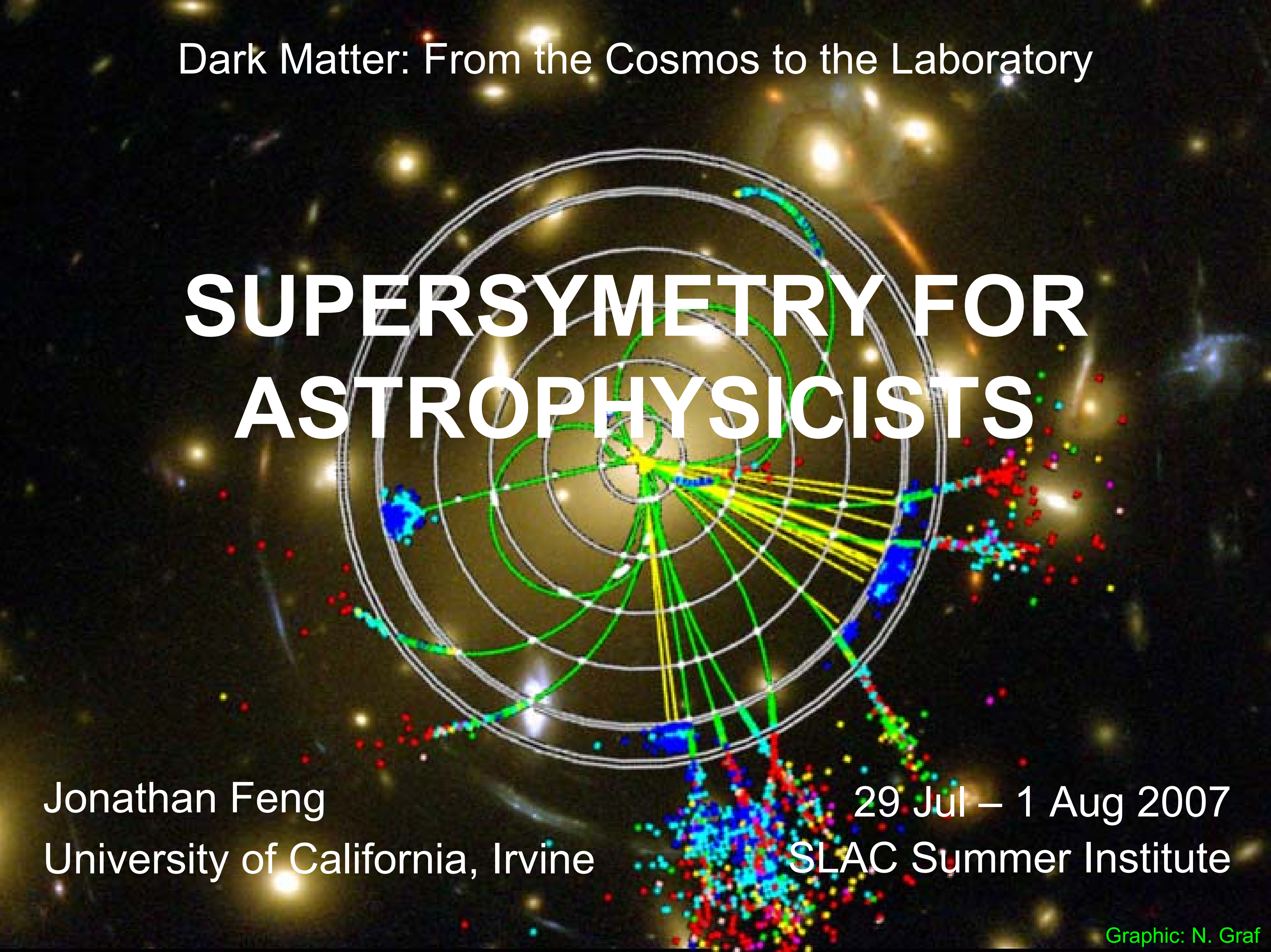
Dark Matter: From the Cosmos to the Laboratory

SUPERSYMETRY FOR ASTROPHYSICICISTS



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POLLING DATA

I’m giving summer school lectures titled, “Supersymmetry for Astrophysicists.” What should I talk about?

- Astrophysicist #1: “Beats me. I couldn’t care less about supersymmetry. Maybe you can get out of it somehow.”
- Astrophysicist #2: “Dark matter, of course. Isn’t that the only motivation for supersymmetry?”

OUTLINE

LECTURE 1: SUSY ESSENTIALS

Standard Model; SUSY Motivations; LSP Stability and Candidates

LECTURE 2: NEUTRALINOS

Properties; Production; Direct Detection; Indirect Detection; Collider Signals

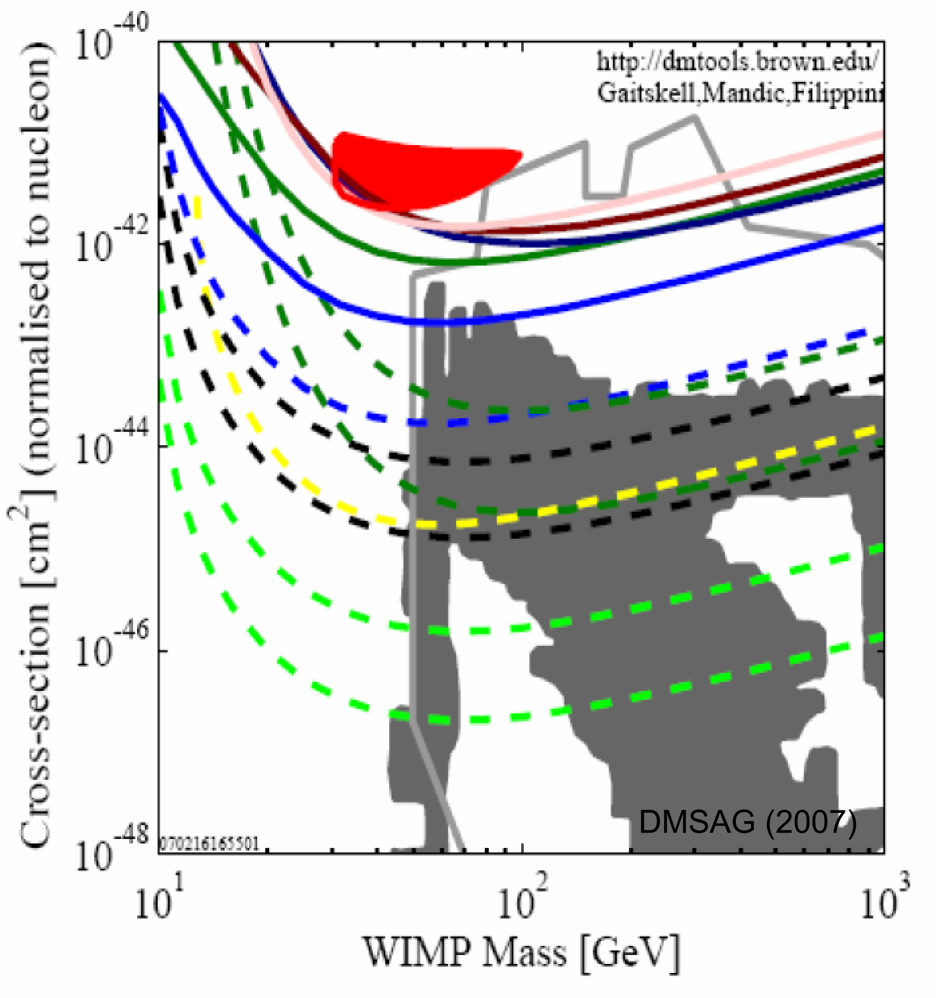
LECTURE 3: GRAVITINOS

Properties; Production; Astrophysical Detection; Collider Signals

SUSY ESSENTIALS

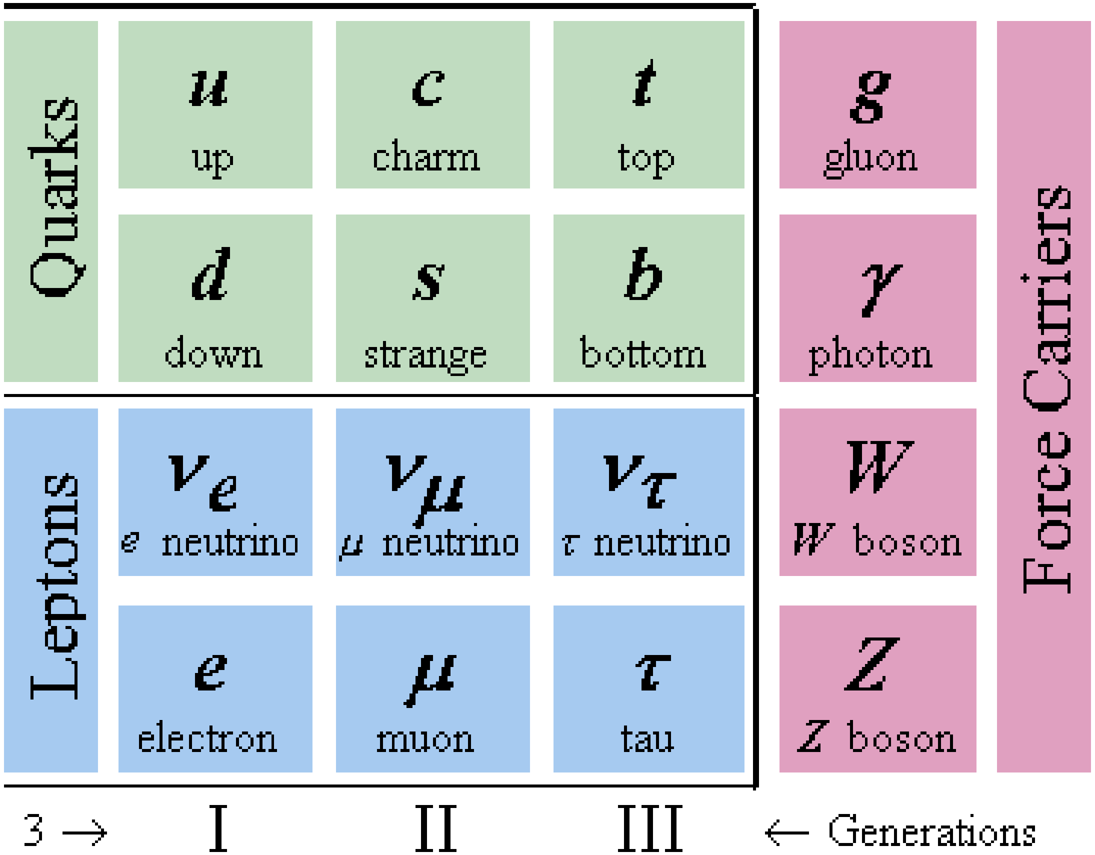
First discuss motivations for supersymmetry. Why?

- Supersymmetry is the best motivated framework for new particle physics
- Generic properties vs. special models (What do these shaded regions mean?)
- Direct implications for astrophysics



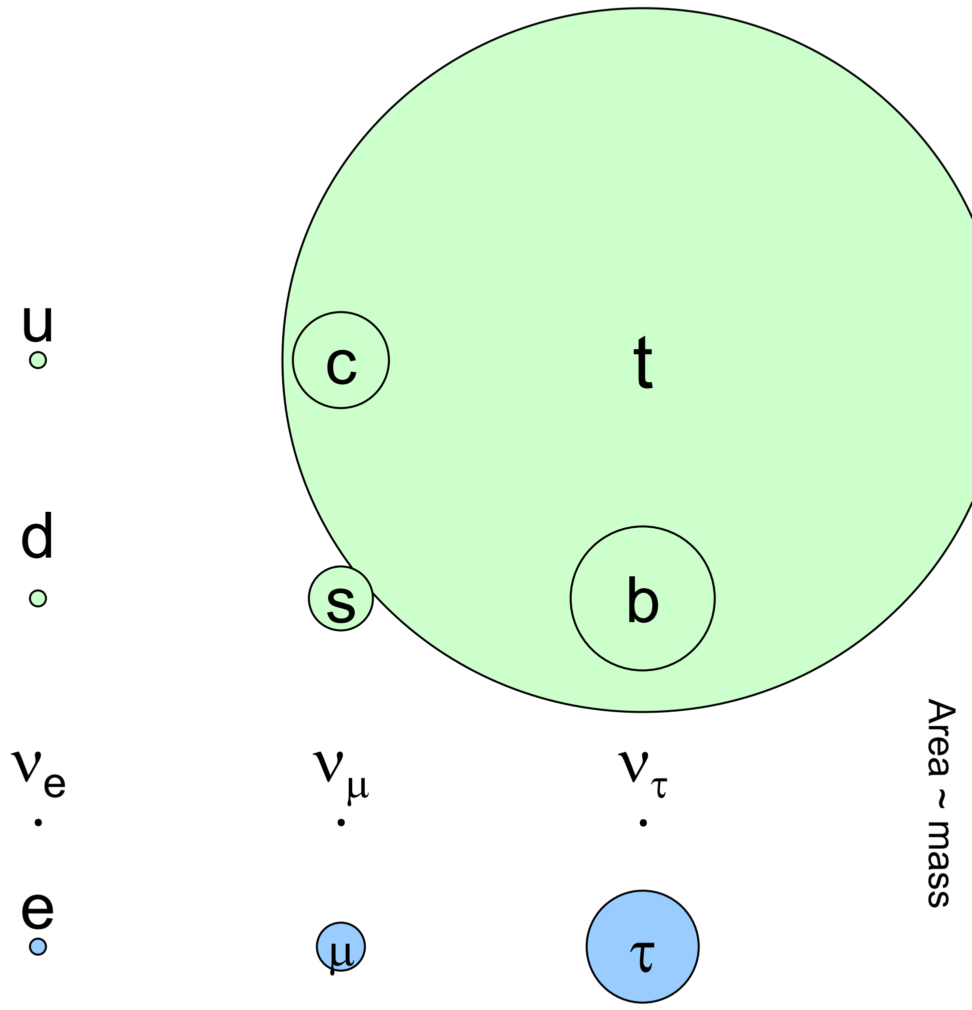
STANDARD MODEL

- Matter Particles
  - Quarks and leptons
  - Spin ½ fermions
- Force Particles
  - Photon (EM)
  - *W*, *Z* (weak)
  - Gluons (strong)
  - Spin 1 bosons
- Higgs Particle
  - Undiscovered
  - Spin 0 boson



Matter Particles

- Most of the unexplained parameters of the SM are here
- Interactions determined by unusual quantum numbers
- Masses span at least 11 orders of magnitude
  - Neutrinos ~ eV
  - Electron: 511 keV
  - Top quark: 171 GeV
- The top quark is heavy!

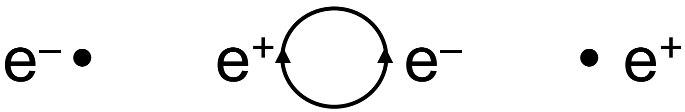


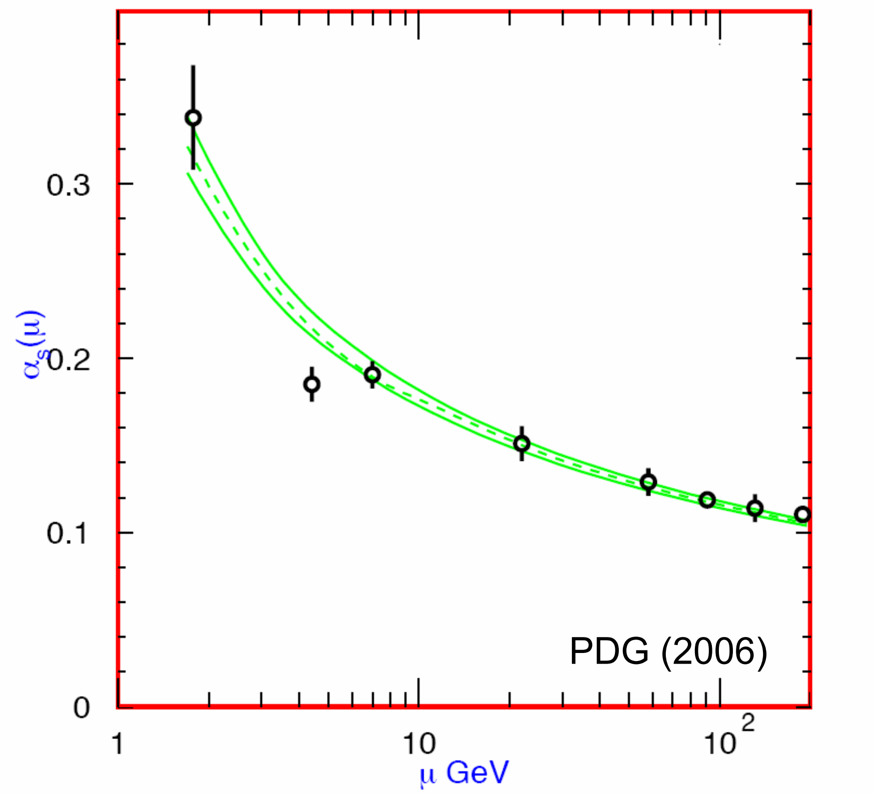
Force Particles

- Couplings $\alpha \equiv g^2/(4\pi)$ at m_Z
  - $\alpha_{EM} = 0.007818 \pm 0.000001$
  - $\alpha_{weak} = 0.03381 \pm 0.00002$
  - $\alpha_s = 0.118 \pm 0.002$
- At observable energies,

  $$\alpha_{EM} < \alpha_{weak} < \alpha_s$$

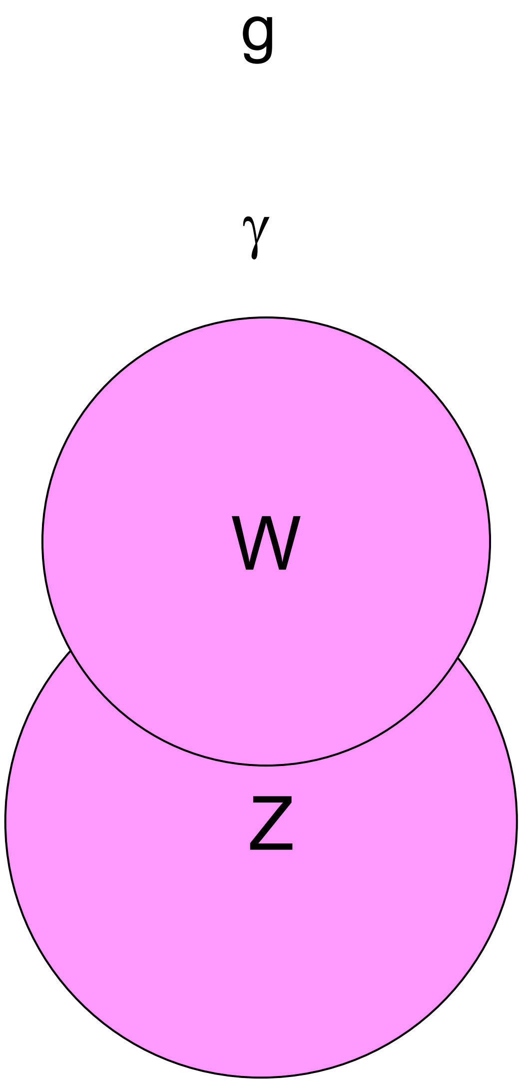
- Precisely measured
- Scale-dependent – the quantum vacuum has dielectric properties





Force Particles

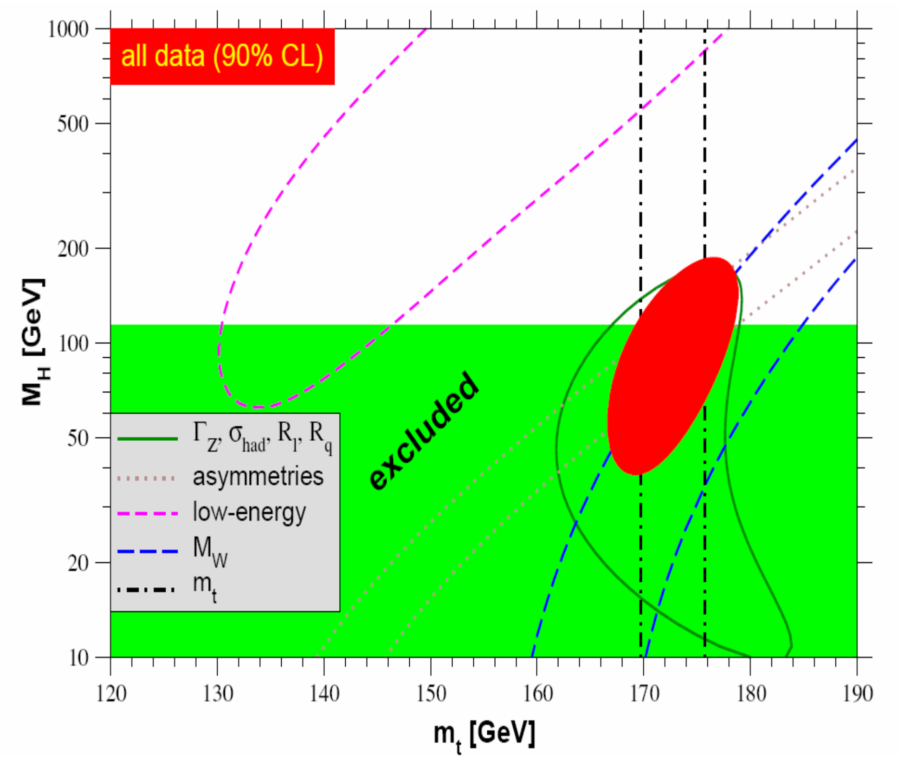
- Masses
  - $m_\gamma = 0$: U(1) conserved
  - $m_g = 0$: SU(3) conserved
  - $m_W = 80$ GeV: SU(2) broken
  - $m_Z = 91$ GeV: SU(2) broken

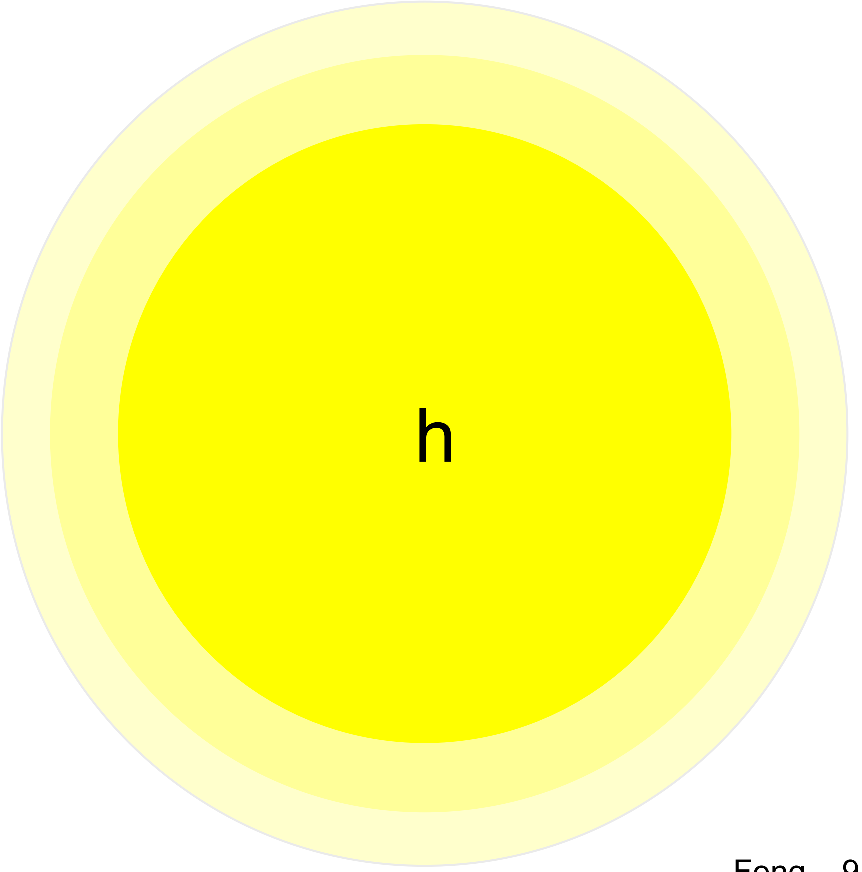


- SU(2) is broken, the others aren't

Higgs Particle

- Mass
  - Direct searches: m_h > 115 GeV
  - Indirect constraints from precision data: 40 GeV < m_h < 200 GeV





NATURALNESS

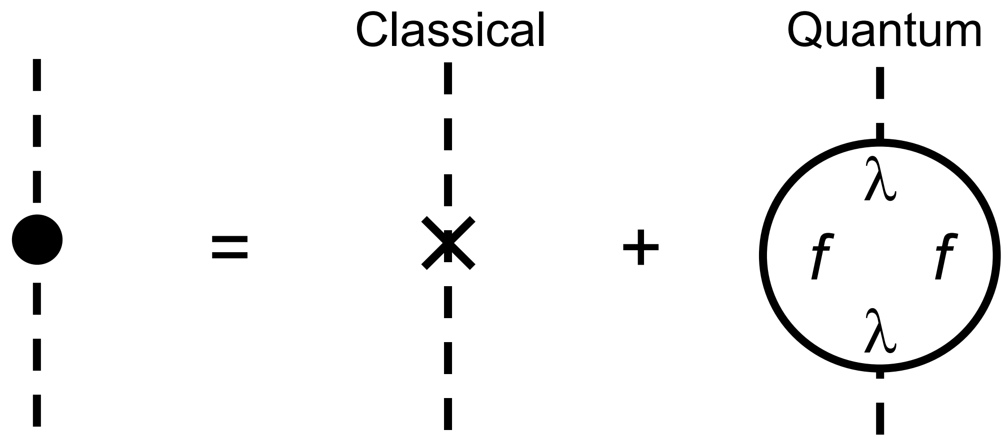
- We know 3 fundamental constants
  - Special relativity: speed of light c
  - Quantum mechanics: Planck's constant h
  - General relativity: Newton's constant G

- From these we can form the Planck mass

$$M_{\mathrm{Pl}} = \sqrt{\frac{hc}{G}} \approx 10^{19} \text{ GeV}$$

- Why are m_h, m_W, m_Z, … << M_{Pl}?

Gauge Hierarchy Problem



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

In the SM, m_h is naturally ~ Λ, the largest energy scale

m_h ~ 100 GeV, Λ ~ 10^{19} GeV → cancellation of 1 part in 10^{34}

SUPERSYMMETRY

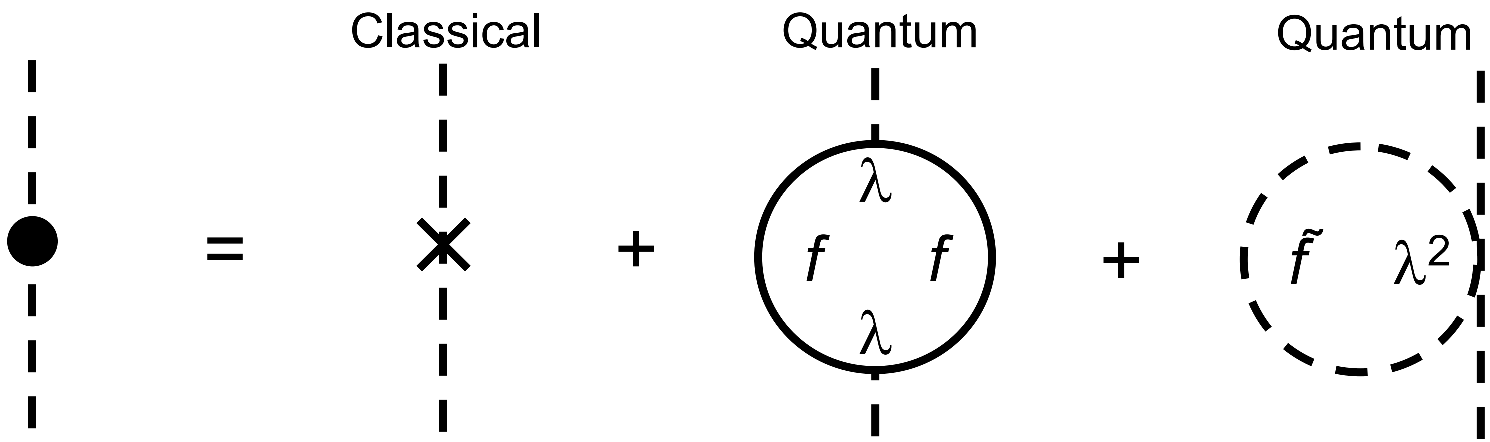
SYMMETRIES OF NATURE	Exact	Broken
Gauge	$U(1)_{EM,}$ $SU(3)_c$	$SU(2) \times U(1)_Y$
Global	B, L	L_e , L_μ , L_τ
Spacetime	Rotations, Boosts, Translations	SUSY

Supersymmetry is a qualitatively new class of symmetry

Superpartners

- Translations: particle P at x → particle P at x’
- SUSY: particle P at x → particle $\tilde{P}$ at x, where
  - P and $\tilde{P}$ differ in spin by ½: fermions ↔ bosons
  - P and $\tilde{P}$ are identical in all other ways (mass, couplings)
- New particles
  - Superpartners of matter particles: Spin 0 bosons, add “s” (selectron, sneutrinos, squark, …)
  - Superpartners of force particles: Spin ½ fermions, add “ino” (photino, Wino, …)
  - Superpartners of Higgs particles: Spin ½ fermions, “Higgsinos”

SUSY AND NATURALNESS



$$m_h^2 = (m_h^2)_0 - \underbrace{\frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2}$$

$$+ \frac{1}{16\pi^2}\lambda^2(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_h)$$

Dependence on Λ is softened to a logarithm

SUSY solves the gauge hierarchy problem, even if broken, provided superpartner masses are ~ 100 GeV

Higgs Doubling

- SUSY requires 2 Higgs doublets to cancel anomalies and to give mass to both up- and down-type particles

- E.g., anomaly cancelation requires $\Sigma Y^3 = 0$, where Y is hypercharge and the sum is over fermions. This holds in the SM

- SUSY adds an extra fermion with Y = –1:

$$\begin{pmatrix} h^0 \\ h^- \end{pmatrix} \equiv \begin{pmatrix} h_d^0 \\ h_d^- \end{pmatrix} \Rightarrow \begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$$

- To cancel the anomaly we add another Higgs doublet with Y = +1:

$$\begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix} \Rightarrow \begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$$

SUSY PARAMETERS

SUSY breaking introduces many unknown parameters. These are

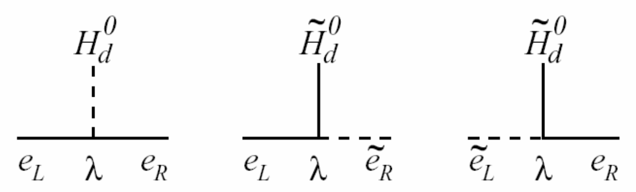
- Masses for sleptons and squarks: $m^2_{\tilde{f}\,ij}$
- Masses for gauginos: M_1 , M_2 , M_3
- Trilinear scalar couplings (similar to Yukawa couplings): A^f_{ij}
- Mass for the 2 Higgsinos: $\mu \tilde{H}_u \tilde{H}_d$
- Masses for the 2 neutral Higgs bosons: $B H_u H_d + m^2_{Hu} |H_u|^2 + m^2_{Hd} |H_d|^2$
- The 2 neutral Higgs bosons both contribute to electroweak symmetry breaking:

$$v^2 = (174 \text{ GeV})^2 \rightarrow v_u^2 + v_d^2 = (174 \text{ GeV})^2$$

The extra degree of freedom is called $\tan\beta = v_u/v_d$

TAKING STOCK

- SUSY is a single symmetry, which implies many new particles
- Many new parameters, but
  - Dimensionless couplings are fixed (no "hard" breaking)

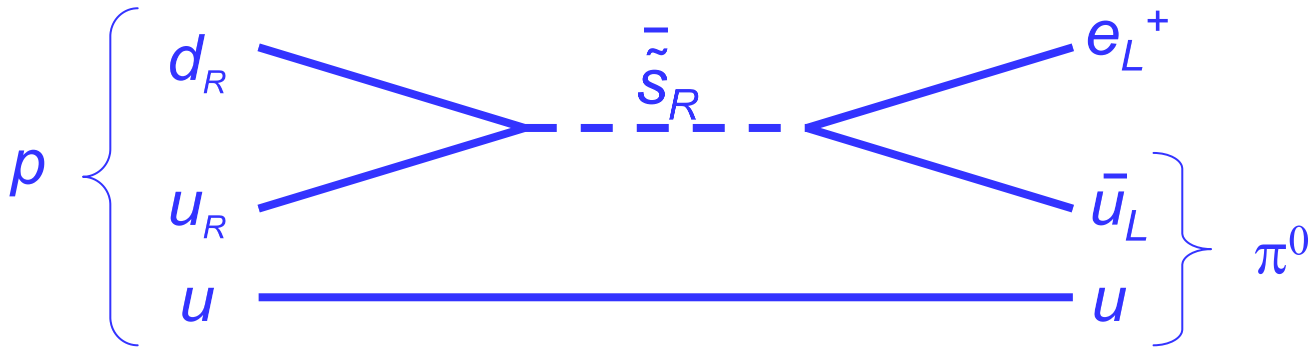


  - Dimensionful parameters are allowed (soft breaking), but should be ~ 100 GeV
  - Even the dimensionful parameters cannot be arbitrary

Analogy	Soap Bubble	SM
Large Parameter	Length L Height H	M_{Pl}
Small Parameter	L - H	m_h
Symmetry explanation	Rotational invariance	SUSY
Symmetry breaking	Gravity	M_{SUSY}
Natural if	Gravity weak	M_{SUSY} small

R-PARITY AND STABLE SUPERPARTNERS

- One problem: proton decay



- Forbid this with R-parity conservation: $R_p = (-1)^{3(B-L)+2S}$
  - SM particles have $R_p = 1$, SUSY particles have $R_p = -1$
  - Requires 2 superpartners in each interaction

- Consequence: the lightest SUSY particle (LSP) is stable and cosmologically significant. What is the LSP?

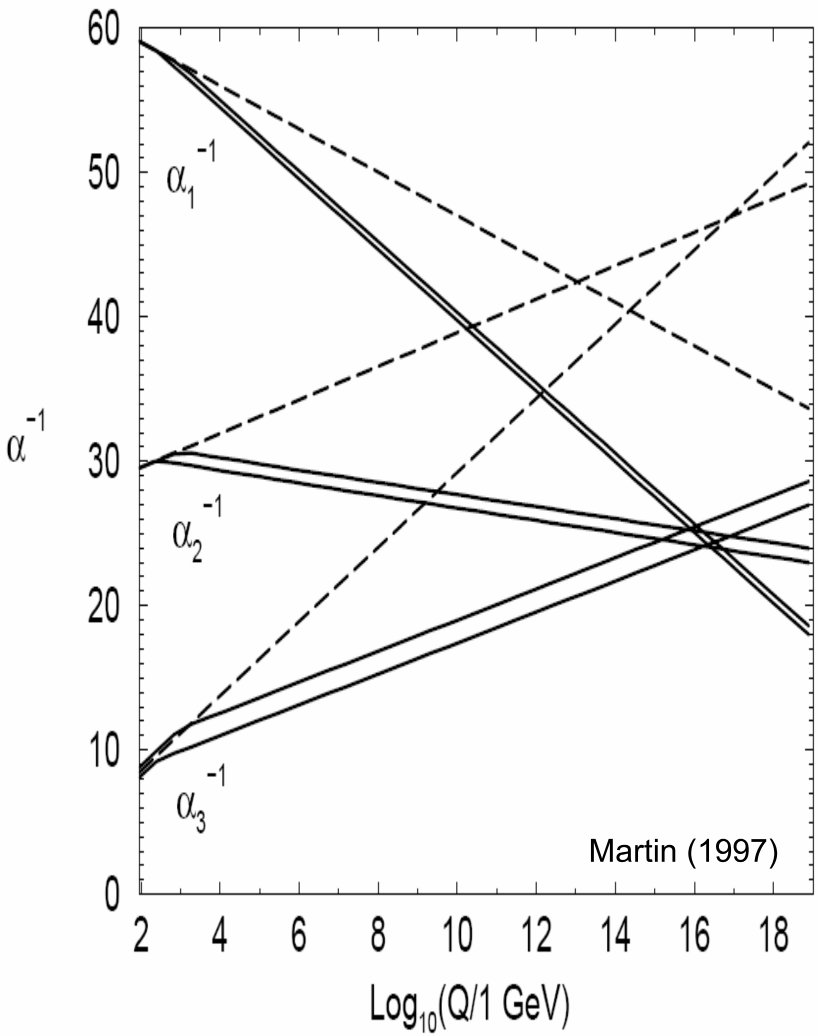
Neutral SUSY Particles

Spin	U(1) M_1	SU(2) M_2	Up-type μ	Down-type μ	$m_{\tilde{\nu}}$	$m_{3/2}$
2						G graviton
3/2						$\tilde{G}$ gravitino
1	B	W^0				
1/2	$\tilde{B}$ Bino	$\tilde{W}^0$ Wino	$\tilde{H}_u$ Higgsino	$\tilde{H}_d$ Higgsino	ν	
0			H_u	H_d	$\tilde{\nu}$ sneutrino	

Neutralinos: $\{\chi \equiv \chi_1, \chi_2, \chi_3, \chi_4\}$

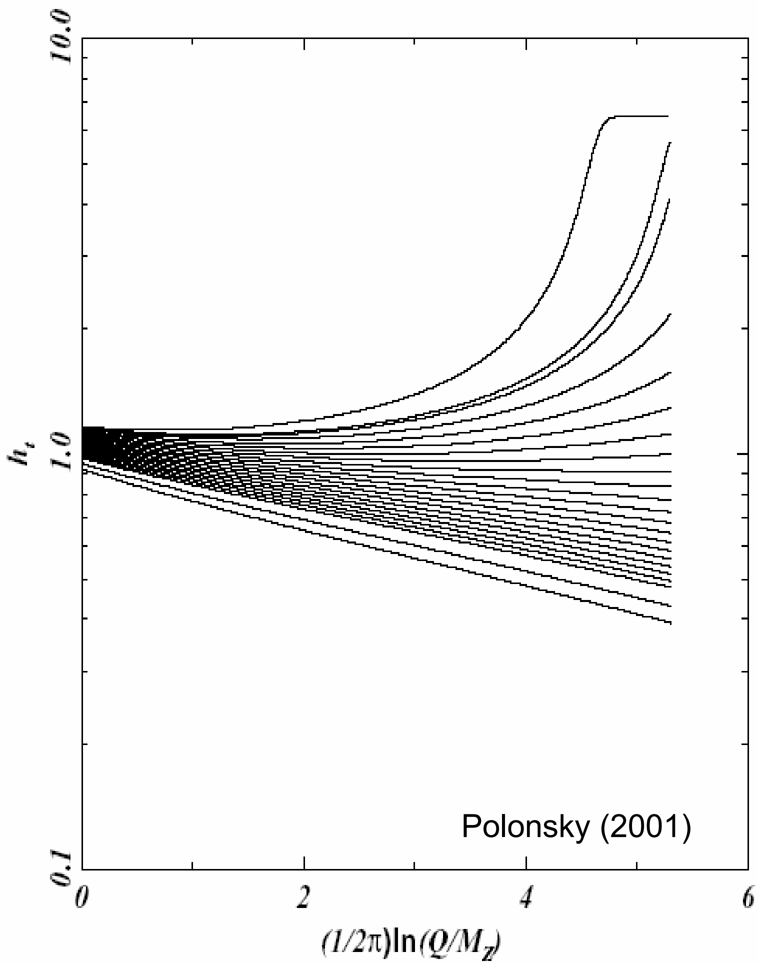
FORCE UNIFICATION

- Can the 3 forces be unified, e.g., SU(3) x SU(2) x U(1) → SO(10)?
- Superpartners modify the scale dependence of couplings
- With TeV superpartners, 3 couplings meet at a point!
  - No free parameters
  - % level "coincidence"
  - Coupling at unification: $\alpha^{-1} > 1$
  - Scale of unification
    - Q > 10^{16} GeV (proton decay)
    - Q < 10^{19} GeV (quantum gravity)
- SUSY explains $\alpha_{EM} < \alpha_{weak} < \alpha_s$
- Gaugino mass unification implies $M_1:M_2:M_3 \approx \alpha_1:\alpha_2:\alpha_3 \approx$ 1:2:7, the Bino is the lightest gaugino



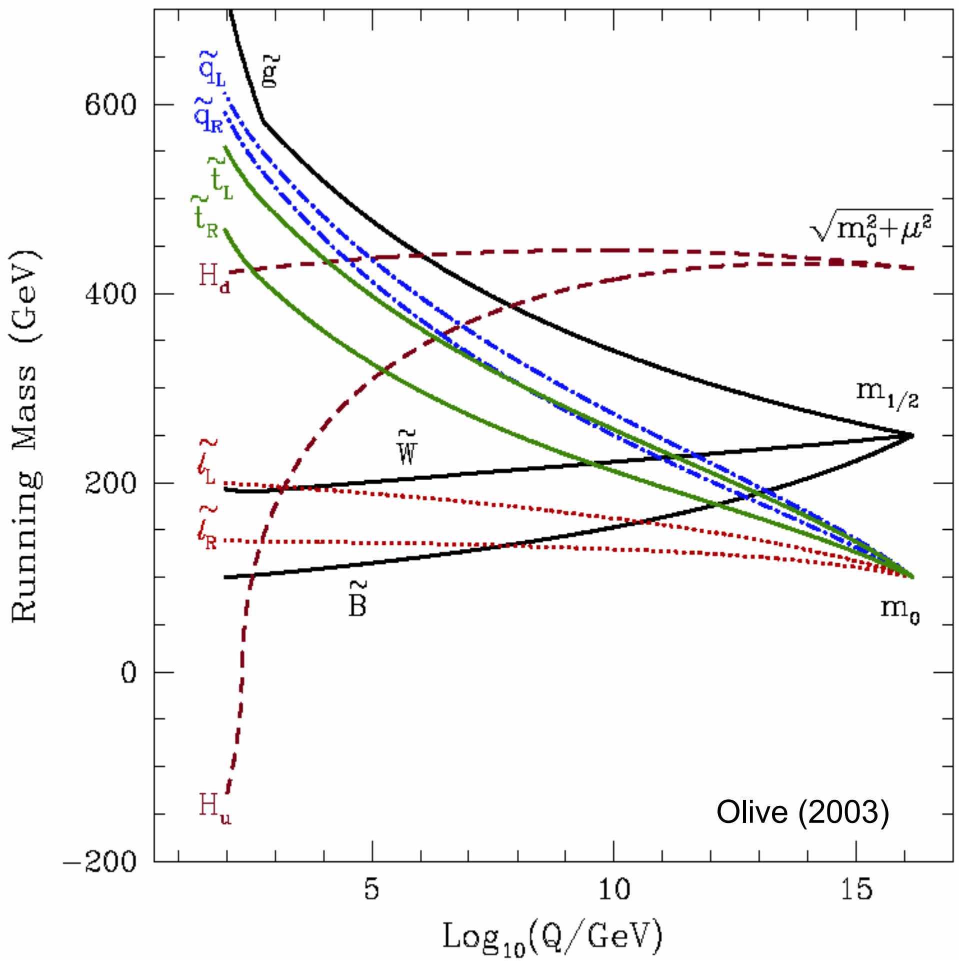
TOP QUARK MASS

- Force unification suggests we can extrapolate to very high energy scales
- All parameters (masses, couplings) have scale dependence
- The top quark Yukawa coupling has a quasi-fixed point near its measured value
- SUSY "explains" heavy top



SCALAR MASSES

- How do scalar masses change with scale?
- Gauge couplings increase masses; Yukawa couplings decrease masses
- H_u has large top quark Yukawa, but no compensating strong interaction
- H_u is the lightest scalar. In fact, it's typically tachyonic!



ELECTROWEAK SYMMETRY BREAKING

- The Higgs boson potential is

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

- Minimizing this, one finds (for moderate/large tanβ)

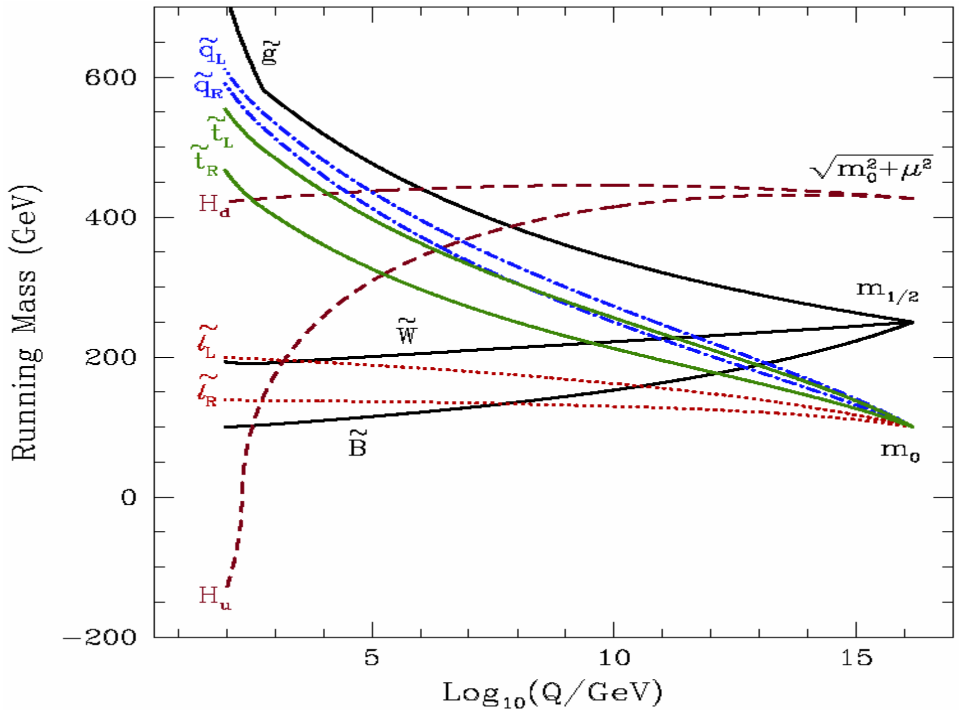
$$\frac{1}{2} m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - |\mu|^2 \approx -m_{H_u}^2 - |\mu|^2$$

- EWSB requires $m_{Hu}^2 < 0$

SUSY explains why SU(2) is broken and SU(3) and U(1) aren't

SNEUTRINOS AND HIGGSINOS

- Lightest physical scalars are typically the right-handed sleptons
- Sneutrinos
  - have SU(2) interactions, and so are typically heavier
  - Disfavored as LSPs by direct searches
- EWSB also fixes Higgsino mass μ



$$\frac{1}{2} m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - |\mu|^2$$

LECTURE 1 SUMMARY

- The Standard Model is incomplete
- SUSY provides elegant solutions
  - Naturalness
  - Force unification
  - Electroweak symmetry breaking
- Proton decay → R-parity, stable LSP
- Natural LSPs: neutralino (Bino/Higgsino), gravitino