Physics Beyond the Standard Model II: Supersymmetry

David E Kaplan

HCP Summer School 2007

CERN

Natural EWSB

The Higgs is very sensitive to new mass scales in the theory.

The Higgs needs a symmetry.

Options

- electron mass multiplicitively renormalized: chiral symmetry
- photon mass not generated by quantum effects: gauge invariance
- pion mass naturally small compared to the rho mass: goldstone's theorem

Symmetries Relating Spins

Spin 1/2

Chiral Symmetry

Spin 0

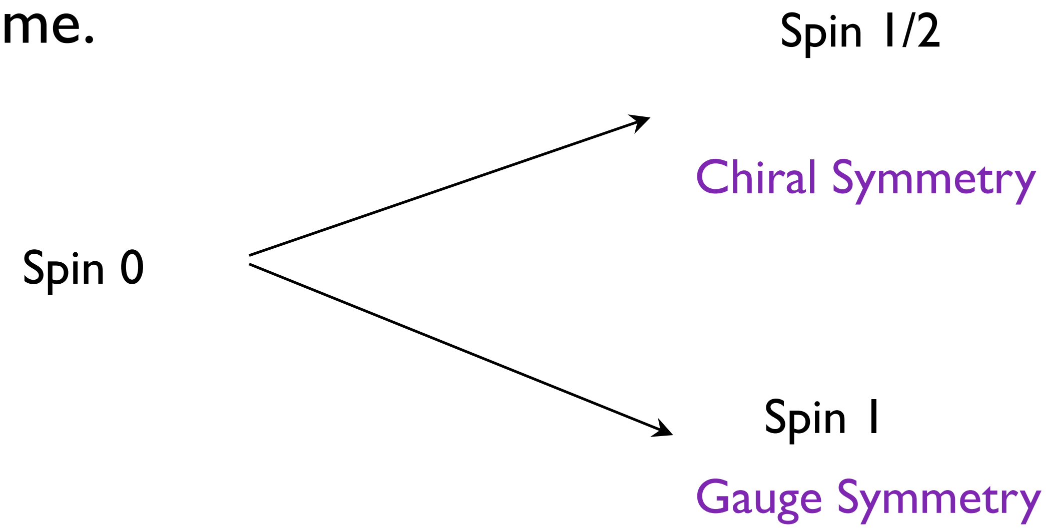
Spin 1

Gauge Symmetry

Symmetries Relating Spins

Masses and scattering cross sections

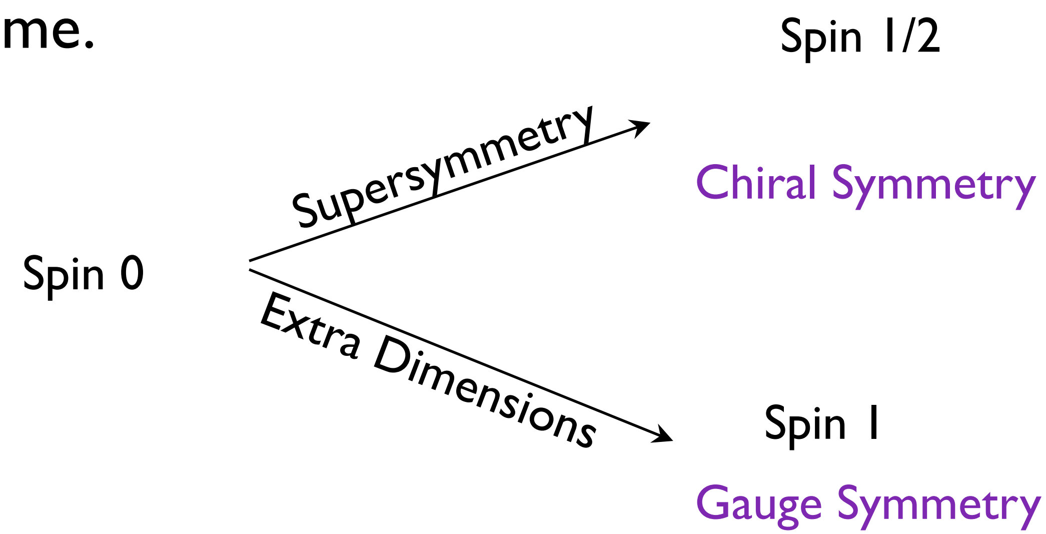
would be the same.



Symmetries Relating Spins

Masses and scattering cross sections

would be the same.



Supersymmetry

Definitely the more exotic of the two

Fermionic (or purely quantum mechanical) extra dimensions

Mixes with symmetries of relativity -
extends the Poincare group

Simple Example

$$\mathcal{L} \;=\; -|\partial\phi|^2 - i\psi^\dagger\bar{\sigma}\cdot\partial\psi - |m\phi|^2 - \frac{1}{2}(m\psi\psi + \text{h.c.})$$

Invariant under:

$$\delta\phi = \epsilon\psi \qquad\qquad \delta\psi_\alpha \;=\; i(\sigma^\mu\epsilon^\dagger)_\alpha\,\partial_\mu\phi$$

Simple Example

$$\mathcal{L} \;=\; -|\partial\phi|^2 - i\psi^\dagger\bar{\sigma}\cdot\partial\psi - |m\phi|^2$$

$$-\frac{1}{2}(m+y\phi)\psi\psi - \text{h.c.} - \frac{1}{2}m^* y|\phi|^2\phi - \text{h.c.} + \frac{1}{4}|y\phi^2|^2$$

Invariant under:

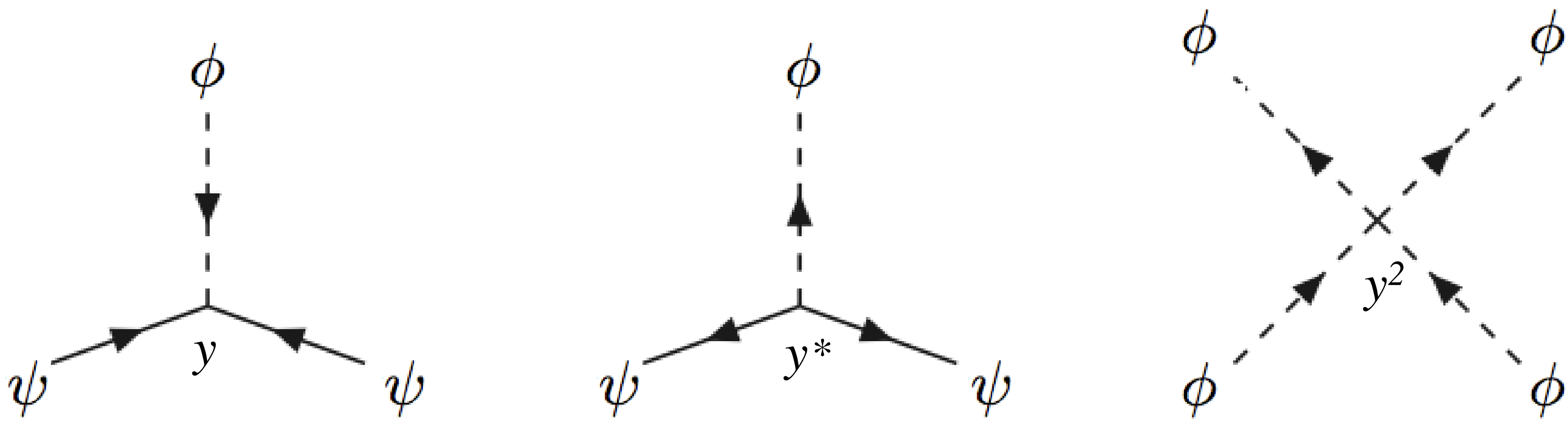
$$\delta\phi = \epsilon\psi \qquad\qquad \delta\psi_\alpha \;=\; i(\sigma^\mu\epsilon^\dagger)_\alpha\,\partial_\mu\phi$$

Implications

ϕ complex - two bosons, spin 0

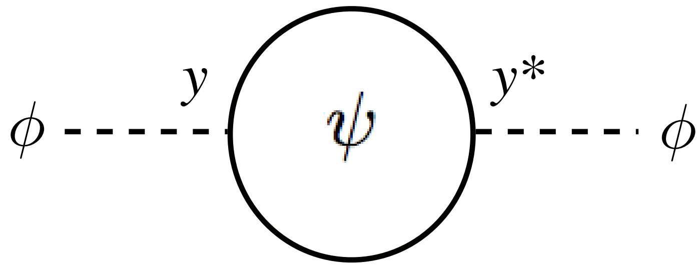
ψ Weyl spinor - two fermions, spin 1/2

All particles of mass *m* - degenerate

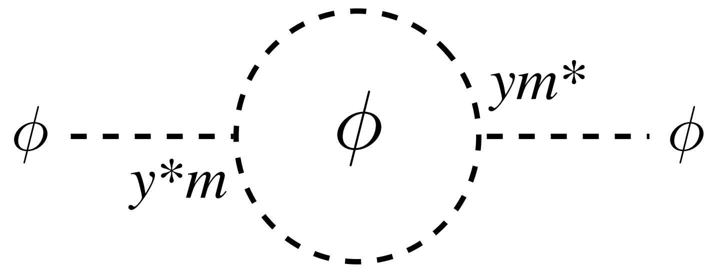


couplings related

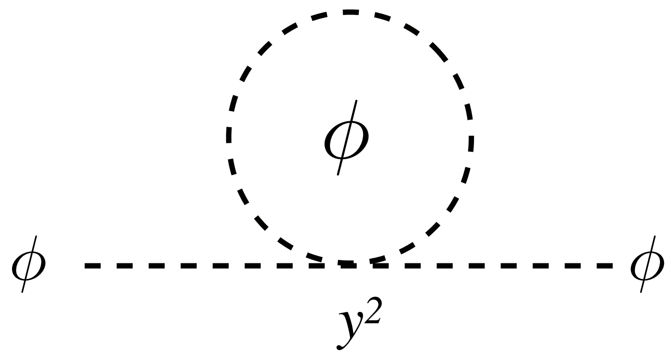
Canceling Contributions



$+$



$+$



$= 0$ (at zero momentum)

The Superpotential

$$W = \frac{1}{2} m\phi^2 + \frac{1}{6} y\phi^3$$

$$\frac{\partial W}{\partial \phi} = m\phi + \frac{1}{2} y\phi^2$$

$$\frac{\partial^2 W}{\partial \phi^2} = m + y\phi$$

The Superpotential

$$W = \frac{1}{2} m\phi^2 + \frac{1}{6} y\phi^3$$

$$\frac{\partial W}{\partial \phi} = m\phi + \frac{1}{2} y\phi^2$$

$$\frac{\partial^2 W}{\partial \phi^2} = m + y\phi$$

$$V(\phi, \psi) = \left| \frac{\partial W}{\partial \phi} \right|^2 + \frac{1}{2} \frac{\partial^2 W}{\partial \phi^2} \psi\psi + \mathrm{h.c.}$$

The Superpotential

$$W = \frac{1}{2} m\phi^2 + \frac{1}{6} y\phi^3$$

$$\frac{\partial W}{\partial \phi} = m\phi + \frac{1}{2} y\phi^2$$

$$\frac{\partial^2 W}{\partial \phi^2} = m + y\phi$$

fermion partner of phi

$$V(\phi, \psi) = \left| \frac{\partial W}{\partial \phi} \right|^2 + \frac{1}{2} \frac{\partial^2 W}{\partial \phi^2} \psi\psi + \text{h.c.}$$

General Superpotential

You pick a superpotential W, generate the potential V using the rules below, and you have a supersymmetric theory.

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

General Superpotential

You pick a superpotential W, generate the potential V using the rules below, and you have a supersymmetric theory.

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

$$V(\phi, \psi) = -\frac{1}{2} \left(W^{ij} \psi_i \psi_j + W^*_{ij} \psi^{\dagger i} \psi^{\dagger j} \right) - W^i W^*_i$$

General Superpotential

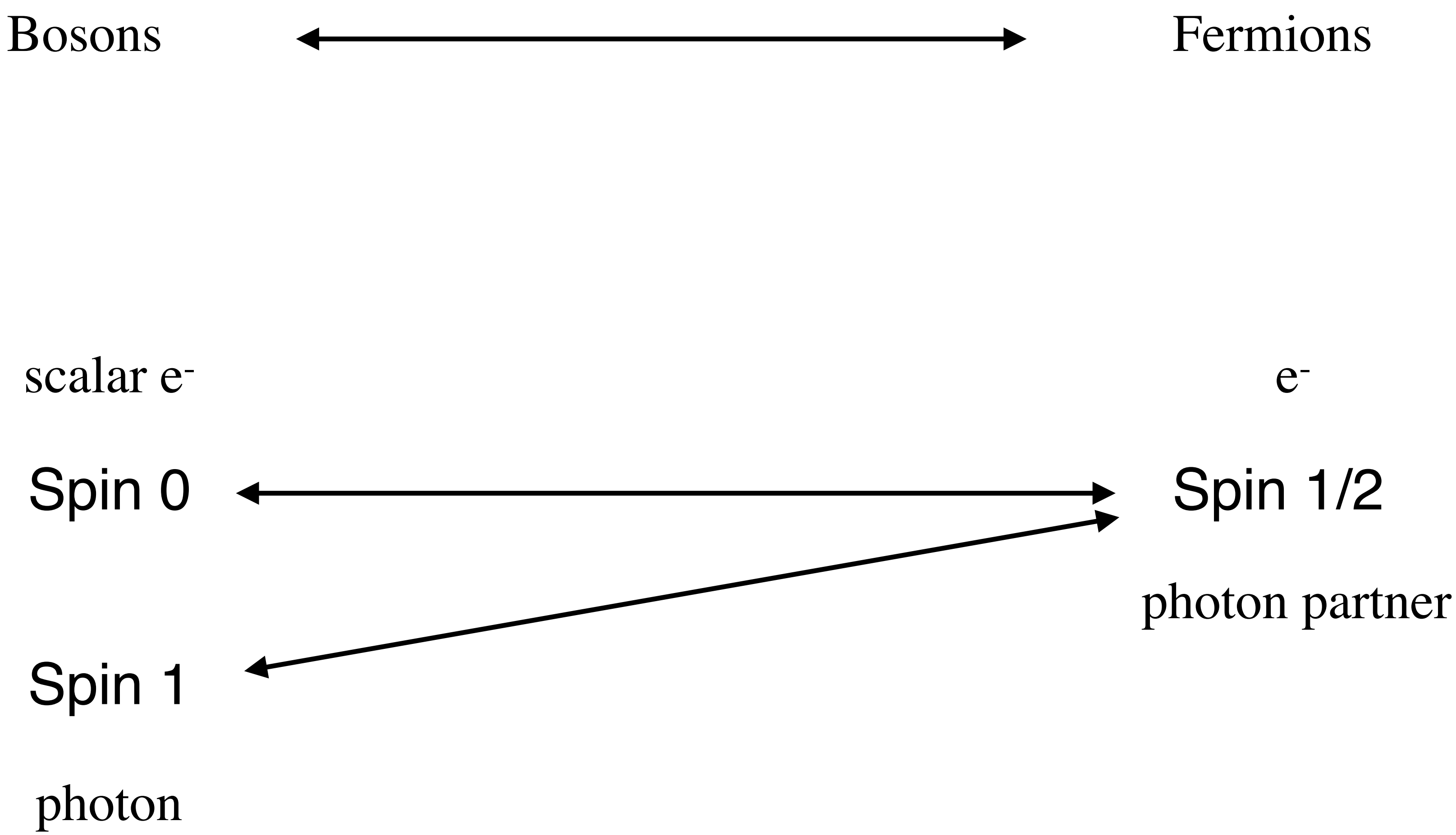
You pick a superpotential W, generate the potential V using the rules below, and you have a supersymmetric theory.

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

$$V(\phi,\psi) = -\frac{1}{2}\left(W^{ij}\psi_i\psi_j + W^*_{ij}\psi^{\dagger i}\psi^{\dagger j}\right) - W^i W^*_i$$

$$W^{ij} = \frac{\delta^2}{\delta\phi_i\delta\phi_j}W \qquad W^i = \frac{\delta W}{\delta\phi_i}$$

Additional Partners



Additional Potential

$$V = +\frac{1}{2}g^2\left(\sum_k \phi_k^* t^a \phi_k\right)^2 - \sqrt{2}g(\phi^* \lambda^{aT} t^a c\psi - \psi^\dagger c\lambda^{a*} t^a \phi)$$

SU(3): t^a - Gellman matrices
SU(2): t^a - Pauli matrices
U(1): t^a - hypercharges

Supersymmetrize the SM

$$e^-$$

$$\gamma$$

$$q$$

$$W$$

$$h$$

Supersymmetrize the SM

$$e^- \rightarrow e^-$$

$$\gamma \rightarrow \gamma$$

$$q \rightarrow q$$

$$W \rightarrow W$$

$$h \rightarrow h$$

Supersymmetrize the SM

$$e^- \to \tilde{e}^-$$

$$\gamma \to \tilde{\gamma}$$

$$q \to \tilde{q}$$

$$W \to \tilde{W}$$

$$h \to \tilde{h}$$

Supersymmetrize the SM

$$W = H\ QD^c + H\ QU^c$$

Need two Higgses.

Supersymmetrize the SM

$$W = H\ QD^c + \cancel{H\ QU^c}$$

Need two Higgses.

Supersymmetrize the SM

$$W = H\ QD^c + H^{c} QU^c$$

Need two Higgses.

Supersymmetrize the SM

$$W = H_1 Q D^c + H_2 Q U^c$$

Need two Higgses.

Supersymmetrize the SM

$$W = H_1 Q D^c + H_2 Q U^c$$

Need two Higgses.

$$H_1 = H_d = H \qquad H_2 = H_u = \bar{H} = H^c$$

$$\tan\beta = \langle H_2 \rangle / \langle H_1 \rangle$$

Supersymmetrize the SM

$$W = H_1 Q D^c + H_2 Q U^c$$

Need two Higgses.

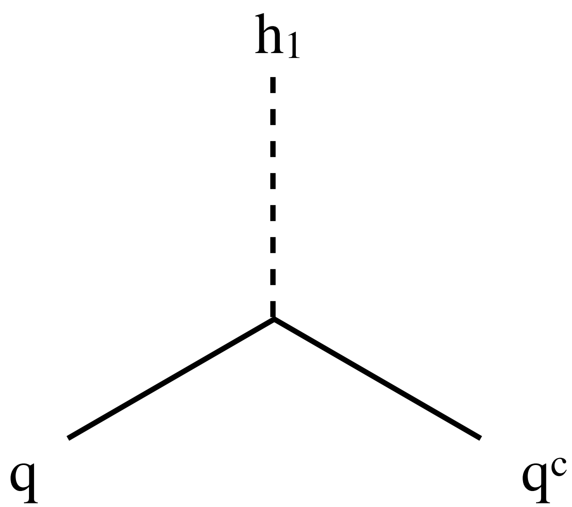
Another reason: require two higgsinos for anomaly cancelation.

$$H_1 = H_d = H \qquad H_2 = H_u = \bar{H} = H^c$$

$$\tan\beta = \langle H_2 \rangle / \langle H_1 \rangle$$

MSSM

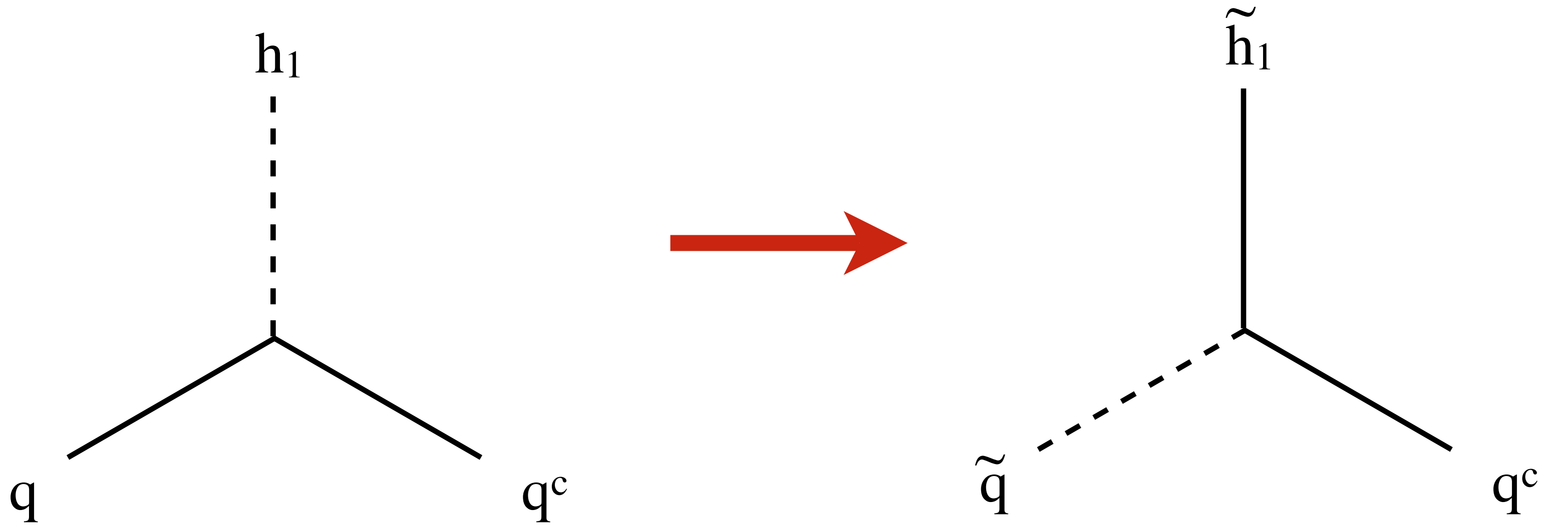
$$W = H_1 Q D^c + H_2 Q U^c + H_1 L E^c + \mu H_1 H_2$$



Take any SM diagram and switch the spins of two lines.

MSSM

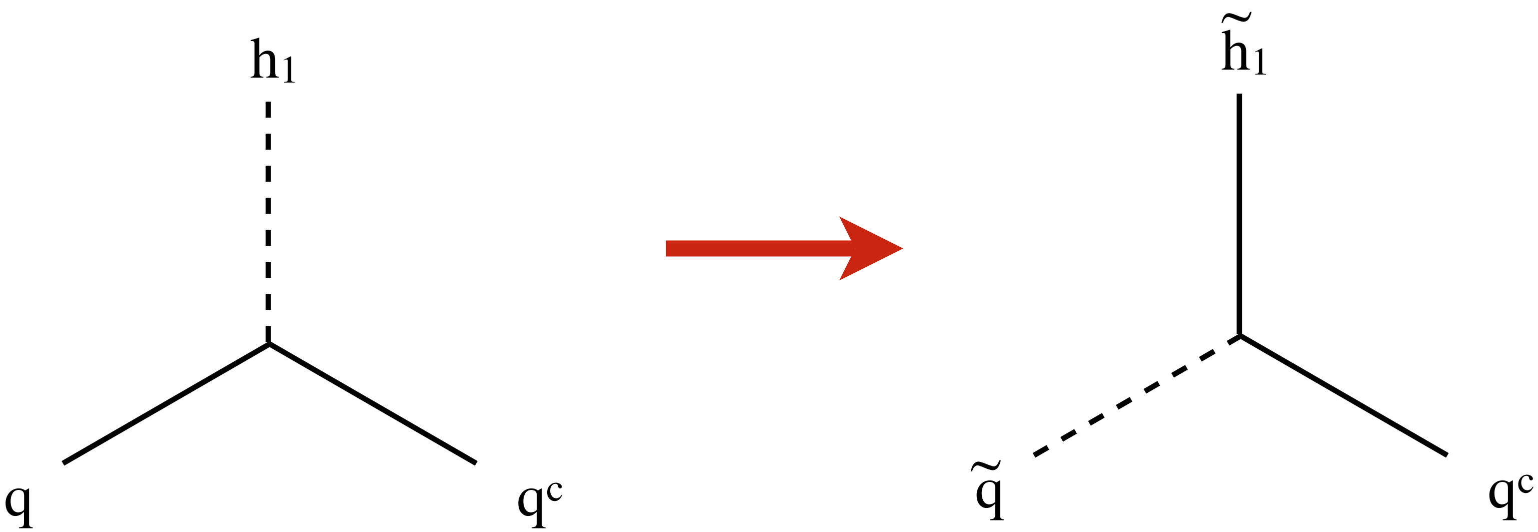
$$W = H_1 Q D^c + H_2 Q U^c + H_1 L E^c + \mu H_1 H_2$$



Take any SM diagram and switch the spins of two lines.

MSSM

$$W = H_1QD^c + H_2QU^c + H_1LE^c + \mu H_1H_2$$



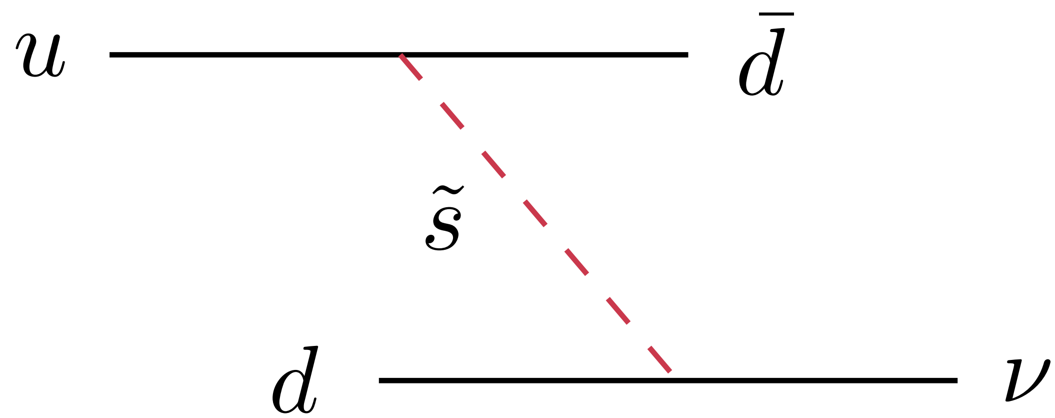
Take any SM diagram and switch the spins of two lines.

Dimension 4 Operators

$$W = H_1 Q D^c + H_2 Q U^c + H_1 L E^c + \mu H_1 H_2$$
$$+ L Q D^c + U^c D^c D^c + L L E^c + \mu_L L H_2$$

Dimension 4 Operators

$$W = H_1 Q D^c + H_2 Q U^c + H_1 L E^c + \mu H_1 H_2$$
$$+ L Q D^c + U^c D^c D^c + L L E^c + \mu_L L H_2$$



$p \longrightarrow \pi^+ \nu$ ~ 1 hour

Dimension 4 Operators

$$W = H_1 Q D^c + H_2 Q U^c + H_1 L E^c + \mu H_1 H_2$$
$$+ L Q D^c + U^c D^c D^c + L L E^c + \mu_L L H_2$$

Introduce a parity symmetry

$$Q \rightarrow -Q$$
$$H \rightarrow +H$$

Equivalent to:

$$\phi_{SM} \rightarrow +\phi_{SM}$$
$$\tilde{\phi}_{SP} \rightarrow -\tilde{\phi}_{SP}$$

Dimension 4 Operators

$$W = H_1 Q D^c + H_2 Q U^c + H_1 L E^c + \mu H_1 H_2$$

$$+L Q D^c + U^c D^c D^c + L L E^c + \mu_L L H_2$$

Introduce a parity symmetry

$$Q \to -Q$$
$$H \to +H$$

Equivalent to:

$$\phi_{SM} \to +\phi_{SM}$$
$$\tilde{\phi}_{SP} \to -\tilde{\phi}_{SP}$$

Dimension 4 Operators

$$W = H_1 Q D^c + H_2 Q U^c + H_1 L E^c + \mu H_1 H_2$$

$$+LQD^c + U^c D^c D^c + LLE^c + \mu_L L H_2$$

Introduce a parity symmetry

$$Q \to -Q$$
$$H \to +H$$

Equivalent to:

$$\phi_{SM} \to +\phi_{SM}$$
$$\tilde{\phi}_{SP} \to -\tilde{\phi}_{SP}$$

R Parity

Consequences of R_P

- Reduce effect on Electroweak Precision observables
- Must pair produce superpartners
- Missing E_T if the LSP is neutral
- Dark Matter candidate

MSSM

Two remaining problems:

MSSM

Two remaining problems:

There are no observed superpartners with the same masses as standard model particles.

MSSM

Two remaining problems:

There are no observed superpartners with the same masses as standard model particles.

The names are silly.

MSSM

Two remaining problems:

There are no observed superpartners with the same masses as standard model particles.

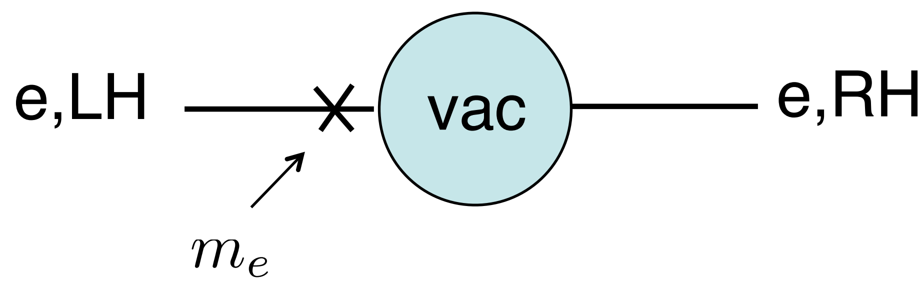
~~The names are silly.~~

Give Masses to SP's

Remember the electron:

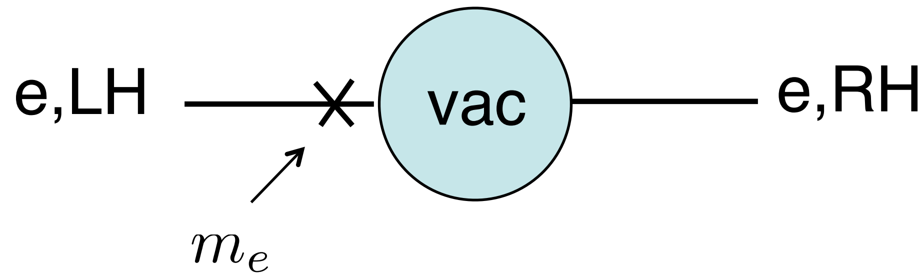
Give Masses to SP's

Remember the electron:



Give Masses to SP's

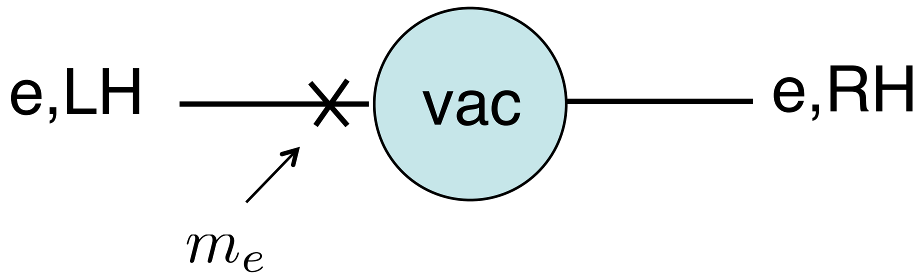
Remember the electron:



$\delta m_e \sim \epsilon\, m_e \ln \Lambda$ (dimensional analysis)

Give Masses to SP's

Remember the electron:

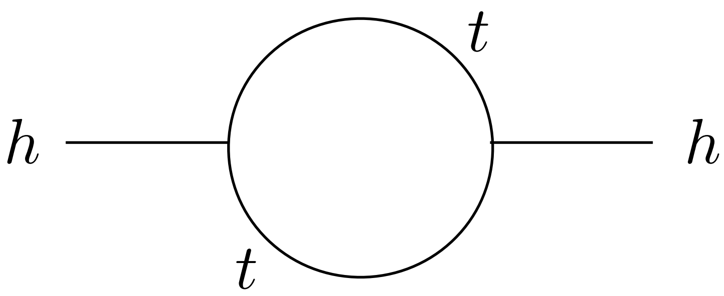


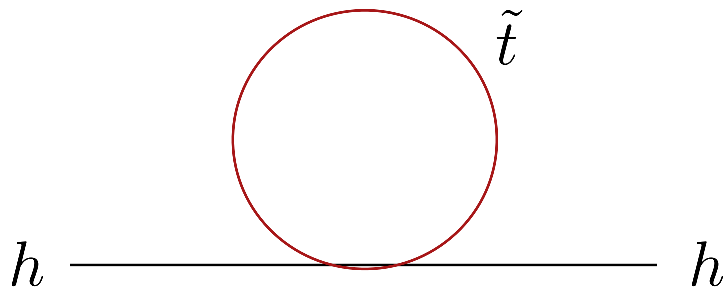
$$\delta m_e \sim \epsilon\, m_e \ln \Lambda$$ (dimensional analysis)

Similarly, contributions to the Higgs mass will be proportional to the mass of superpartners (the 'mass' of supersymmetry breaking).

Supersymmetry could be an approximate symmetry and still stabilize the Higgs mass scale (solve the hierarchy problem).

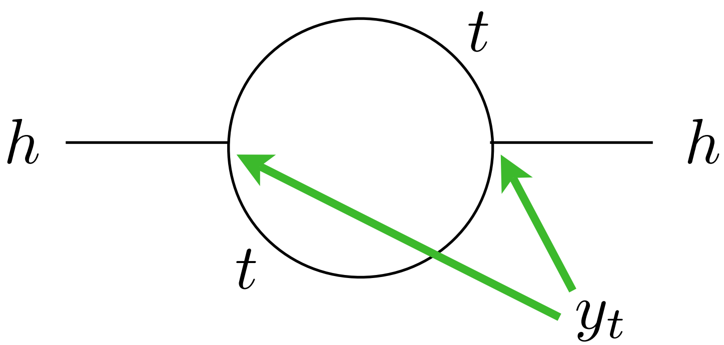
Top Loop Cancelation

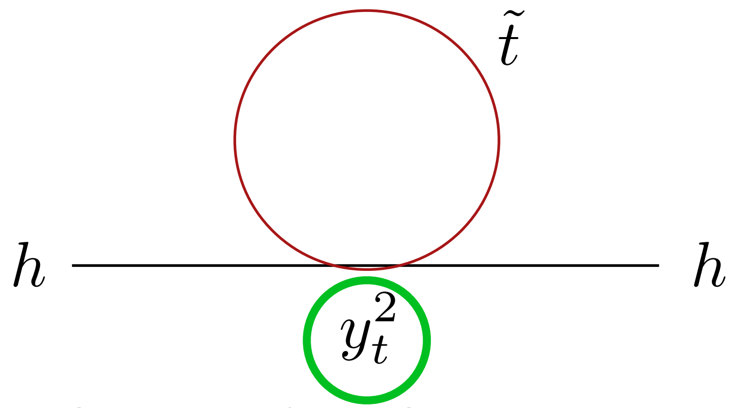




Exact supersymmetry - cancelation exact (up to w.f. ren.)

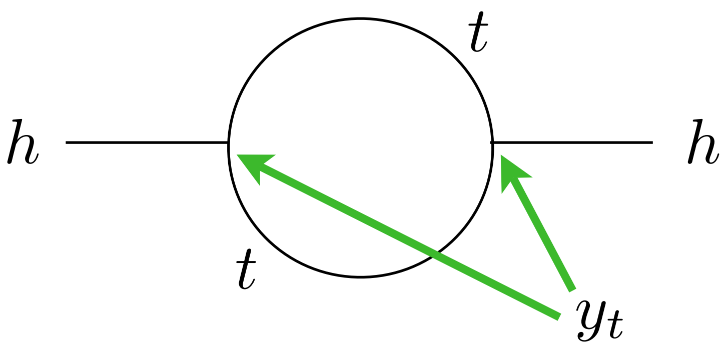
Top Loop Cancelation

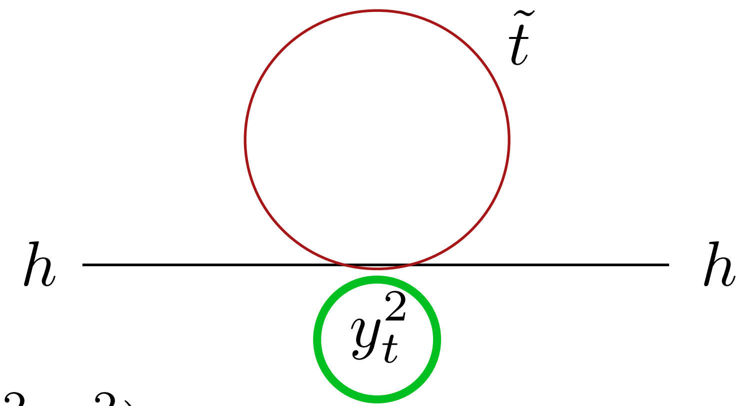




Exact supersymmetry - cancelation exact (up to w.f. ren.)

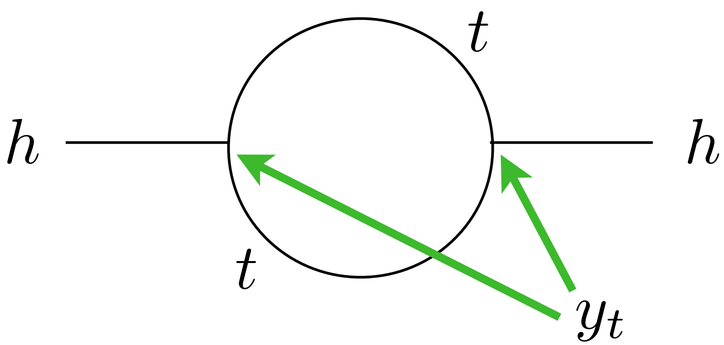
Top Loop Cancelation

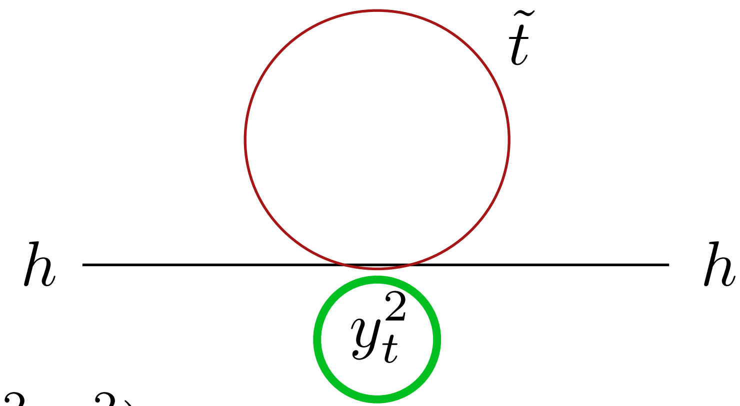




Broken SUSY $\delta m_h^2 = f(m_t^2, m_{\tilde{t}}^2, y_t^2)$

Top Loop Cancelation

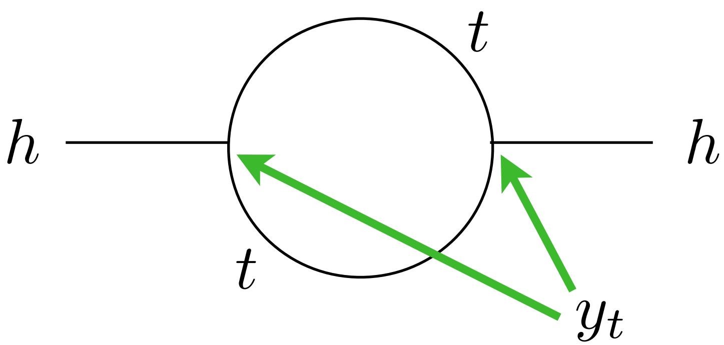


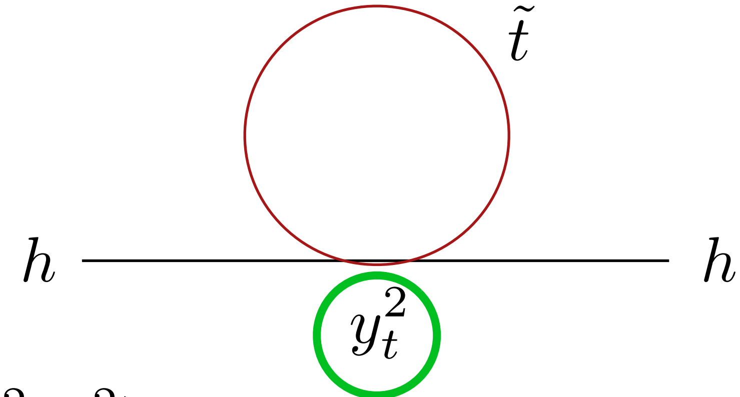


Broken SUSY $\quad \delta m_h^2 = f(m_t^2, m_{\tilde{t}}^2, y_t^2)$

$m_{\tilde{t}}^2 \neq m_t^2 \quad \rightarrow \quad \delta m_h^2 \propto (m_{\tilde{t}}^2 - m_t^2) \ln \Lambda$ Soft breaking

Top Loop Cancelation



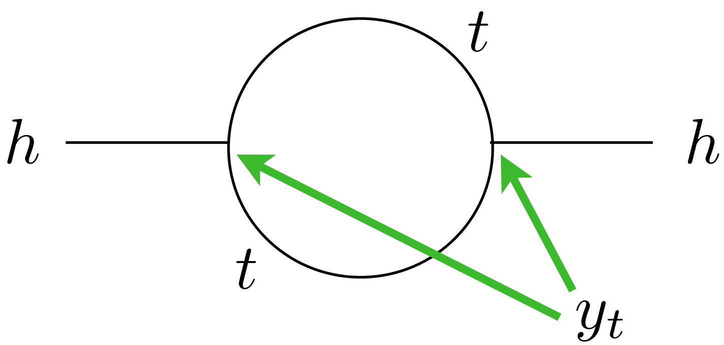


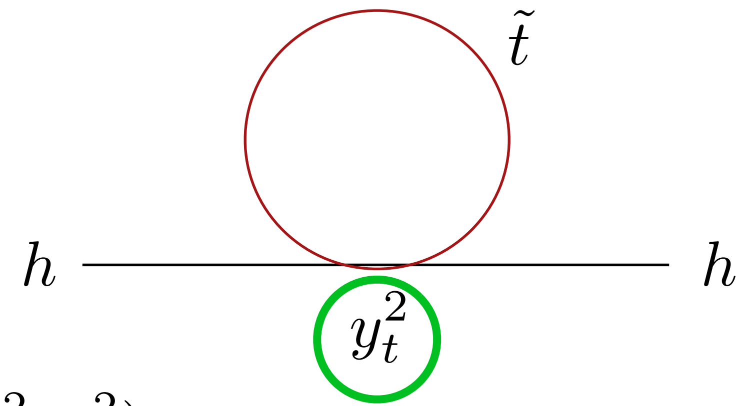
Broken SUSY $\delta m_h^2 = f(m_t^2, m_{\tilde{t}}^2, y_t^2)$

$m_{\tilde{t}}^2 \neq m_t^2 \quad \rightarrow \quad \delta m_h^2 \propto (m_{\tilde{t}}^2 - m_t^2) \ln \Lambda$ Soft breaking

$y_{\tilde{t}}^2 \neq y_t^2 \quad \rightarrow \quad \delta m_h^2 \propto (y_{\tilde{t}}^2 - y_t^2) \Lambda^2$ Hard breaking

Top Loop Cancelation





Broken SUSY $\qquad \delta m_h^2 = f(m_t^2, m_{\tilde{t}}^2, y_t^2)$

$m_{\tilde{t}}^2 \neq m_t^2 \quad \rightarrow \quad \delta m_h^2 \propto (m_{\tilde{t}}^2 - m_t^2) \ln \Lambda$ — Soft breaking

$y_{\tilde{t}}^2 \neq y_t^2 \quad \rightarrow \quad \delta m_h^2 \propto (y_{\tilde{t}}^2 - y_t^2) \Lambda^2$ — Hard breaking

remove the scalar top (“stop”) — Hard breaking

Number of Parameters

Masses for everybody.

- Scalar partners of LH fermions
- Scalar partners of RH fermions
- L-R masses after the Higgs gets a vev (A terms)
- Higgs mass parameters

Number of Parameters

Masses for everybody.

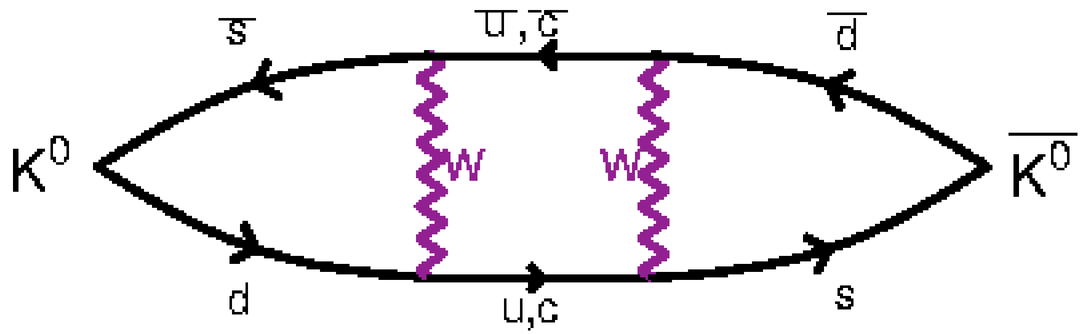
- Scalar partners of LH fermions
- Scalar partners of RH fermions
- L-R masses after the Higgs gets a vev (A terms)
- Higgs mass parameters

108 New Parameters (minus 1)

Parameters: Soft Masses

$$
\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} \;=\; & -\frac{1}{2}\left(M_3 \widetilde{g}\widetilde{g} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B} + {\rm c.c.} \right) \\
& -\left(\widetilde{\overline{u}}\, \mathbf{a_u}\, \widetilde{Q} H_u - \widetilde{\overline{d}}\, \mathbf{a_d}\, \widetilde{Q} H_d - \widetilde{\overline{e}}\, \mathbf{a_e}\, \widetilde{L} H_d + {\rm c.c.} \right) \\
& -\widetilde{Q}^\dagger\, \mathbf{m^2_Q}\, \widetilde{Q} - \widetilde{L}^\dagger\, \mathbf{m^2_L}\, \widetilde{L} - \widetilde{\overline{u}}\, \mathbf{m^2_{\overline{u}}}\, \widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\, \mathbf{m^2_{\overline{d}}}\, \widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\, \mathbf{m^2_{\overline{e}}}\, \widetilde{\overline{e}}^\dagger \\
& - m^2_{H_u} H_u^* H_u - m^2_{H_d} H_d^* H_d - (b H_u H_d + {\rm c.c.}) \,.
\end{aligned}
$$

Flavor Constraints



$\sim m_c^2$

Small in the standard model because the CKM matrix is unitary

$$V_{ud}^* V_{us} + V_{cd}^* V_{cs} + V_{td}^* V_{ts} = 0$$

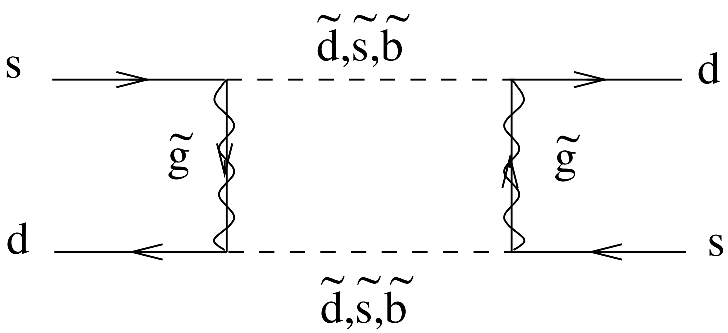
Soft Masses and Flavor

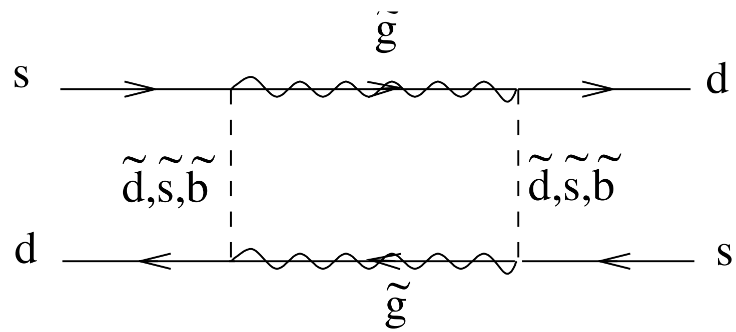
$$\begin{pmatrix} \tilde{d} & \tilde{s} & \tilde{b} \end{pmatrix}^* \cdot \begin{pmatrix} \tilde{m}^2_{dd} & \tilde{m}^2_{ds} & \tilde{m}^2_{db} \\ \tilde{m}^2_{sd} & \tilde{m}^2_{ss} & \tilde{m}^2_{sb} \\ \tilde{m}^2_{bd} & \tilde{m}^2_{bs} & \tilde{m}^2_{bb} \end{pmatrix} \cdot \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix}$$

Soft Masses and Flavor

$$\begin{pmatrix} \tilde{d} & \tilde{s} & \tilde{b} \end{pmatrix}^* \cdot \begin{pmatrix} \tilde{m}^2_{dd} & \tilde{m}^2_{ds} & \tilde{m}^2_{db} \\ \tilde{m}^2_{sd} & \tilde{m}^2_{ss} & \tilde{m}^2_{sb} \\ \tilde{m}^2_{bd} & \tilde{m}^2_{bs} & \tilde{m}^2_{bb} \end{pmatrix} \cdot \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix}$$

$$\frac{m^2_{\tilde{d}\tilde{s}}}{m^2_{\tilde{s}\tilde{s}}} < few \times 10^{-4} \quad \text{for} \quad m^2_{\tilde{q}} = 500\,\text{GeV}$$



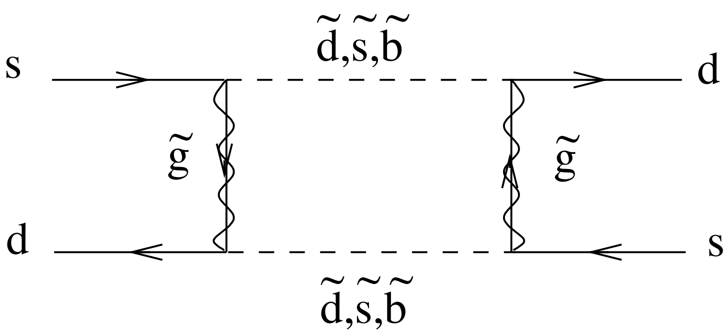


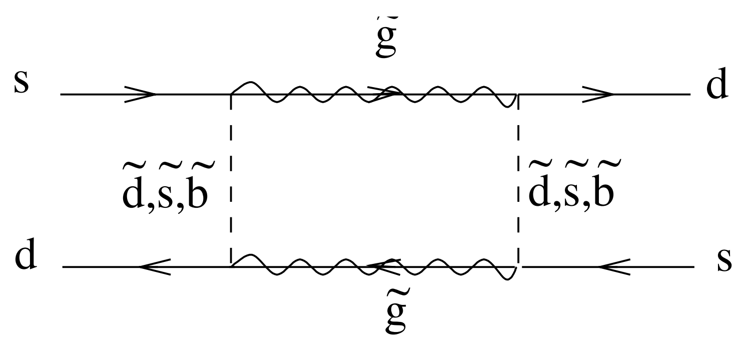
Soft Masses and Flavor

Important because standard model process is also a loop

The problem goes away if the scalar masses are degenerate.

$$\frac{m^2_{\tilde{d}\tilde{s}}}{m^2_{\tilde{s}\tilde{s}}} < few \times 10^{-4} \qquad \text{for} \qquad m^2_{\tilde{q}} = 500\,\text{GeV}$$





Soft Masses

$$
\begin{aligned}
\mathcal{L}_{\text{soft}}^{\text{MSSM}} \;=\; & -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
& -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\
& -\widetilde{Q}^\dagger\,\mathbf{m_Q^2}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m_L^2}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m_{\overline{u}}^2}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m_{\overline{d}}^2}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m_{\overline{e}}^2}\,\widetilde{\overline{e}}^\dagger \\
& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + \text{c.c.})\,.
\end{aligned}
$$

Soft Masses

$$
\begin{aligned}
\mathcal{L}_{\text{soft}}^{\text{MSSM}} \;=\; & -\frac{1}{2}\left(M_3 \widetilde{g}\widetilde{g} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
& -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\
& -\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger \\
& - m^2_{H_u} H_u^* H_u - m^2_{H_d} H_d^* H_d - (bH_uH_d + \text{c.c.}) \,.
\end{aligned}
$$

single
parameters
times the
identity
matrix

Soft Masses

proportional
to Yukawa
couplings

$$
\begin{aligned}
\mathcal{L}^{\rm MSSM}_{\rm soft} = & -\frac{1}{2}\left(M_3 \widetilde{g}\widetilde{g} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
& - \left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\
& -\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger \\
& - m^2_{H_u} H_u^* H_u - m^2_{H_d} H_d^* H_d - (b H_u H_d + \text{c.c.})\,.
\end{aligned}
$$

single
parameters
times the
identity
matrix

$$\mathbf{a_u} = \mathbf{y_u}\, A_u$$

Simplified Parameter Space

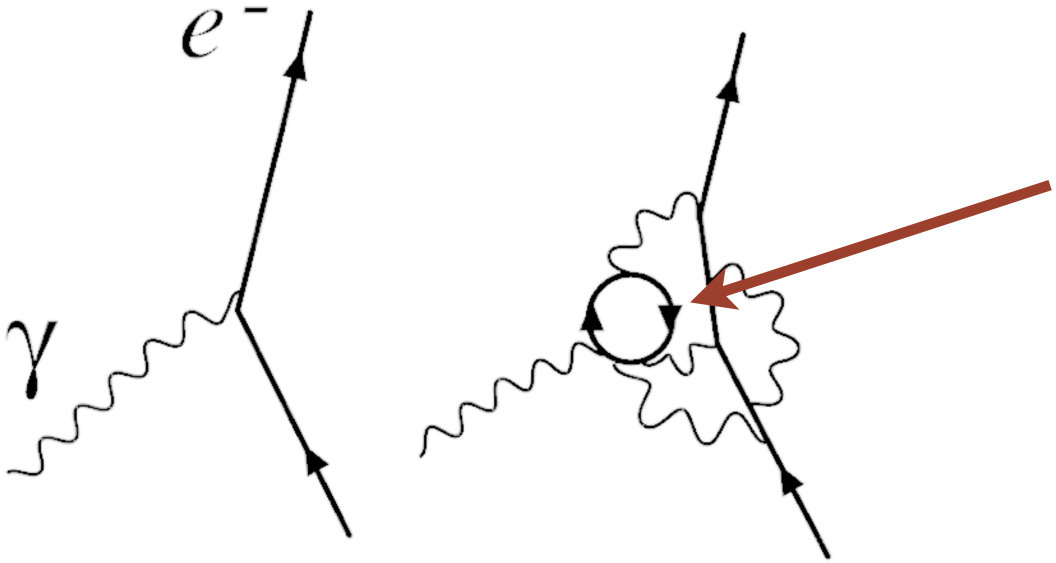
gaugino masses: $M_{1,2,3}$
squarks and sleptons: $m_{q,u,d,l,e}$
scalar^3 : $A_{u,d,l}$
higgs masses: $m_{1,2}$ & b

All real: 14 parameters (mu is exchanged for the Z-mass)
b can be exchanged for $\tan\beta$

Sign of mu remains

Interlude: Unification

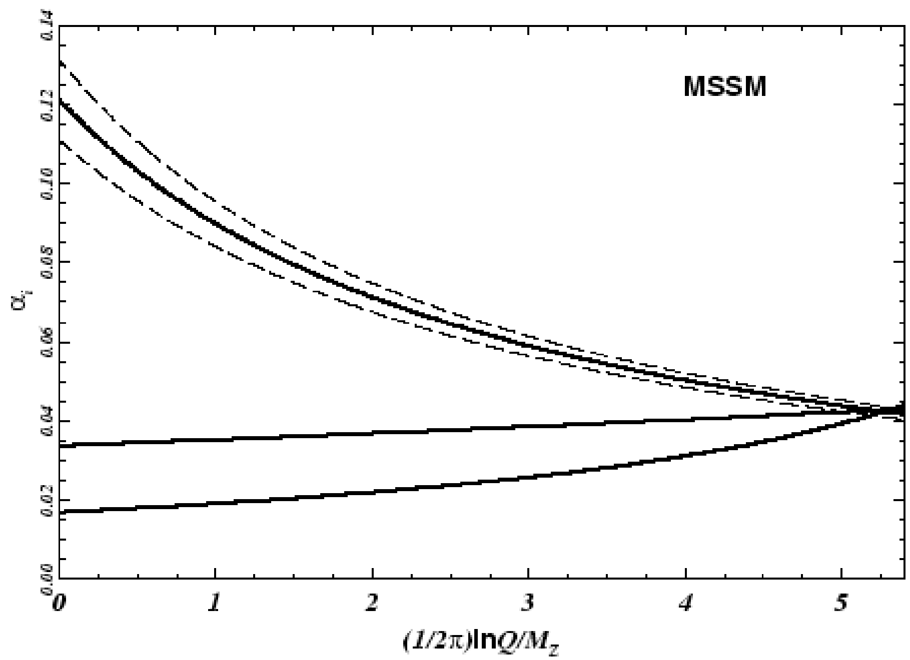
Renormalizing Couplings



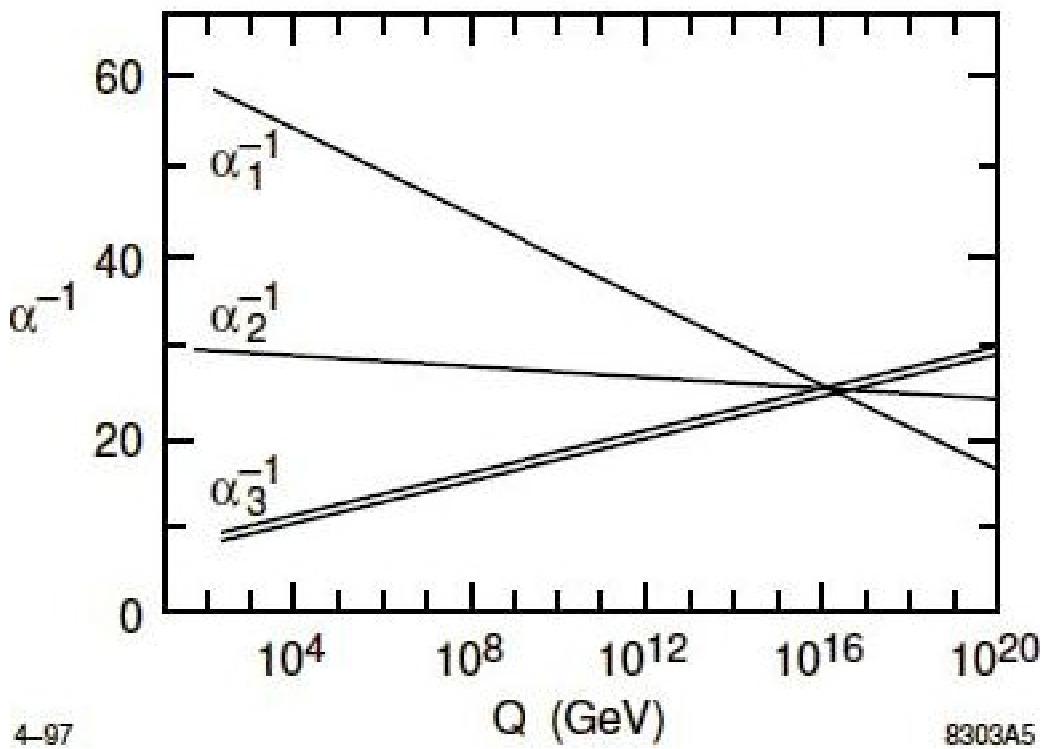
new particles could run in this loop if they were lighter than the Z boson

$$\alpha(1\,\mathrm{eV}) \simeq \frac{1}{137} \qquad \alpha(M_Z) \simeq \frac{1}{128}$$

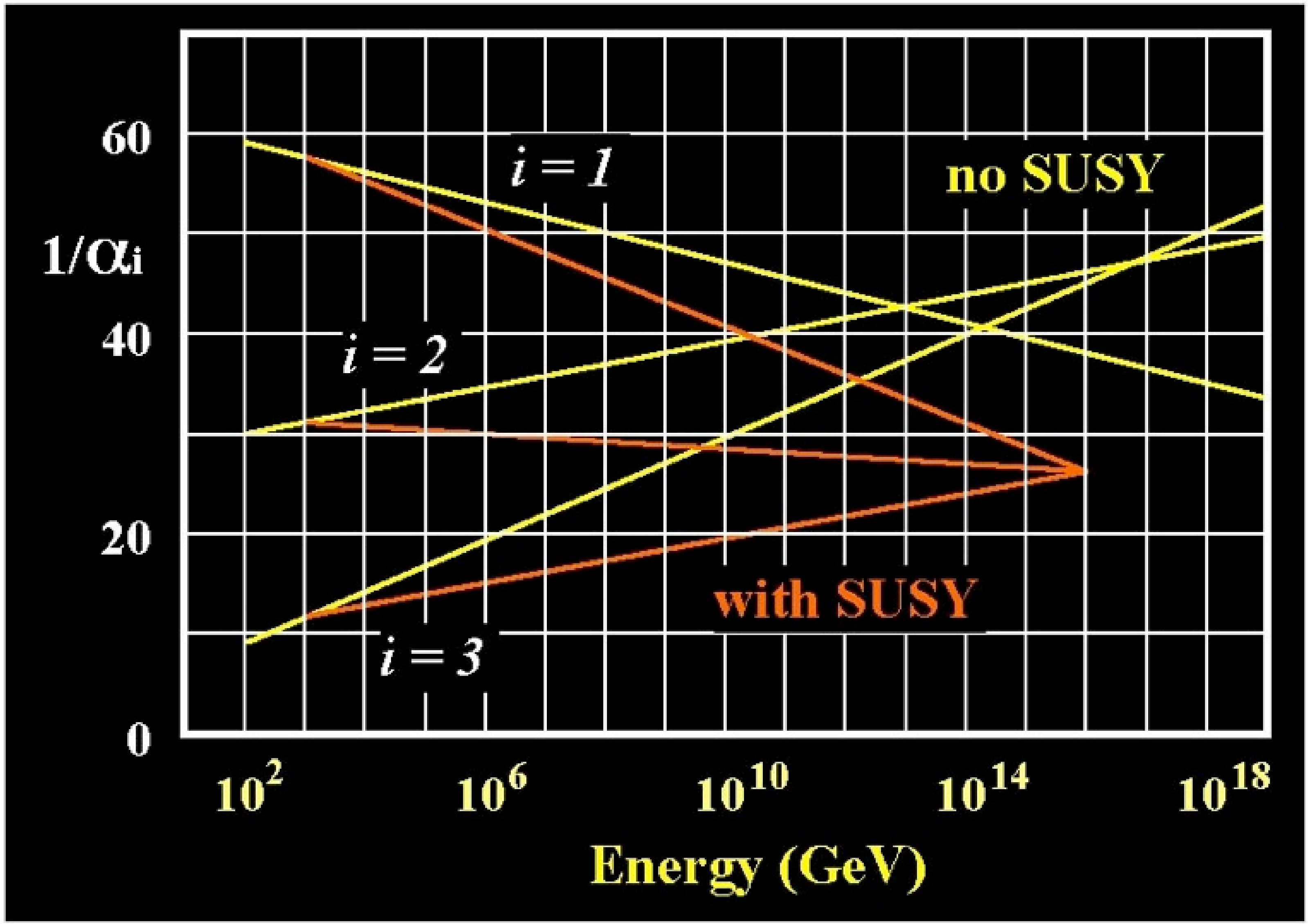
Running Gauge Couplings



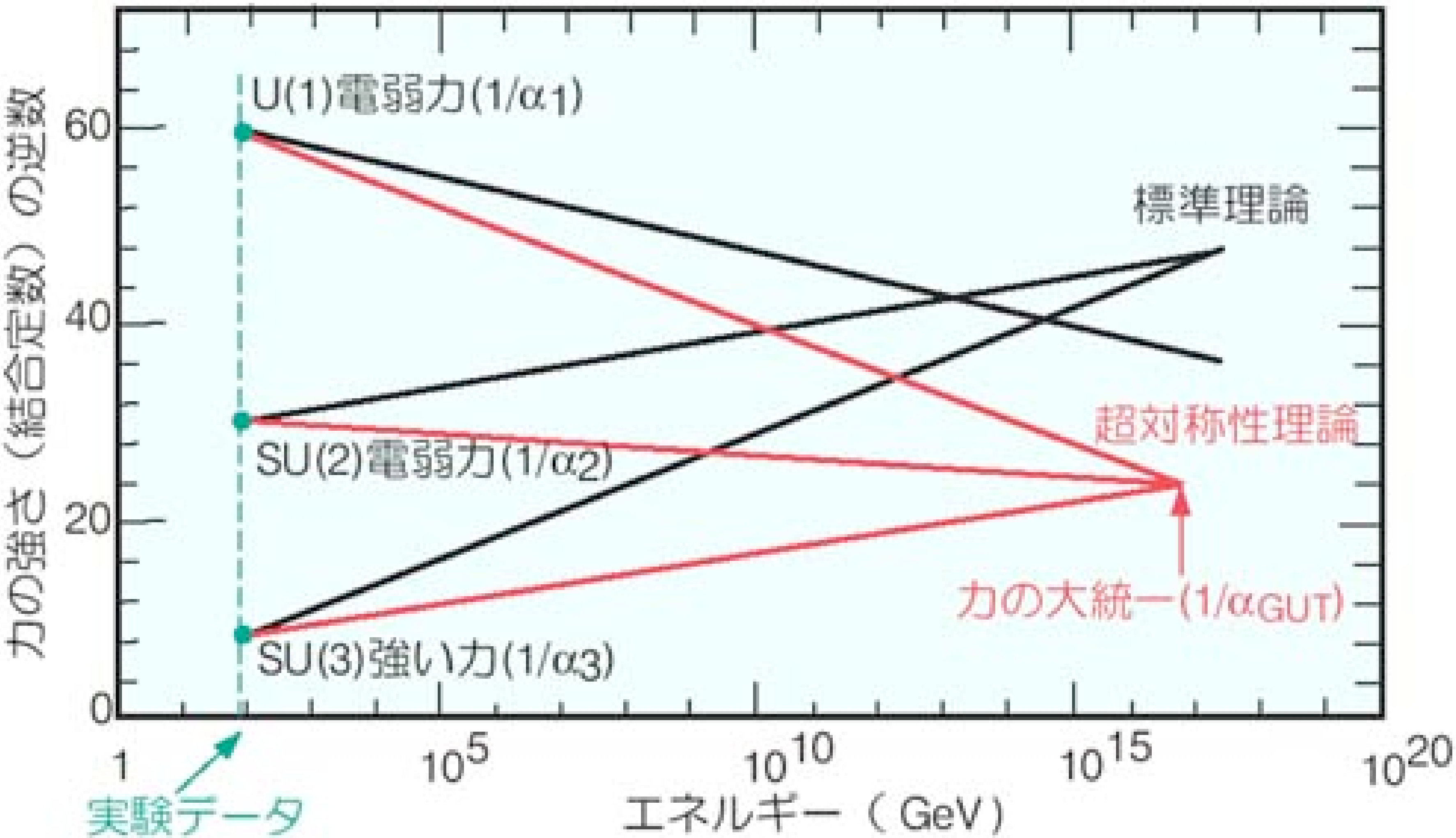
Running Gauge Couplings



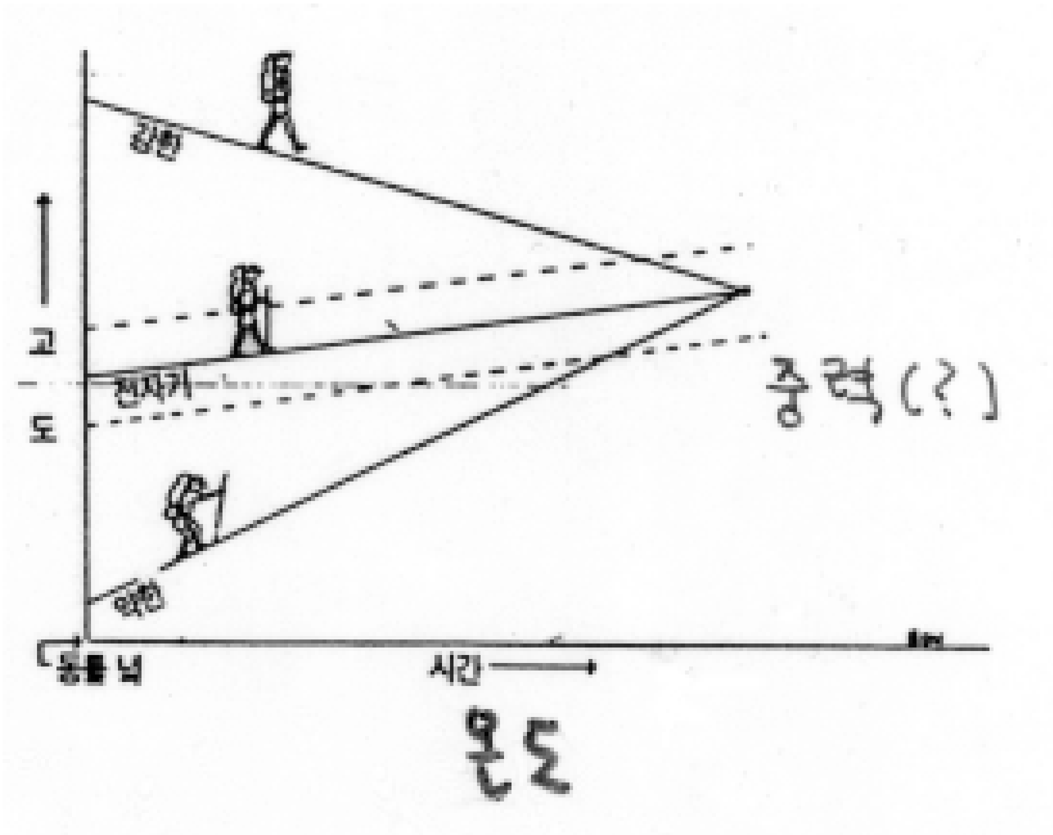
Running Gauge Couplings



Running Gauge Couplings



Running Gauge Couplings



Simplification or Model

Pick a universal mass for all scalar partners, and another for all gauginos.

mSUGRA

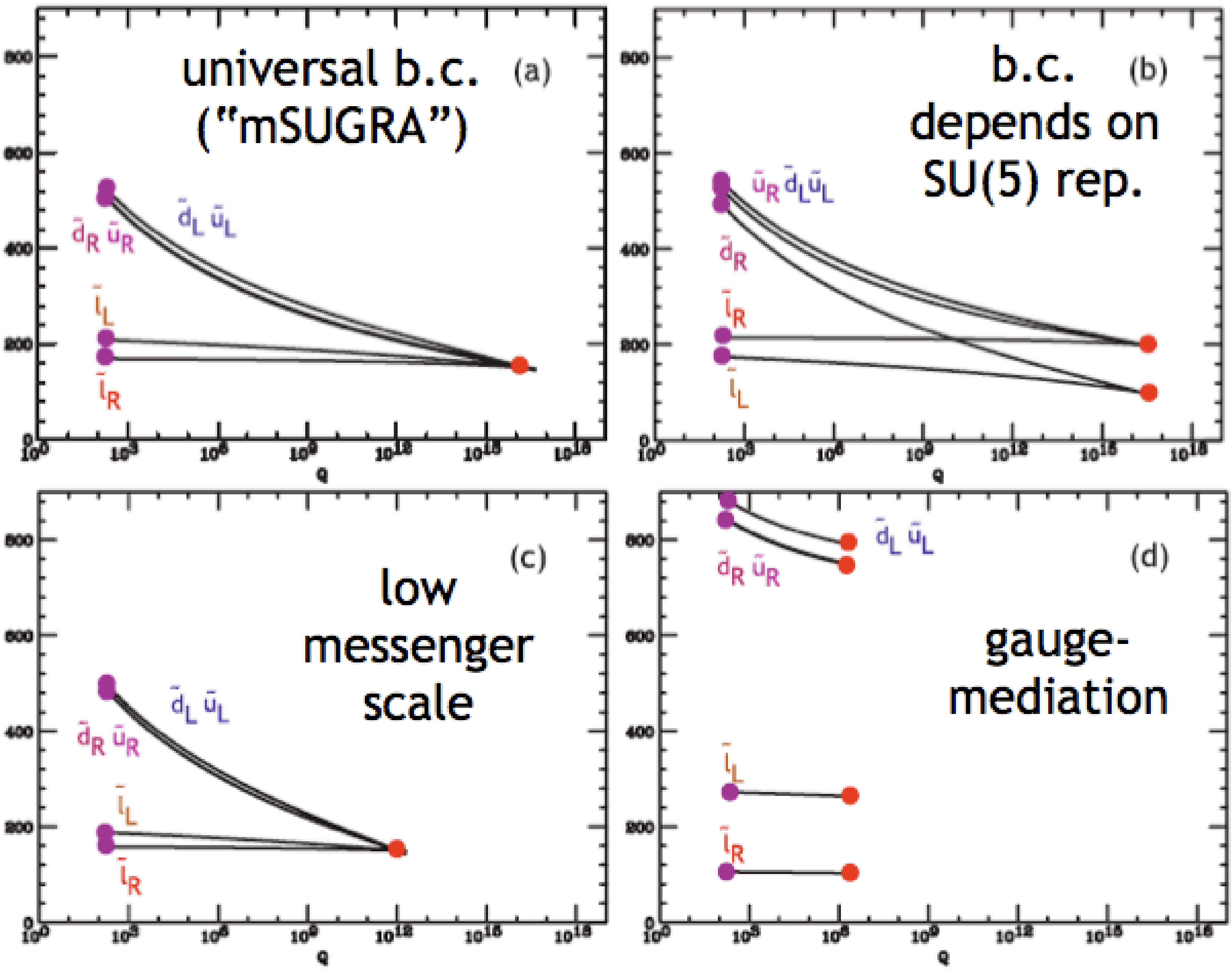
$$m_0, M_{1/2}, A, \tan\beta,\ \mathrm{sgn}(\mu)$$

Models that automatically solve the flavor problem

- Gauge Mediation: 3.5
- Anomaly Mediation: 2.5-5.5
- Gaugino Mediation: 1.5-4.5
- ...

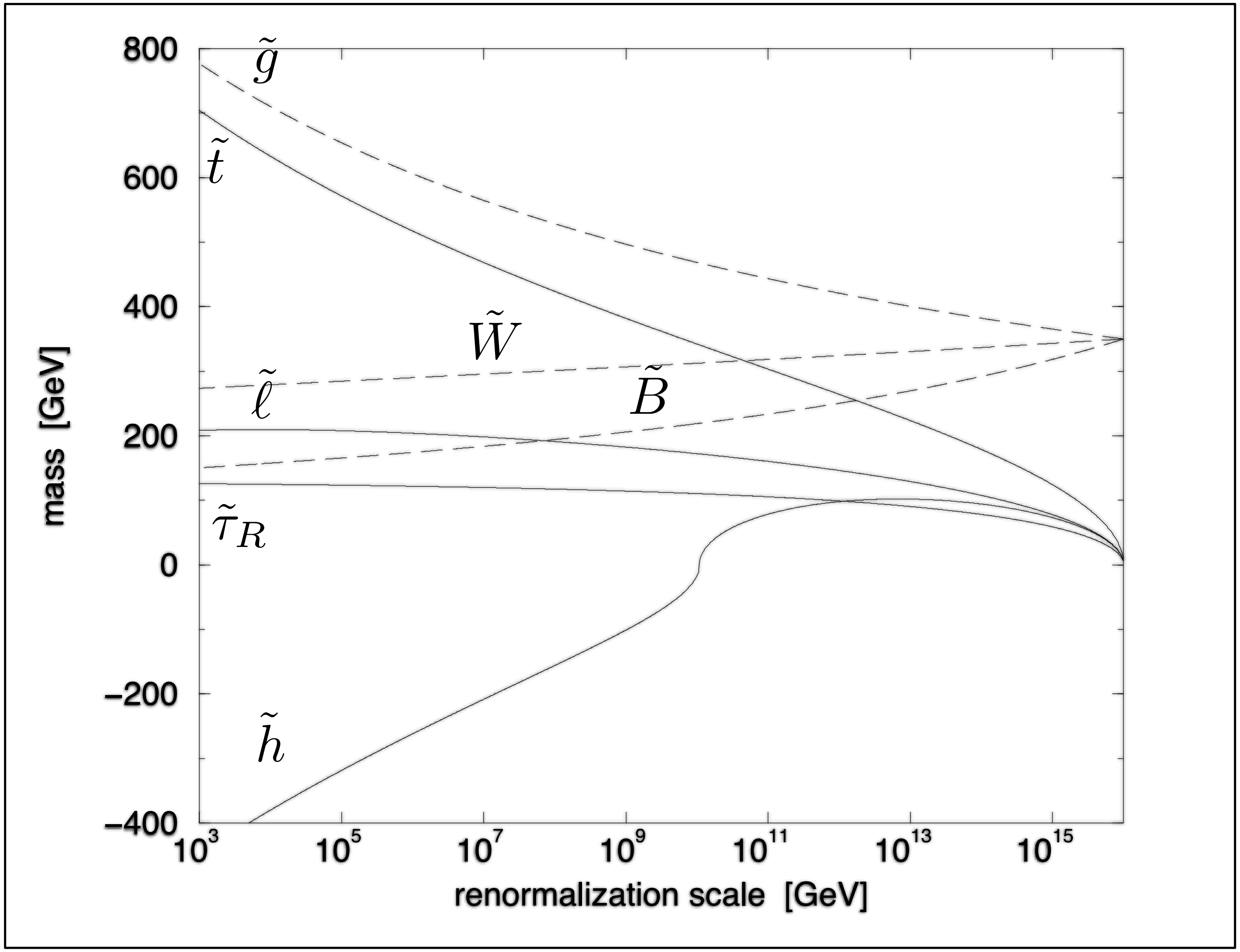
Simplified parameter spaces

Typical Spectra

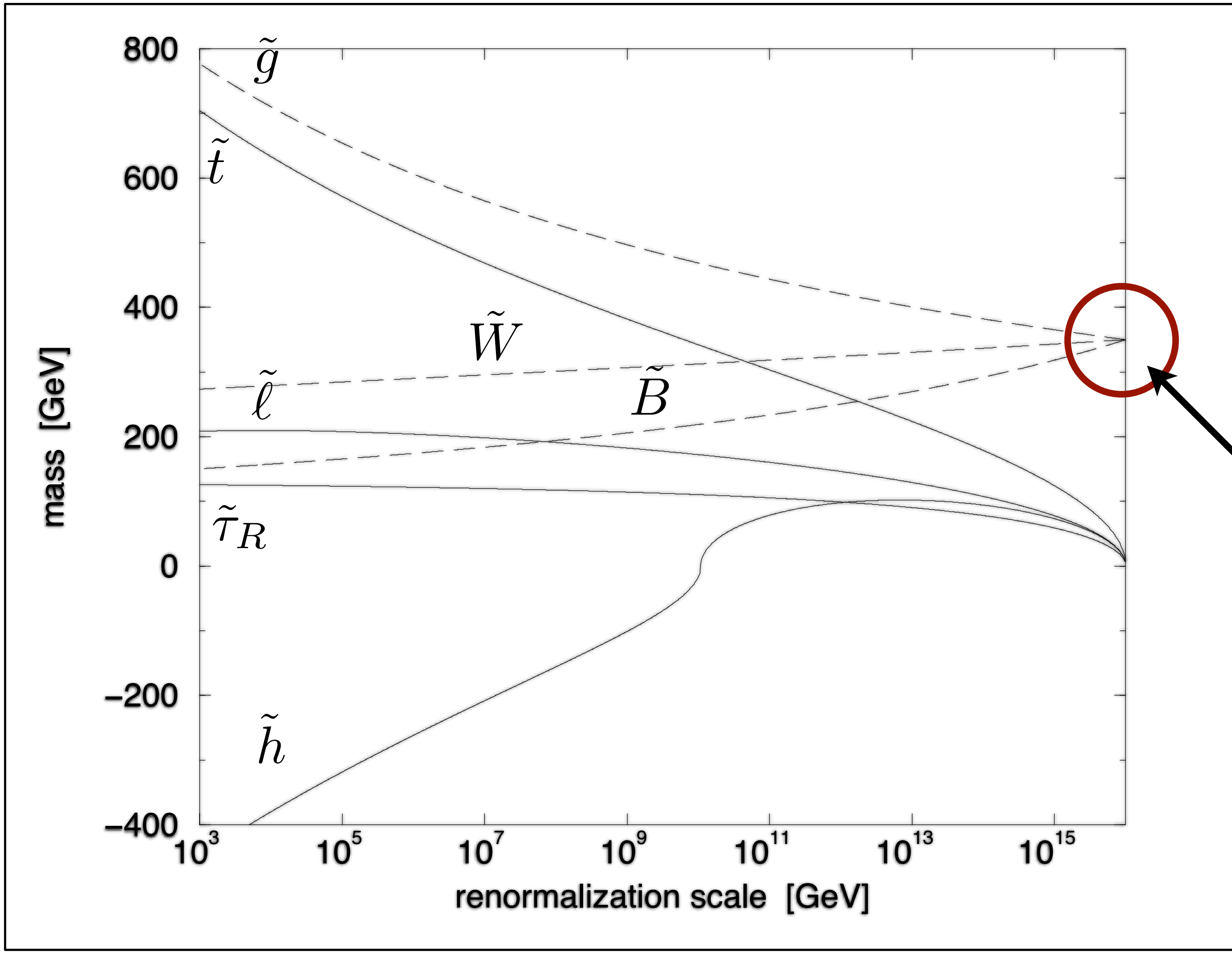


M. Peskin

Scalars Driven by Gauginos



Scalars Driven by Gauginos



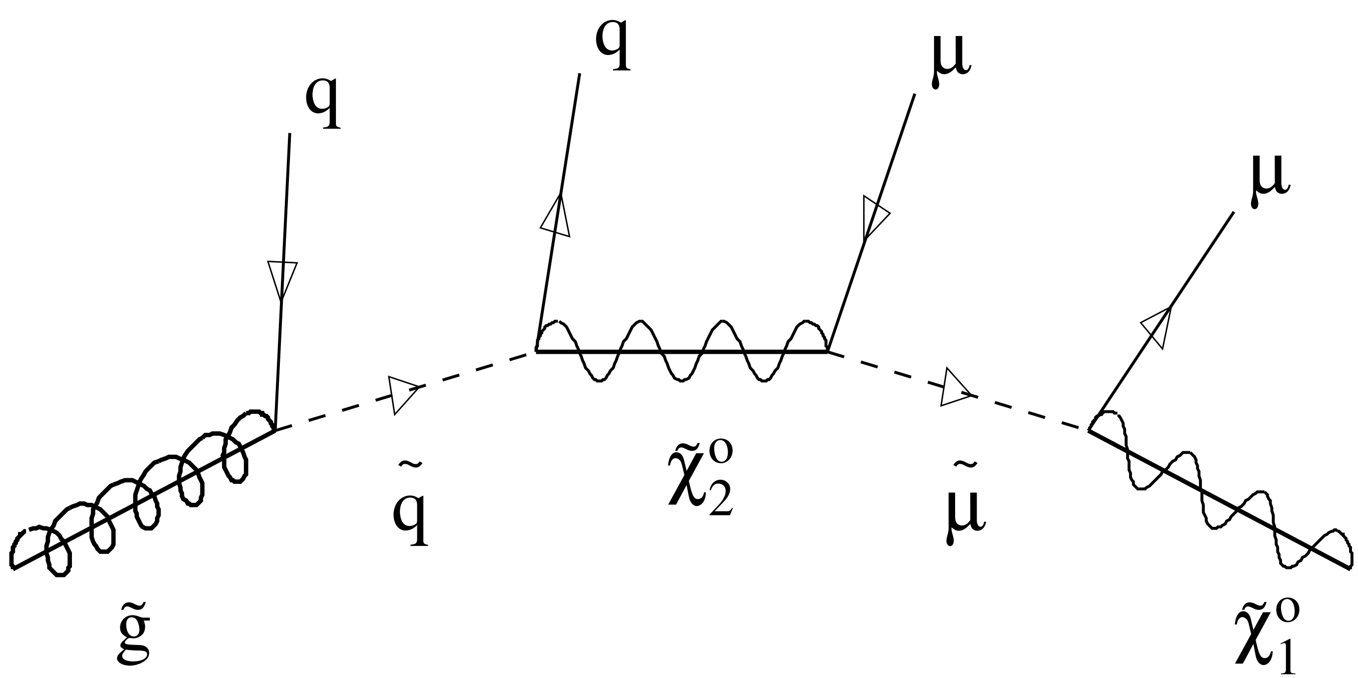
assume unified

Cascades

Goal: SUSY spectra via cascade decay kinematics

e.g. $\tilde{g} \to \tilde{q}\bar{q} \to \chi_2^0 q\bar{q} \to \mu^+\mu^- q\bar{q}\chi_1^0$

for $m_{\tilde{g}} > m_{\tilde{q}}$

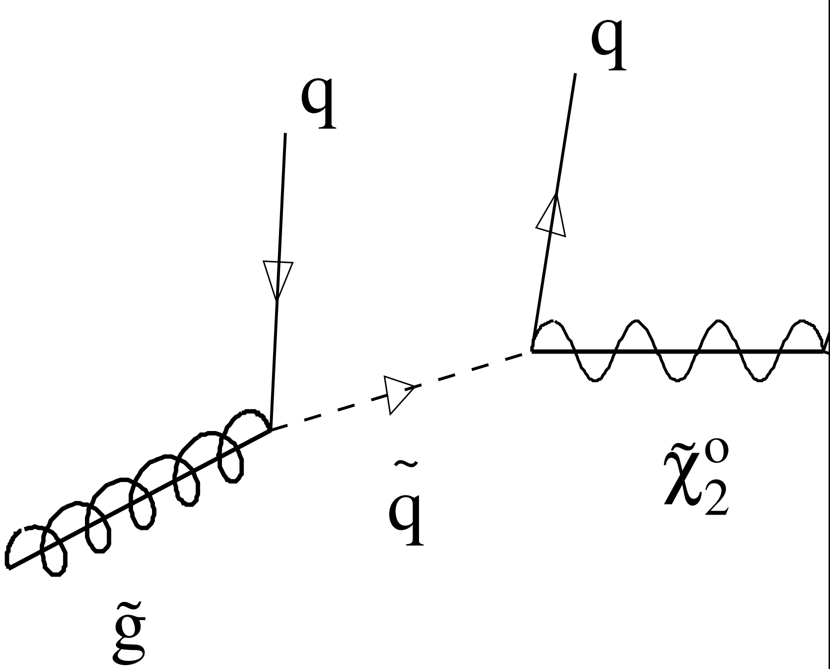


Cascades

Goal: SUSY spectra via cascade decay kinematics

e.g. $\tilde{g} \rightarrow \tilde{q}\bar{q} \rightarrow \chi_2^0 q\bar{q} \rightarrow \mu^+\mu^- q\bar{q}\chi_1^0$

for $m_{\tilde{g}} > m_{\tilde{q}}$



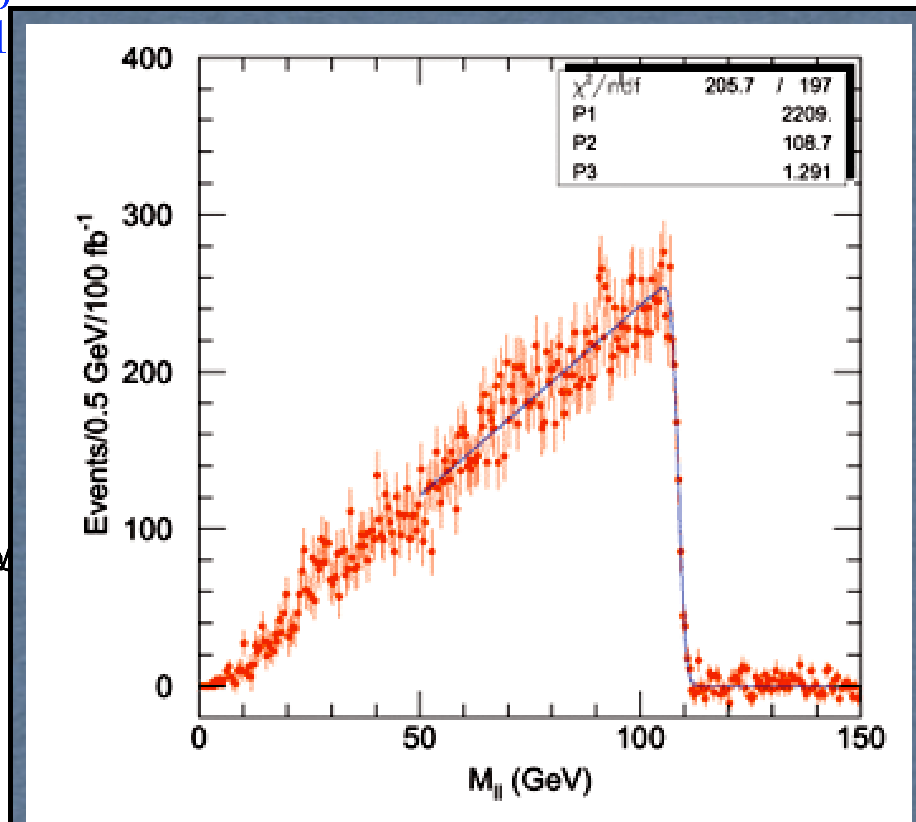
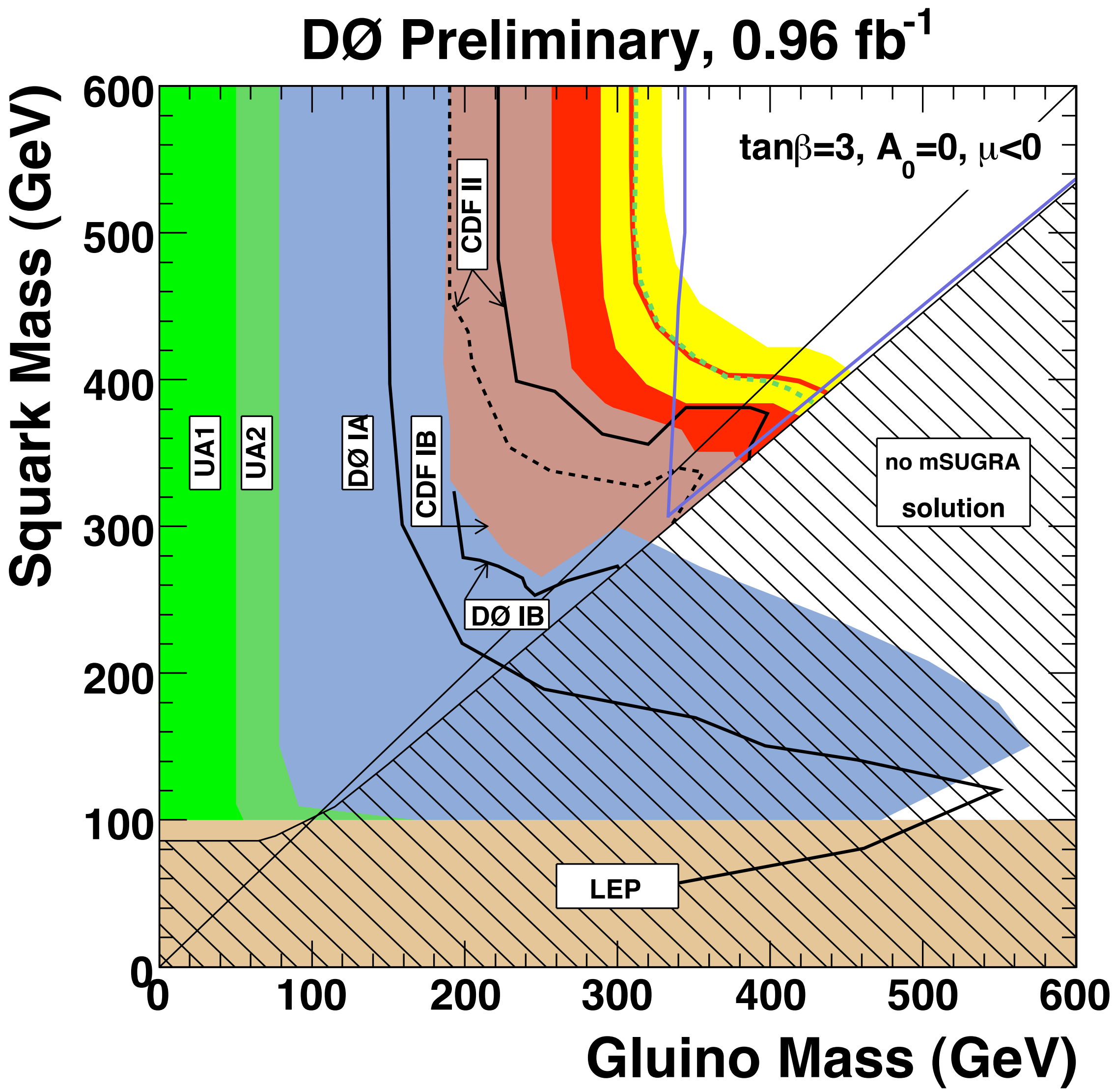
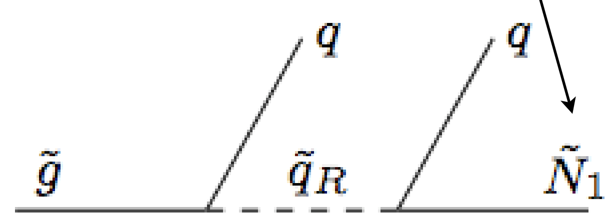


Figure 9. Dilepton kinematic edge in $\tilde{\chi}_2^0$ decay (Atlas TDR).

Squarks/Gluinos

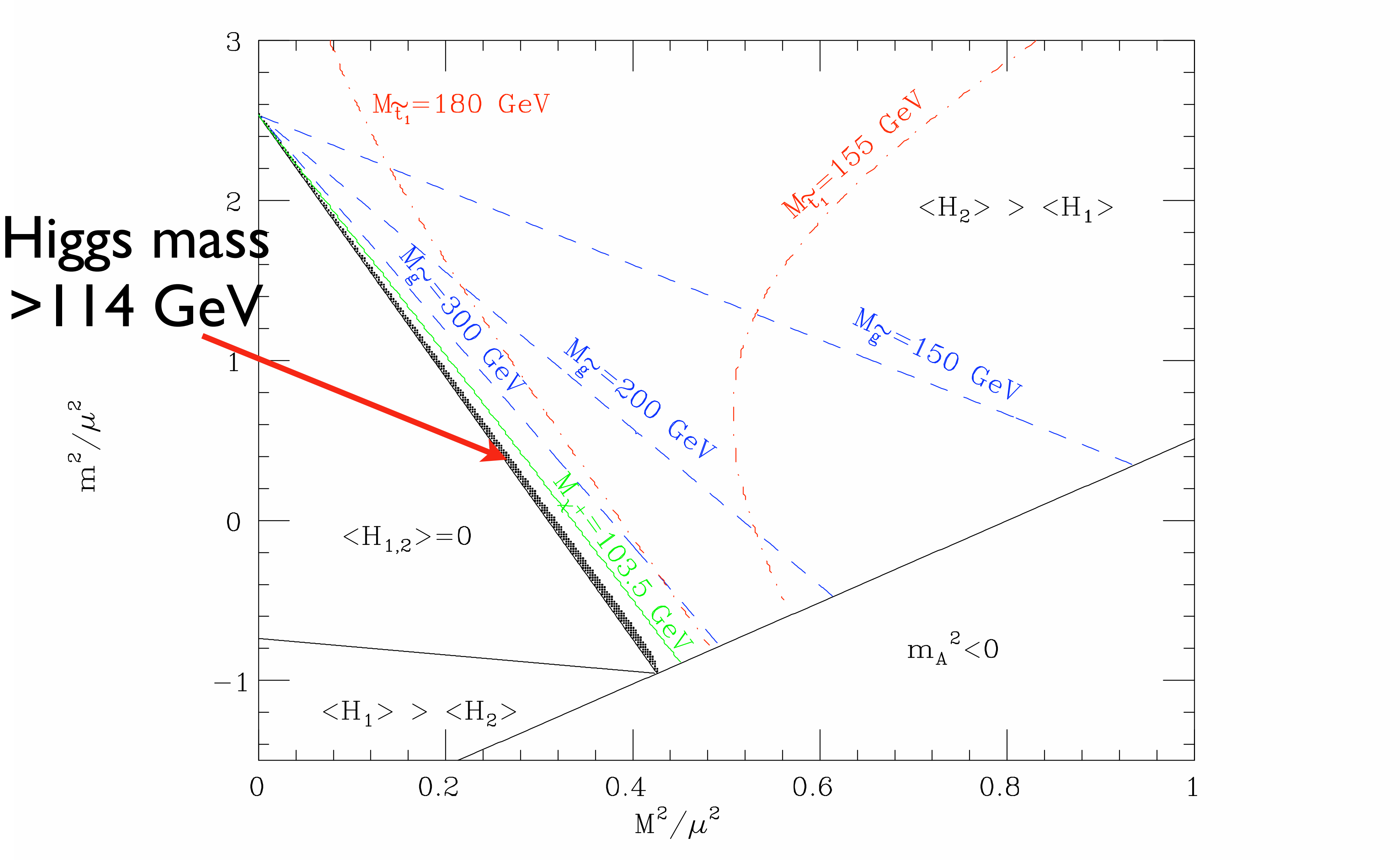


Jets + missing E_T



Unfortunately, mSUGRA
is a bit unNatural

State of mSUGRA



Giudice, Rattazzi '06

Problem with Higgs

$$\lambda|h|^4 \to \frac{g^2}{8}\left[|H_1|^2 - |H_2|^2\right]^2$$

$$m_h = M_Z|\cos 2\beta|$$

$$(m_h^2)_{tree} + \delta m_h^2 > (114\,\mathrm{GeV})^2$$

(Big Susy-breaking in top sector)

Problem with Higgs

$$\lambda|h|^4 \rightarrow \frac{g^2}{8}\left[|H_1|^2 - |H_2|^2\right]^2$$

$$m_h = M_Z|\cos 2\beta|$$

$$(m_h^2)_{tree} + \delta m_h^2 > (114\,\mathrm{GeV})^2$$

(Big Susy-breaking in top sector)

New tree-level contribution requires new fields:

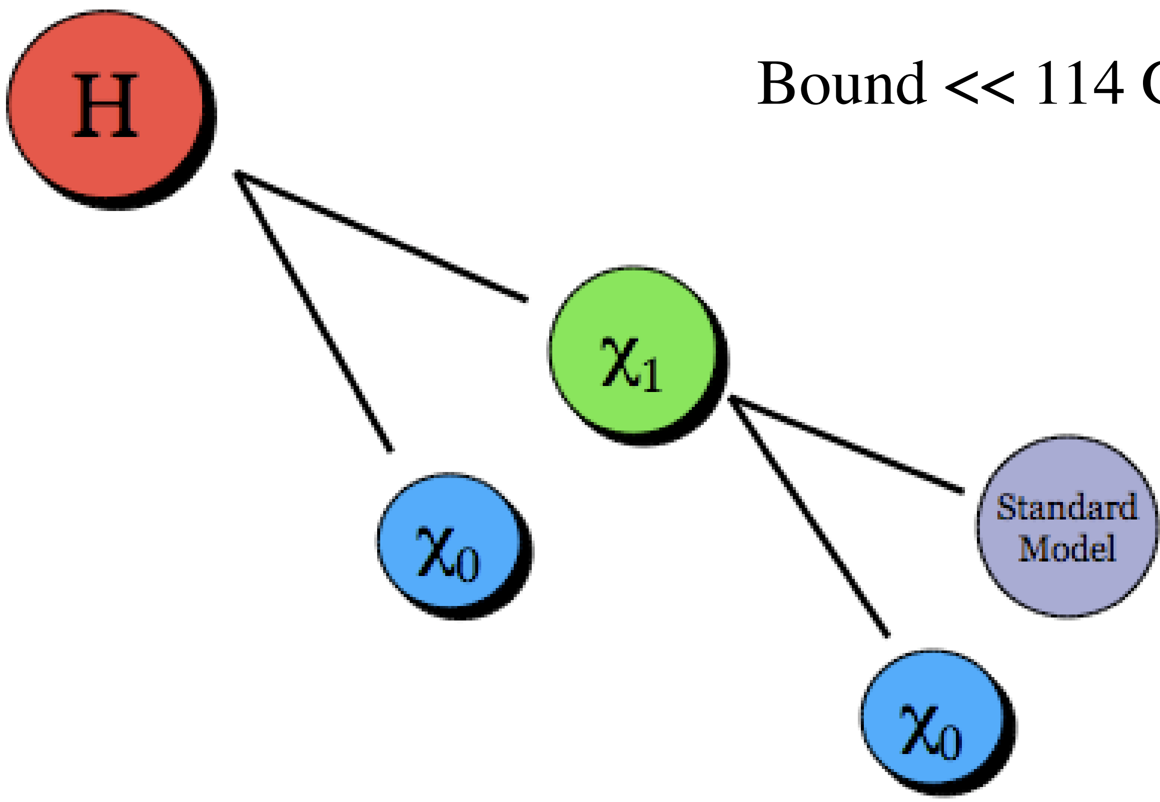
$$W = ySH_1H_2 \;\rightarrow\; y^2\,|H_1H_2|^2$$

Adding a Singlet

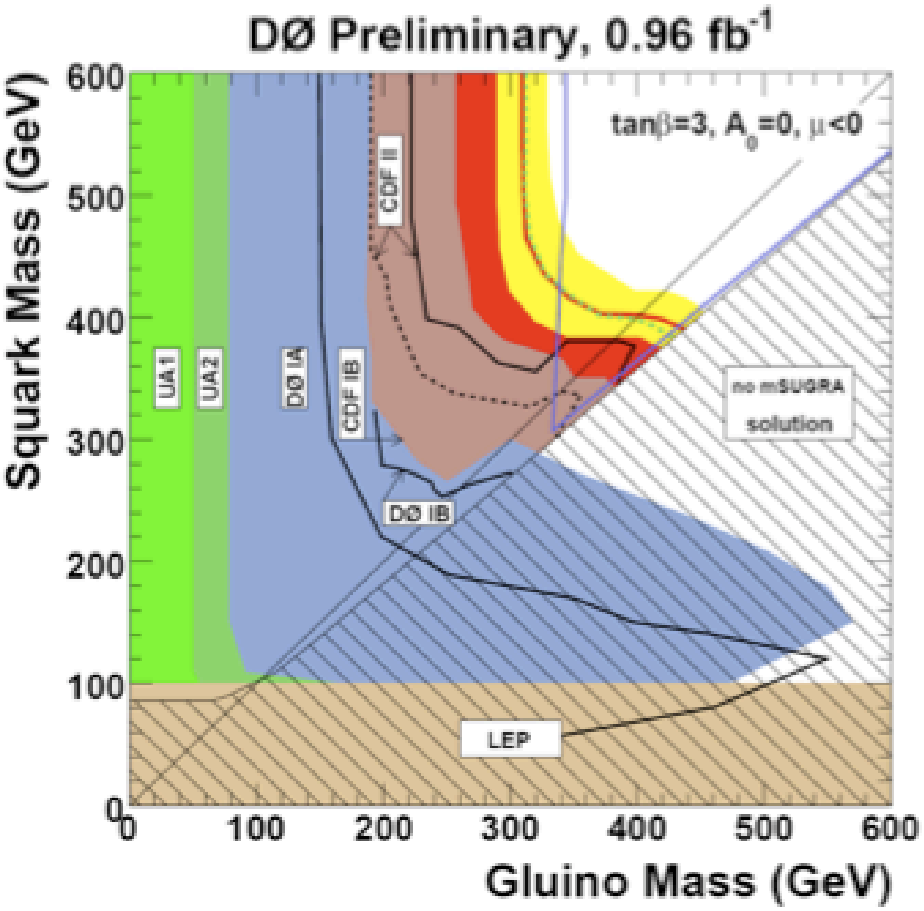
$$W = \lambda \hat{H}_u \hat{H}_d \hat{S} + \frac{\kappa}{3} \hat{S}^3$$

$$\mathbf{M}_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -g' v_d/\sqrt{2} & g' v_u/\sqrt{2} & 0 \\ 0 & M_2 & g v_d/\sqrt{2} & -g v_u/\sqrt{2} & 0 \\ -g' v_d/\sqrt{2} & g v_d/\sqrt{2} & 0 & -\lambda s & -\lambda v_u \\ g' v_u/\sqrt{2} & -g v_u/\sqrt{2} & -\lambda s & 0 & -\lambda v_d \\ 0 & 0 & -\lambda v_u & -\lambda v_d & 2\kappa s \end{pmatrix}$$

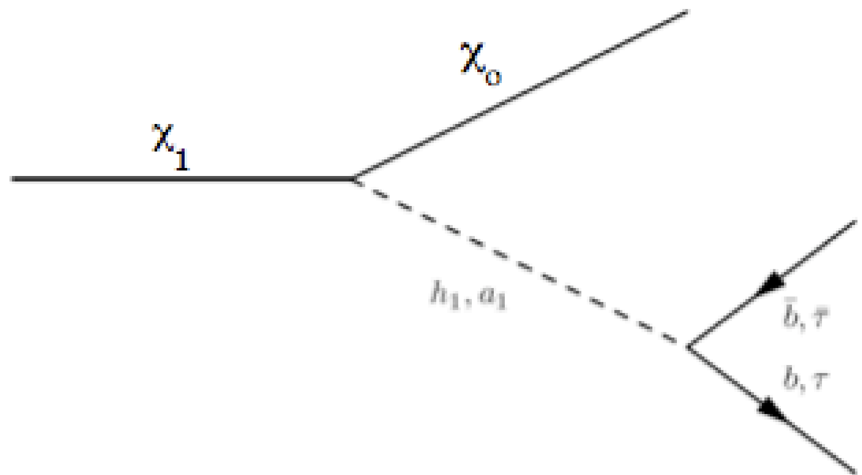
Higgs to Neutralinos



Bound << 114 GeV ??



Missing Energy signature suppressed, e.g.



As m_a approaches m_{χ_1}, missing energy is reduced

Spectrum deviations

Add a light singlet and the squark bounds reduce by ~100 GeV

Chang, Fox, Weiner - in progress

Change gaugino mass relations and a 70 GeV gluino may be allowed

Wacker, et al - in progress

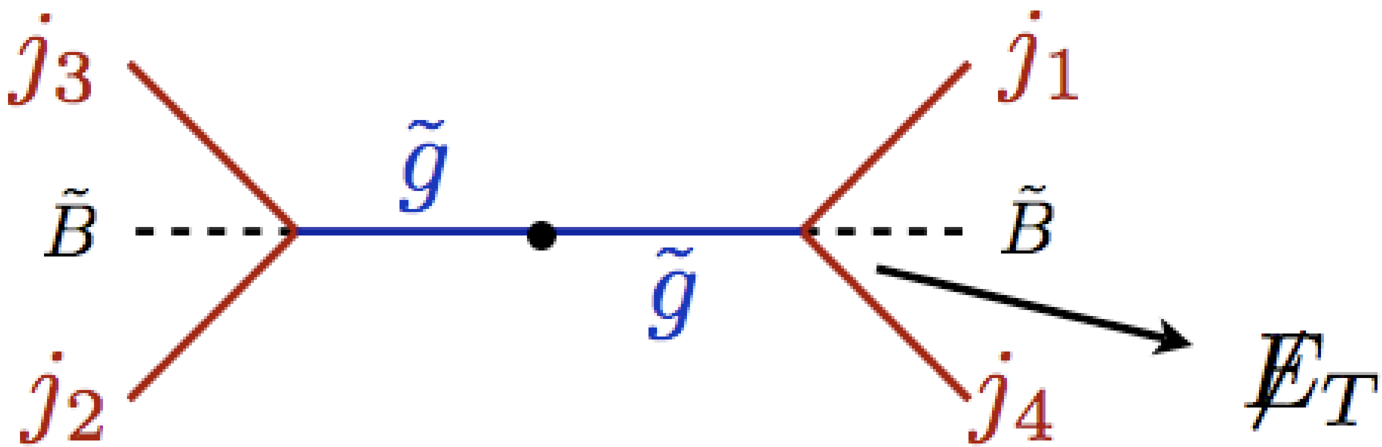
Gaugino Mass Ratio

$$M_3 : M_2 : M_1 \simeq 7 : 2 : 1$$

What if, for example, $M_2 > M_3 \gtrsim M_1$?

Generalizing the Ratio

What if, for example, $M_2 > M_3 \gtrsim M_1$?



$Q = M_{\tilde{g}} - M_{\tilde{B}}$

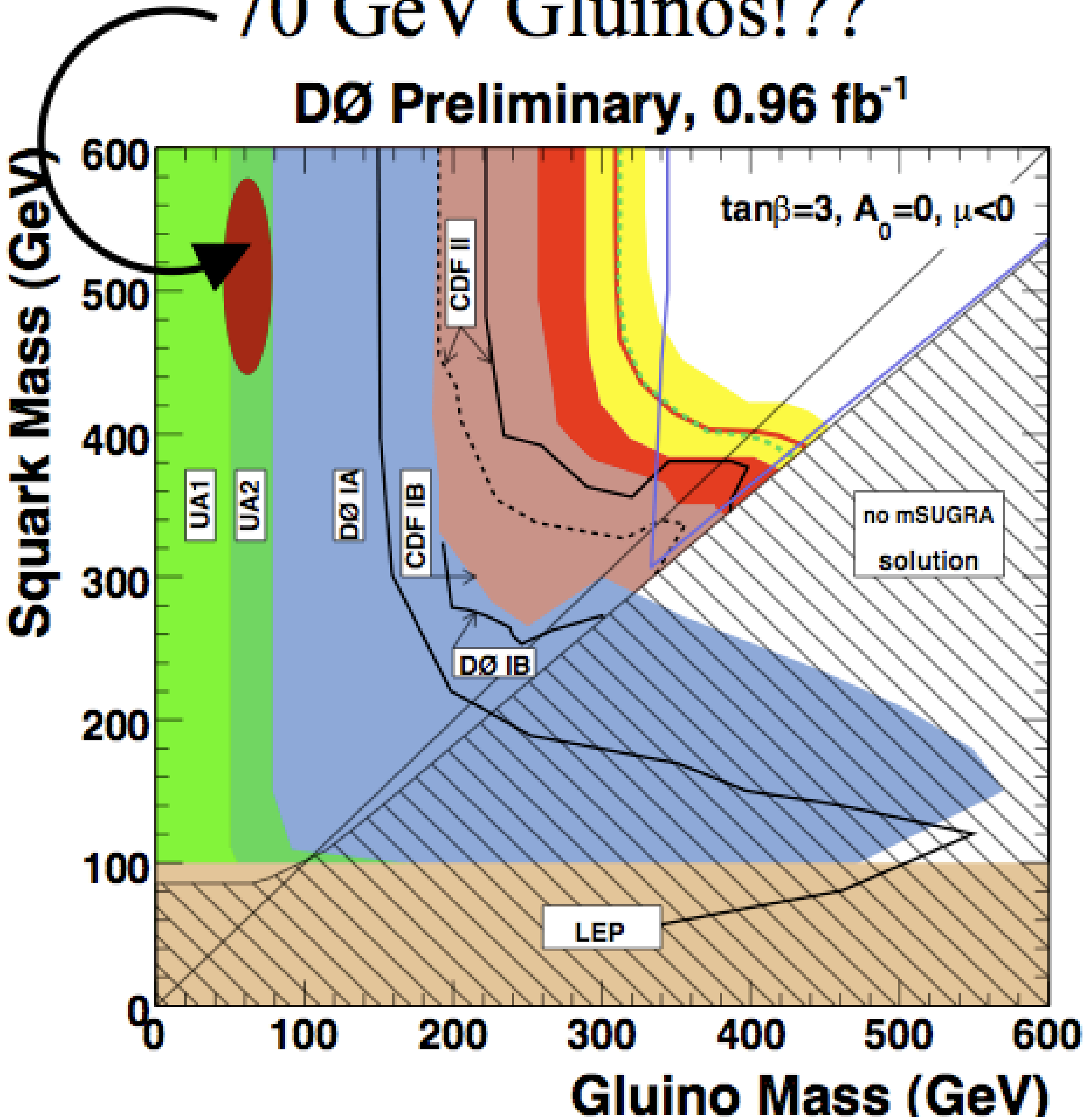
If $Q < M_{\tilde{B}}$

Bino carries away energy but not momentum

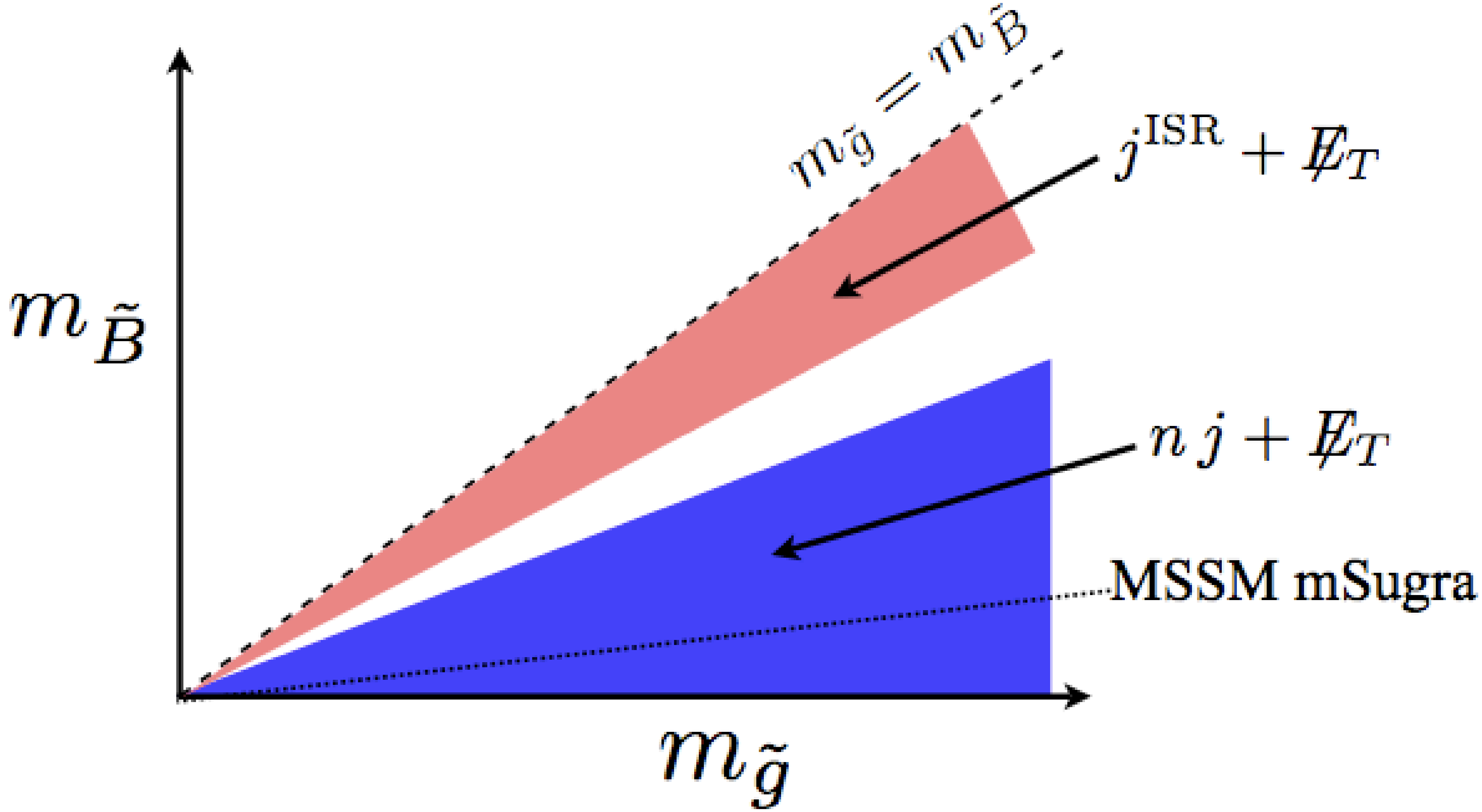
$$\not{E}_T \sim \frac{Q^2}{M_{\tilde{B}}}$$

Take $M_{\tilde{B}} = 60$ GeV...

70 GeV Gluinos!??



Preferred Bino/Gluino Plot

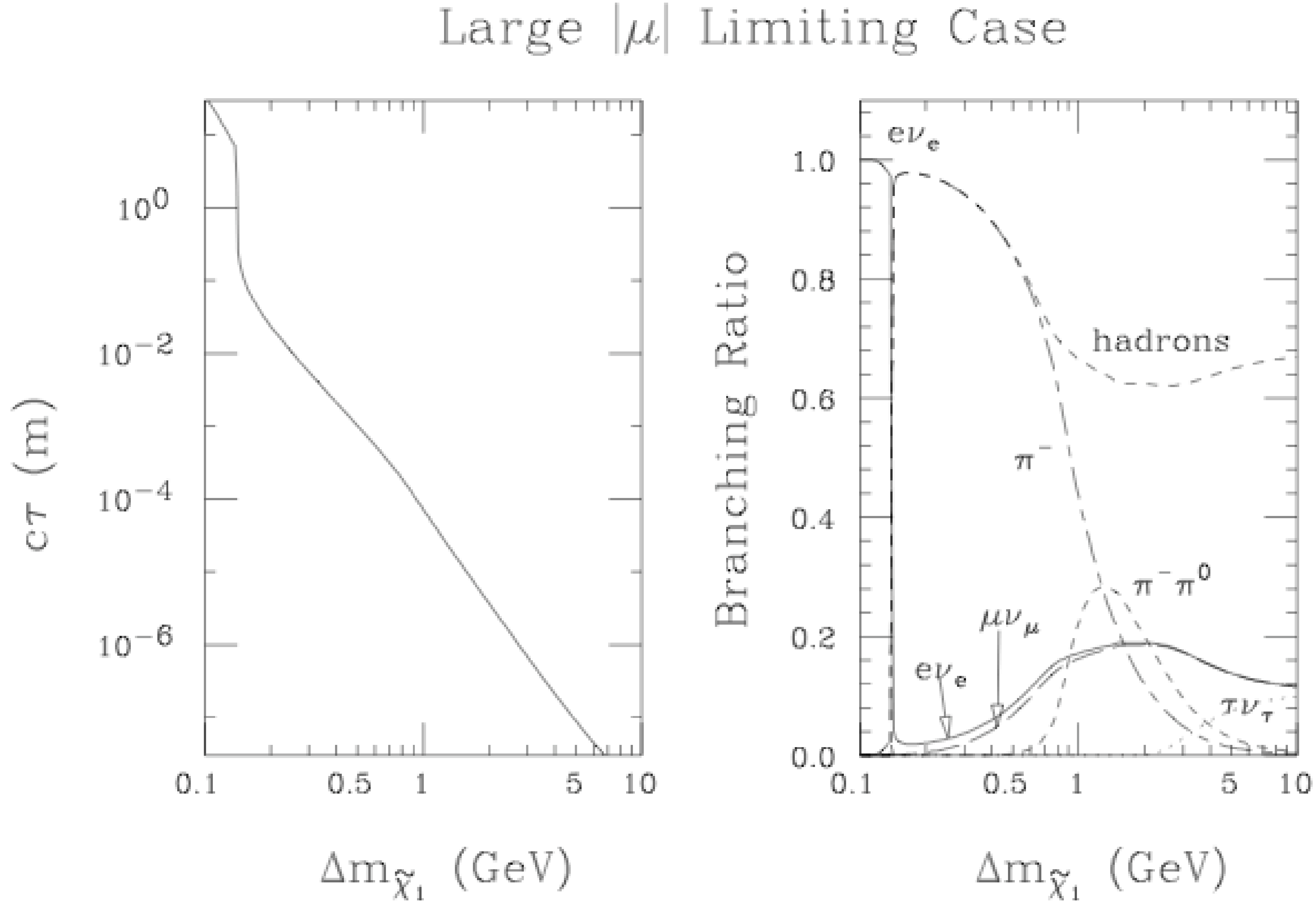


Wacker, et. al.

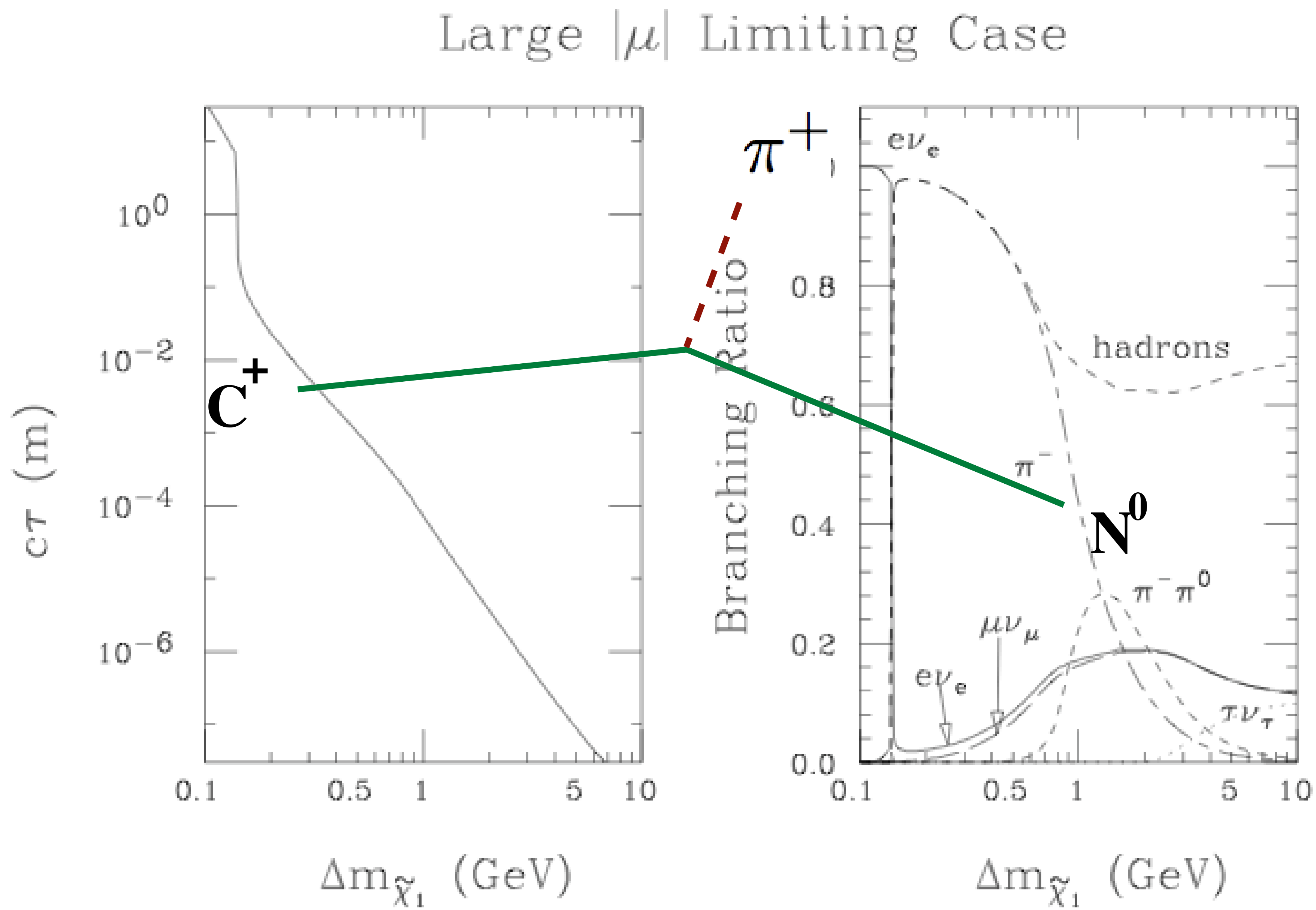
Ratio of 'ino's

$M_3 > M_1 > M_2$	AMSB - cascades with leptons. LL charged particle
$M_2 > M_3 > M_1$	Only jets + missing E_T
$M_1 > M_3 > M_2$	Jets plus missing E_T and/or LL charged particle
$M_2 > M_1 > M_3$	Gluino may be long lived - at least 4-body decay

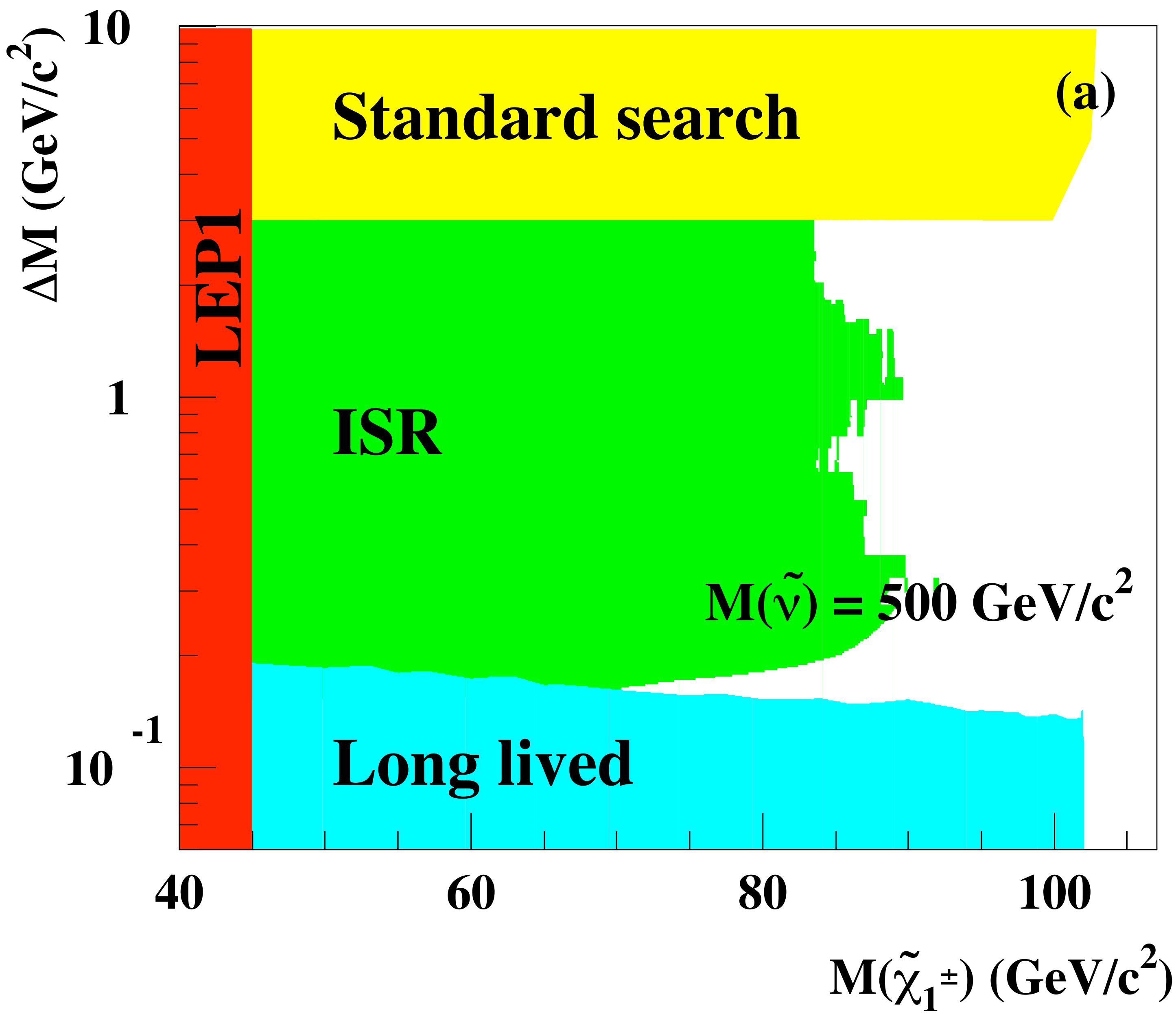
Lightest Chargino Decay



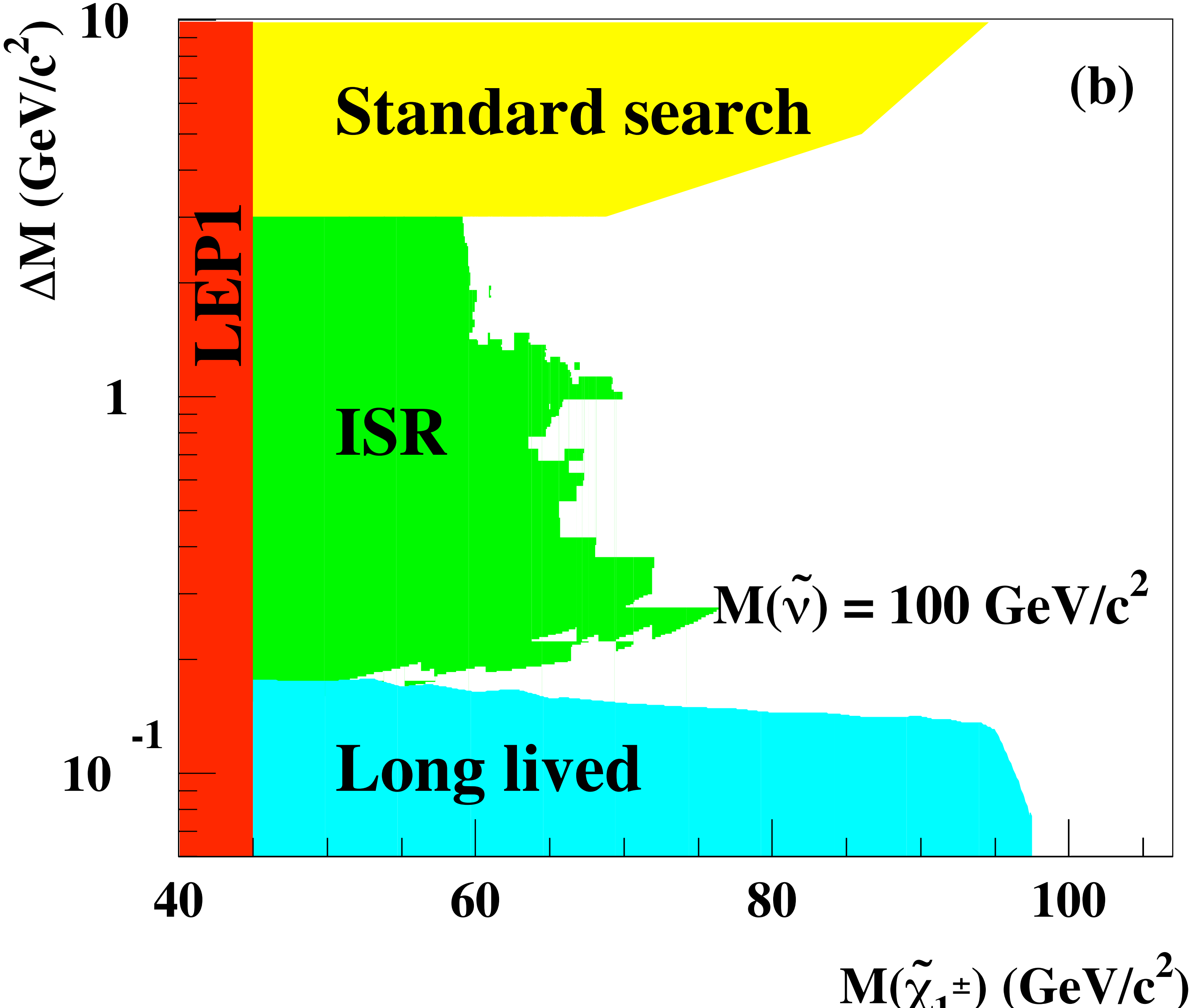
Lightest Chargino Decay



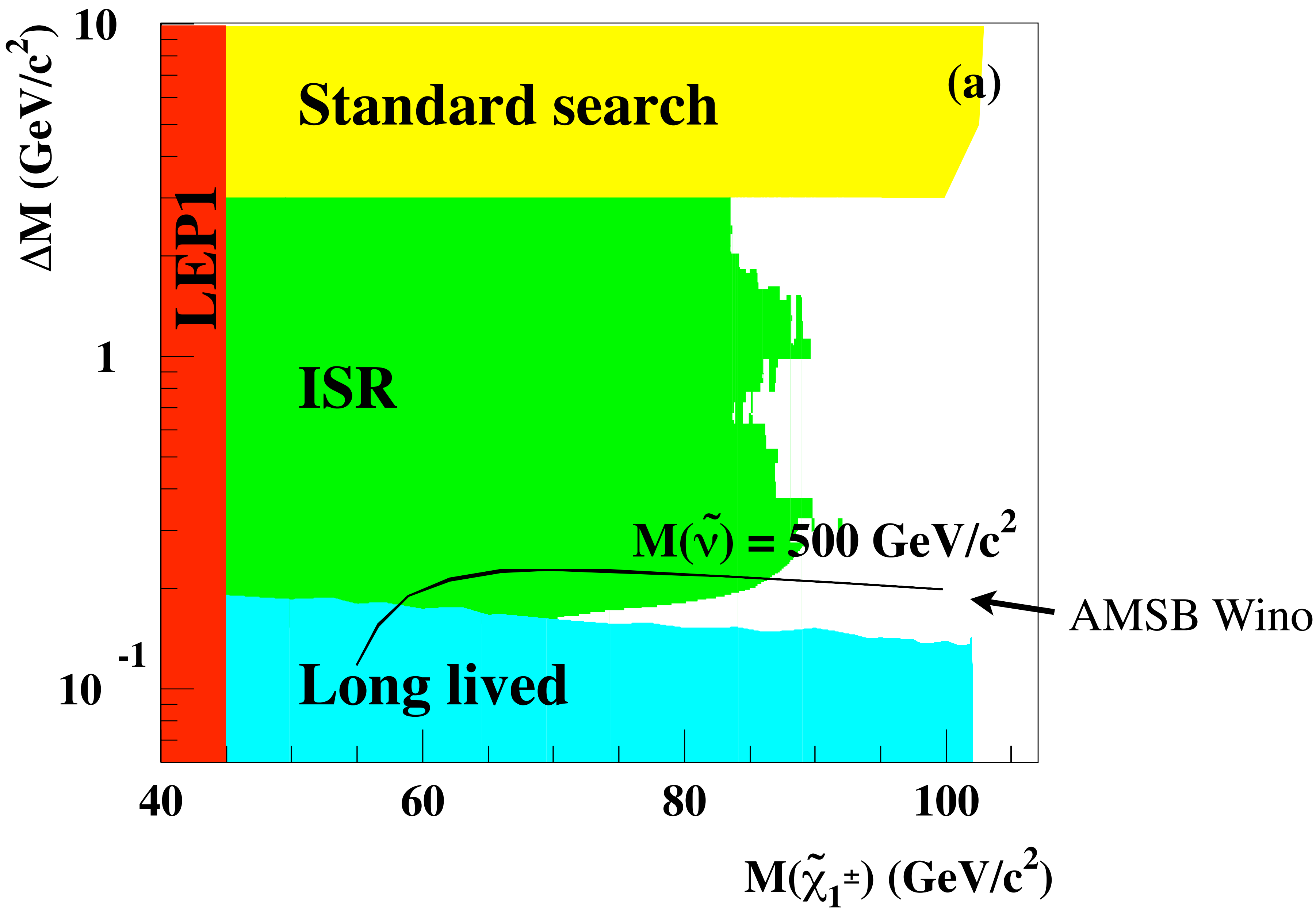
Delphi Chargino Search



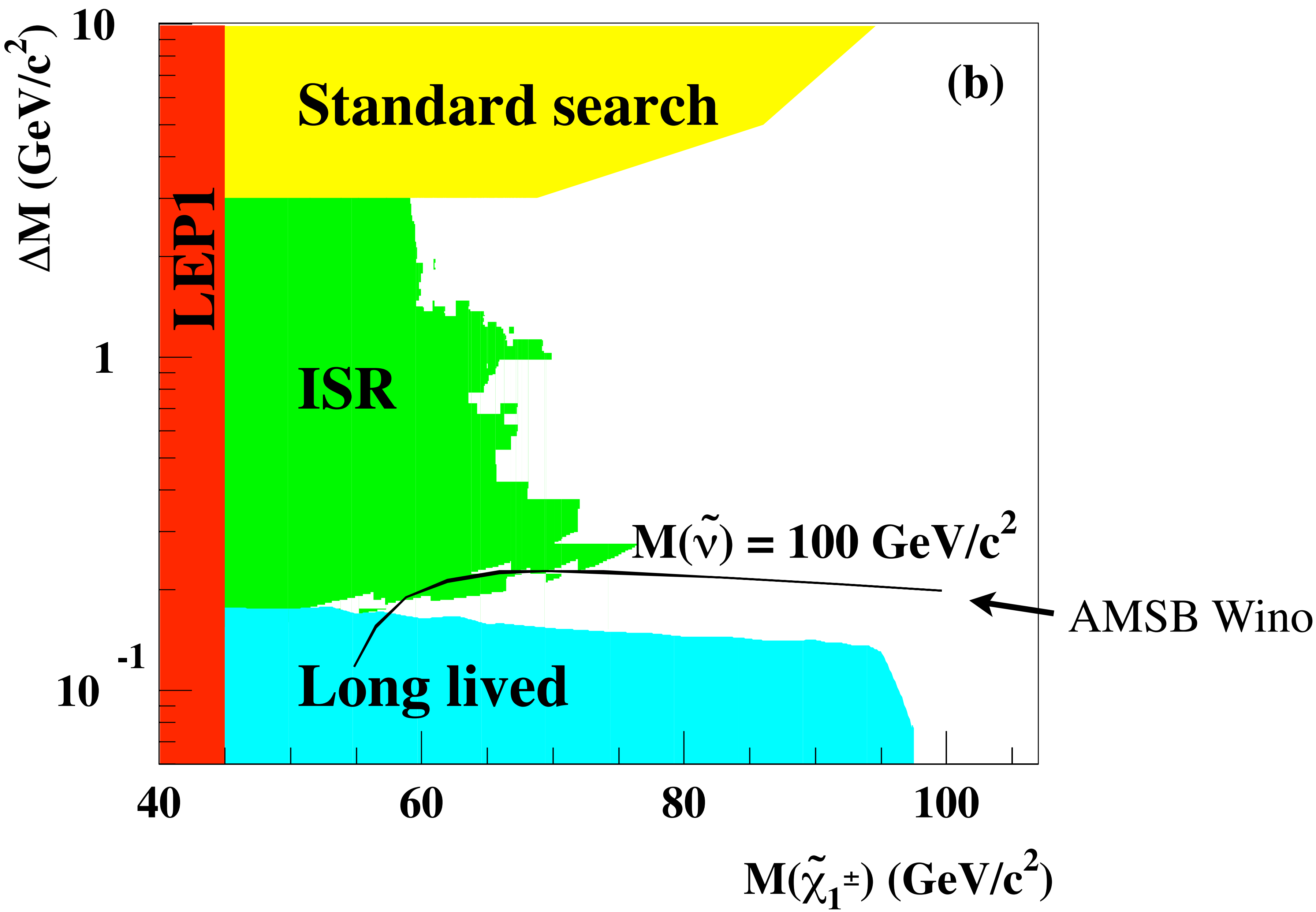
Delphi Chargino Search



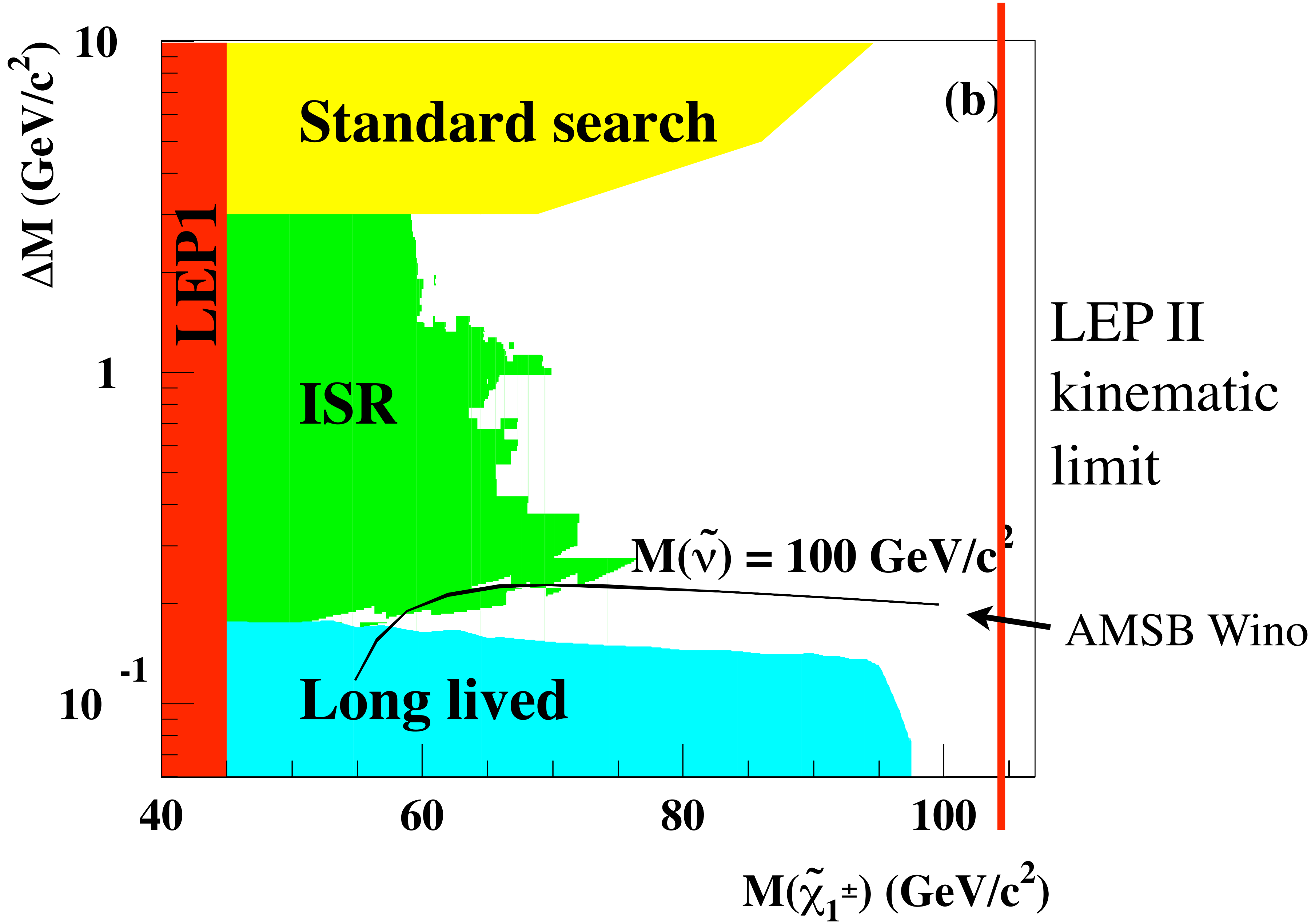
Delphi Chargino Search



Delphi Chargino Search



Delphi Chargino Search



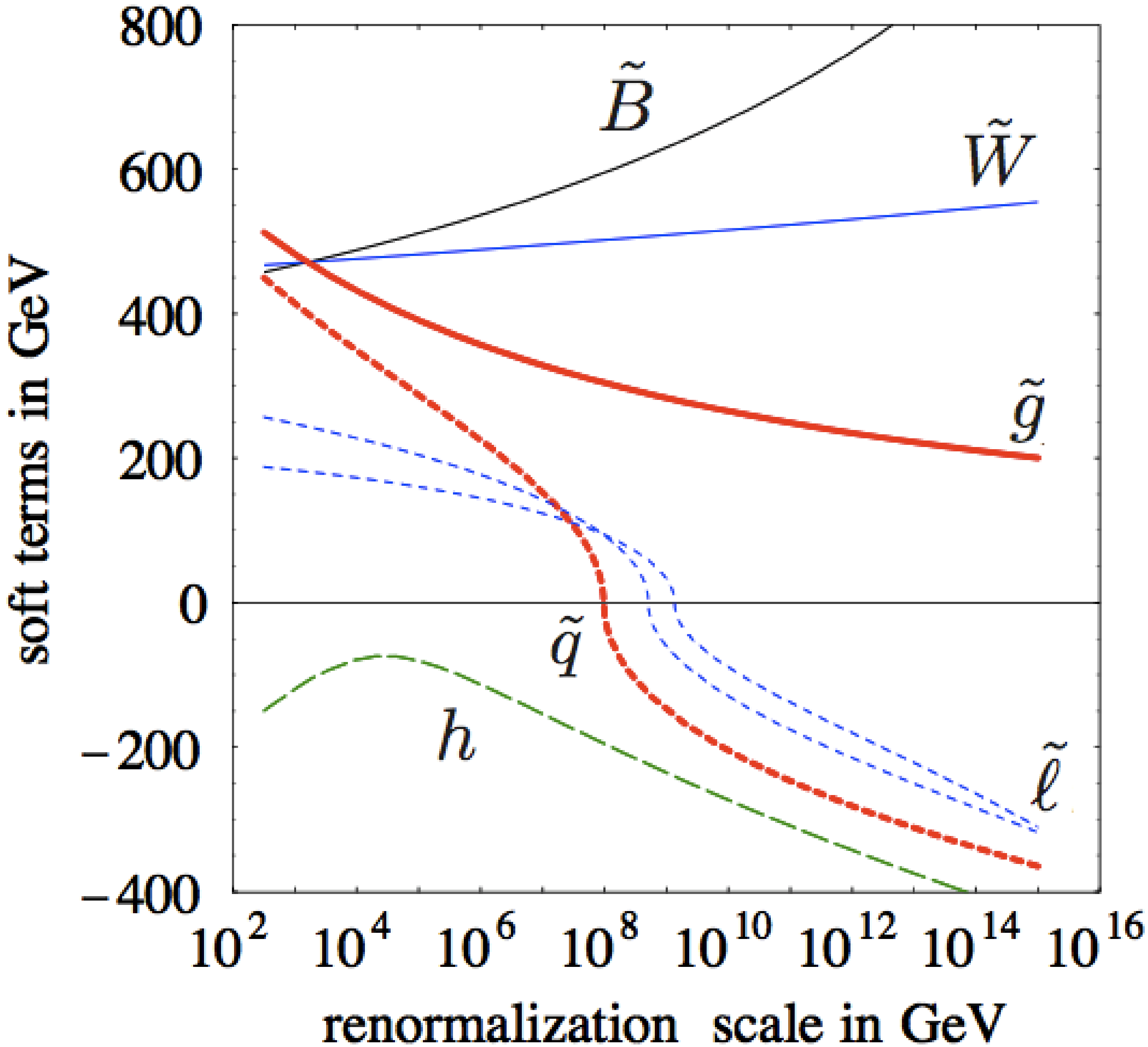
Supersymmetry Breaking with ‘Squashed’ Spectrum

Deflected Anomaly Mediation

Mirage Mediation

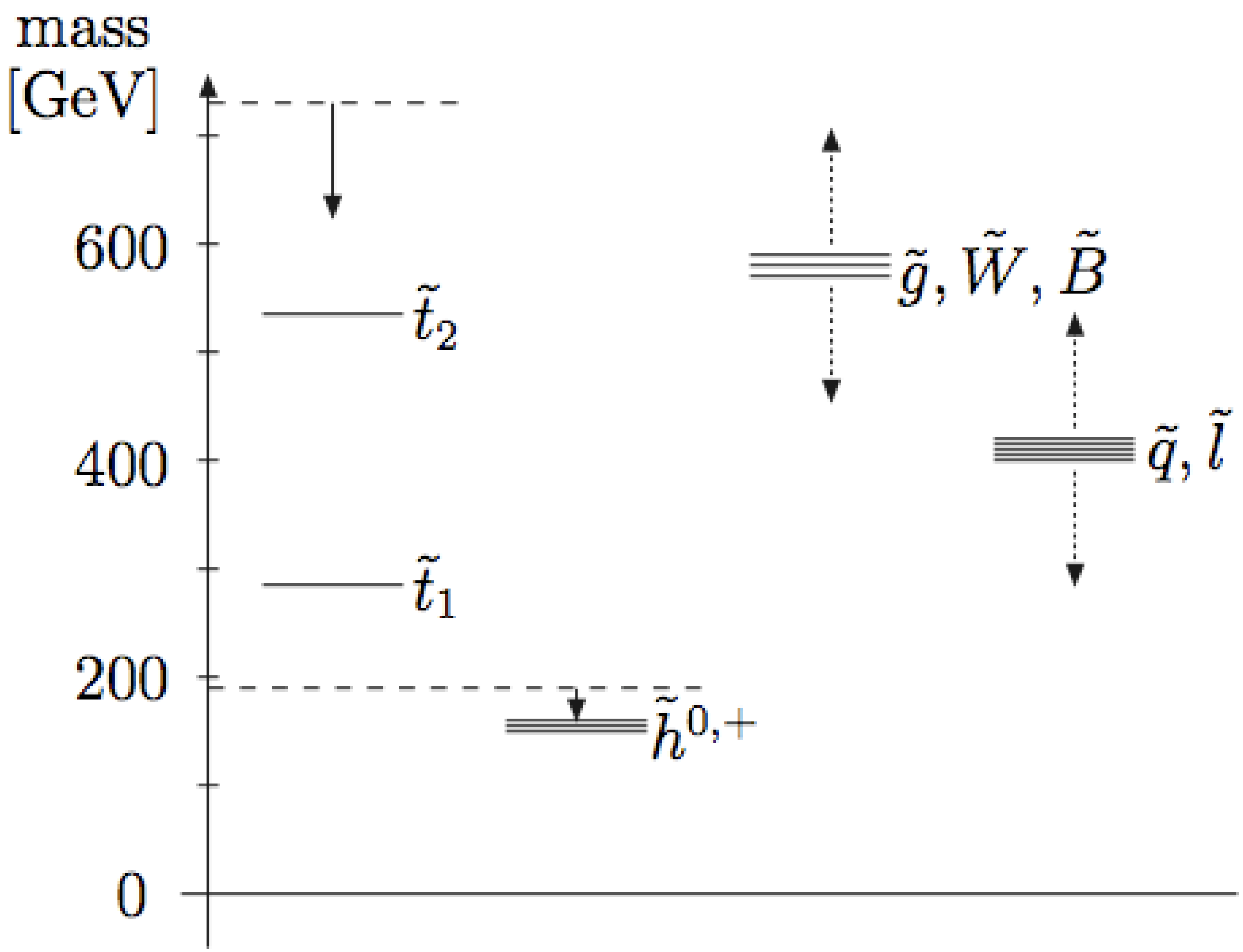
Dirac Gauginos

DAMSB



800
600
400
200
0
−200
−400
soft terms in GeV
$\tilde{B}$
$\tilde{W}$
$\tilde{g}$
$\tilde{q}$
h
$\tilde{\ell}$
10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14} 10^{16}
renormalization scale in GeV

Mirage Mediation



“New” Parameter Set At the Weak Scale

$$
\begin{aligned}
\mathcal{L}_{\text{soft}}^{\text{MSSM}} = & -\frac{1}{2}\left(M_3 \widetilde{g}\widetilde{g} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
& - \left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\
& - \widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger \\
& - m^2_{H_u} H_u^* H_u - m^2_{H_d} H_d^* H_d - \left(bH_uH_d + \text{c.c.}\right).
\end{aligned}
$$

parameter x identity matrix

Use this to fix the Z mass.

$\tan\beta$

μ sets higgsino mass

"New" Parameter Set At the Weak Scale

$$
\begin{aligned}
\mathcal{L}_{\text{soft}}^{\text{MSSM}} &= -\frac{1}{2}\left(M_3 \widetilde{g}\widetilde{g} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
&- \left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\
&- \widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger \\
&- m^2_{H_u} H_u^* H_u - m^2_{H_d} H_d^* H_d - \left(b H_u H_d + \text{c.c.}\right).
\end{aligned}
$$

$\mathbf{a_u} = \mathbf{y_u} A_u$

parameter x identity matrix

Use this to fix the Z mass.

$\tan\beta$

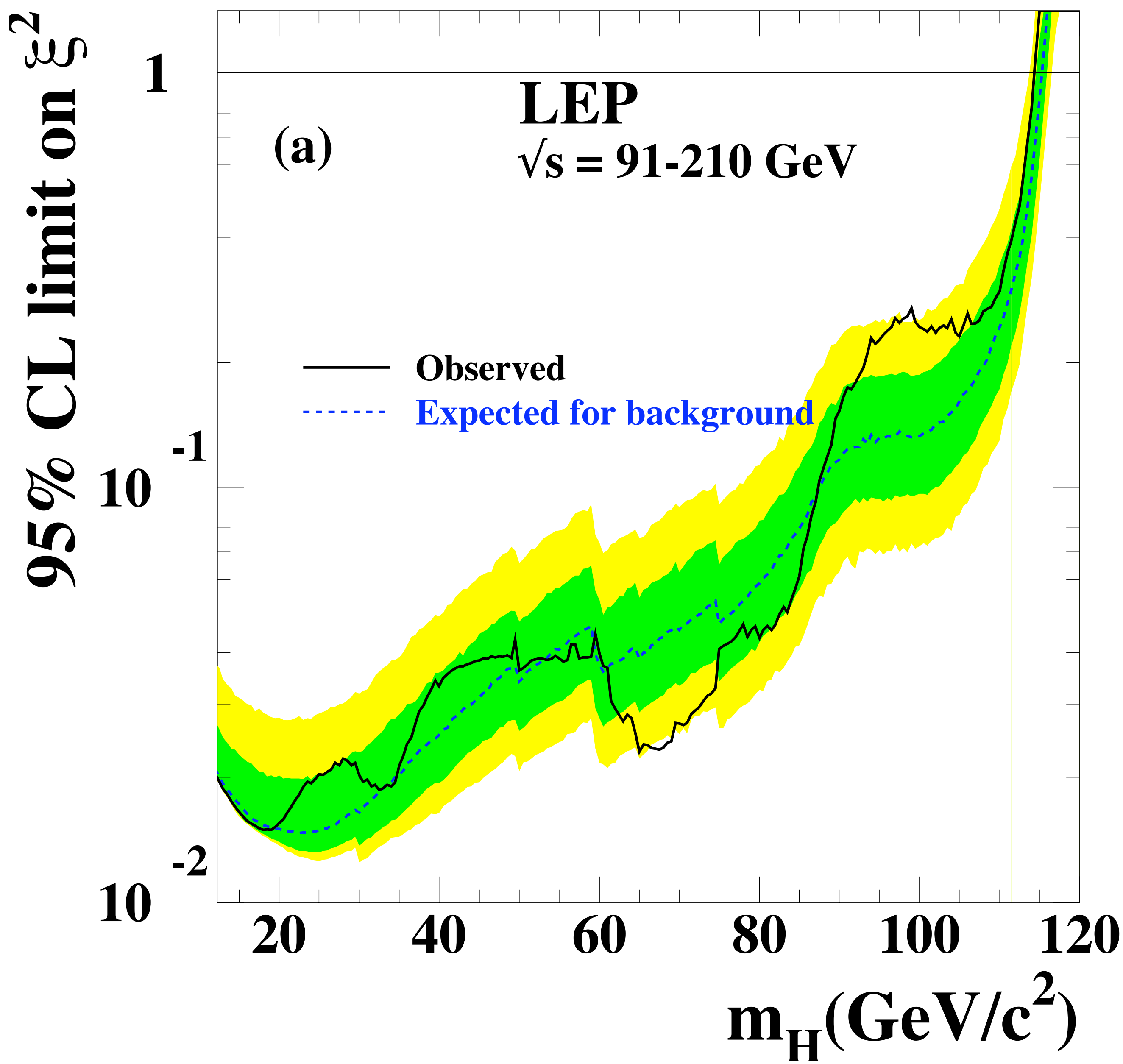
μ sets higgsino mass

Back to the Extra Singlet

$$h^0 \rightarrow a^0 a^0$$

And then the pseudo-scalars decay.

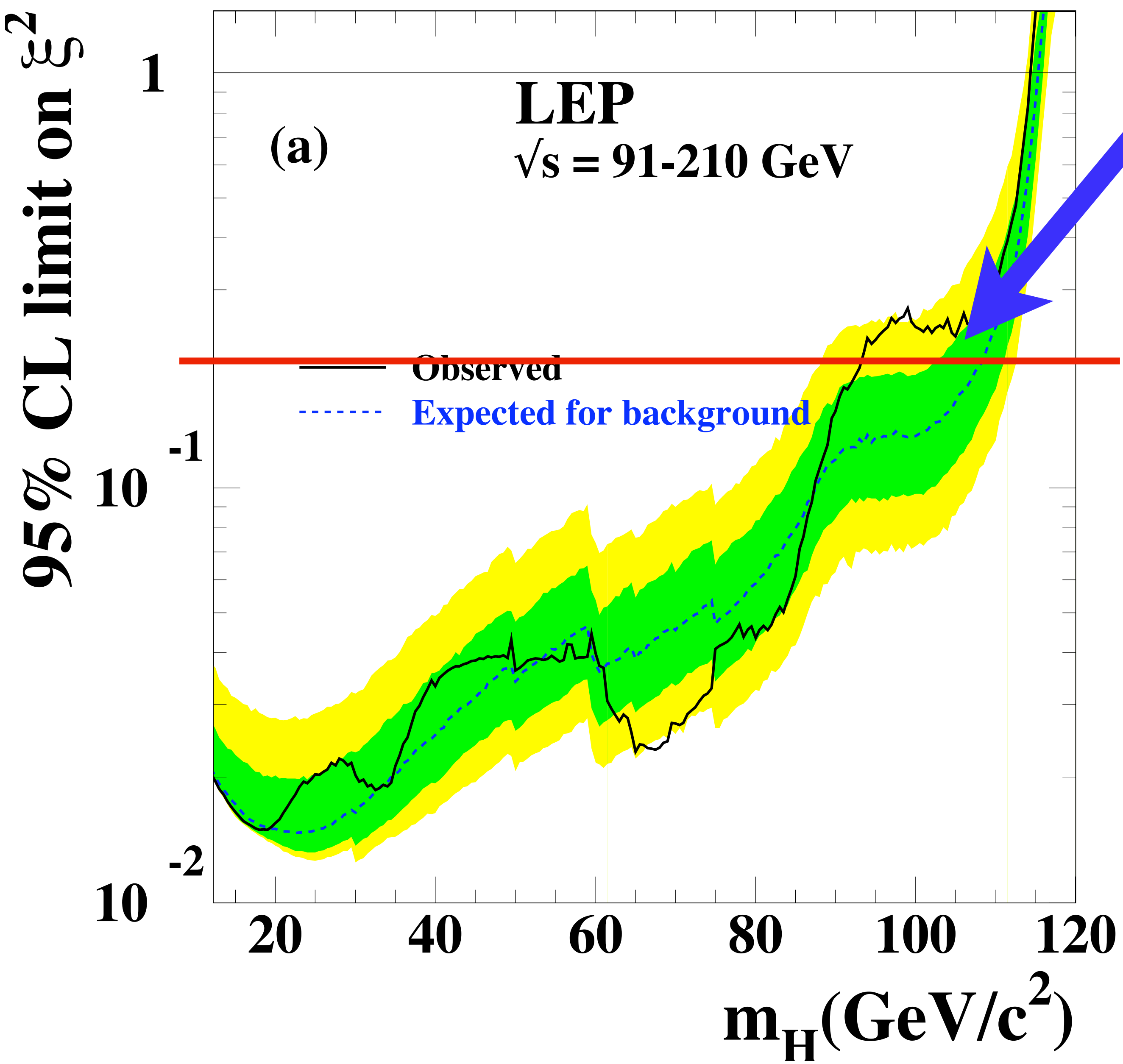
SM Higgs



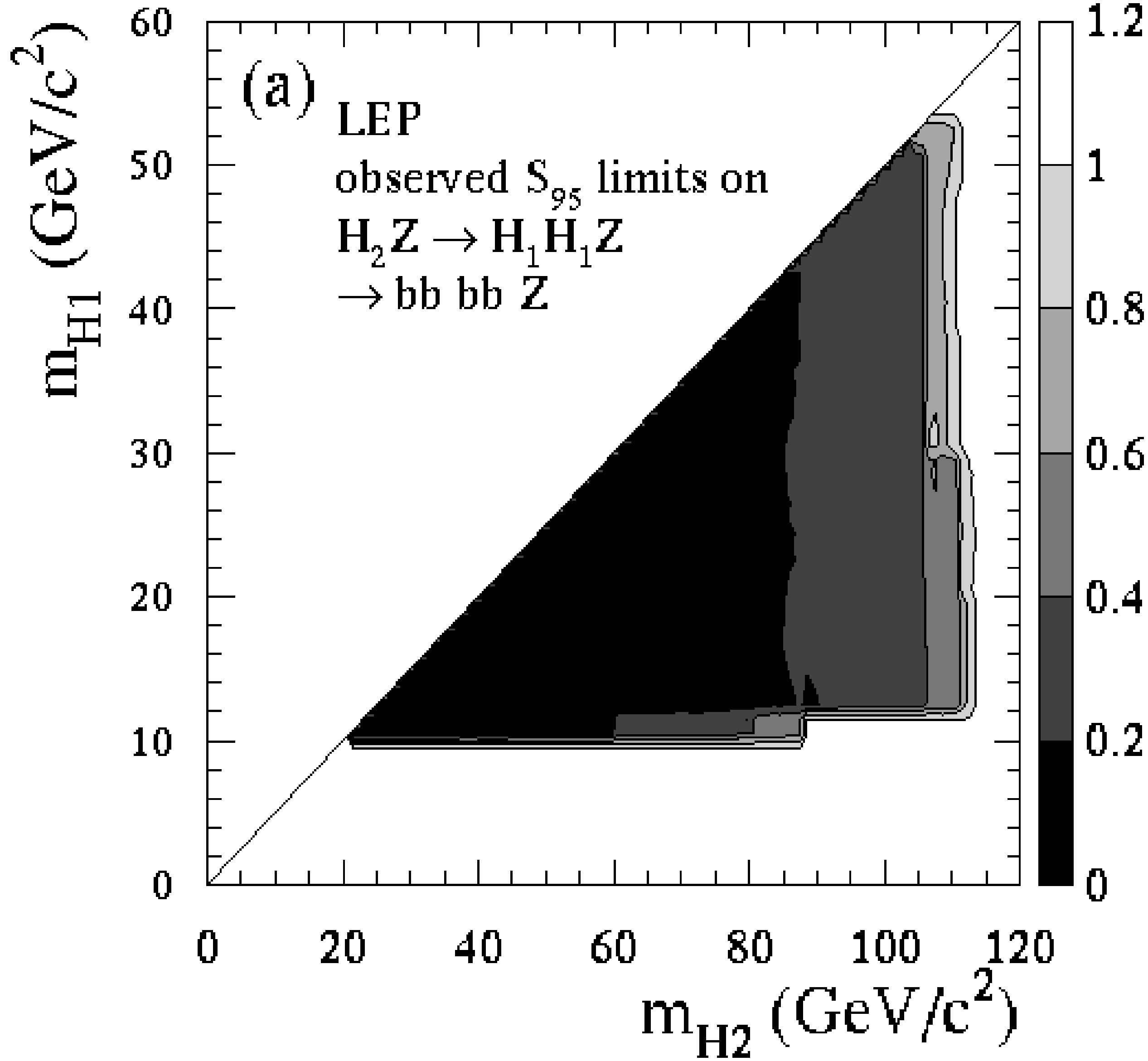
95% CL limit on ξ^2
1
10^{-1}
10^{-2}
LEP
(a)
$\sqrt{s}$ = 91-210 GeV
Observed
Expected for background
20
40
60
80
100
120
$m_H(GeV/c^2)$

SM Higgs

Suppress cross section or BR to standard model modes to ~20%

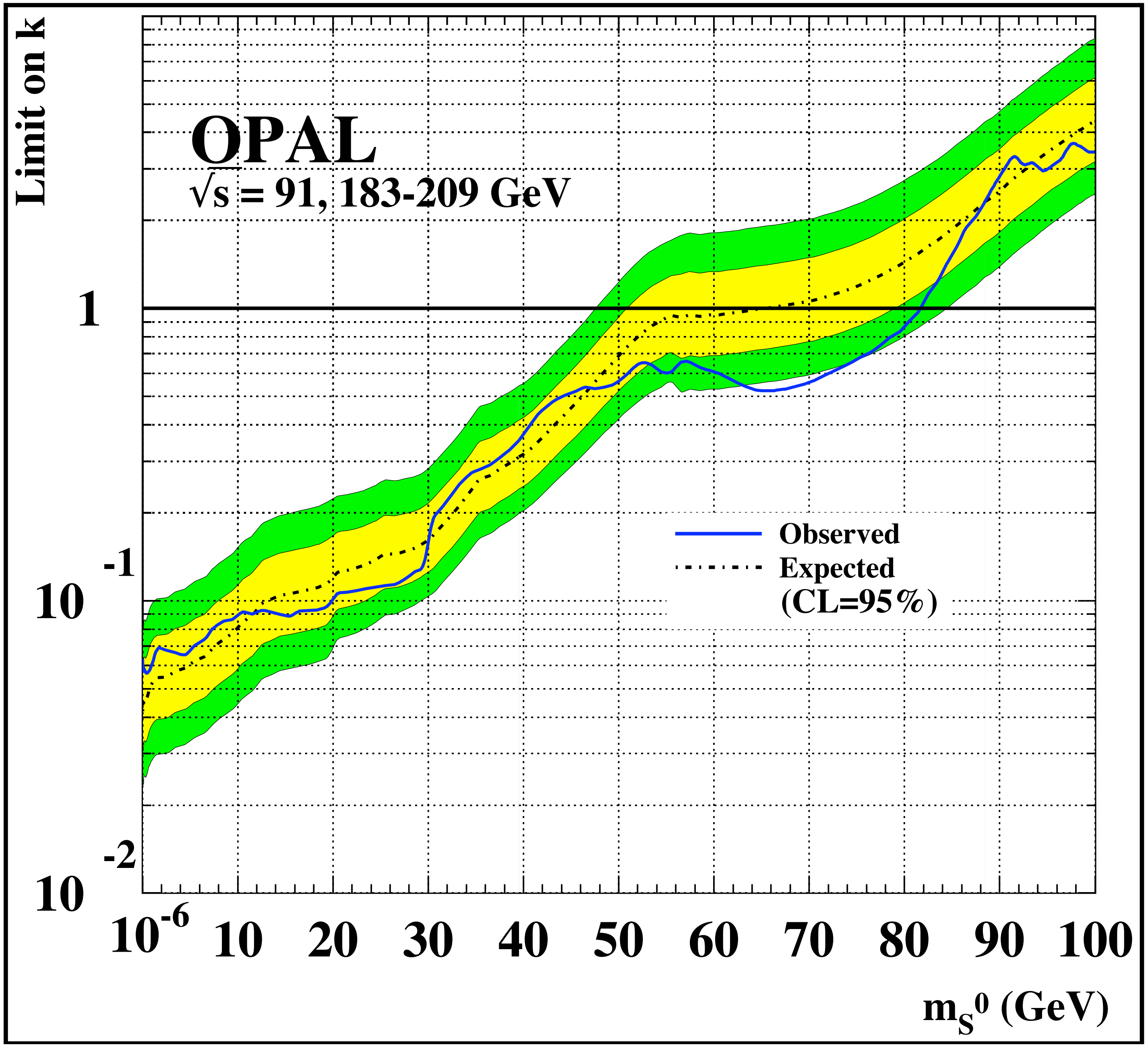


Higgs to 4b's



But NOT 4 taus!

Non-standard Decays



New Higgs Decays

LEP Bounds

$h \to aa \to \bar{b}b\bar{b}b$	$m_h > 110$ GeV
$h \to aa \to \bar{\tau}\tau\bar{\tau}\tau$	$m_h > 86$ GeV
$h \to aa \to gggg$	$m_h > 82 - 95$ GeV ?
$h \to ss \to aaaa \to \bar{b}b\bar{b}b\bar{b}b\bar{b}b$	$m_h > 82$ GeV????

Dermisek, Gunion, Dobrescu, Matchev, Landsberg, Chang, Fox, Weiner, Graham, Pierce, Wacker, plus plenty of older literature.

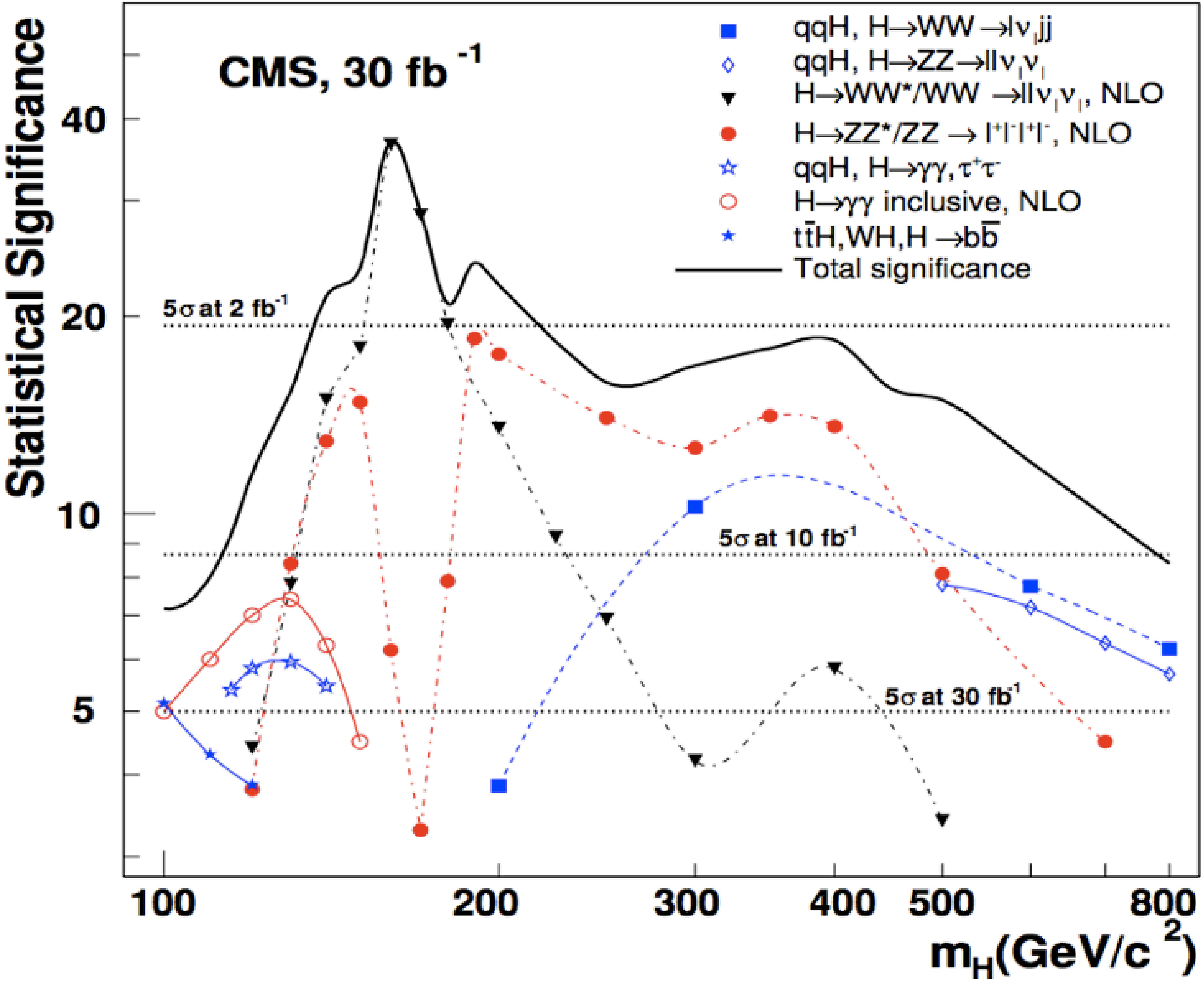
New Higgs Decays

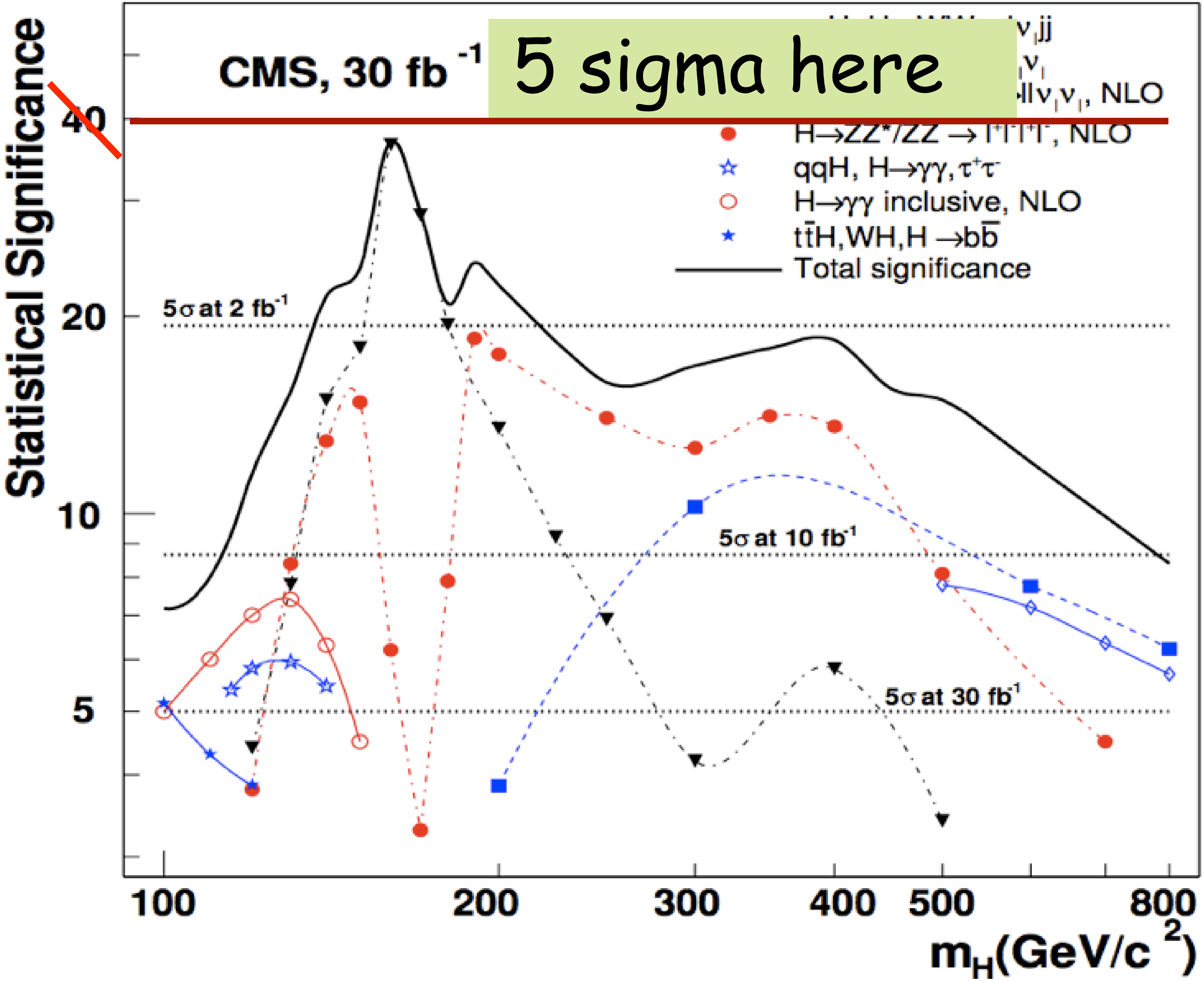
LEP Bounds

New analysis on-going

$h \to aa \to \bar{b}b\bar{b}b$	$m_h > 110$ GeV
$h \to aa \to \bar{\tau}\tau\bar{\tau}\tau$	$m_h > 86$ GeV
$h \to aa \to gggg$	$m_h > 82 - 95$ GeV ?
$h \to ss \to aaaa \to \bar{b}b\bar{b}b\bar{b}b\bar{b}b$	$m_h > 82$ GeV????

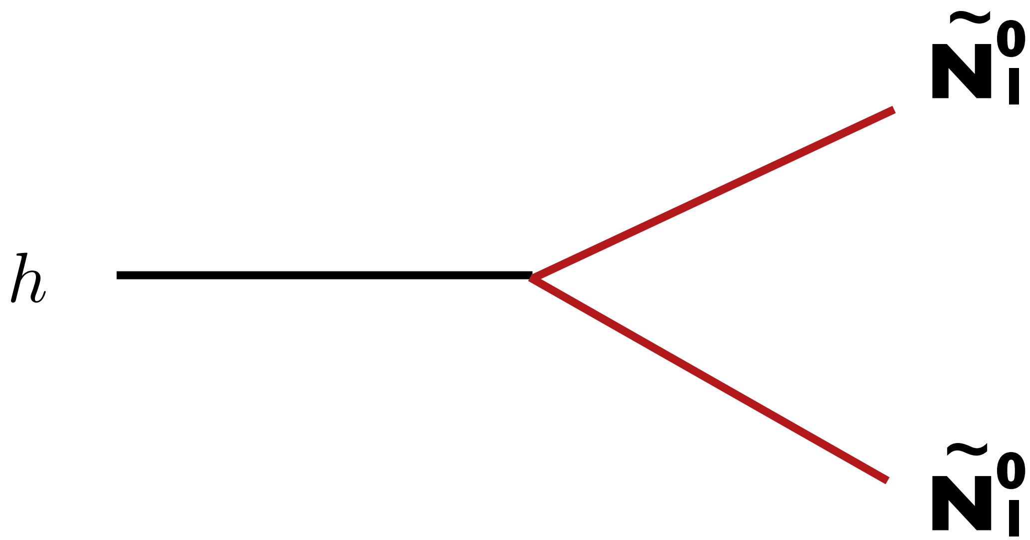
Dermisek, Gunion, Dobrescu, Matchev, Landsberg, Chang, Fox, Weiner, Graham, Pierce, Wacker, plus plenty of older literature.


CMS, 30 fb⁻¹
Statistical Significance
qqH, H→WW→lν_l jj
qqH, H→ZZ→llν_lν_l
H→WW*/WW →llν_lν_l, NLO
H→ZZ*/ZZ → l⁺l⁻l⁺l⁻, NLO
qqH, H→γγ,τ⁺τ⁻
H→γγ inclusive, NLO
tt̄H,WH,H →bb̄
Total significance
5σ at 2 fb⁻¹
5σ at 10 fb⁻¹
5σ at 30 fb⁻¹
40
20
10
5
100
200
300
400
500
800
m_H(GeV/c²)


5 sigma here
CMS, 30 fb^{-1}
H→ZZ*/ZZ → l$^+$l$^-$l$^+$l$^-$, NLO
qqH, H→γγ, τ$^+$τ$^-$
H→γγ inclusive, NLO
t$\bar{t}$H,WH,H →b$\bar{b}$
Total significance
5σ at 2 fb^{-1}
5σ at 10 fb^{-1}
5σ at 30 fb^{-1}
Statistical Significance
40
20
10
5
100
200
300
400
500
800
m$_H$(GeV/c^2)

Higgs Decays to Superpartners

Straight MSSM possibility:



Bound still 114 GeV!

Neutralinos (like neutrinos) are invisible.

Potential at LHC better via VBF

Violation of R Parity

$$W = H_1 Q D^c + H_2 Q U^c + H_1 L E^c + \mu H_1 H_2$$
$$+ L Q D^c + U^c D^c D^c + L L E^c + \mu_L L H_2$$

Violation of R Parity

$$W = H_1 Q D^c + H_2 Q U^c + H_1 L E^c + \mu H_1 H_2$$
$$+ L Q D^c \sout{+ U^c D^c D^c} + L L E^c + \mu_L L H_2$$

Could have "Baryon Parity".

Violation of R Parity

$$W = H_1QD^c + H_2QU^c + H_1LE^c + \mu H_1H_2$$

$$\cancel{+LQD^c} + U^cD^cD^c \cancel{+ LLE^c + \mu_L LH_2}$$

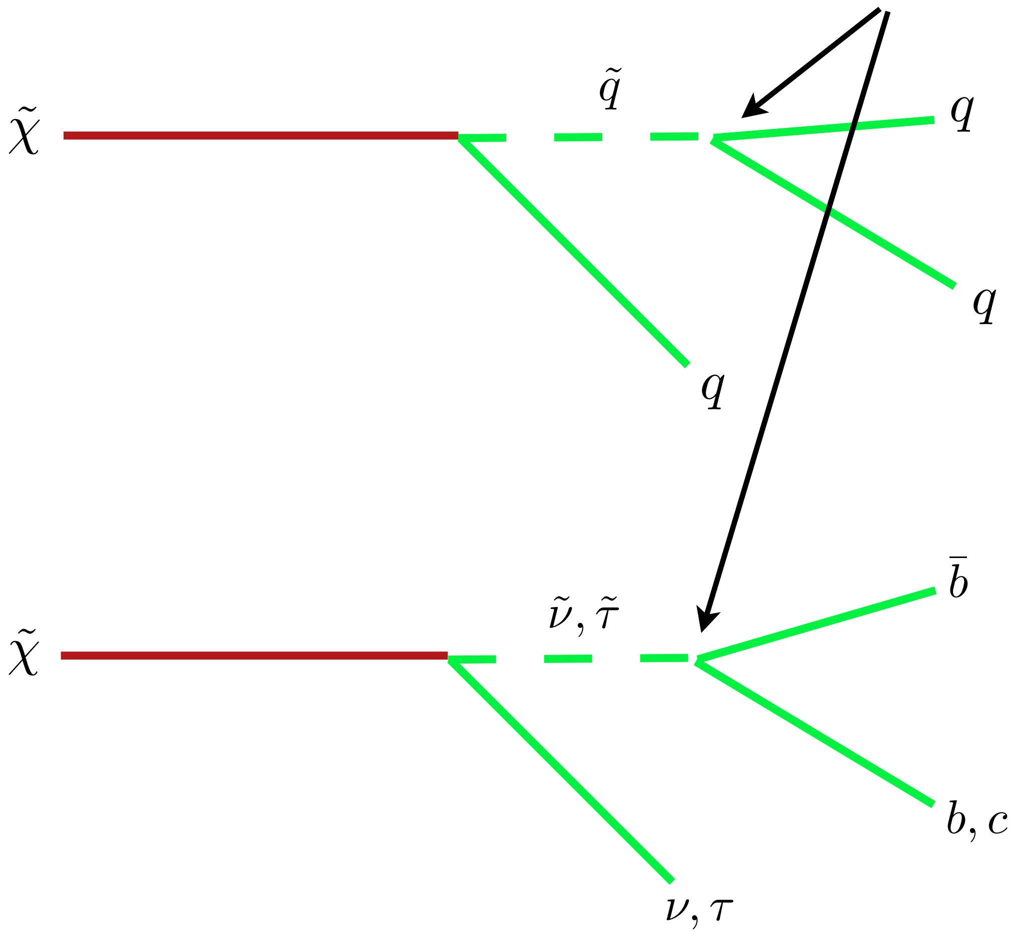
or "Lepton Parity"

$$p \not\to X$$

X must have an odd number of fermions, thus its lepton number $L = 2n + 1$. No lepton parity violation, no decay.

LSP decays

R parity violation



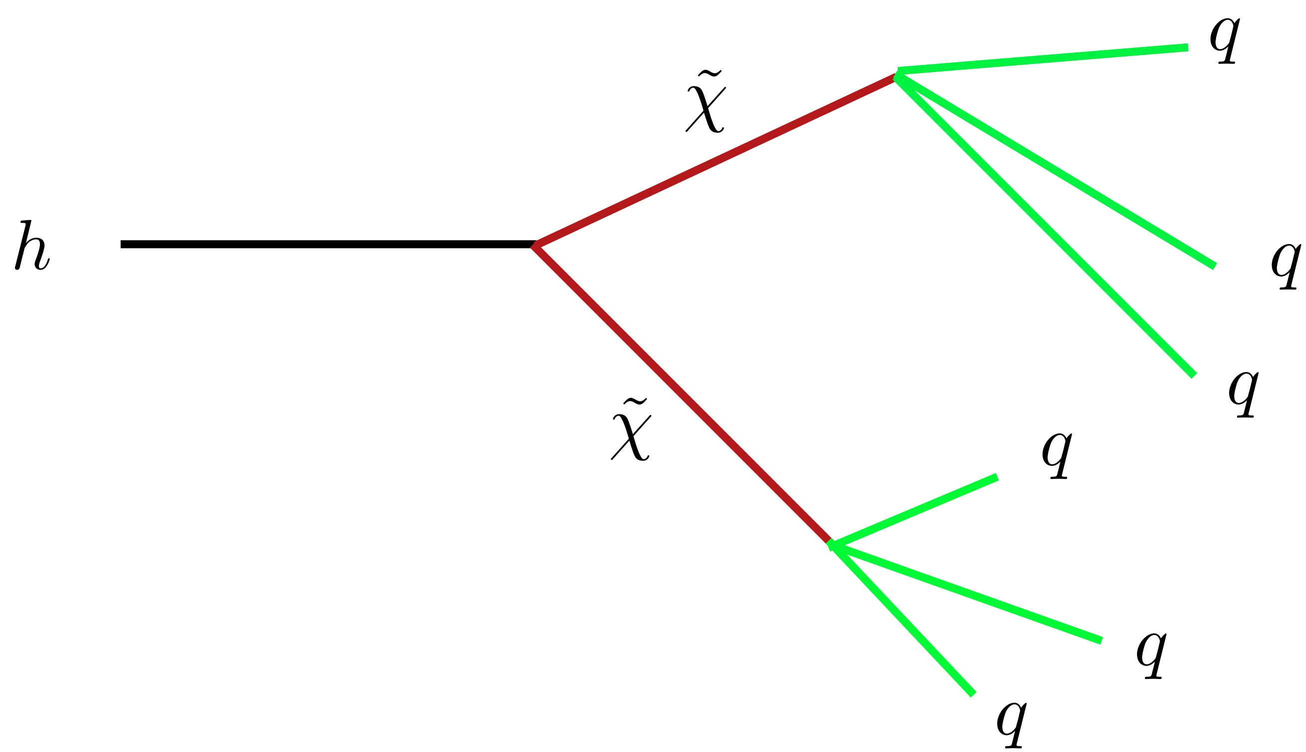
Decreases missing E_T signal

Typical Bounds on Superpartners with B

Sleptons (R)	94,85,70 GeV (A)
Sneutrinos	88,65,65 GeV (A)
Squarks ($u_{L/R}$,$d_{L/R}$)	87,80,86,56 GeV (L)
Stop	77 GeV (O,D,L)
Sbottom	7.5 (>55, <30) GeV (L)
Gluino	80 GeV ? (UA2)

Only Chargino bound roughly the same (102.5 GeV)

Higgs decays with B-violation



Higgs to 6 jets!

$m_h > 87$ GeV

Could be a source of new displaced vertices.

L. Carpenter, D. Kaplan, E.J. Rhee

Tomorrow

Technicolor, the Higgs is a K^0,
and what the hell are extra dimensions?