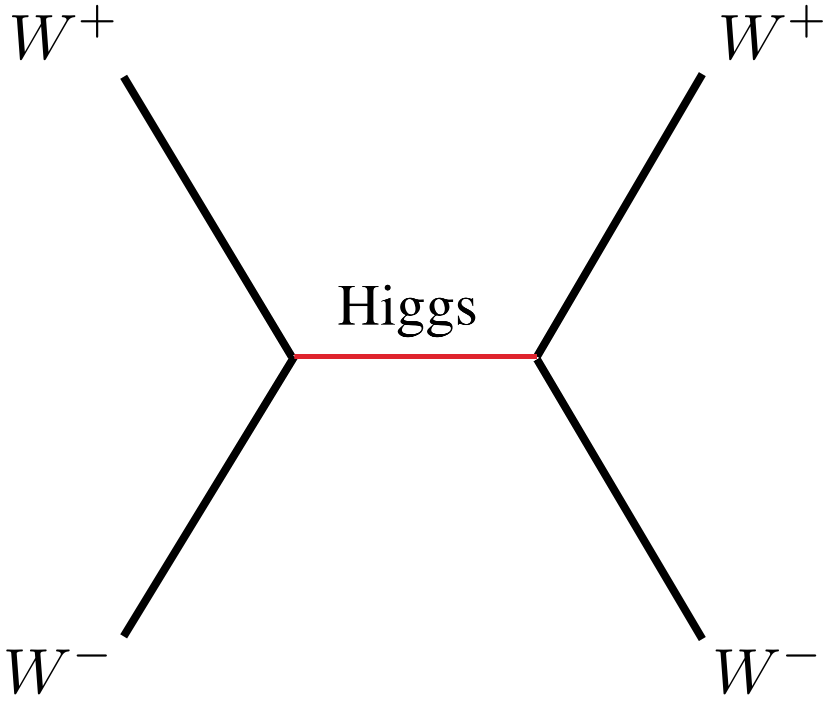
The Higgs Completes the Standard Model



$$\lim_{E\to\infty} \mathcal{A} \propto \text{const.}$$

With the inclusion of the Higgs particle, the theory remains predictive.

Theory requires a Higgs mass < 1 TeV

III

Models of Softly Broken Supersymmetry (and their phenomenology)

Higgs Potential

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

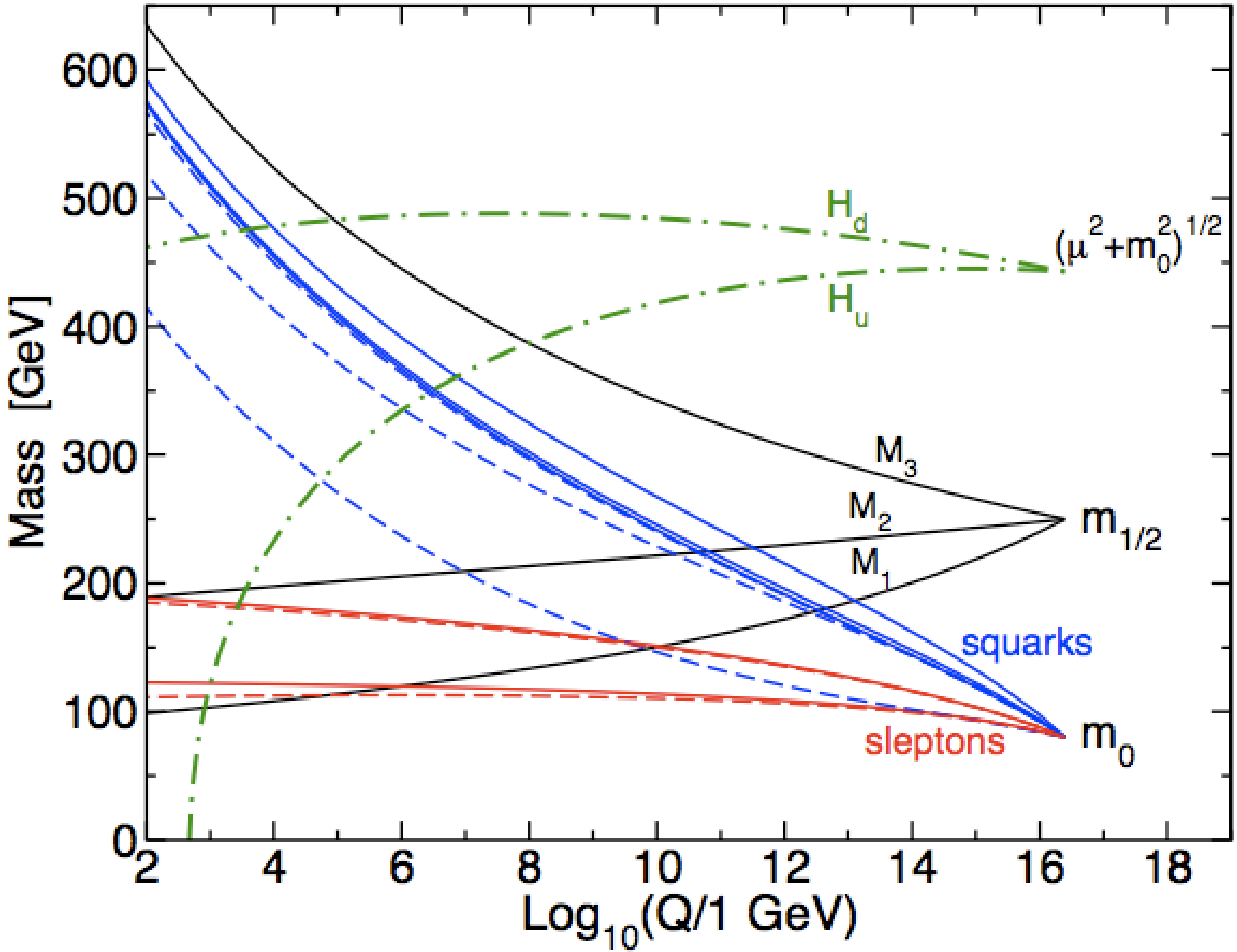
$$m_h = M_Z|\cos 2\beta|$$

SUSY-breaking loop required - same size as tree.

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

(Big Susy-breaking in top sector)

Source of Tuning



Forging ahead

We will now go through the "standard" models of supersymmetry and ignore the painful fine-tuning. Tomorrow we will see what could fix it.

Breaking Supersymmetry

What gets a “vev” to break supersymmetry?

$$V(\phi_i) = \sum_j \left| \frac{\partial W}{\partial \phi_j} \right|^2 \neq 0$$

The potential itself breaks supersymmetry?

Breaking SUSY: Example

$$W = S(\phi^2 - v^2) + mX\phi$$

The Superpotential

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

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

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

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

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Breaking SUSY: Example

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$$W = S(\phi^2 - v^2) + mX\phi$$

$$\left|\frac{\partial W}{\partial S}\right|^2 = \left|\phi^2 - v^2\right|^2 = v^4 - v^2(\phi^2 + \phi^{*2}) + |\phi|^4$$

$$\left|\frac{\partial W}{\partial X}\right|^2 = m^2|\phi|^2$$

$$\left|\frac{\partial W}{\partial \phi}\right|^2 = |2S\phi + mX|^2$$

Breaking SUSY: Example

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$$\left|\frac{\partial W}{\partial X}\right|^2 = m^2|\phi|^2$$

$$\left|\frac{\partial W}{\partial \phi}\right|^2 = |2S\phi + mX|^2$$

If $m \gg v$, then $\langle\phi\rangle = 0$.

Breaking SUSY: Example

$$W = S(\phi^2 - v^2) + mX\phi$$

Boson masses:

Mass of X is m, mass of S is 0

$$m^2|\phi|^2 - v^2(\phi^2 + \phi^{*2}) = (m^2 - 2v^2)\phi_R^2 + (m^2 + 2v^2)\phi_I^2$$

Fermion masses:

Mass of $\tilde{X}$, $\tilde{\phi}$, and $\tilde{S}$ are m, m, and 0.

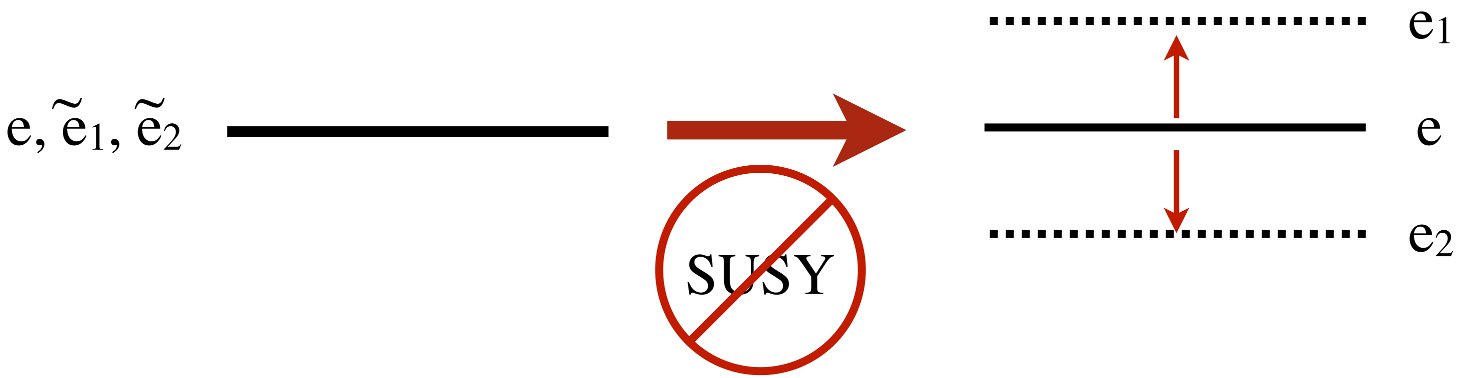
SUSY Breaking: Lesson 1

Supersymmetry breaks when:

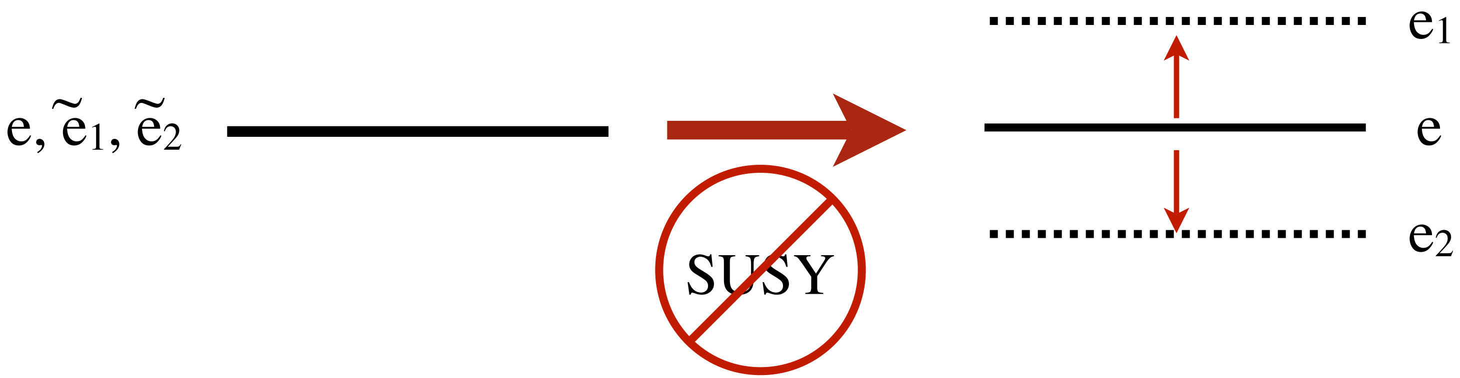
$$F_i \equiv \frac{\partial W}{\partial \phi_i} \neq 0$$

Called "F-term breaking".

SUSY Breaking: Lesson 2



SUSY Breaking: Lesson 2

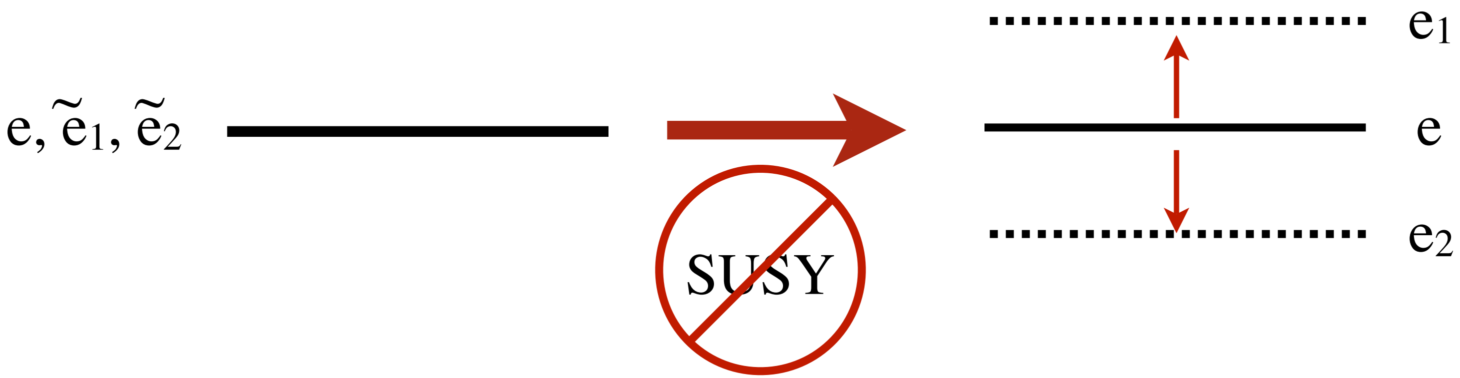


At tree-level in a renormalizable theory, the following is satisfied[1]:

$$\mathrm{Tr}(\mathbf{m_S^2}) - 2\mathrm{Tr}(\mathbf{m_F^\dagger m_F}) + 3\mathrm{Tr}(\mathbf{m_V^2}) = 0$$ "Supertrace"

[1]Except for anomalous U(1)

SUSY Breaking: Lesson 2



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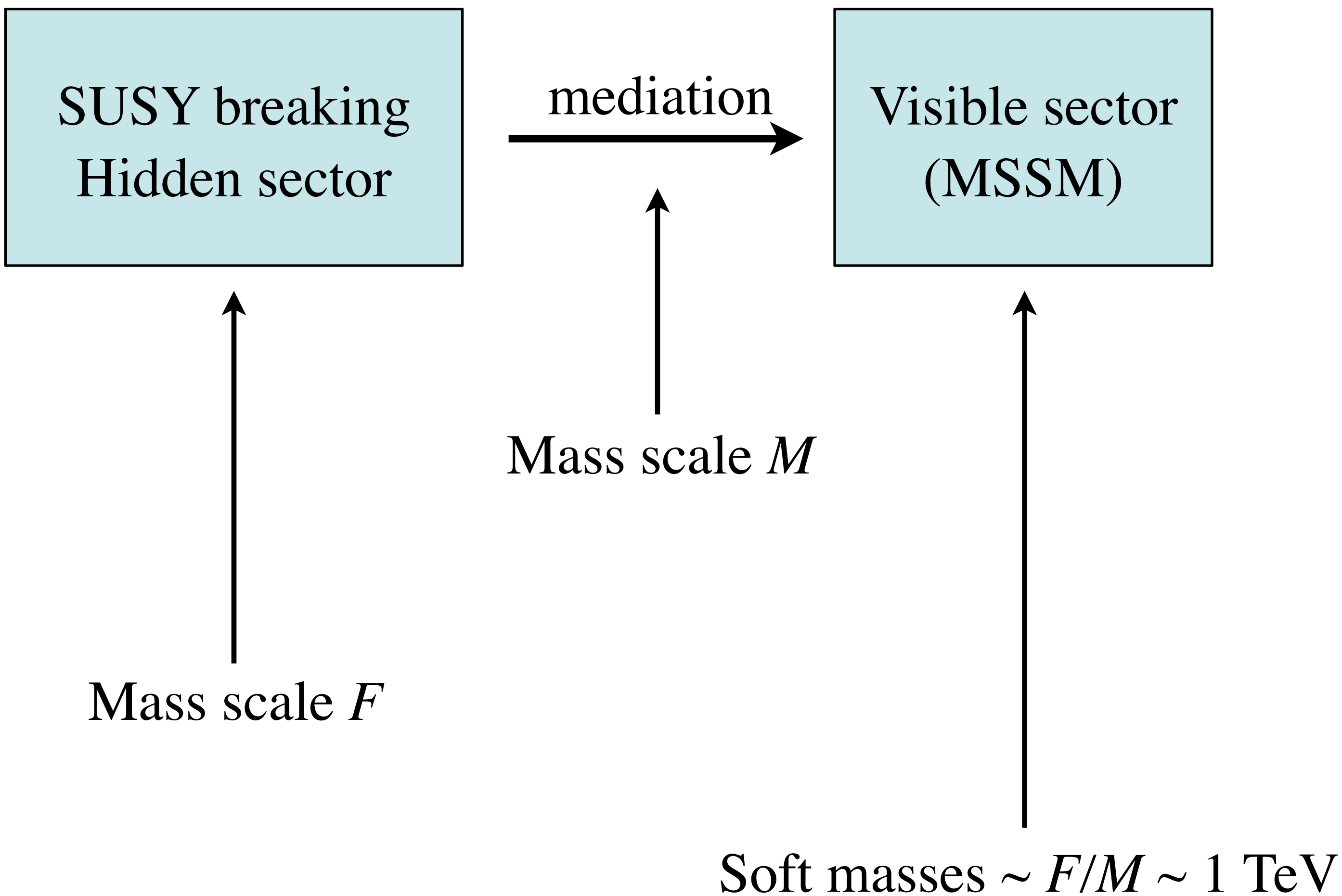
$$\mathrm{Tr}(\mathbf{m_S^2}) - 2\mathrm{Tr}(\mathbf{m_F^\dagger m_F}) + 3\mathrm{Tr}(\mathbf{m_V^2}) = 0$$ "Supertrace"

This is why supersymmetry breaking is "mediated".

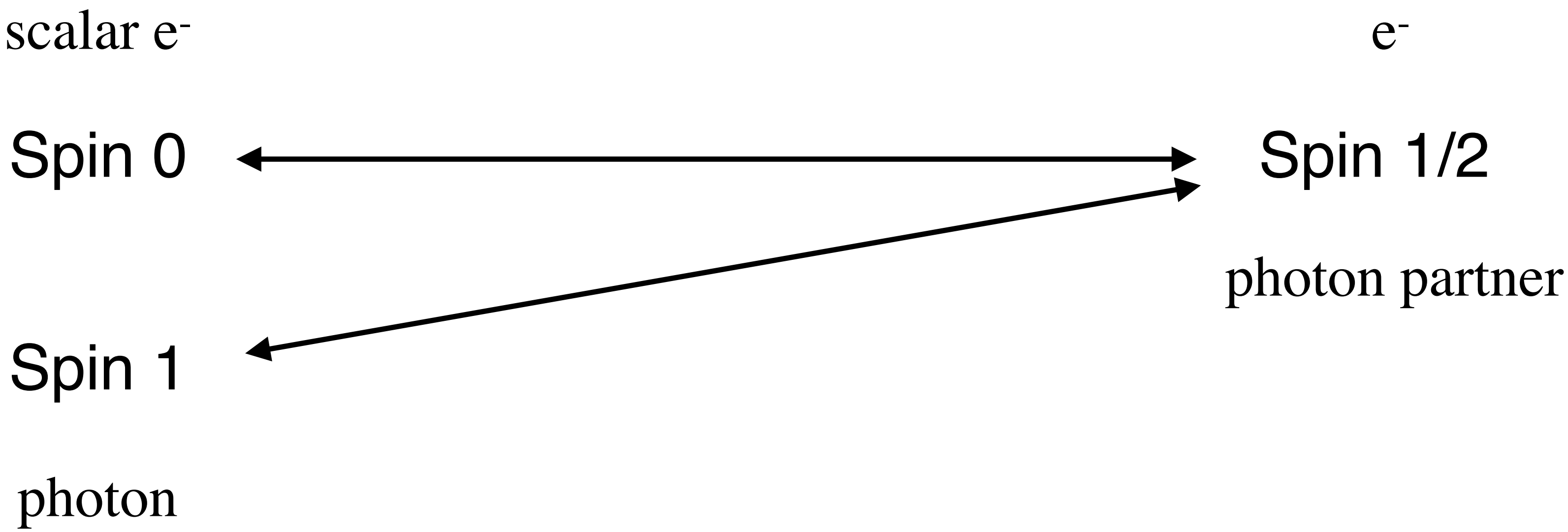
[1]Except for anomalous U(1)

Supersymmetry Breaking

Supersymmetry Breaking



One More Superpartner



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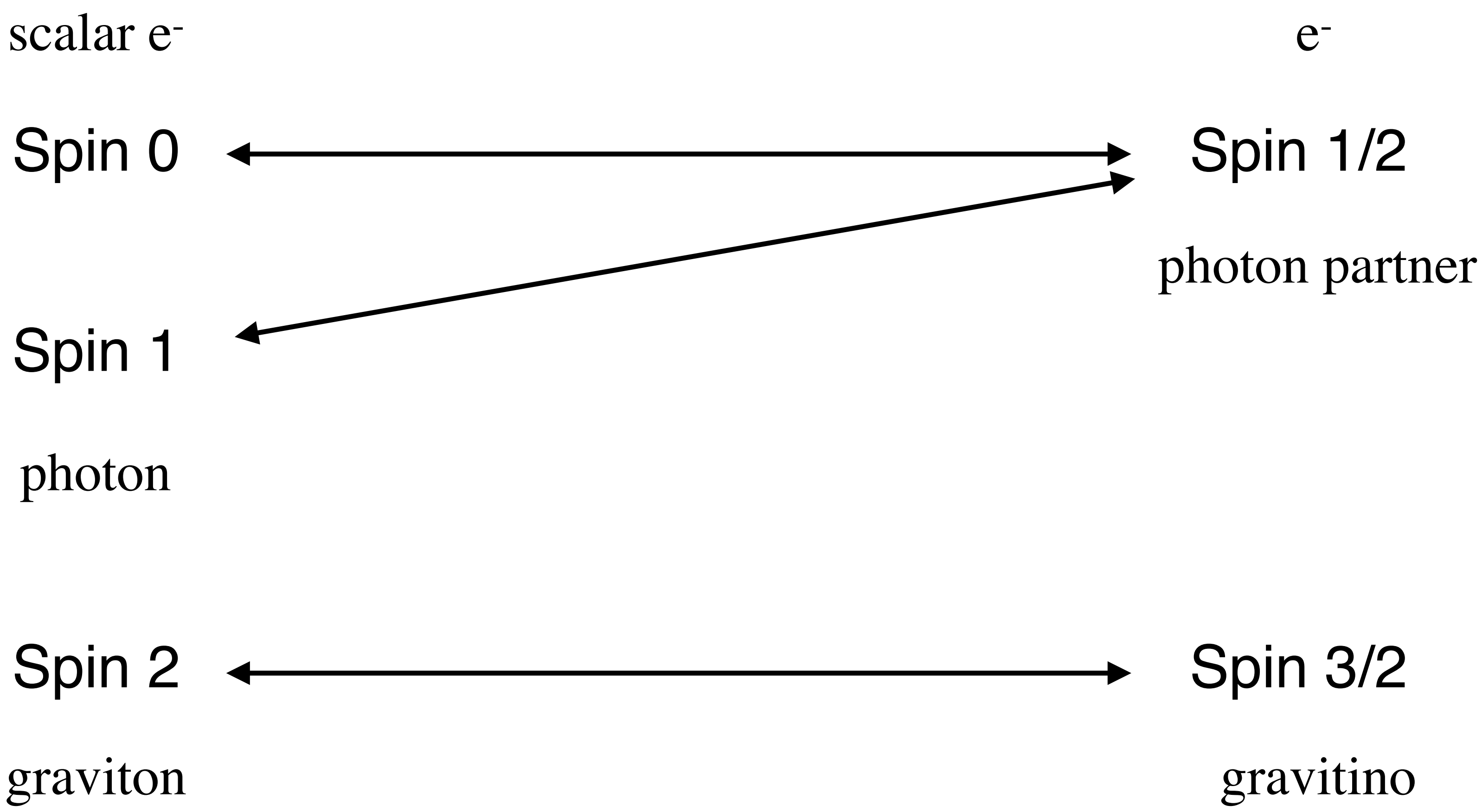


One More Superpartner

Mass of the gravitino:

$$m_{3/2} = F/M_{Planck}$$

In standard "gravity mediated supersymmetry breaking", of which mSUGRA is a subset, the soft masses are:

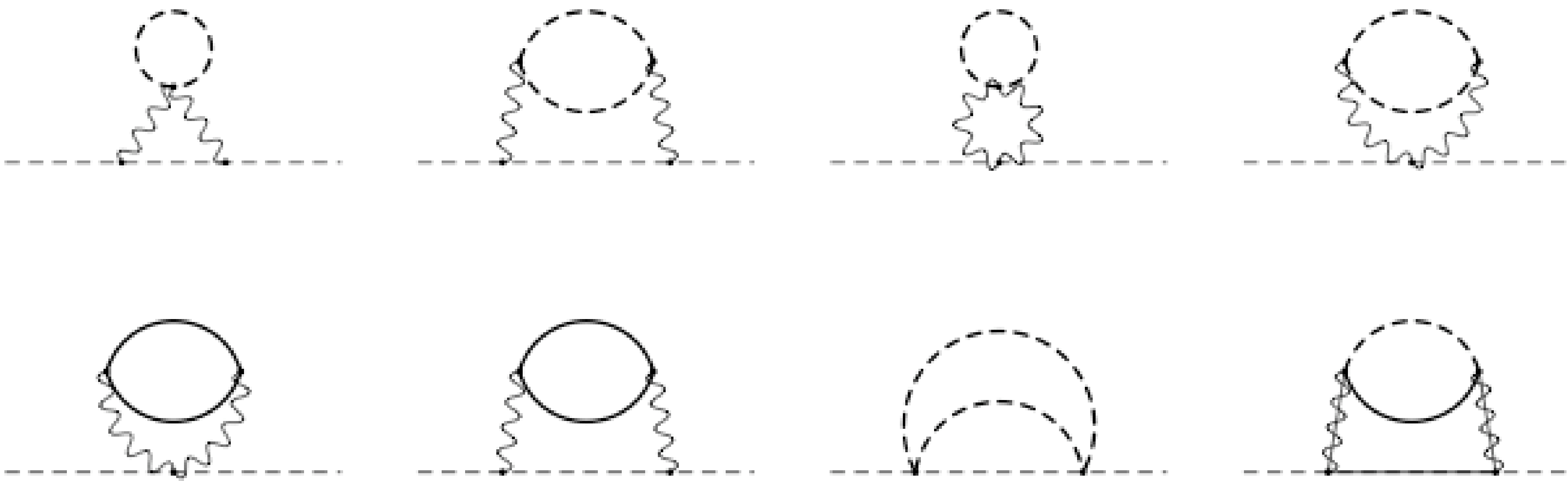
$$m_{\text{soft}} \sim 100 \text{ GeV - } 1 \text{ TeV} \sim F/M_{Planck} = m_{3/2}$$

Puts F at $\sim (10^{11} \text{ GeV})^2$

Gauge Mediated Supersymmetry Breaking

New particles of mass M (or M_{mess}) are charged under SU(3)xSU(2)xU(1), yet are in the “Hidden Sector”.

Gauge Mediation



$$\Lambda \equiv \frac{F}{M_{mess}}$$

N_5 = number of messengers

Gauge Mediation

$$M_a = \frac{\alpha_a}{4\pi} \Lambda N_5,$$

$$m^2_{\phi_i} = 2\Lambda^2 N_5 \sum_{a=1}^{3} C_a(i) \left(\frac{\alpha_a}{4\pi}\right)^2$$

$$\Lambda \equiv \frac{F}{M_{mess}}$$

N_5 = number of messengers

The Messenger Scale

M_{mess} can be as low as 10 TeV. Only requirement is

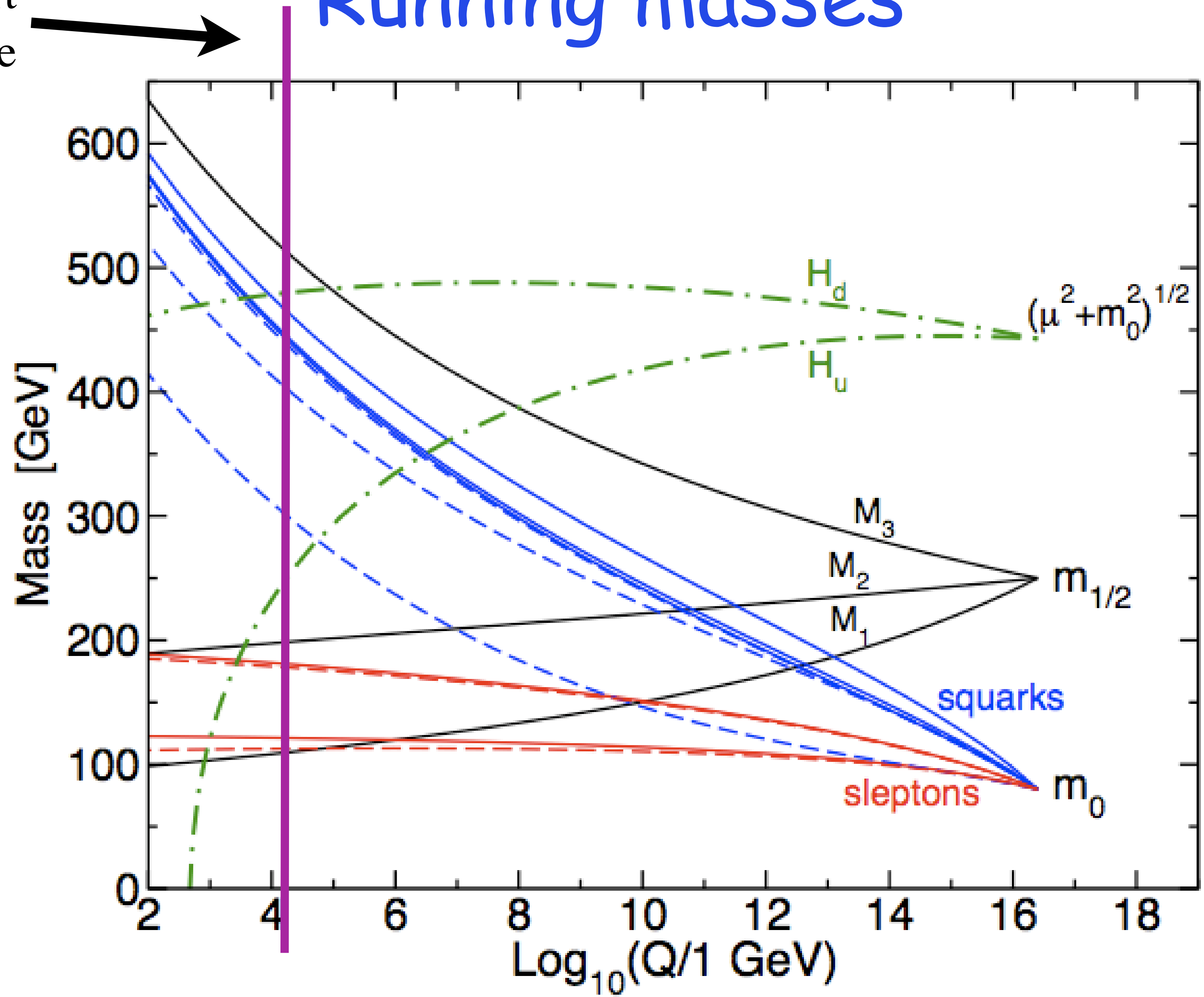
$$\Lambda < M_{mess}$$

(but this can be a factor of a few)

This means when we “run” the soft masses down to the weak scale, we start from a much lower scale than the Planck scale - namely the messenger scale.

Running masses

start here



Running masses

$$M_a = \frac{\alpha_a}{4\pi}\Lambda N_5,$$

$$m^2_{\phi_i} = 2\Lambda^2 N_5 \sum_{a=1}^{3} C_a(i)\left(\frac{\alpha_a}{4\pi}\right)^2$$

But the starting point is NOT unified.

Gaugino masses

mSUGRA

At leading order, and at any scale below the GUT scale, gaugino masses satisfy:

$$\frac{M_1}{\alpha_1} = \frac{M_2}{\alpha_2} = \frac{M_3}{\alpha_3}$$

GMSB

Gauginos already start proportional to the gauge couplings:

$$M_a = \frac{\alpha_a}{4\pi} \Lambda N_5,$$

The gaugino spectrum is the same.

Gaugino masses

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

Gaugino/Higgsino -> Neutralino

$$\mathbf{M}_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$

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

$$\psi^0 = (\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0)$$

Gaugino/Higgsino -> Chargino

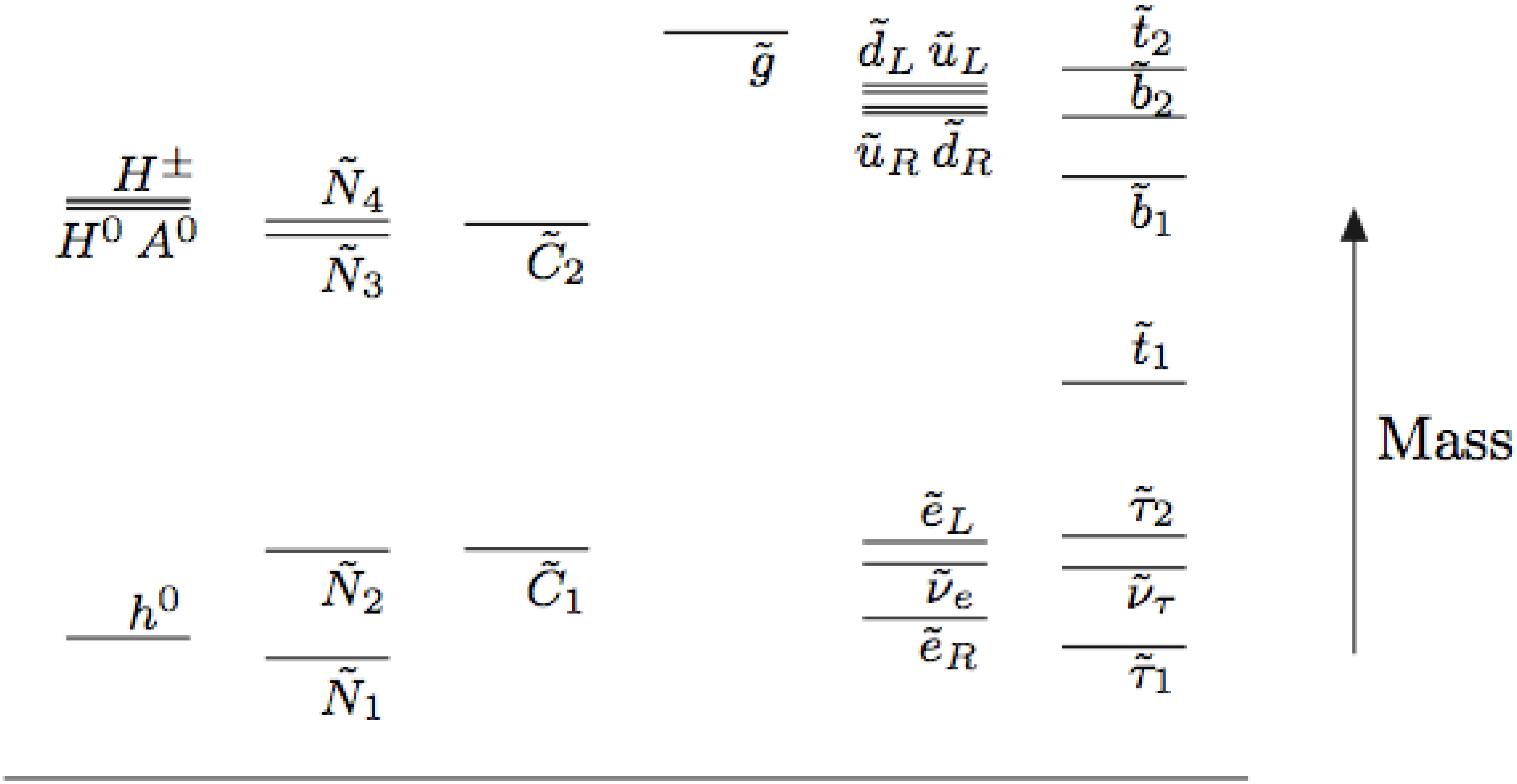
$$\mathbf{M}_{\widetilde{C}} = \begin{pmatrix} \mathbf{0} & \mathbf{X}^T \\ \mathbf{X} & \mathbf{0} \end{pmatrix}$$

$$\mathbf{X} \rightarrow \begin{pmatrix} M_2 & \sqrt{2} s_\beta \, m_W \\ \sqrt{2} c_\beta \, m_W & \mu \end{pmatrix}$$

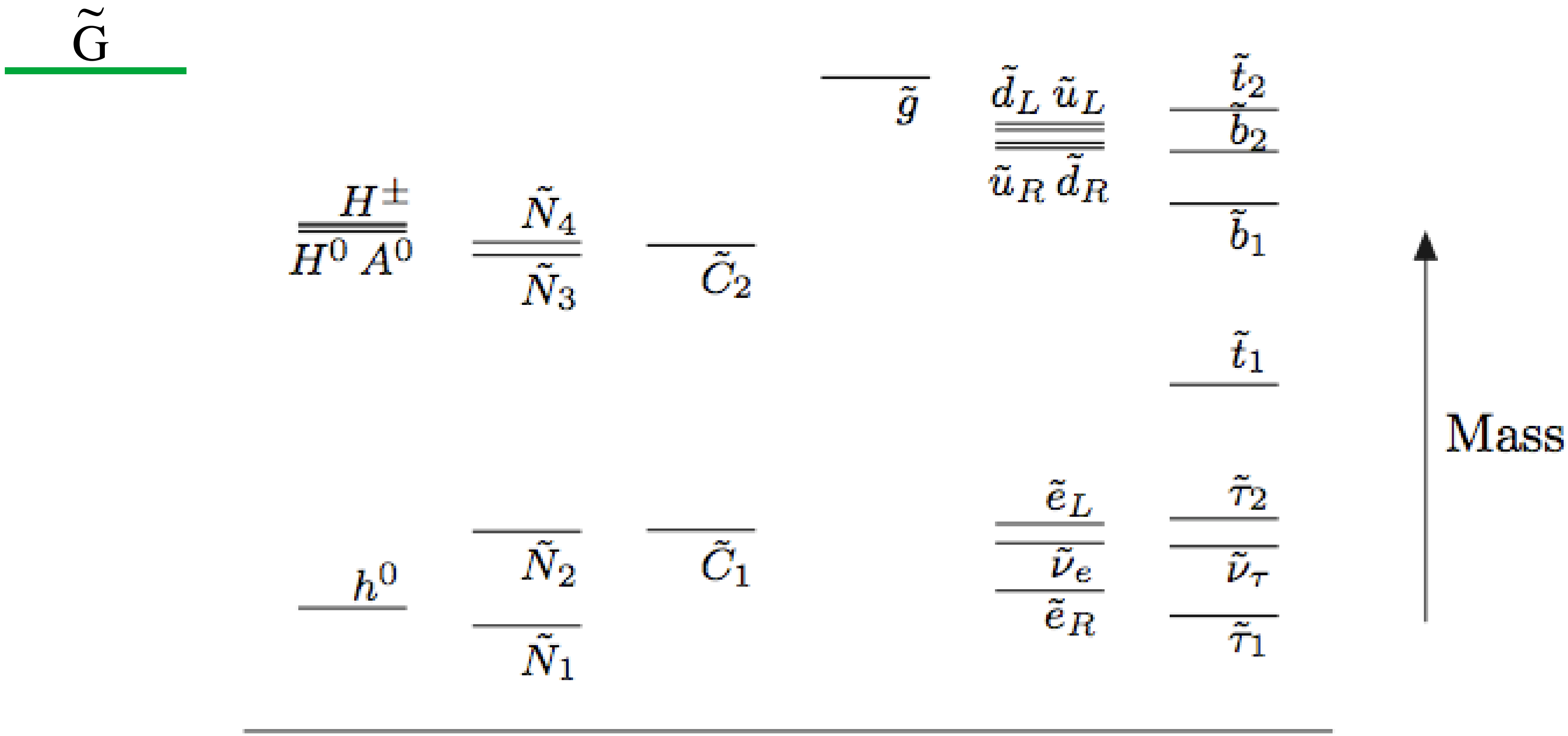
$$\mathcal{L}_{\text{chargino mass}} = -\frac{1}{2} (\psi^\pm)^T \mathbf{M}_{\widetilde{C}} \psi^\pm + \text{c.c.}$$

$$\psi^\pm = (\widetilde{W}^+, \widetilde{H}_u^+, \widetilde{W}^-, \widetilde{H}_d^-)$$

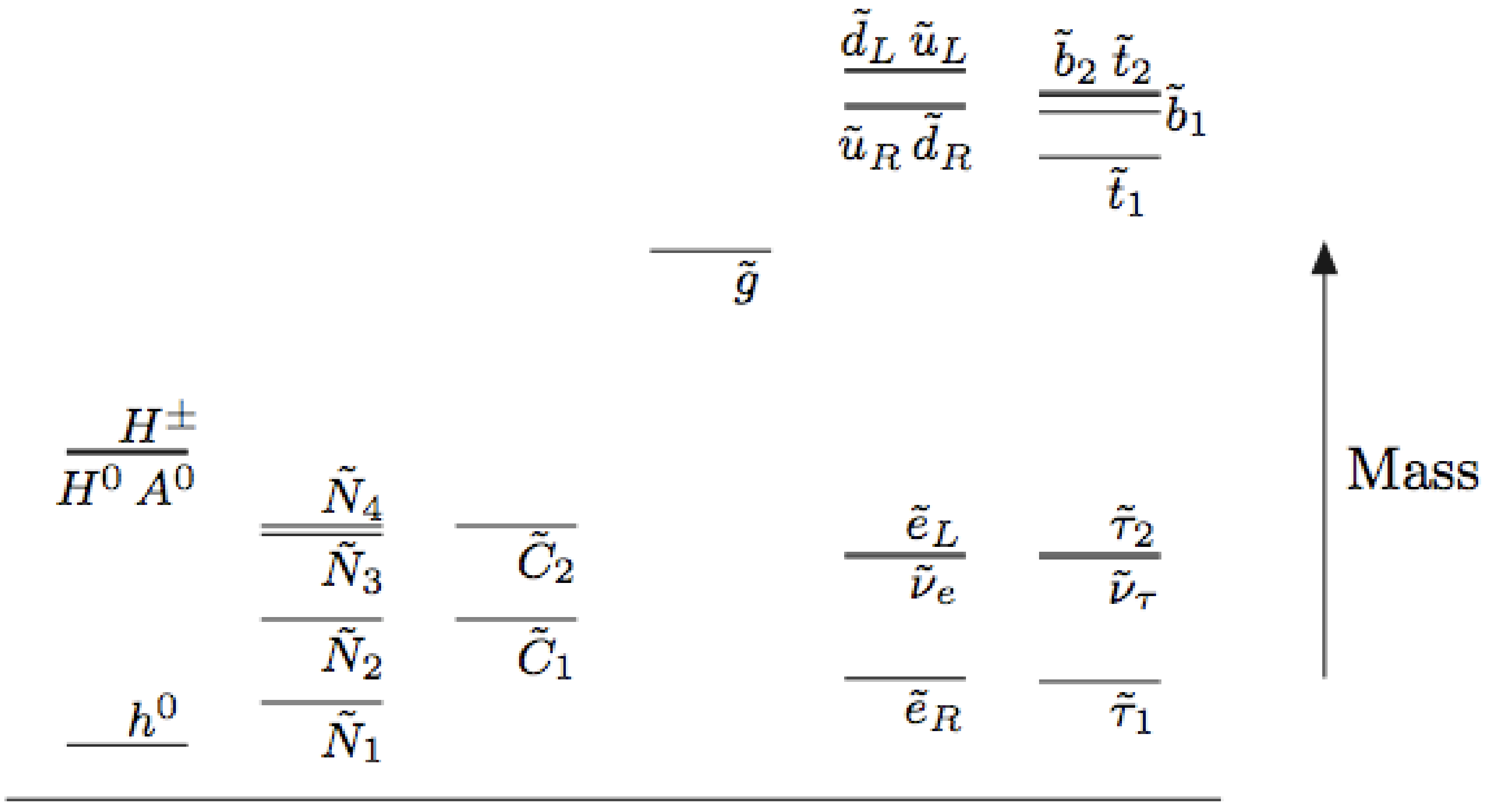
Typical Spectrum - mSUGRA



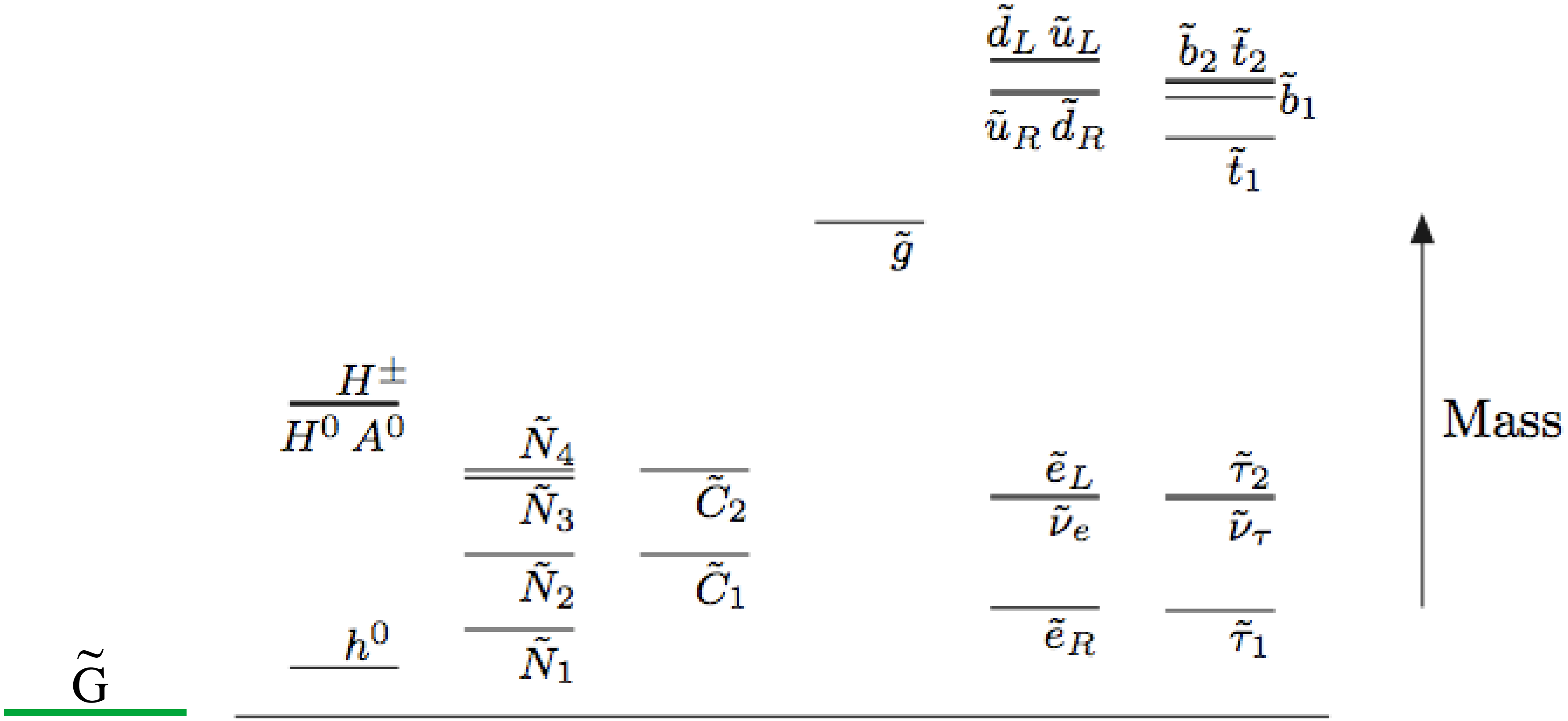
Typical Spectrum - mSUGRA



Typical Spectrum - GMSB



Typical Spectrum - GMSB



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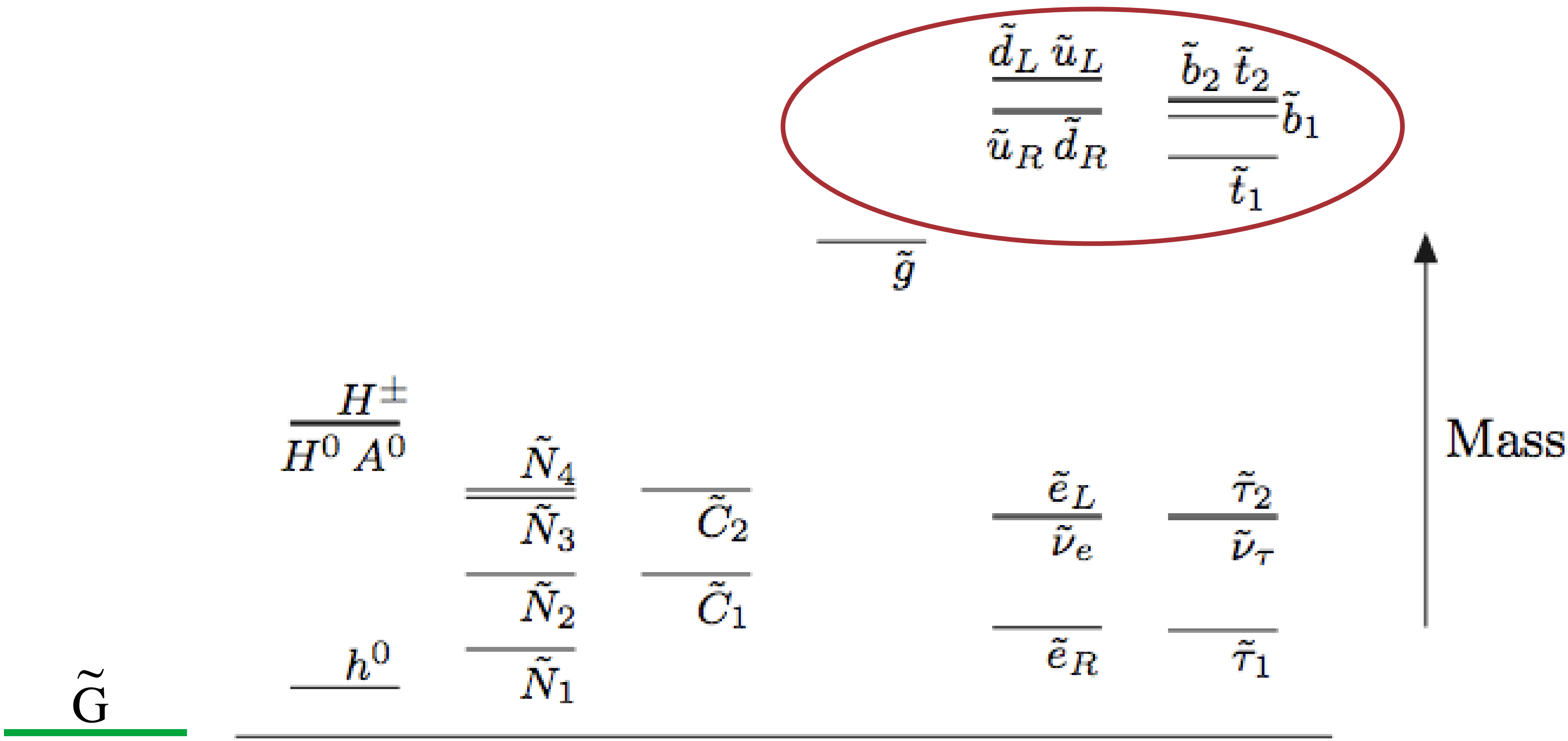
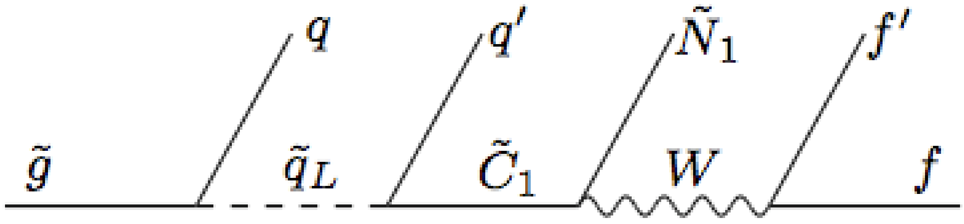


Phenomenology of Standard Scenarios



Cascade decays common - heavy colored particles produced copiously and decay to "inos".

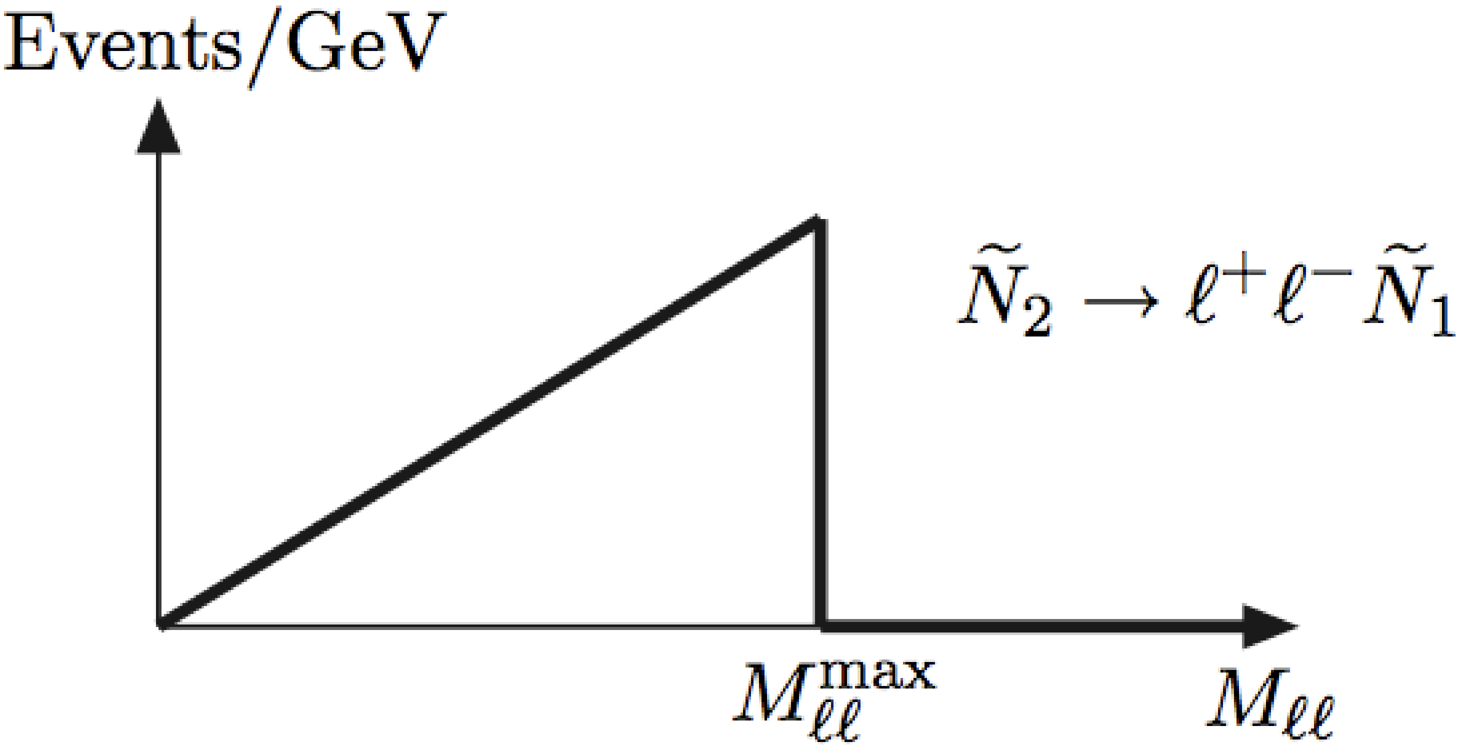
Most visible decays are through leptons:

$$\widetilde{N}_2 \rightarrow \ell^+ \ell^- \widetilde{N}_1$$

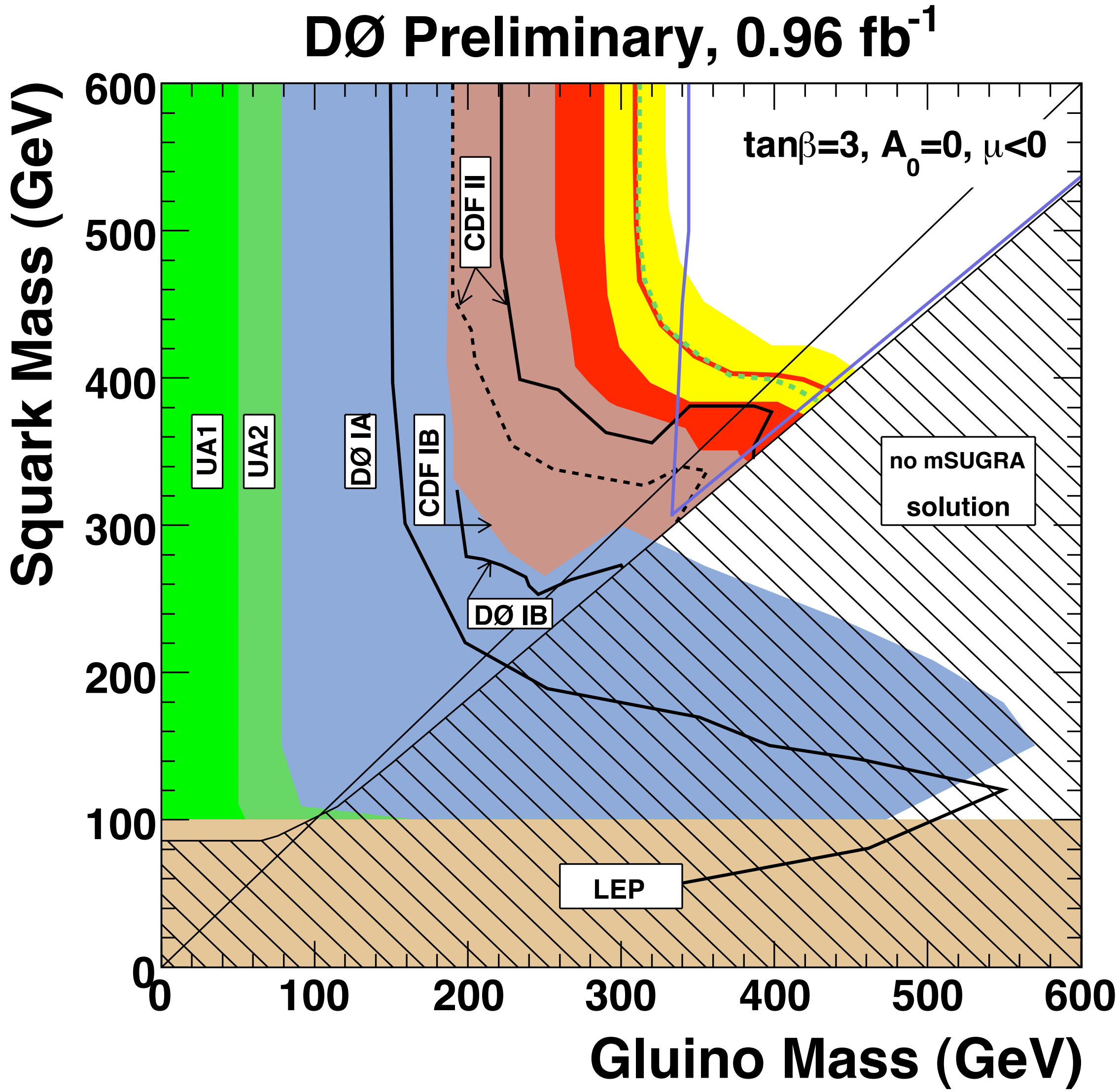
$$\widetilde{C}_1^{\pm} \rightarrow \ell^{\pm} \nu \widetilde{N}_1$$

Phenomenology of Standard Scenarios

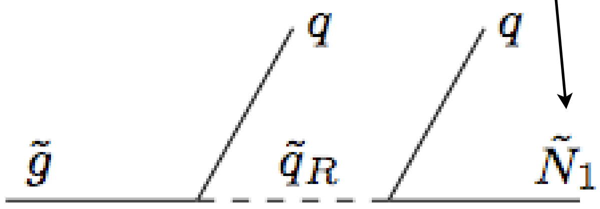
Look for kinematic endpoints.



Squark and Gluino Searches



Jets + missing E_T



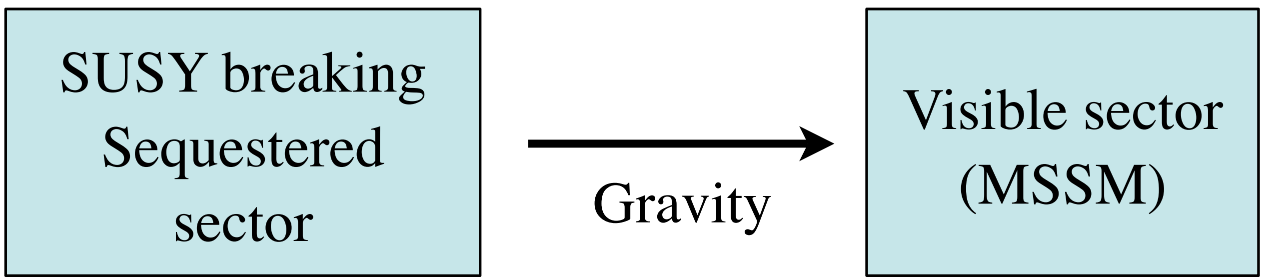
GMSB - Decay to the Gravitino

$$\Gamma(\widetilde{N}_1 \to \gamma\widetilde{G}) = 2 \times 10^{-3}\, \kappa_{1\gamma} \left(\frac{m_{\widetilde{N}_1}}{100\ \mathrm{GeV}}\right)^5 \left(\frac{\sqrt{\langle F \rangle}}{100\ \mathrm{TeV}}\right)^{-4} \mathrm{eV}$$

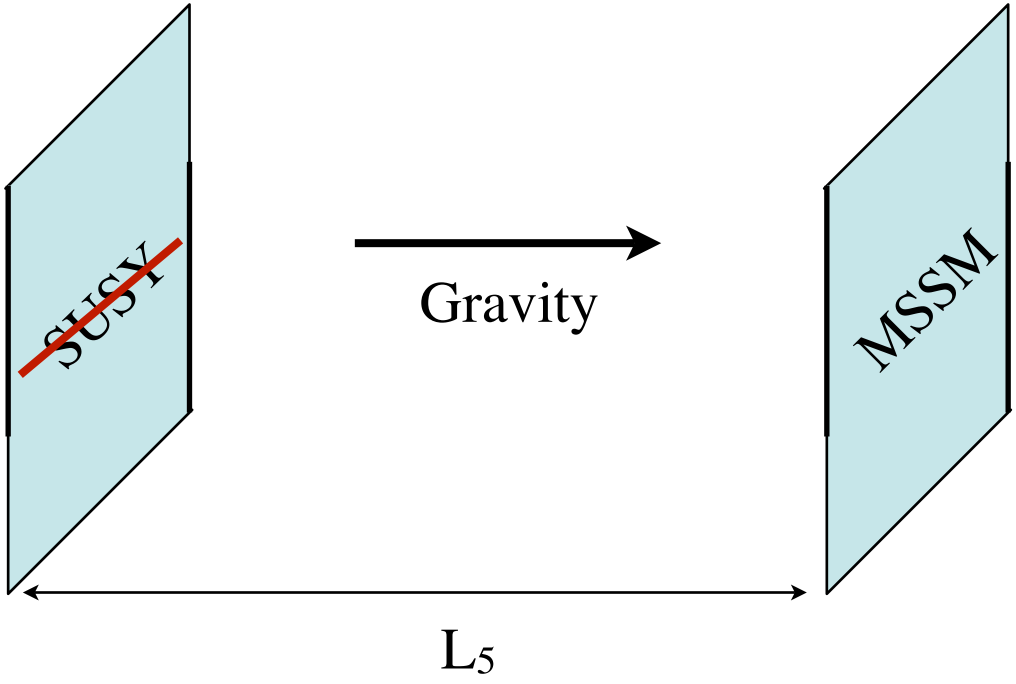
About 100 microns for these values.

If the stau is the next-to-lightest, it could leave a visible stiff track.

Anomaly Mediated Supersymmetry Breaking



Anomaly Mediated Supersymmetry Breaking



Supersymmetry breaking mediated via pure 5-dimensional gravity

Anomaly Mediated Supersymmetry Breaking

All masses can be computed as a function of the gravitino mass:

$$\langle F_\phi \rangle \sim \frac{\langle F \rangle}{M_{\rm P}} \sim m_{3/2}$$

$$\begin{aligned} M_a &= F_\phi \beta_{g_a} / g_a, \\ (m^2)^i_j &= \frac{1}{2} |F_\phi|^2 \frac{d}{dt} \gamma^i_j \\ a^{ijk} &= -F_\phi \beta_{y^{ijk}}, \end{aligned}$$

Anomaly Mediated Supersymmetry Breaking

All masses can be computed as a function of the gravitino mass:

$$\langle F_\phi \rangle \sim \frac{\langle F \rangle}{M_{\mathrm{P}}} \sim m_{3/2}$$

$$m^2_{\tilde{q}} = \frac{|F_\phi|^2}{(16\pi^2)^2}\left(8g_3^4 + \ldots\right),$$

$$m^2_{\tilde{e}_L} = -\frac{|F_\phi|^2}{(16\pi^2)^2}\left(\frac{3}{2}g_2^4 + \frac{99}{50}g_1^4\right)$$

$$m^2_{\tilde{e}_R} = -\frac{|F_\phi|^2}{(16\pi^2)^2}\frac{198}{25}g_1^4$$

Anomaly Mediated Supersymmetry Breaking

All masses can be computed as a function of the gravitino mass:

$$\langle F_\phi \rangle \sim \frac{\langle F \rangle}{M_{\mathrm{P}}} \sim m_{3/2}$$

$$\begin{aligned} M_1 &= \frac{F_\phi}{16\pi^2}\frac{33}{5}g_1^2 \\ M_2 &= \frac{F_\phi}{16\pi^2}g_2^2 \\ M_3 &= -\frac{F_\phi}{16\pi^2}3g_3^2 \end{aligned}$$

(minimal) Anomaly Mediation

Scalar masses - must fix:

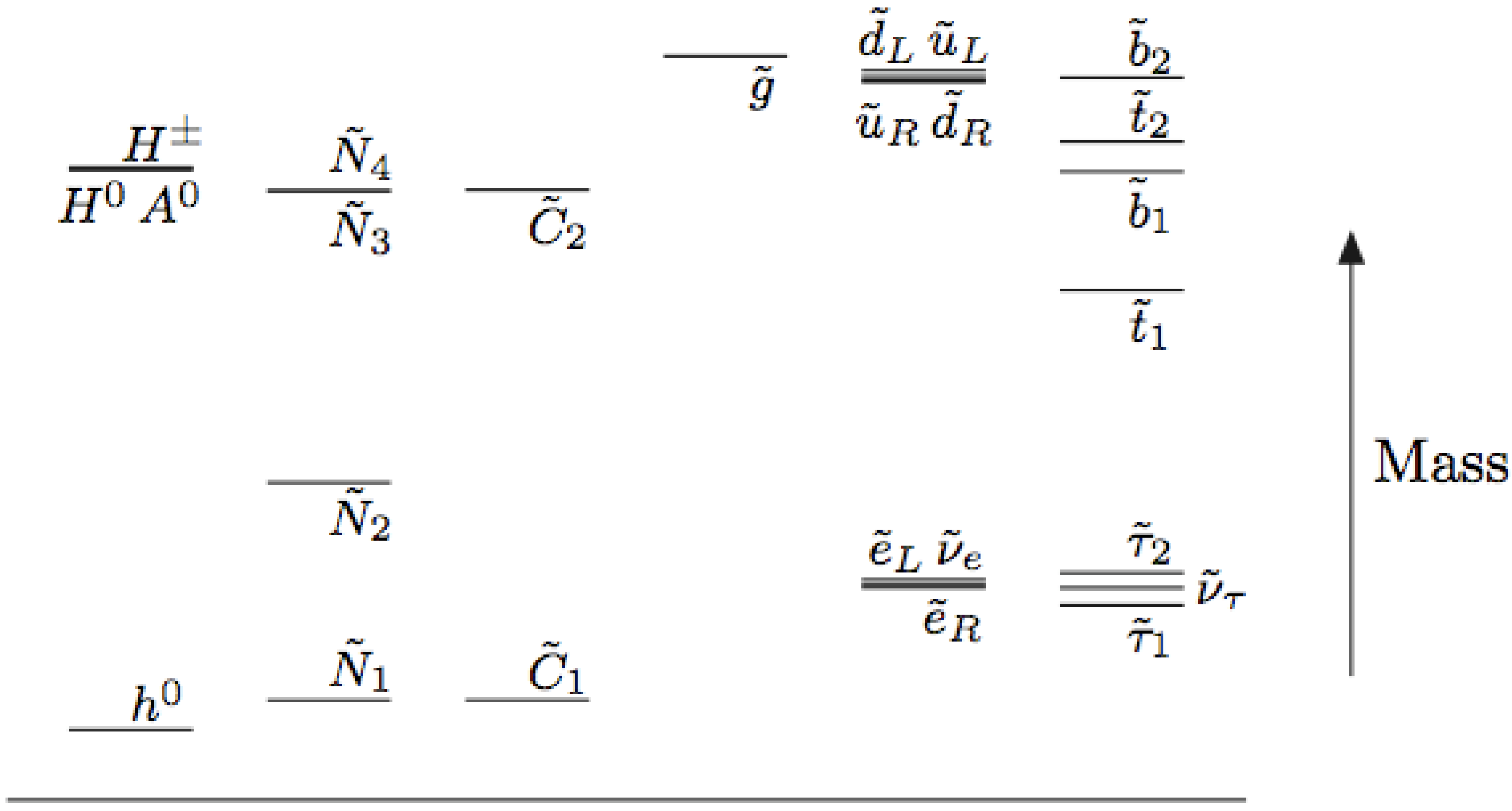
$$\delta m^2_{scalar} = m_0^2$$

(actual models can produce almost this - would prefer to add gauge mediation)

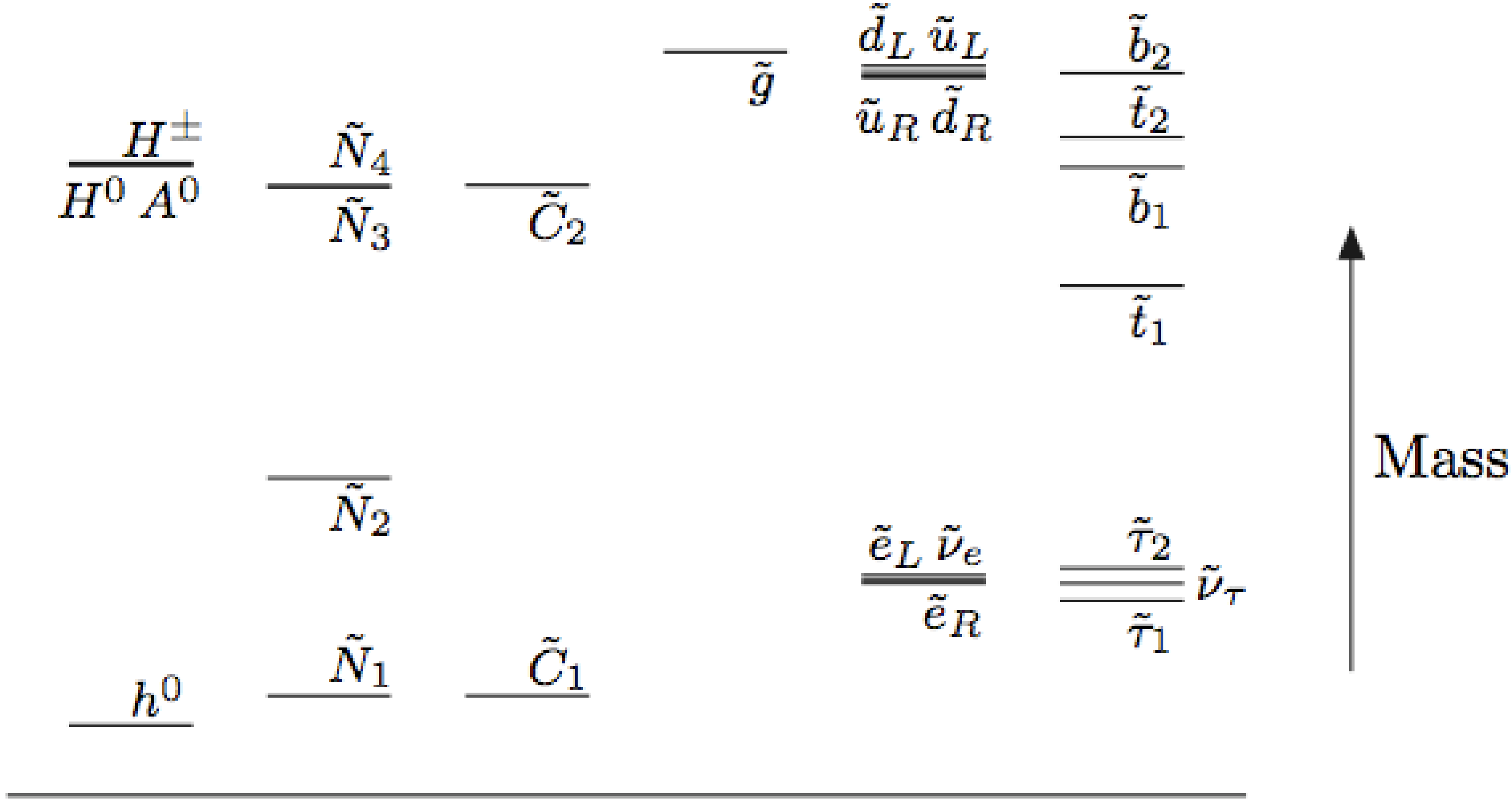
gaugino spectrum new:

$$M_3 : M_2 : M_1 \simeq 7 : 1 : 3$$

Typical Spectrum - mAMSB



Typical Spectrum - mAMSB



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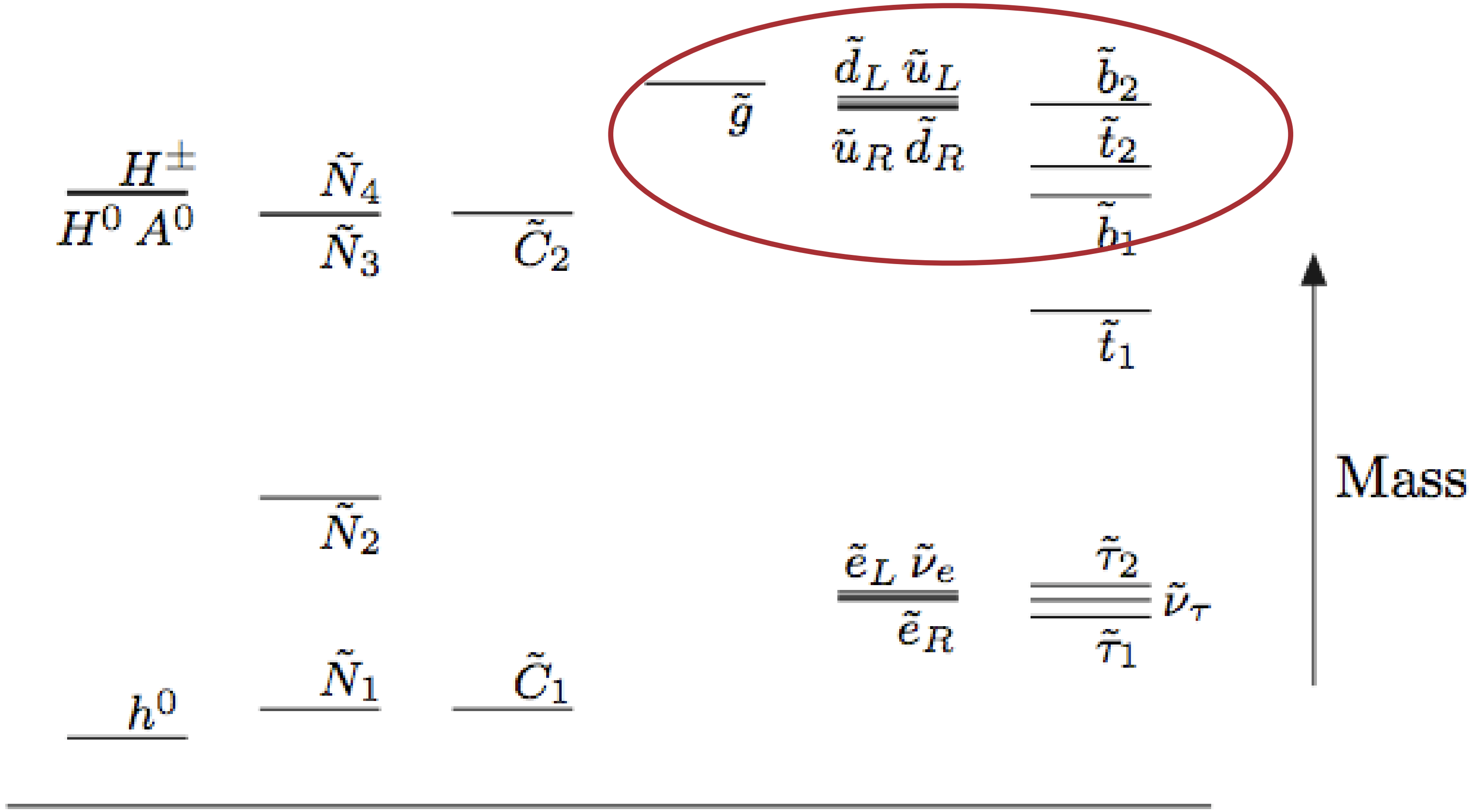

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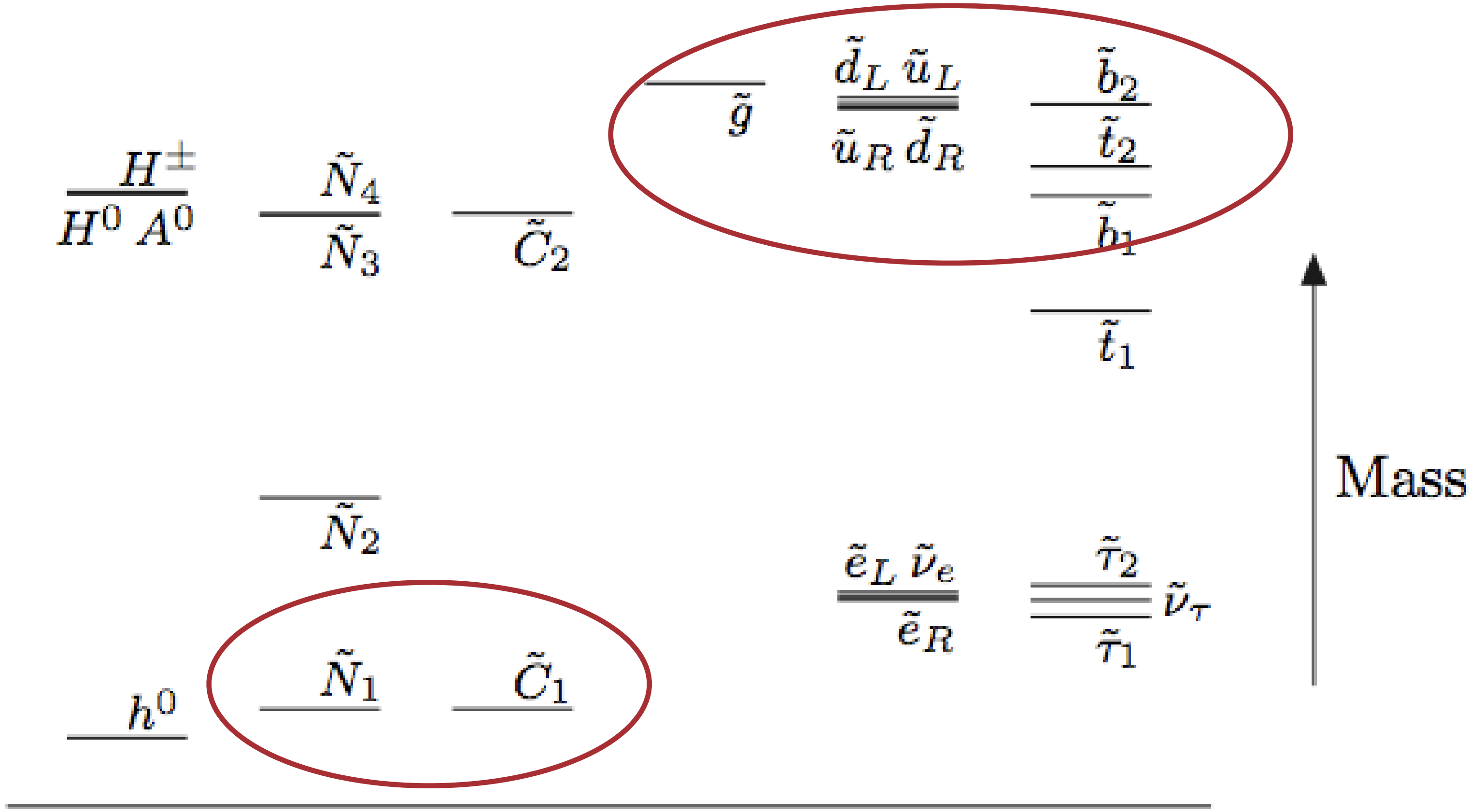
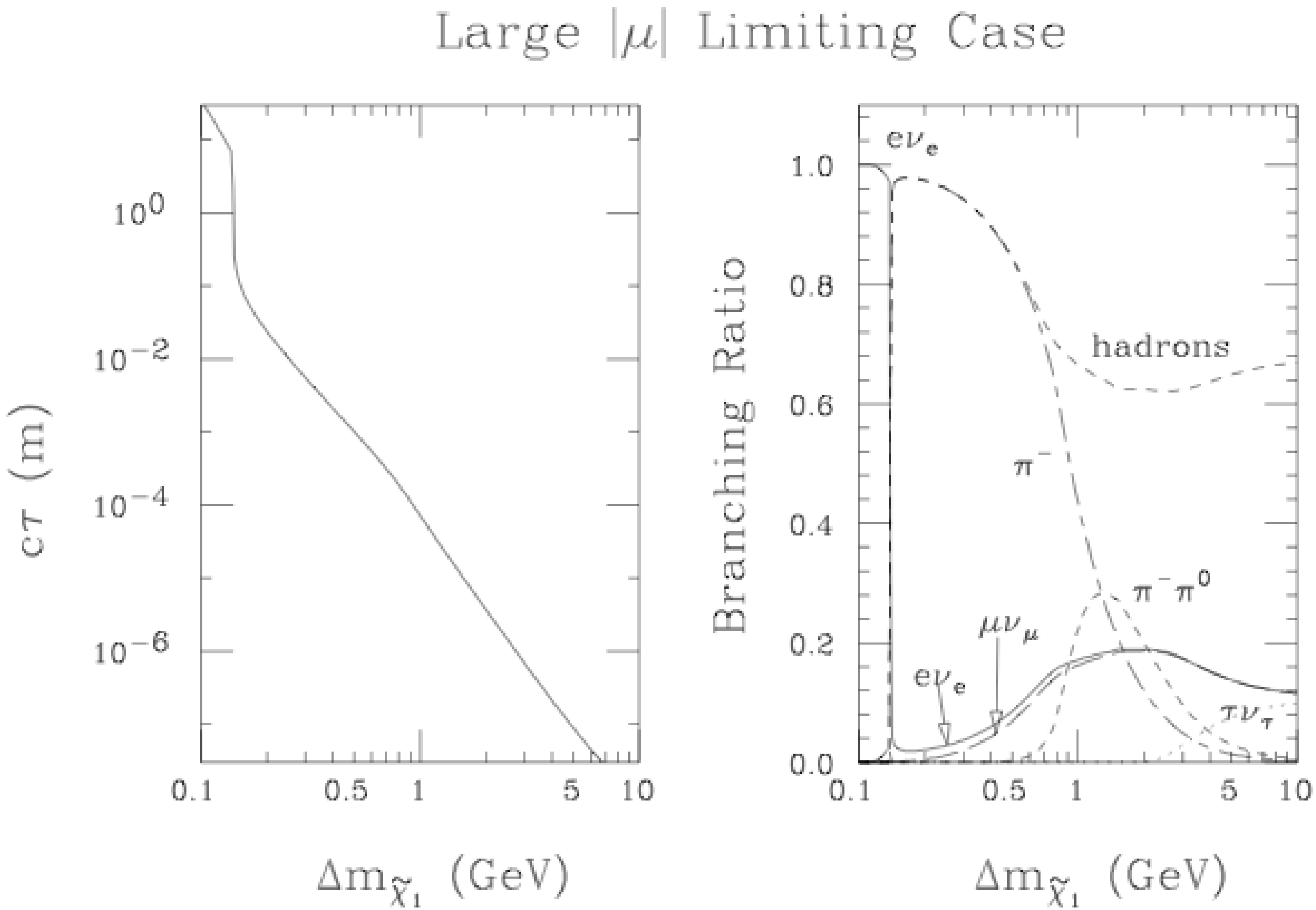
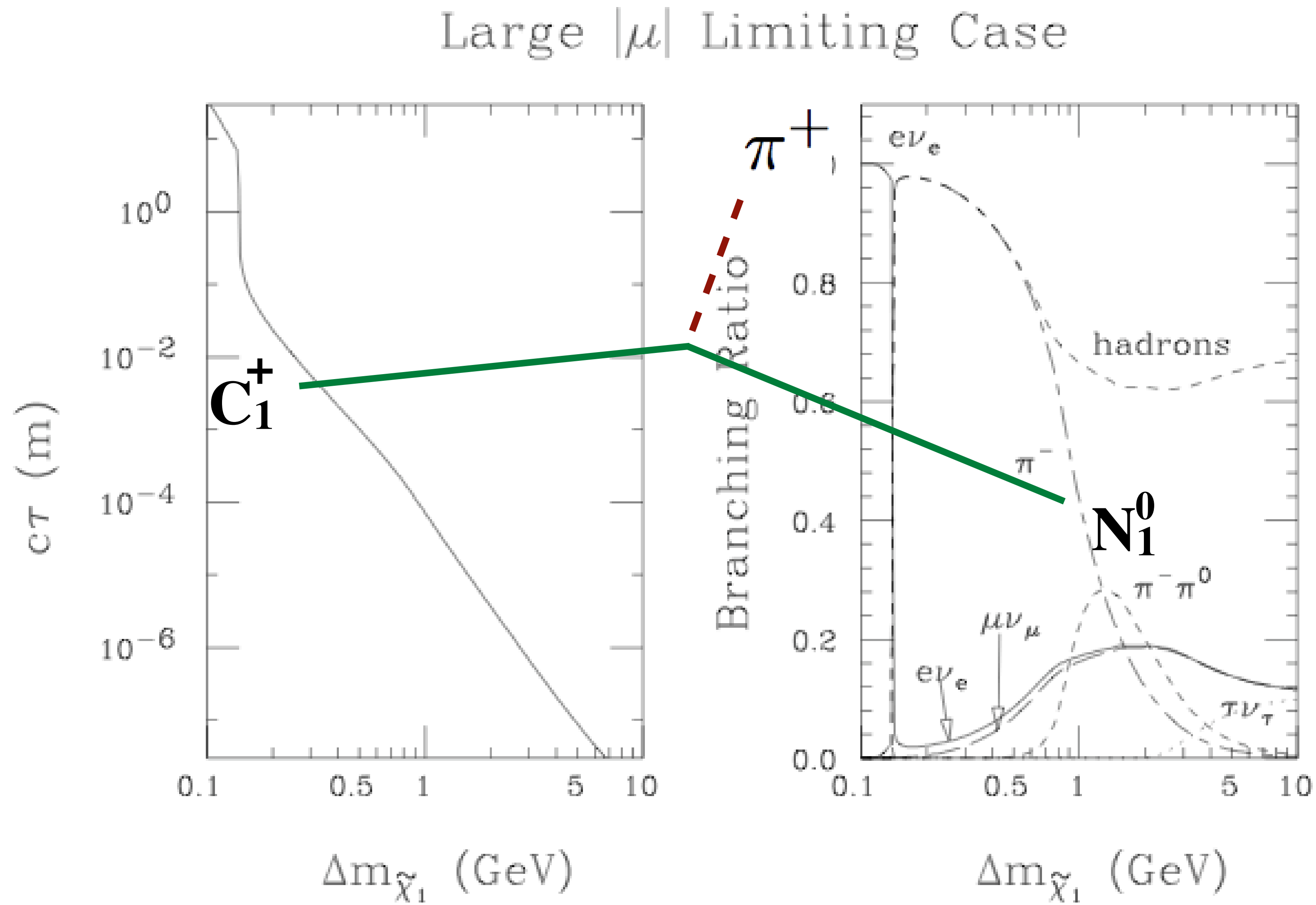


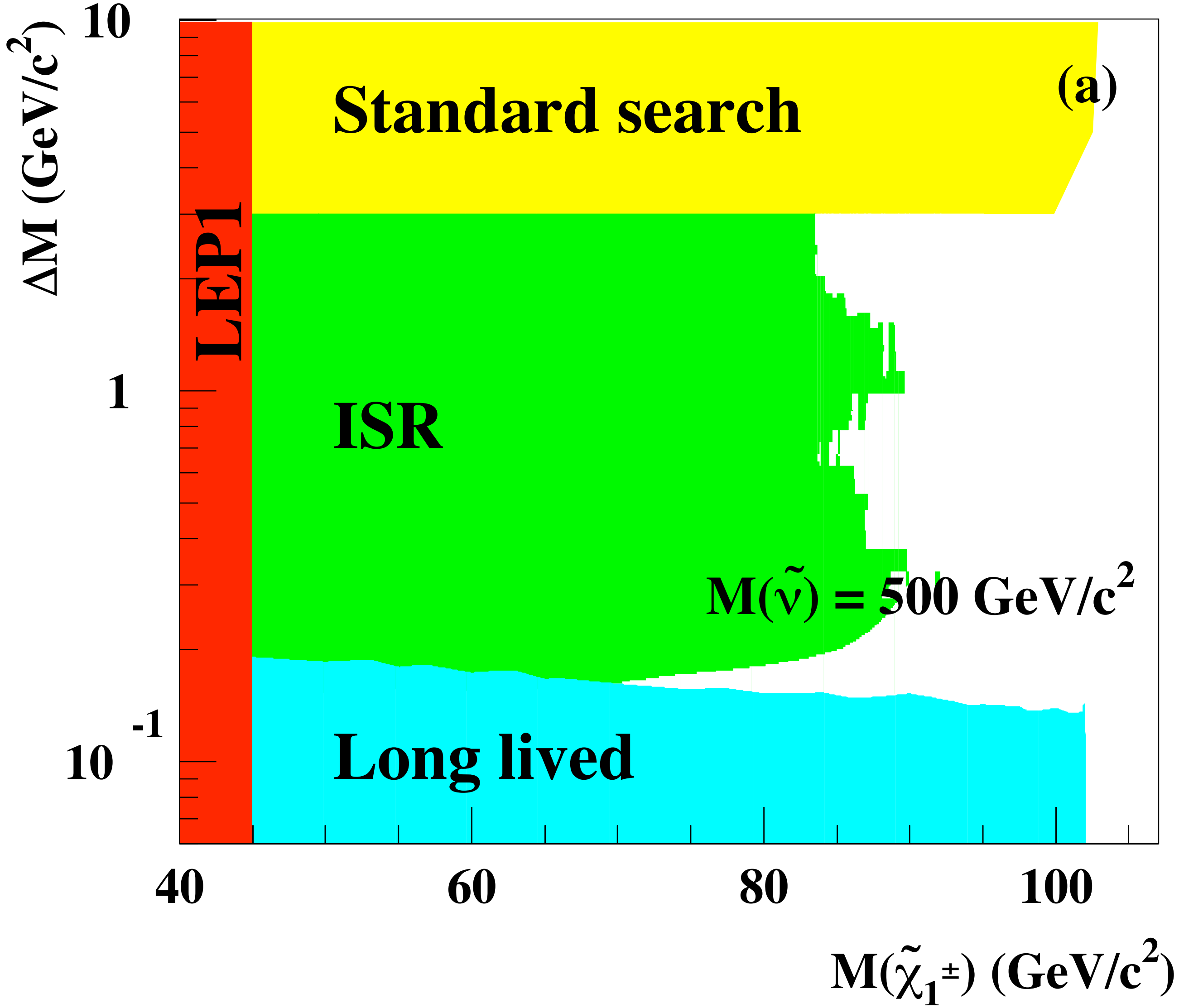
Lightest Chargino Decays



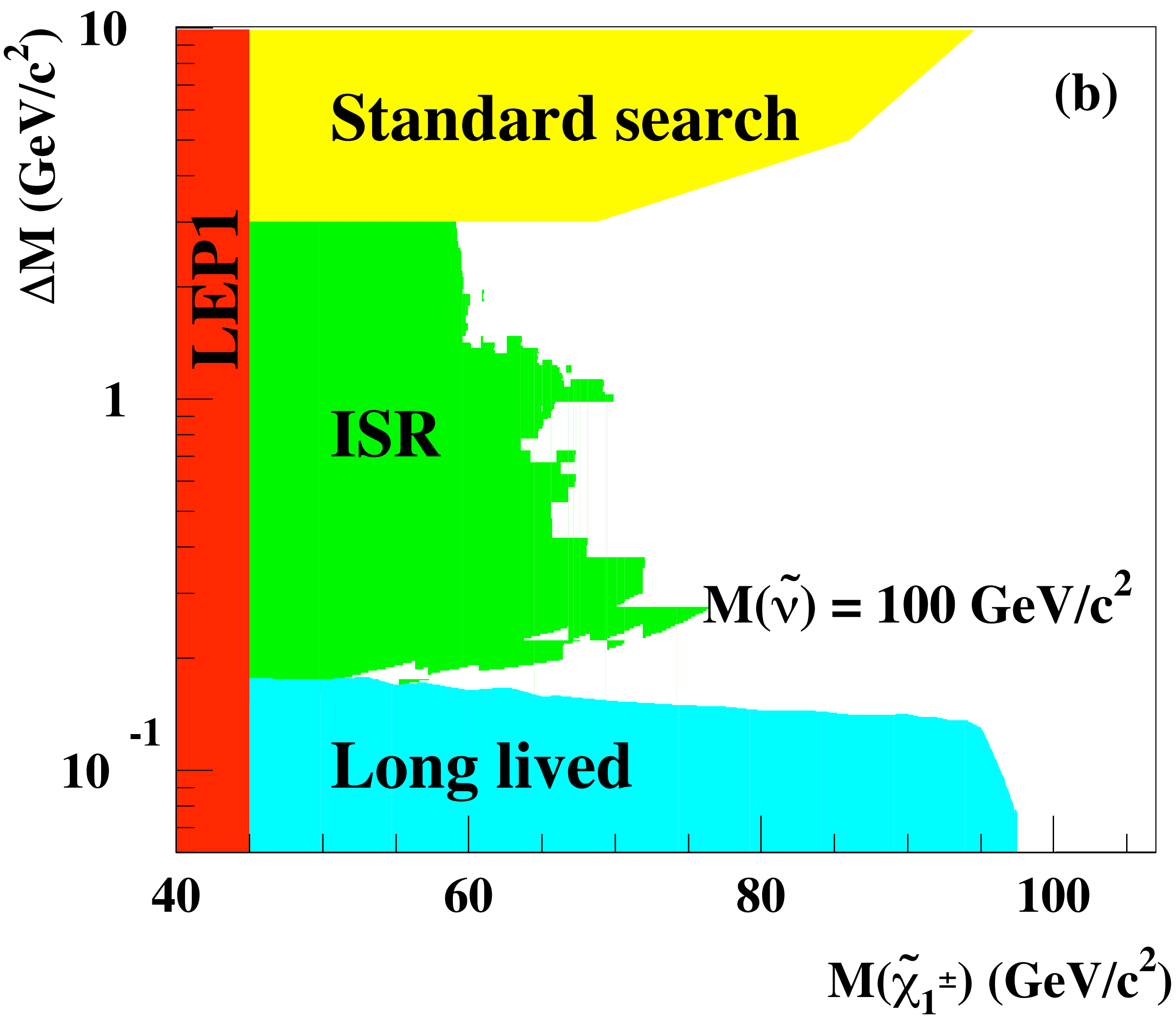
Lightest Chargino Decays



Delphi Chargino Search



Delphi Chargino Search



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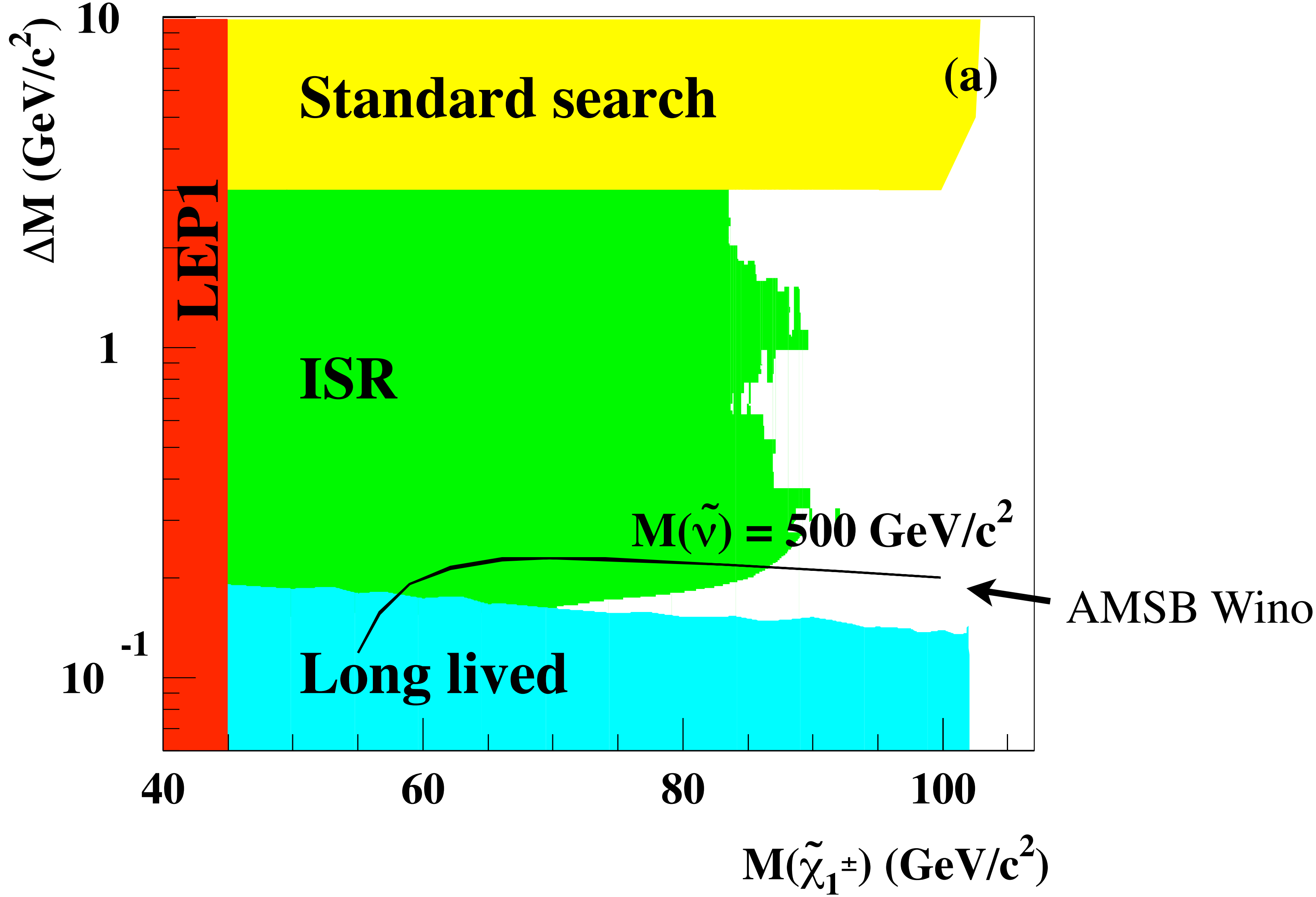

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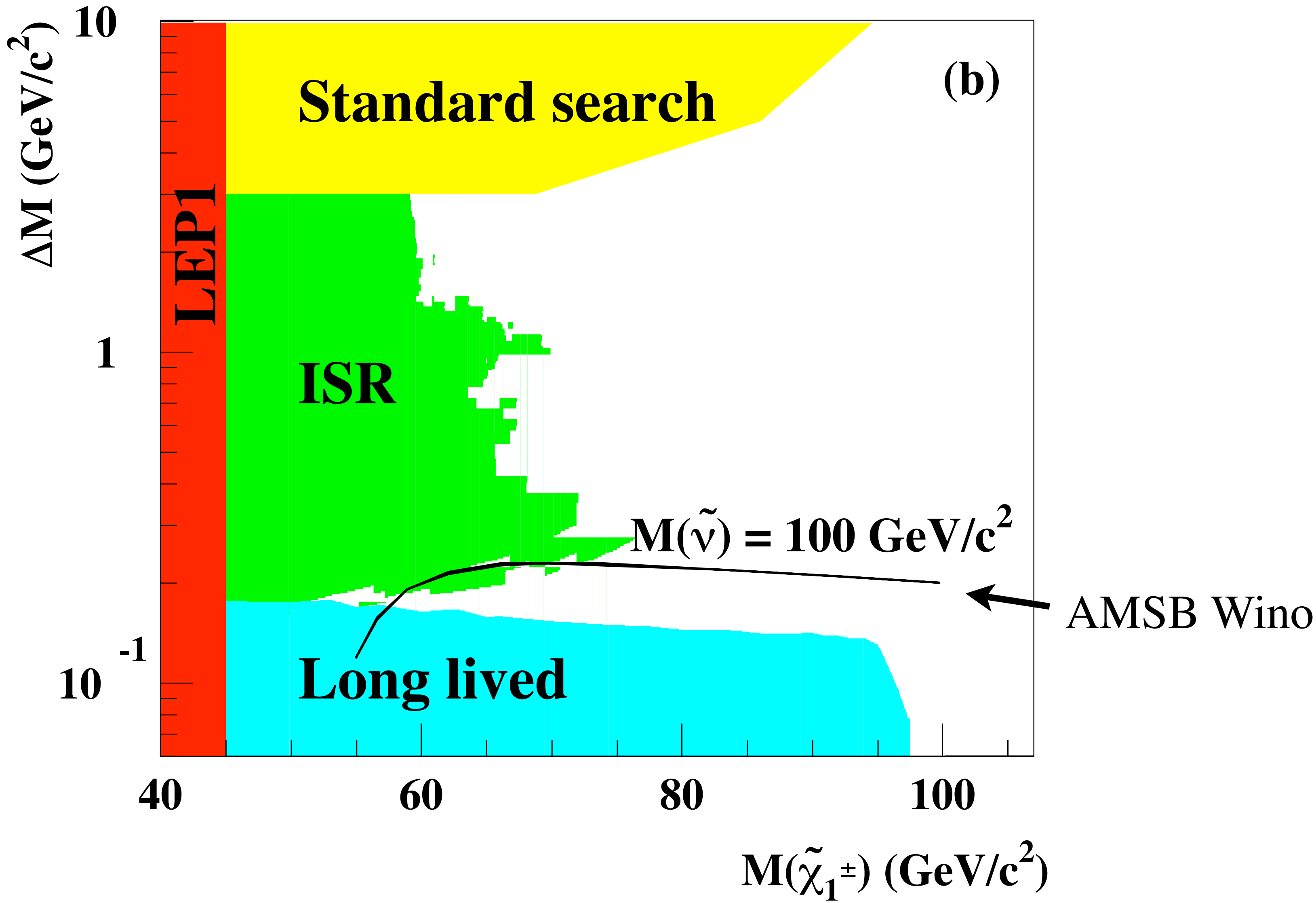

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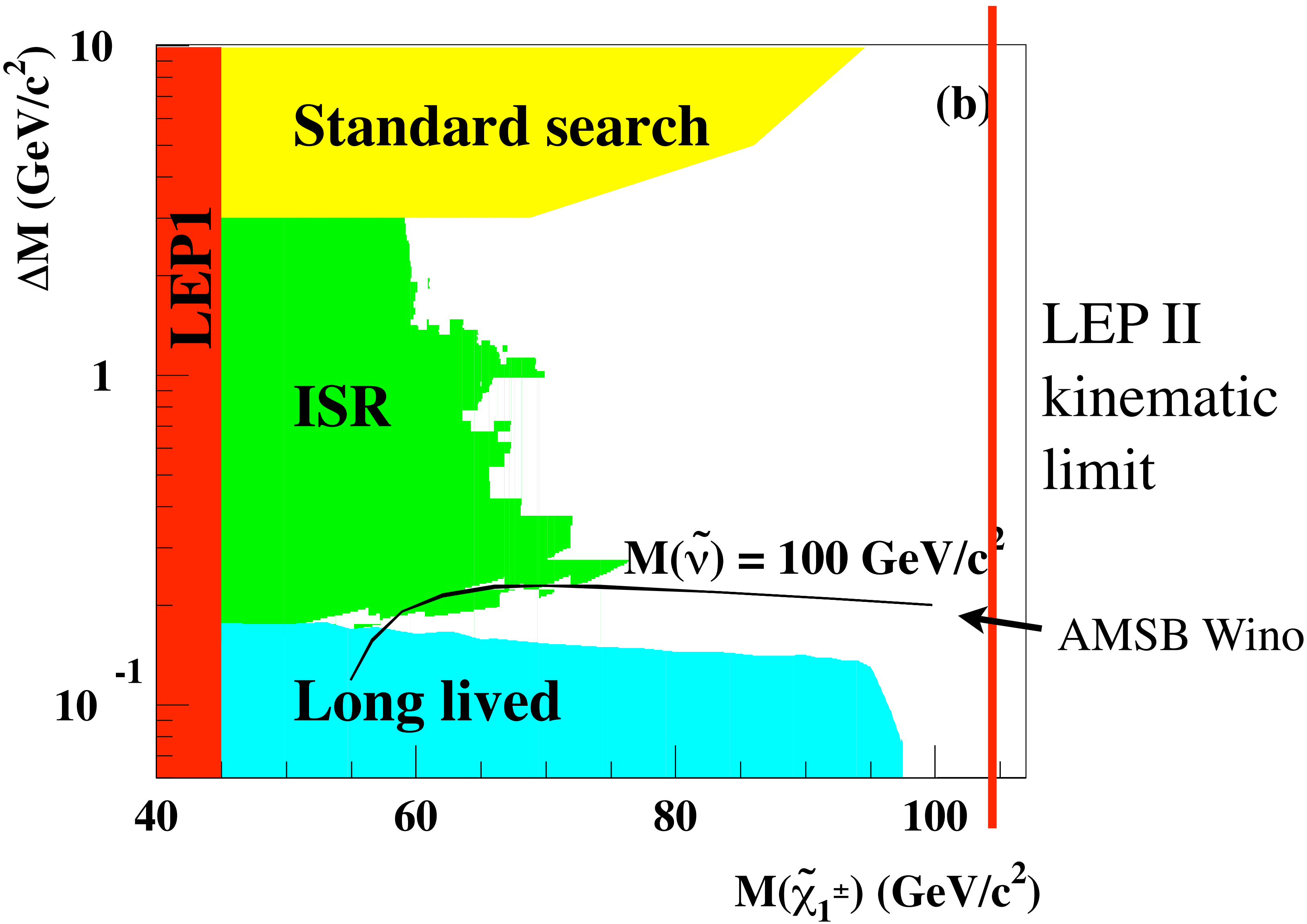

The Higgs Sector

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

The Higgs Sector

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

Conditions for EWSB

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

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

The Higgs Sector

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

Conditions for EWSB

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

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

$$v_u = \langle H_u^0 \rangle, \qquad v_d = \langle H_d^0 \rangle \qquad \tan\beta \equiv v_u/v_d$$

The Higgs Sector

$$\sin(2\beta) = \frac{2b}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2},$$

$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2$$

$$\begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix} = \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{\sqrt{2}} R_\alpha \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} + \frac{i}{\sqrt{2}} R_{\beta_0} \begin{pmatrix} G^0 \\ A^0 \end{pmatrix}$$

$$\begin{pmatrix} H_u^+ \\ H_d^{-*} \end{pmatrix} = R_{\beta_\pm} \begin{pmatrix} G^+ \\ H^+ \end{pmatrix}$$

The Higgs Sector

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

The simplest measure of fine-tuning in your model is one part in:

$$\frac{m_{A^0}^2}{m_Z^2}$$