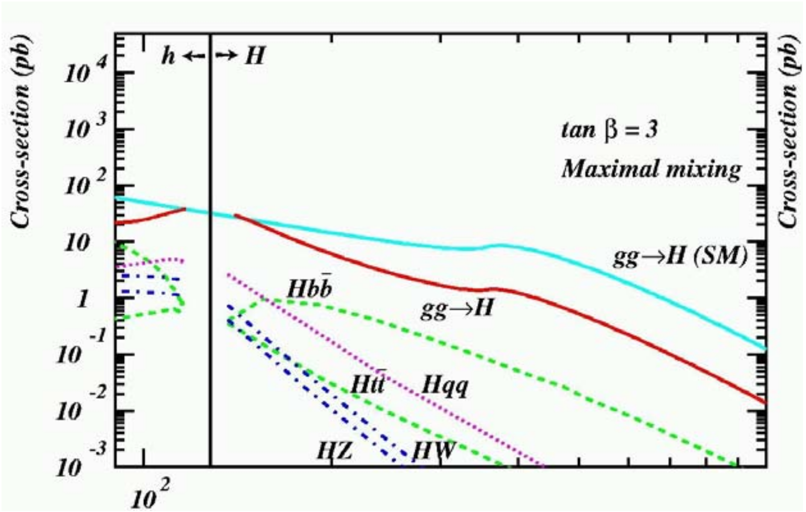


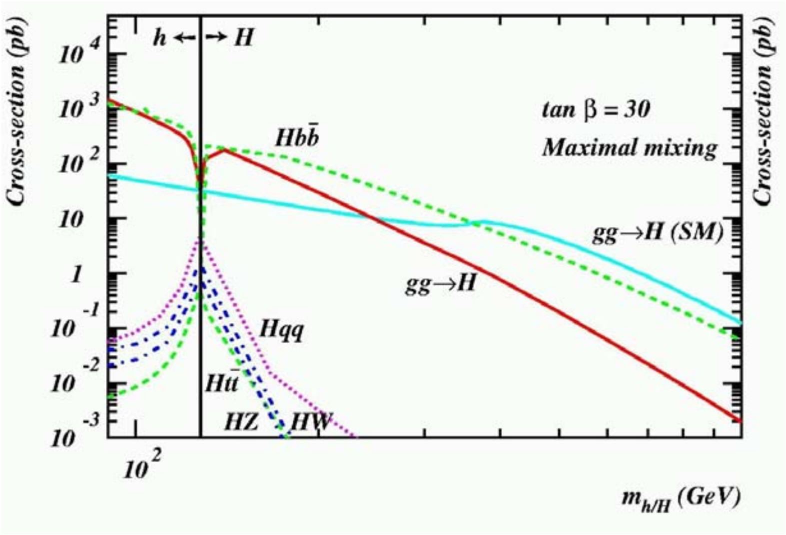
Decays to $\tau^+\tau^-$ needed

Production of SUSY Higgs Bosons

- For large tan β, dominant production mechanism is with b's
- bbh can be 10x's SM Higgs rate in SUSY for large tan β

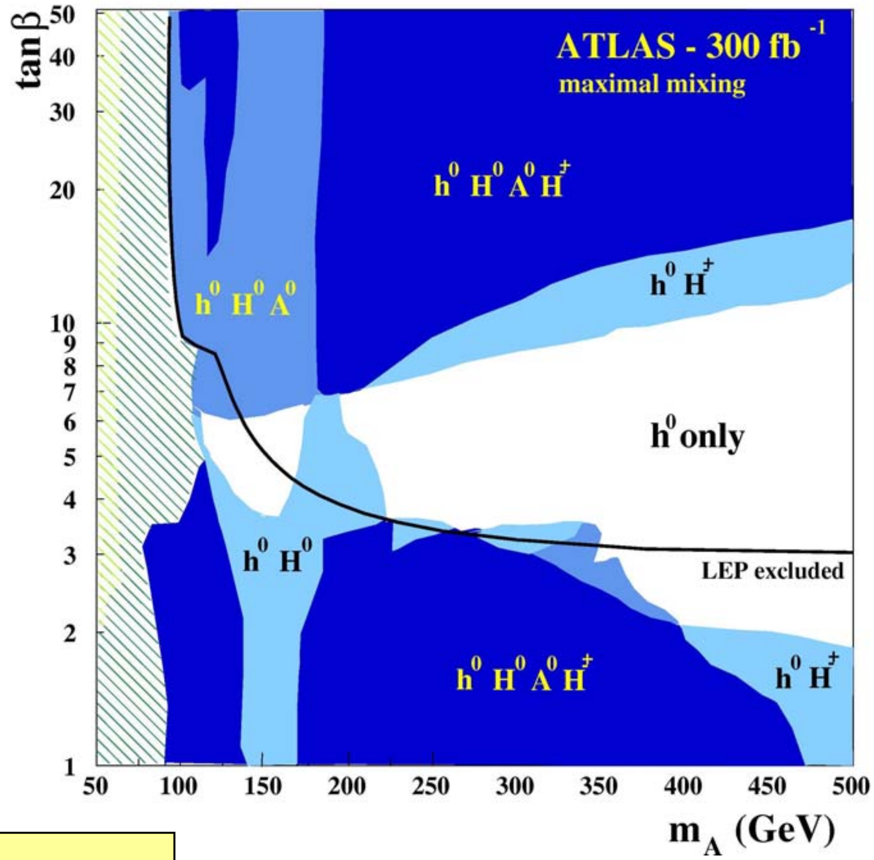
LHC





MSSM discovery

- For large fraction of M_A-$\tan\beta$ space, more than one Higgs boson is observable
- For $M_A \to \propto$, MSSM becomes SM-like
- Plot shows regions where Higgs particles can be observed with > 5σ



Need to observe multiple Higgs bosons and measure their couplings

Add Scalars to MSSM

- Add Higgs singlet S, triplets $T_0, T_{\pm 1}$
- Superpotential, $$W = \lambda_1 H_u H_d S + \lambda_2 H_u T_0 H_d + \chi_1 H_u T_1 H_u + \chi_2 H_d T_{-1} H_d$$
- At tree level, lightest Higgs mass bound becomes,

$$M_H^{\ 2} \leq M_Z^{\ 2} \cos^2 2\beta + v^2 (\lambda_1^{\ 2} + \frac{\lambda_2^{\ 2}}{2}) \sin^2 2\beta + 4v^2 (\chi_1^{\ 2} \cos^4 \beta + \chi_2^{\ 2} \sin^4 \beta)$$

- Higgs mass bound depends on particle content
  - Assume couplings perturbative to M_{GUT} and SUSY scale ≈1 Tev

    $M_h < 150$ –200 GeV with singlet and triplet Higgs

Looking For Gluinos

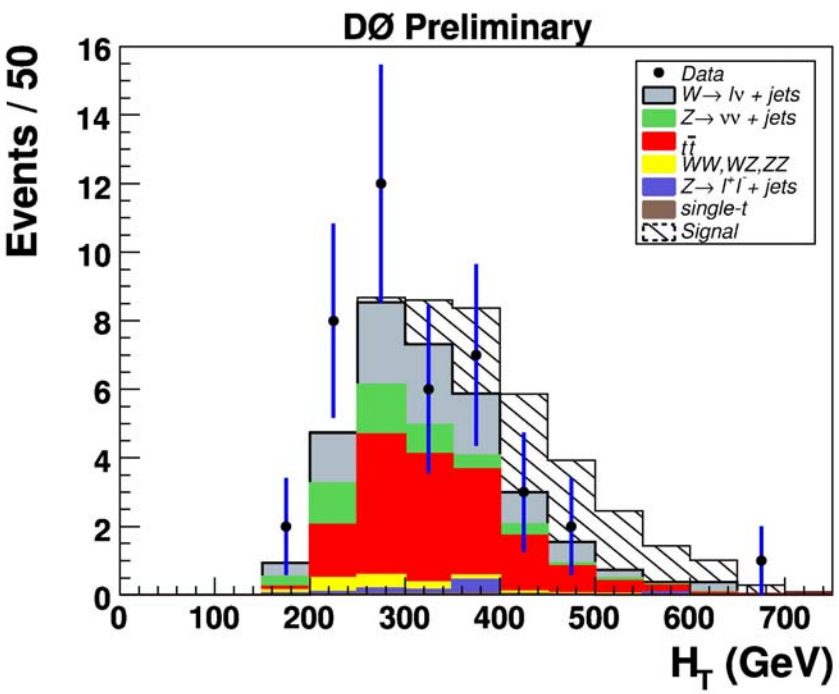
- $gg, q\bar{q} \rightarrow \tilde{g}\tilde{g}$ couplings fixed by gauge invariance
- Gluinos are Majorana

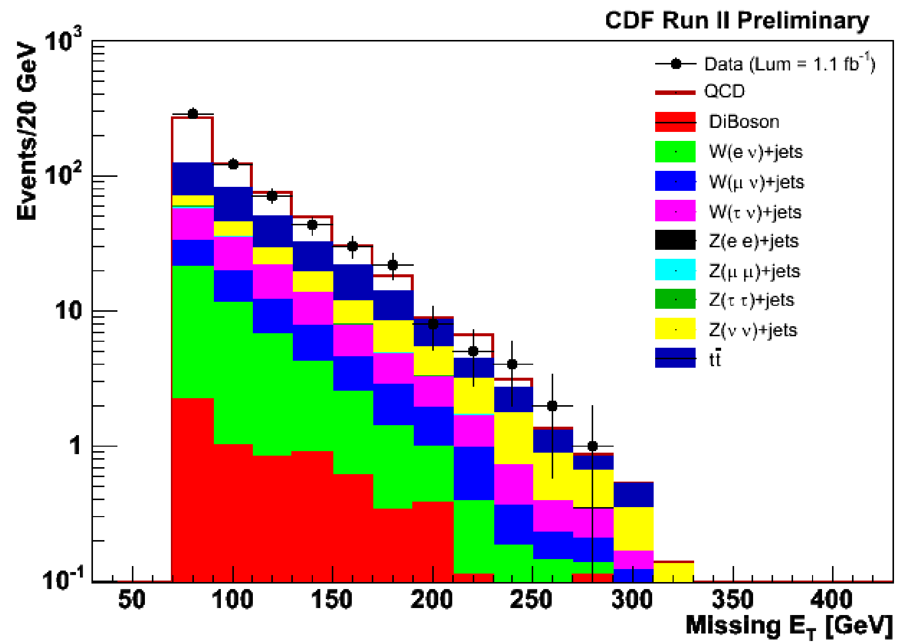
$$\Gamma\left(\tilde{g} \rightarrow l^{+} X\right) = \Gamma\left(\tilde{g} \rightarrow l^{-} X\right)$$

- Classic signature is same sign lepton production

Search for Squark/Gluino Production

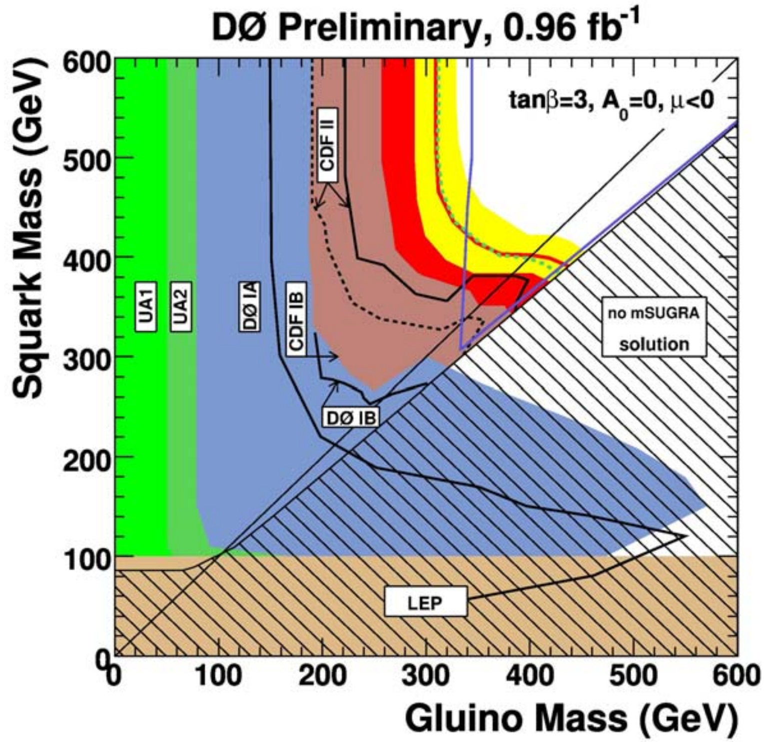
- Generic squark/gluino production → energetic jets & large missing E_T
  - Difficult because of large QCD background

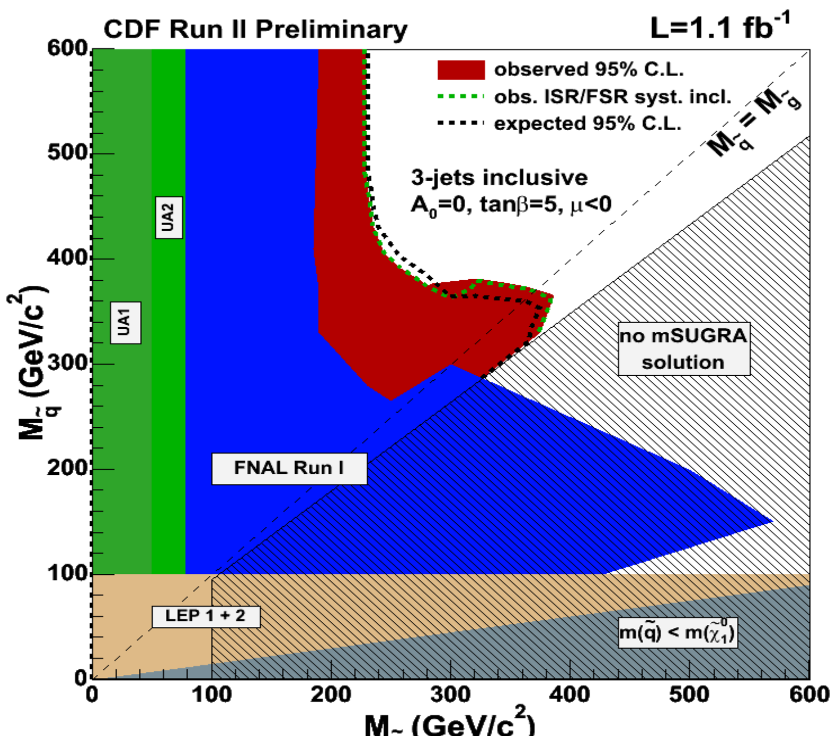




HT = scalar sum of E_T of jets

Limits on Squark/Gluino Production





Mgluino < 402 excluded for Mg~Mq

Mgluino < 380 excluded for Mg~ Mq

Mgluino < 309 excluded – any Mq

Mgluino < 230 excluded -- any Mq

Charginos

- Fermionic partners of $W^{\pm}$ mix with charged fermion partners of Higgs
- Mass eigenstates called charginos

$$\tilde{M}_{\chi^{\pm}} = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu \end{pmatrix}$$

Neutralinos

- Neutral fermions mix:

$$\left(\tilde{B}, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0\right)$$

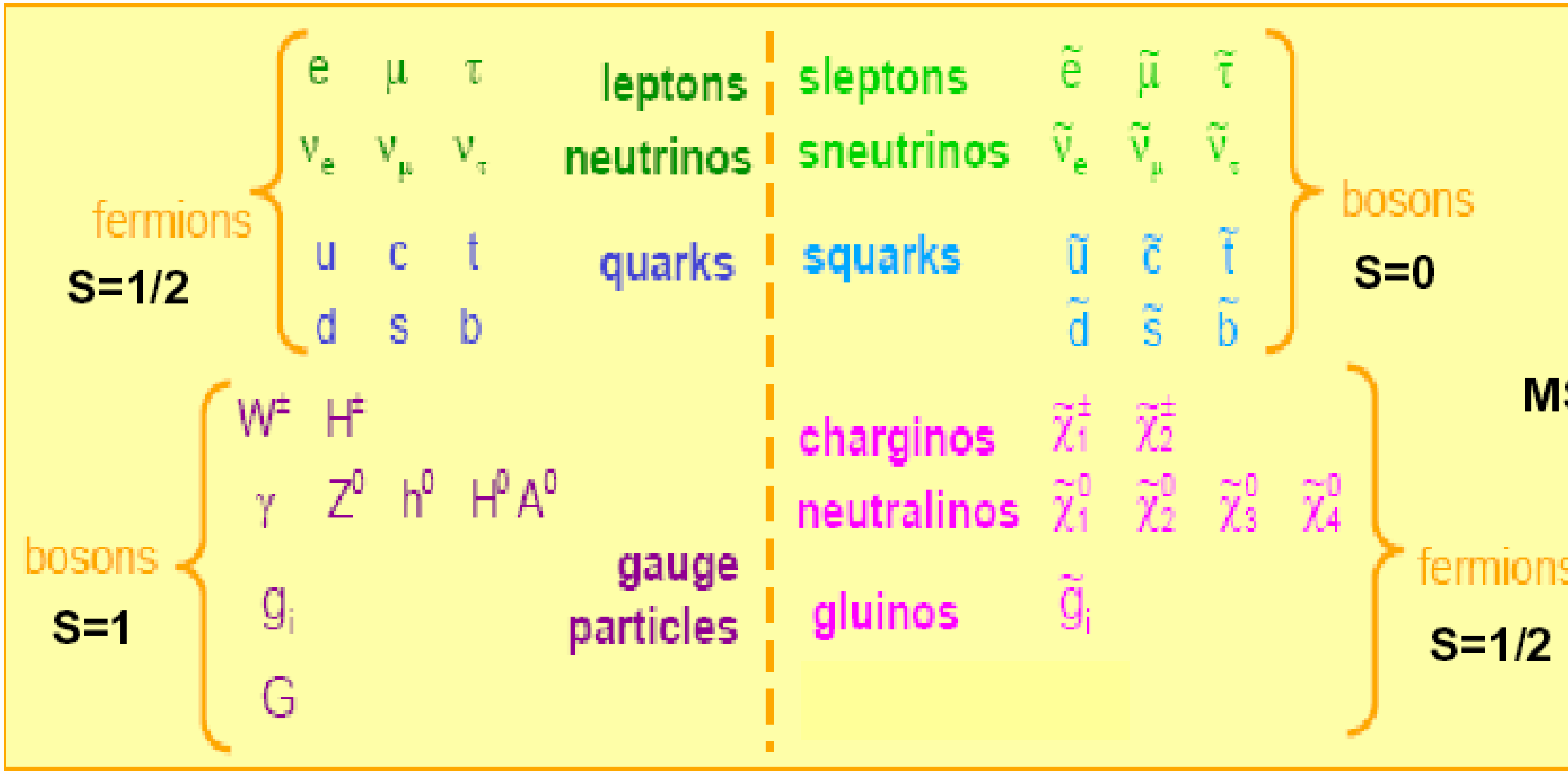
$M_{\chi_0}=$

$$\begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ -M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

- Usually assume lightest SUSY particle is lightest χ^0

SUSY Particles

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



MSSM

MSSM has 124 parameters:

M_1, M_2, M_3, Gaugino masses, Sfermion masses

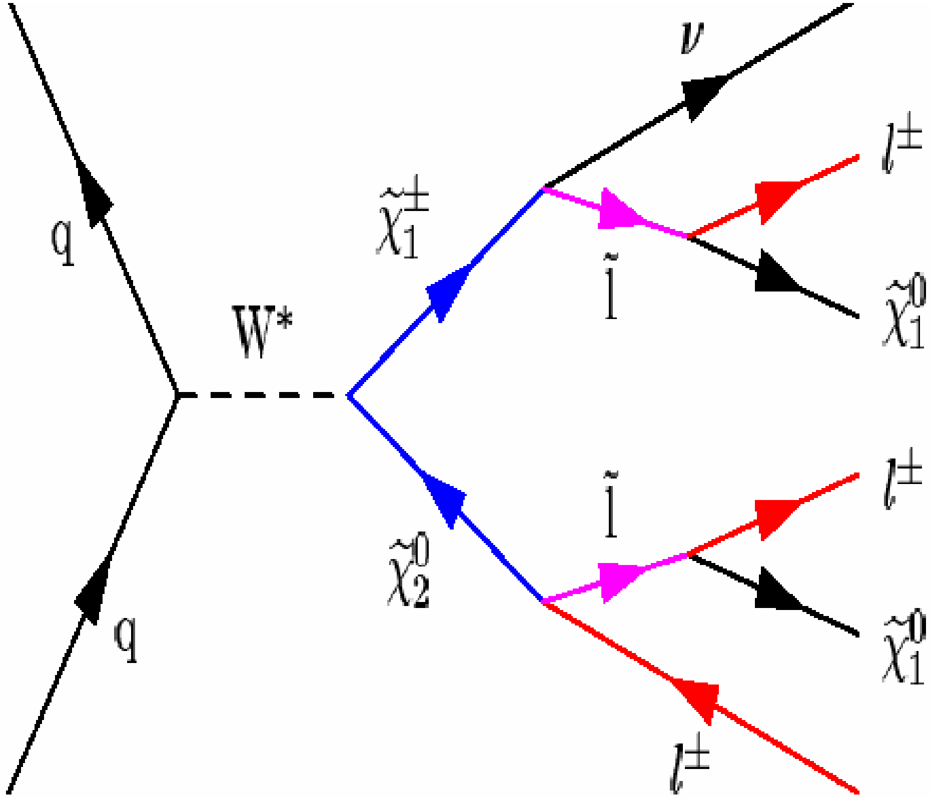
$\tan\beta$, μ, m_A Higgs(ino) mass/mixing

A_τ, A_b, A_t (+45 RPV)

- **SUSY is a broken symmetry**

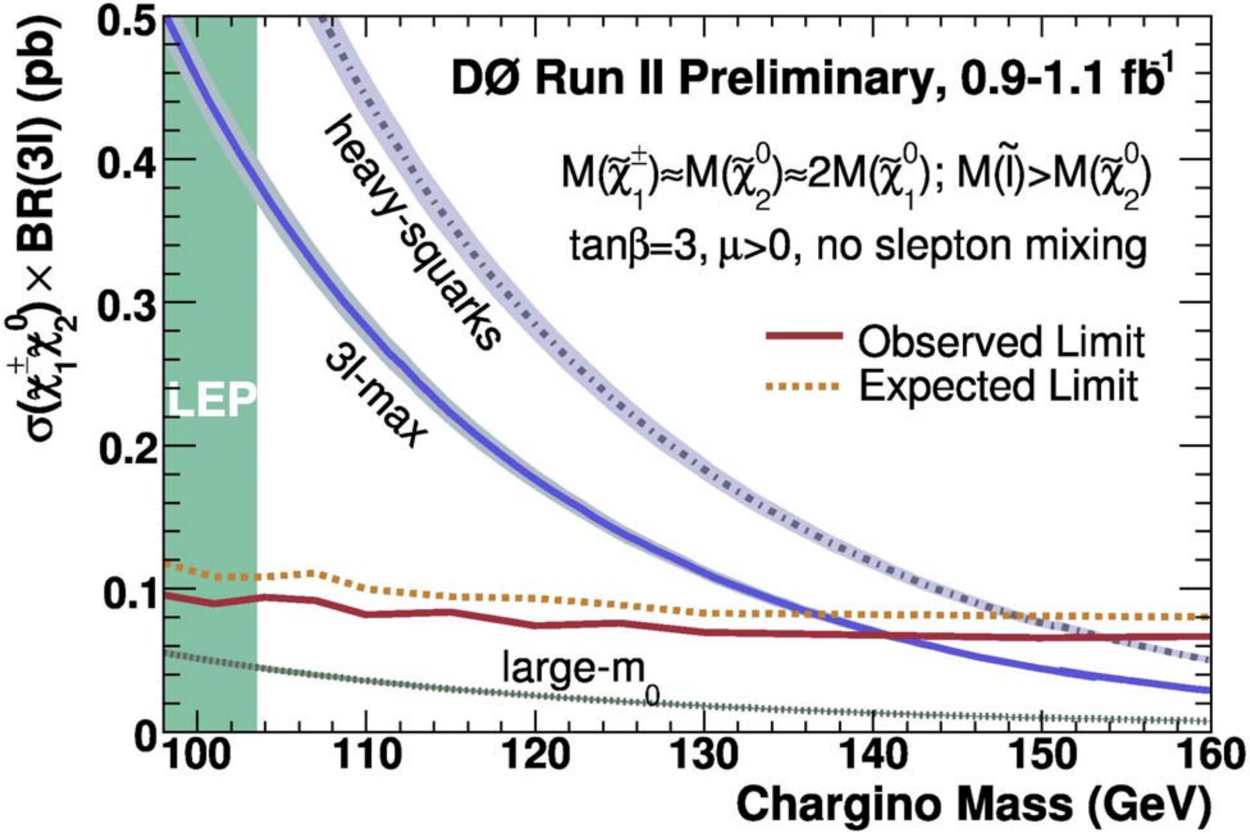
Chargino-Neutralino Production

- Trileptons from chargino-neutralino production: Classic signature



Clear signature – 3 isolated leptons, missing E_T

Tevatron Limits on Tri-leptons



Too Many Unknowns…

Assume soft parameters unify:

Model specified by:

- Common scalar mass, $\tilde{m}_0$
- Common gaugino mass, $M_{1/2}$
- 1 Higgs mass, m_{12}^2
- 1 tri-linear coupling, $A_0 \lambda_F$

This model often called mSUGRA, CMSSM

Evolve all masses to M_Z with boundary condition at M_G:

$$M_{\tilde{Q}}^2(M_G) = M_{\tilde{u}}^2(M_G) = M_{\tilde{d}}^2(M_G) = M_{\tilde{L}}^2(M_G) = M_{\tilde{e}}^2(M_G) = \tilde{m}_0^2$$

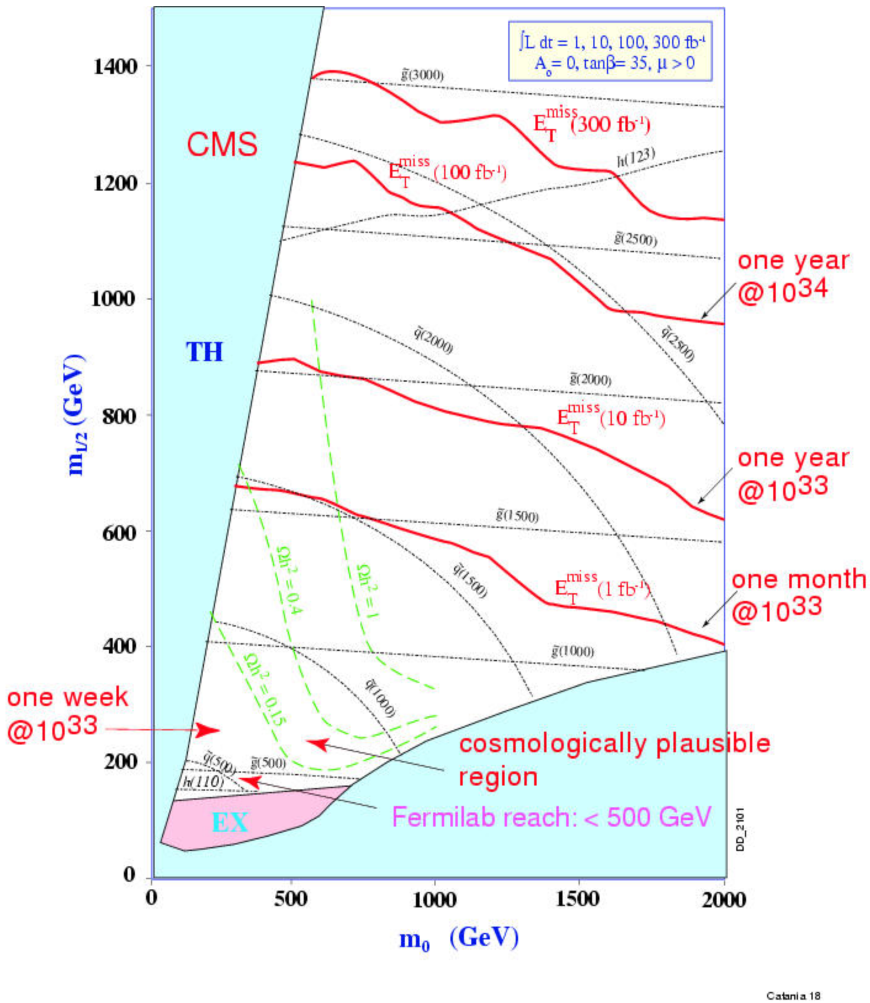
$$m_1^2(M_G) = m_2^2(M_G) = \tilde{m}_0^2$$

$$M_1(M_G) = M_2(M_G) = M_3(M_G) = M_{1/2}$$

$$m_{12}^2(M_G) = m_{12}^2$$

$$A_i(M_G) = A_0 \lambda_i$$

LHC/Tevatron will find SUSY



- Discovery of many SUSY particles is straightforward
- Untangling spectrum is difficult

  ⇒ all particles produced together
- SUSY mass differences from complicated decay chains;eg

$$\tilde{q}_L \rightarrow \tilde{\chi}_2{}^0 q \rightarrow \tilde{l}^{\pm} l^{\mp}$$
$$\rightarrow \tilde{\chi}_1{}^0 l^+ l^- q$$

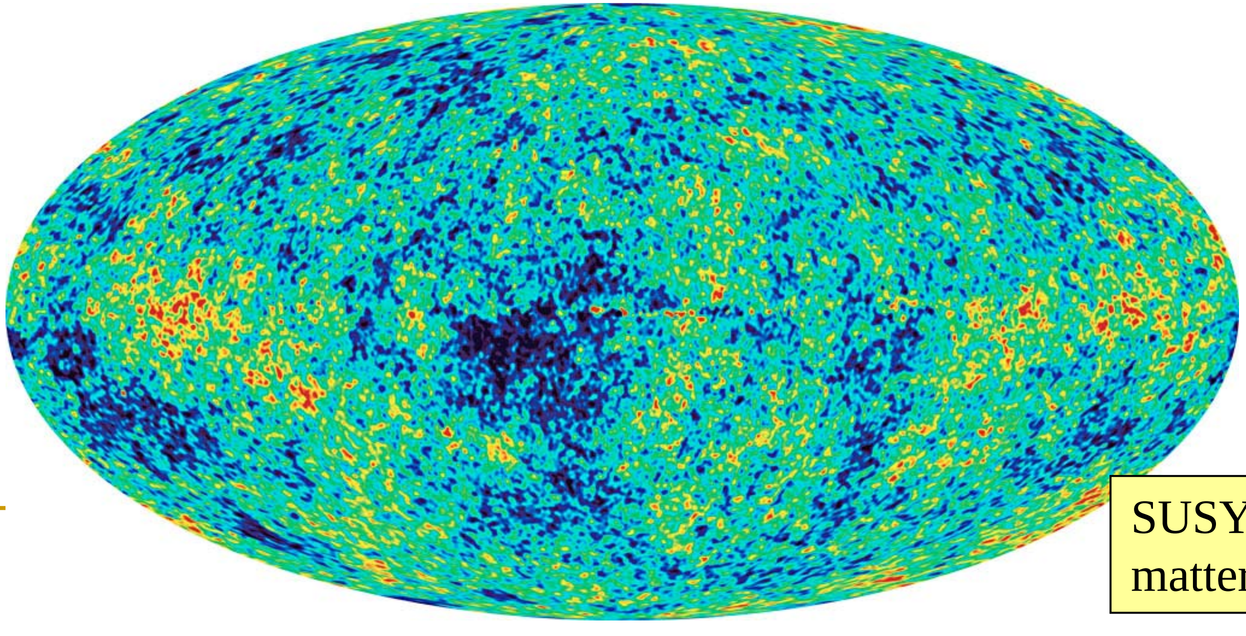
- $M_{\chi 0}$ limits extraction of other masses

SM is incomplete

•23% of universe is cold dark matter:

$\Omega_{CDM}h^2 = .1126^{+.0161}_{-.0181}$

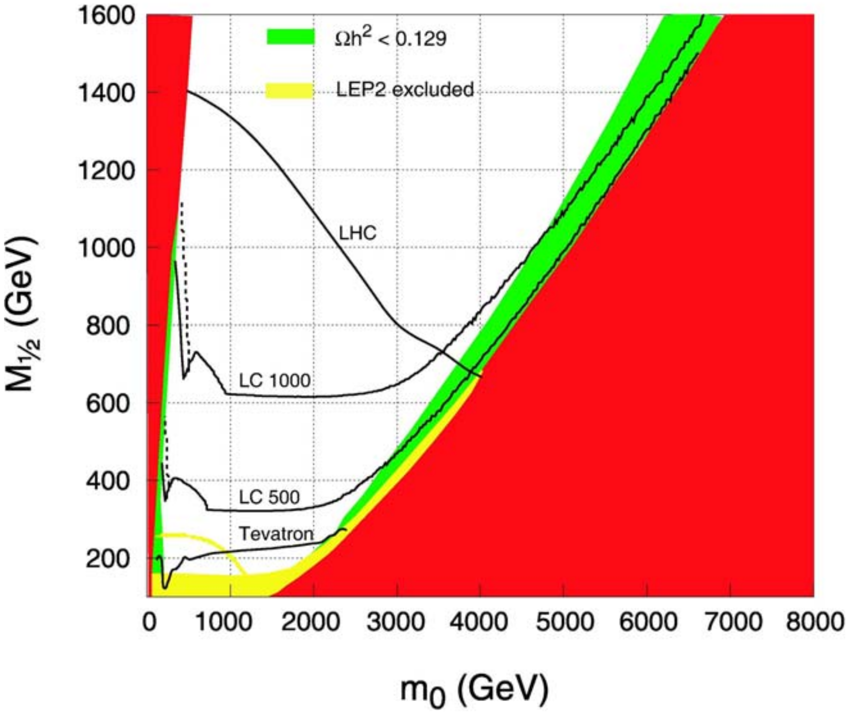
No dark matter candidate in SM



SUSY has dark matter candidate

MSSM has dark matter candidate

- LSP: Lightest supersymmetric particle, χ_0 is neutral and stable (in models with R parity)



Supersymmetry (MSSM version)

- Many positive aspects
  - Gauge coupling unification
  - Dark Matter candidate (LSP)
  - Predicts light Higgs boson
    - $M_H < 140$ GeV
  - Agrees with EW measurements