Supersymmetry
and other theories of Dark Matter Candidates

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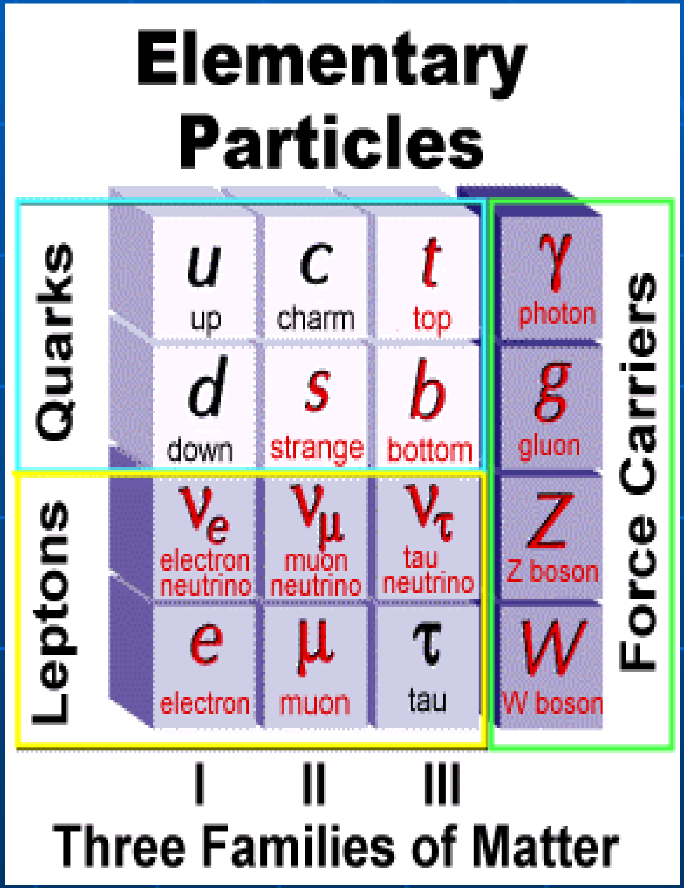
798G Presentation
3/1/07

Overview

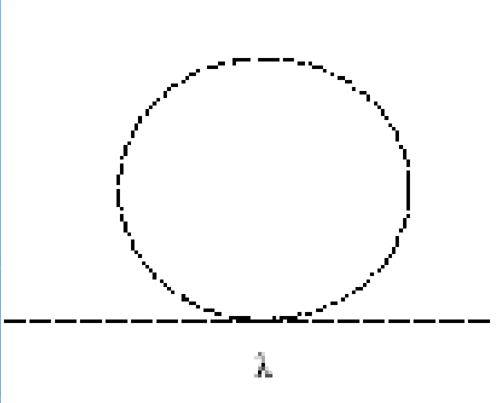
- Why bother with a new theory?
- Why is Supersymmetry a good solution?
- Basics of Supersymmetry
- Why this leads to Dark Matter Candidates
- Other theoretical basis for Dark Matter Candidates

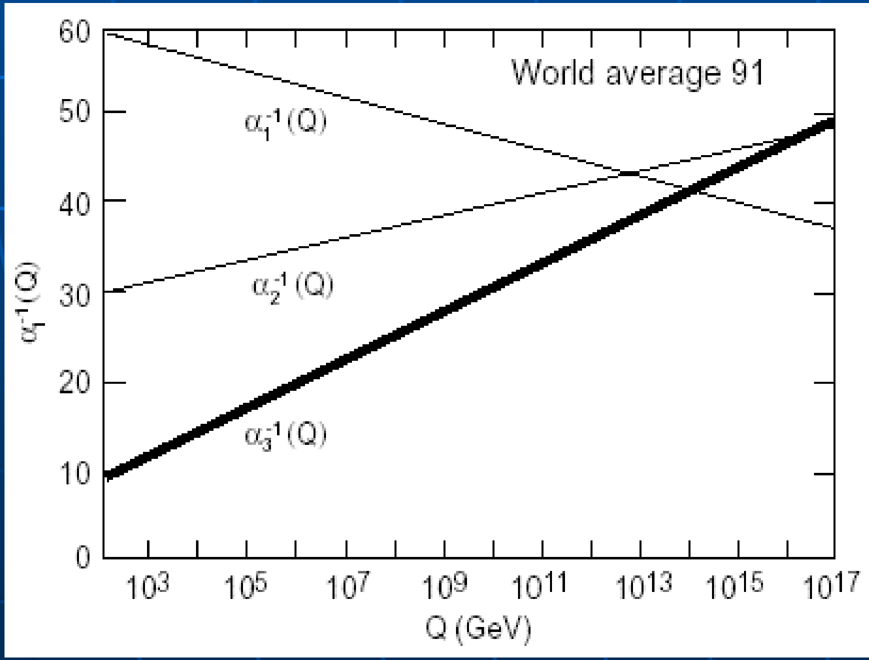
Obligatory Standard Model Slide

- 3 categories of particles:
  - Quarks
  - Leptons
  - Bosons (force mediating)
- Lagragian for 3 of 4 fundamental forces
- Been supported by SIGNIFICANT experimental data
- Requires Scalar Boson (Higgs) as a mechanism to explain why Z, W massive



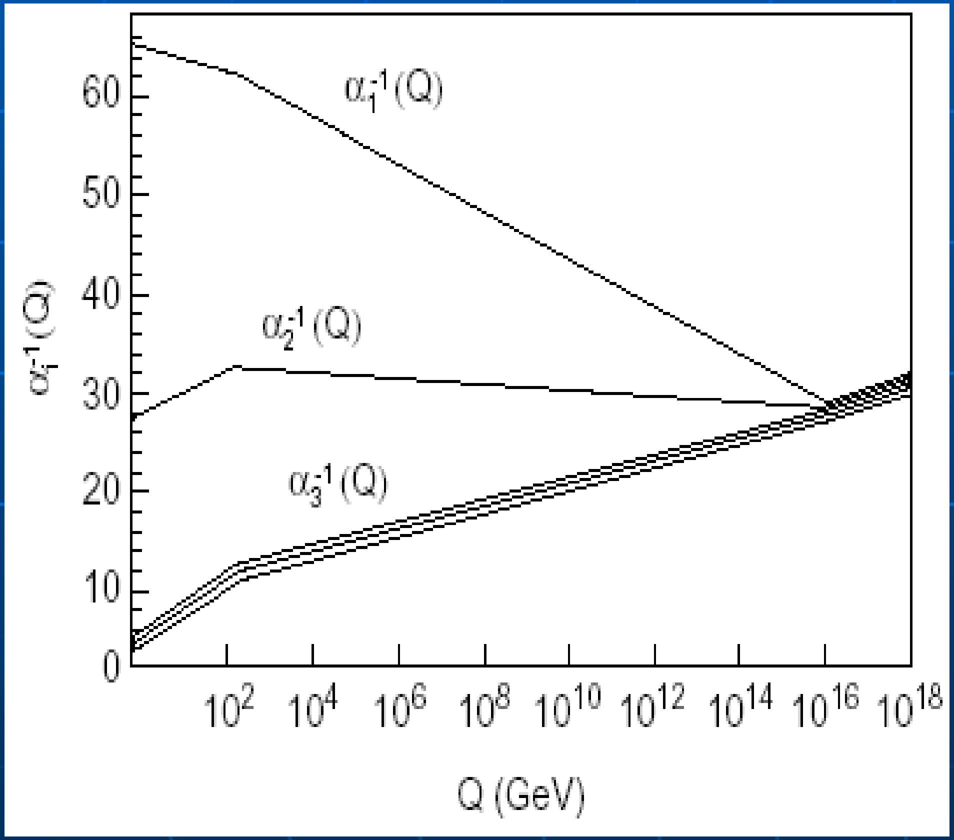
Hierarchy Problem





- Quadratic divergence in Higgs loops
- Can't renormalize Higgs mass without significant cancelations
- Electroweak scale vs. Planck scale

How does SUSY Help?



- Unification of Forces
  - Energy dependent coupling parameters meet with SUSY
- Higgs Mass
  - Divergences cancel due to opposite sign contributions
- Abundance of matter over antimatter, size and age of universe, proton decay, …

Basics of SuSy

- What is a symmetry?
  - Lagrangian remains unchanged under a transformation of the fields
  - Ex: SM Lagrangian doesn't change if fields are "boosted" (transformed to moving frame using Spec. Rel.)
- What is a SUPER symmetry?
  - Transformation of fields include fields of opposite nature
  - Terms cancel in Lagrangian when all fields transformed, leaving it changed by only a derivative

The Mathematics

- Wess-Zumino Model

$$\mathcal{L} = \frac{1}{2}(\partial_\mu A)^2 + \frac{1}{2}(\partial_\mu B)^2 + \frac{i}{2}\bar{\psi}\partial\!\!\!/\,\psi - \frac{1}{2}m\bar{\psi}\psi - \frac{1}{2}m^2A^2 - \frac{1}{2}m^2B^2$$
$$+ mgA(A^2 + B^2) - \frac{1}{2}g^2(A^2 \overset{①}{+} B^2)^2 - ig\overset{②}{\bar{\psi}}A\psi + ig\bar{\psi}\gamma_5 B\psi$$

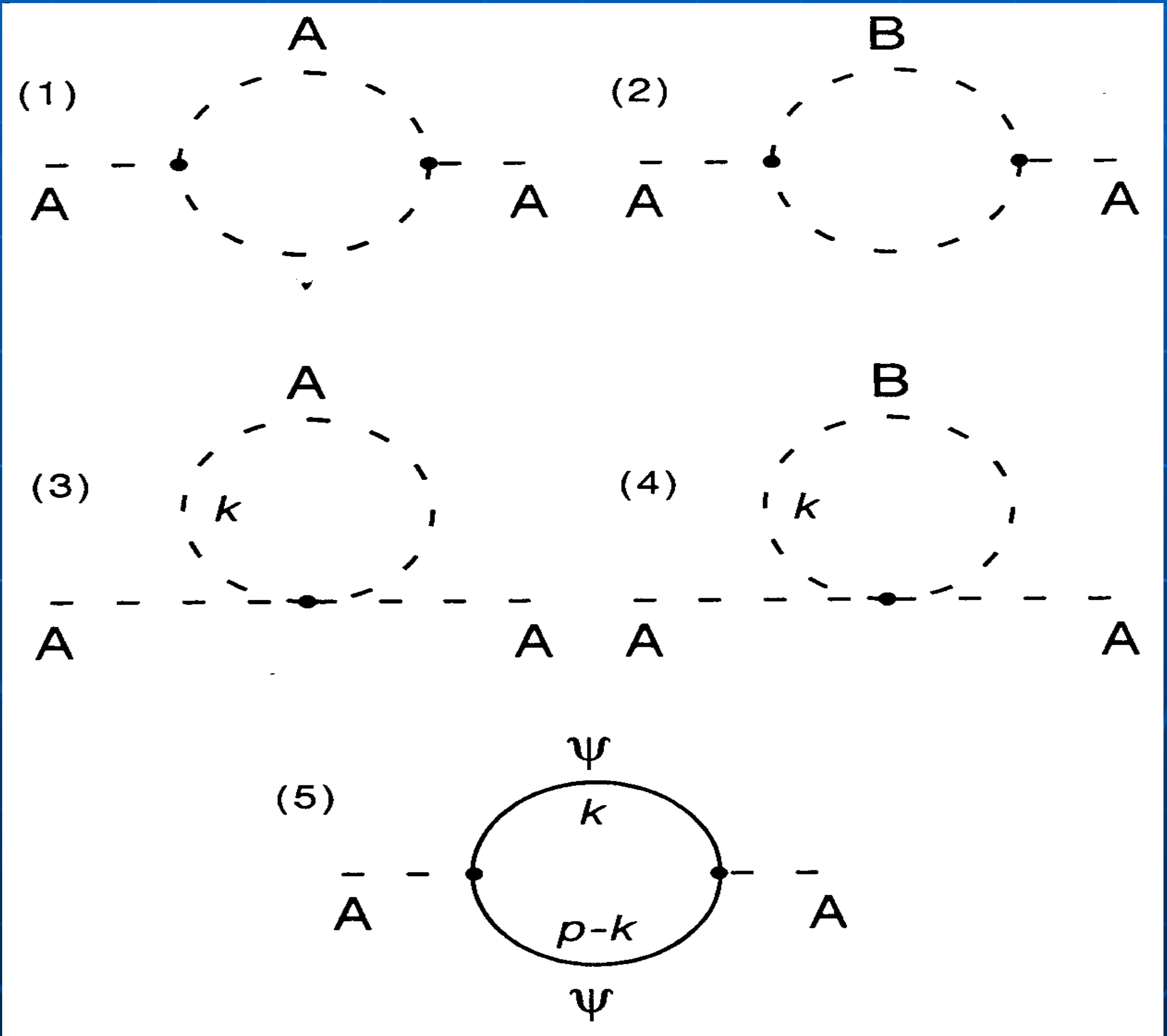
$$A \rightarrow A' = A + \delta A = A + \bar{\alpha}QA$$

$$\delta A = i\bar{\alpha}\gamma^5\psi \qquad \delta B = -\bar{\alpha}\psi$$

$$\delta\psi = F\alpha - iG\gamma^5\alpha + (\partial\!\!\!/\,\gamma^5 A)\alpha + i(\partial\!\!\!/\,B)\alpha$$

where $F = mA - g(A^2 - B^2)$ and $G = mB - 2gAB$.

Eliminating Quadratic Divergences

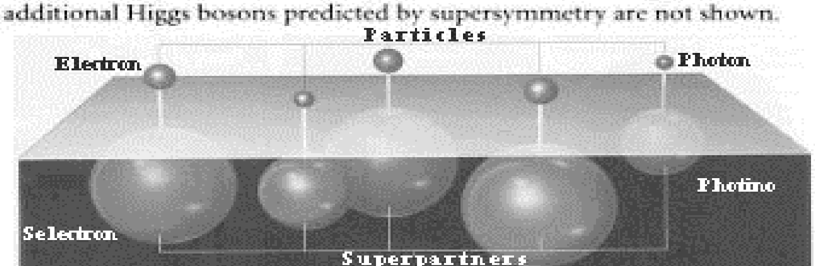


Naming Scheme

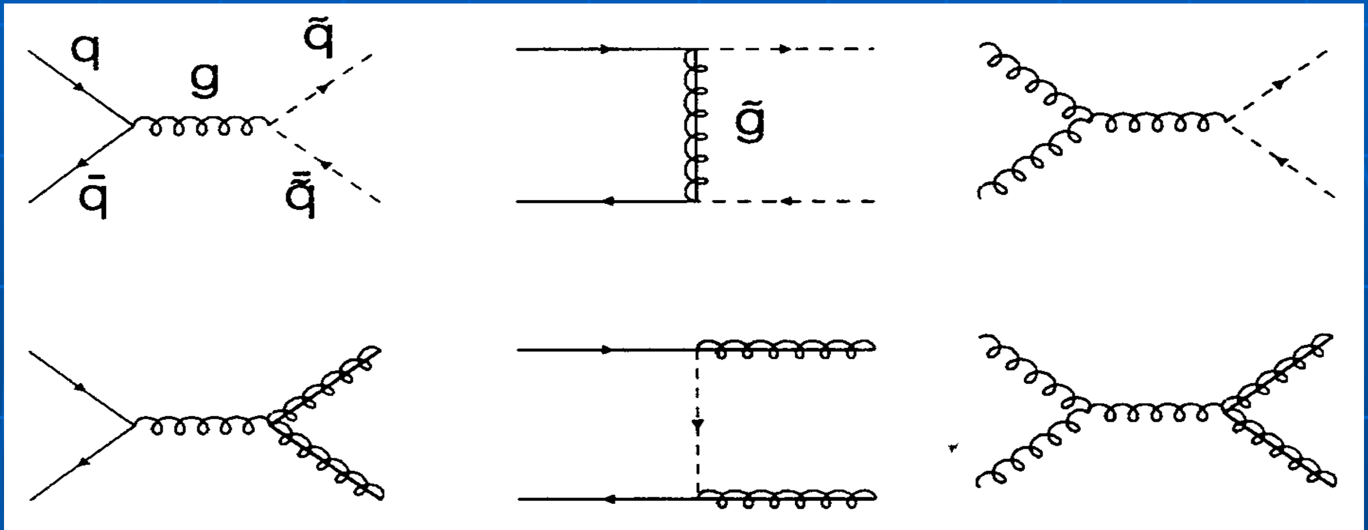
- Fermions get an "s" in front
- Bosons get an "-ino" at the end
- Symbols get a "~" on top.

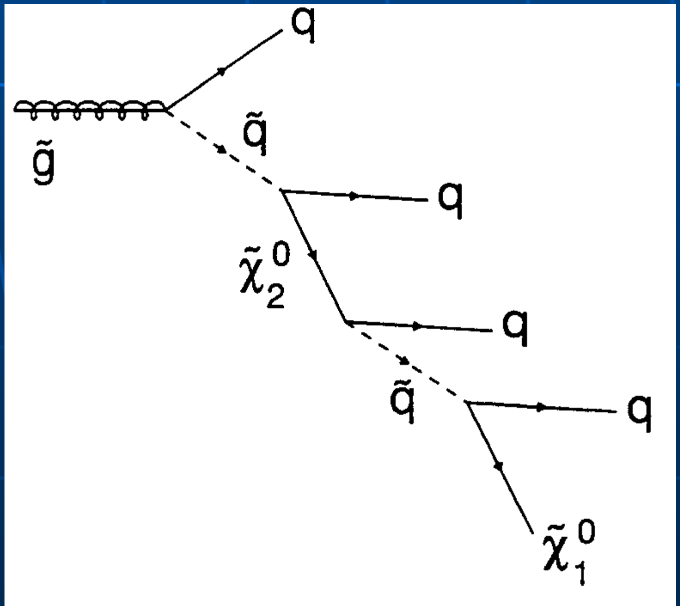
Particle	*Name*	*Feels These Forces*[a]	*Mediates These Forces*[b]	*Superpartner*
e, μ, τ	charged leptons (electron, muon, tau)	EM, W	—	sleptons $\tilde{e}, \tilde{\mu}, \tilde{\tau}$ (selectron, smuon, stau)
ν_e, ν_μ, ν_τ	neutrinos	W	—	sneutrinos $\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$
u, c, t	up, charm, top quarks	EM, W, S	—	squarks $\tilde{u}, \tilde{c}, \tilde{t}$
d, s, b	down, strange, bottom quarks	EM, W, S	—	squarks $\tilde{d}, \tilde{s}, \tilde{b}$
γ	photon	[c]	EM	photino[d] $\tilde{\gamma}$
$W^\pm$	weak boson	EM, W	W	Wino[d] $\tilde{W}^\pm$
Z	weak boson	W	W	Zino[d] $\tilde{Z}$
g	gluon	S	S	gluino $\tilde{g}$
G	graviton	GR	GR	gravitino $\tilde{G}$
h	Higgs boson[e]	W	generates mass	higgsino[e] $\tilde{h}$

[a] All particles feel the gravitational force.
[b] EM = electromagnetic force, W = weak force, S = strong force, GR = gravitational force.
[c] Photons feel only the gravitational force, but they interact with all electrically charged particles.
[d] Mixtures of these particles form charginos and neutralinos (Appendix C).
[e] The additional Higgs bosons predicted by supersymmetry are not shown.



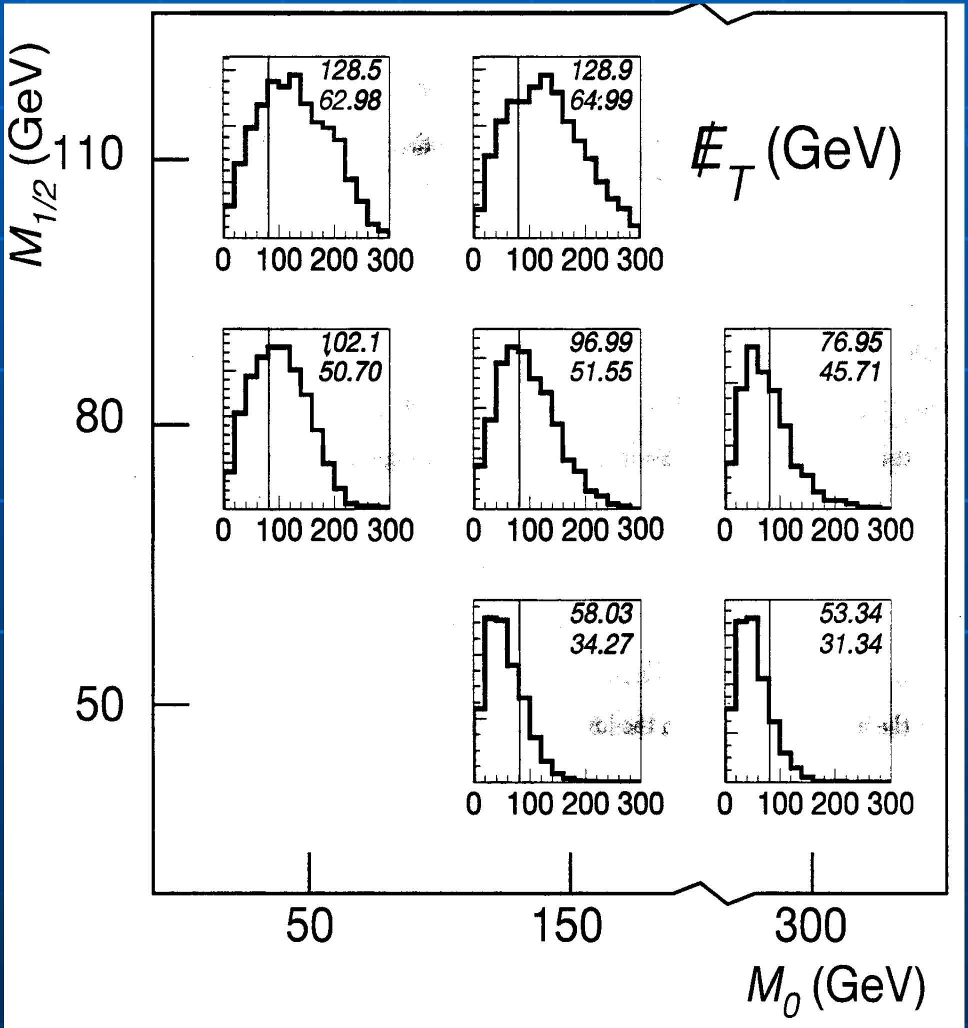
A typical SuSy decay mode





How could we see it?

- The Lightest Supersymmetric Particle (LSP) neutral, so only interact via weak force
- Very hard to detect, so seen as Missing Transverse Energy in decays



Common Types of SuSy

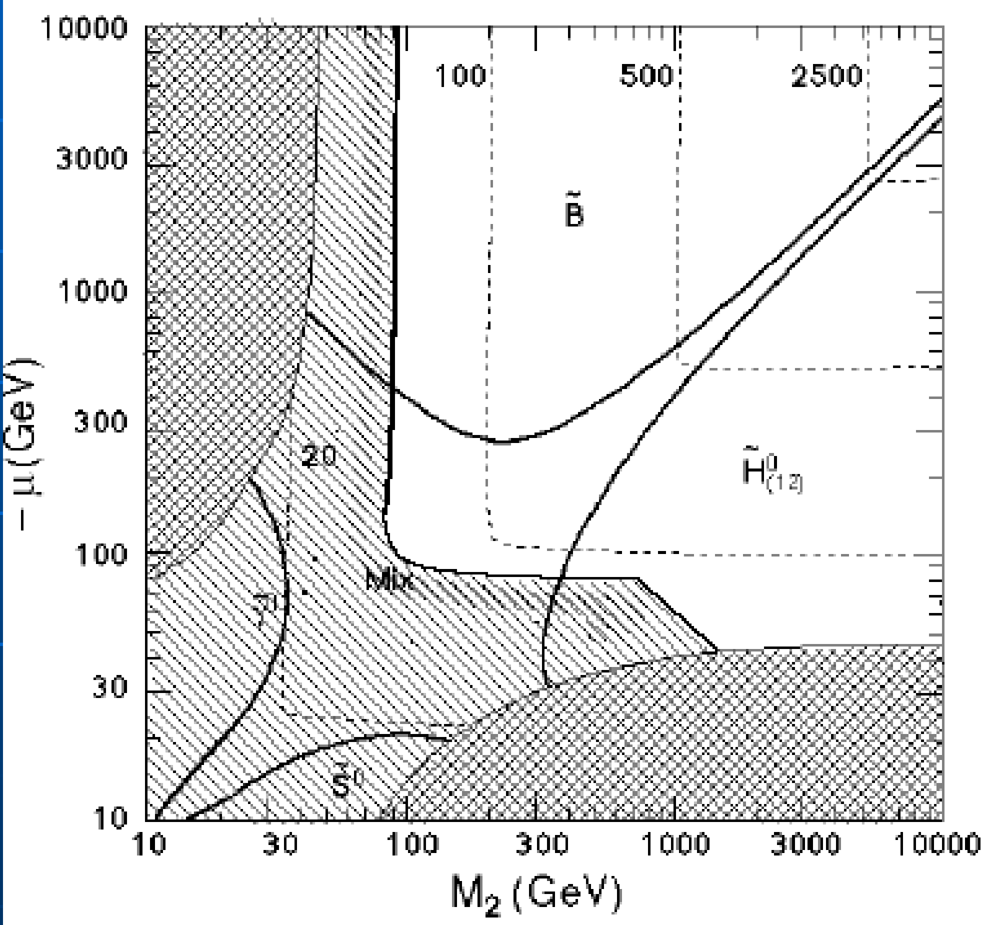
- MSSM
  - Minimal Supersymmetric Model
  - Adds fewest number of new particles
  - Adds new conserved quantum number:
    - $R = (-1)^{3(B-L)+2S}$
- mSUGRA
  - Minimal Supergravity
  - Decreases # of parameters from >100 to 5 by grouping some together and requiring they be equal

Why is this a Dark Matter Candidate?

- Dark matter must interact only via the weak force
  - If electrically or color charged would see it in Nuclear effects such as anomalously heavy ions, "Very hard to hide Baryons."
- If R quantum # conserved the Lightest Supersymmetric Particle (LSP) would be stable
- LSP must be relatively massive since hasn't been detected yet

What are the Candidates?

- Gravitino
  - Very difficult to confirm or exclude
- Sneutrino
  - In MSSM has been excluded by direct and indirect searches
- Neutralino
  - Could be photino, bino, or Higgsinos



$$\chi = \alpha \tilde{B} + \beta \tilde{W}^3 + \gamma \tilde{H}_1 + \delta \tilde{H}_2$$

What if we don’t see SUSY?

- There must be modifications to SM
- SUSY provides an EXTENSION of SM, leaving most of it intact
- Time to scrap SM and start over?
- New theories that avoid quadratic divergences (renormalization?), explain hierarchy problem, unify forces

Other theories that provide DMC

- WIMPs
  - Weakly Interacting Massive Particles
  - Generic name for DMC that interacts only via weak force
  - Could have not seen it yet due to lifetime, mass, small production cross section
- Axions
  - Strong Lagrangian not unchanged under CP transformation, yet no CP violation seen
  - Solution involves introduction of mechanism similar to Higgs, but with a MASSIVE Goldstone boson – Axion.

Summary

- Don't forget, there is very little – if any – evidence for SUSY so far.
- Provides solutions to many problems of the SM, but requires many arbitrary parameters
- Gives a clear prediction for mass ranges of spartners, $(m_B^2 - m_F^2) < 1$ TeV, so we'll know in a few years …

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