Physics and Astronomy

UNIVERSITY OF Southampton

Phenomenology Lectures

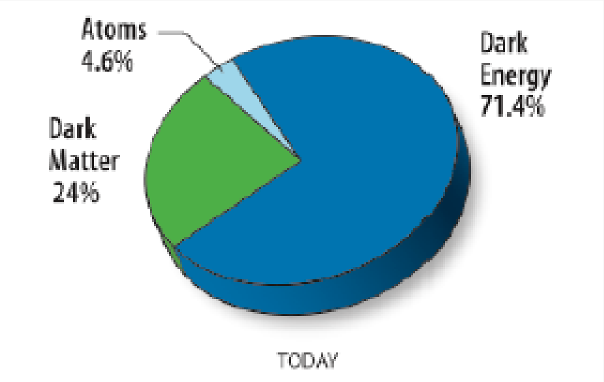
SUSY

Professor Stefano Moretti

July 2020

WHY NEW PHYSICS?

- A feeling that there are too many things we can't explain
- My big questions:
  - Dark matter: Is it a particle we can observe at colliders?
  - The pattern of fermion masses
  - Especially neutrino masses
  - Why are M_W, M_H << M_{planck}?

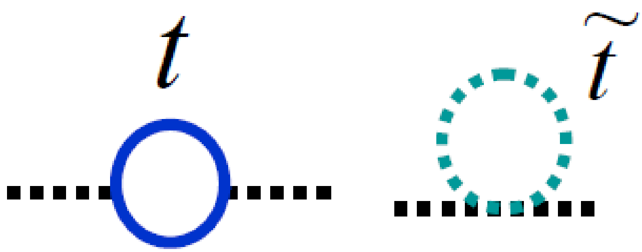


WHY NEW PHYSICS?

- Does the Higgs have anything to do with new physics?
- Singlet Higgs model can be constructed as a portal to dark matter
  - Many more complicated models share features of singlet model
- Why should there be only one Higgs doublet?
- The case for supersymmetry remains strong, although theorists are discouraged by lack of experimental evidence

SUSY….Our favorite model

- Quadratic sensitivity to high scale physics cancelled automatically if SUSY particles at TeV scale
- Cancellation result of ***supersymmetry***, so happens at every order



$$\delta M_h^2 \approx (\ldots.)G_F \Lambda^2 (M_t^2 - M_{\tilde{t}}^2)$$

- Stop mass should be TeV scale

No naturalness problem

Supersymmetric Models as Alternative to Standard Model

Many New Particles:

- Spin ½ quarks $\Rightarrow$ spin 0 squarks
- Spin ½ leptons $\Rightarrow$ spin 0 sleptons
- Spin 1 gauge bosons $\Rightarrow$ spin ½ gauginos
- Spin 0 Higgs $\Rightarrow$ spin ½ Higgsino

Unbroken supersymmetry $\Rightarrow$ degenerate masses of partners

SUSY must be a broken symmetry

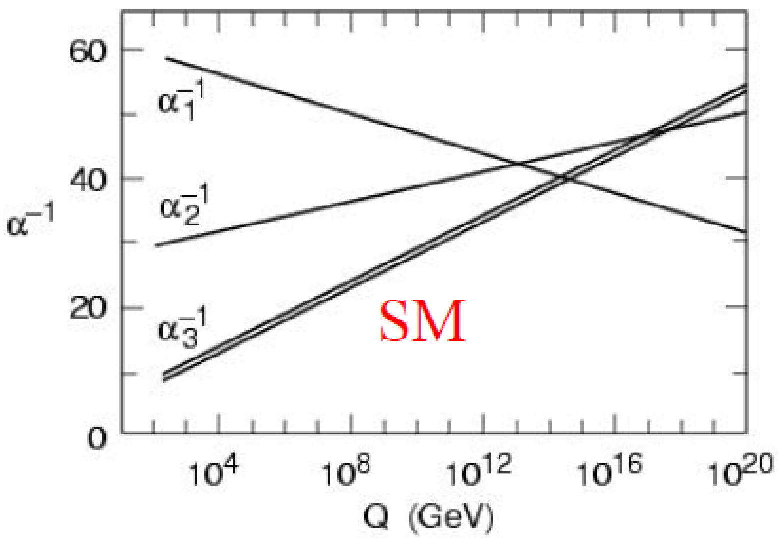
Supersymmetric Theories

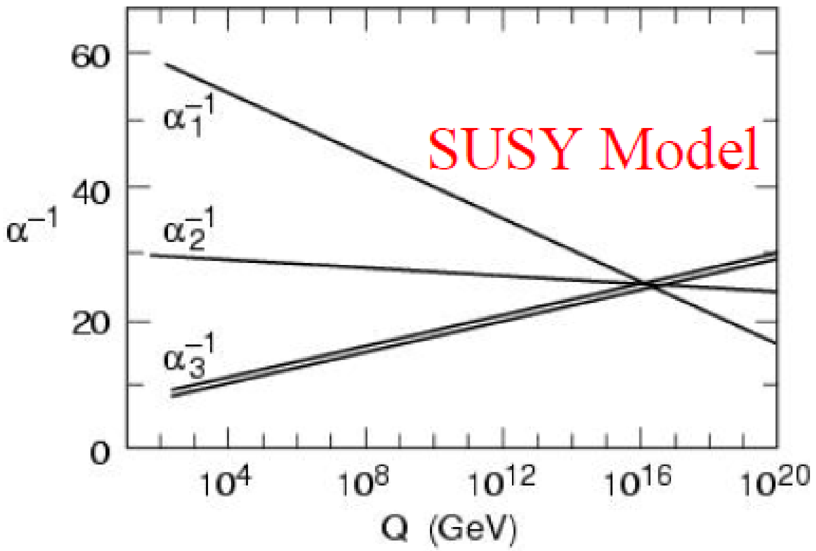
- Predict many new undiscovered particles (>29!)
- Very predictive models
  - Can calculate particle interactions in terms of a few parameters
  - Solve naturalness problem of Standard Model
- Any Supersymmetric particle eventually decays to the lightest supersymmetric particle (LSP) which is stable and neutral (assuming R parity)
  - Dark Matter Candidate

Also called: hierarchy problem

SUSY Models Unify

- Coupling constants change with energy
- Assume new particles at TeV scale

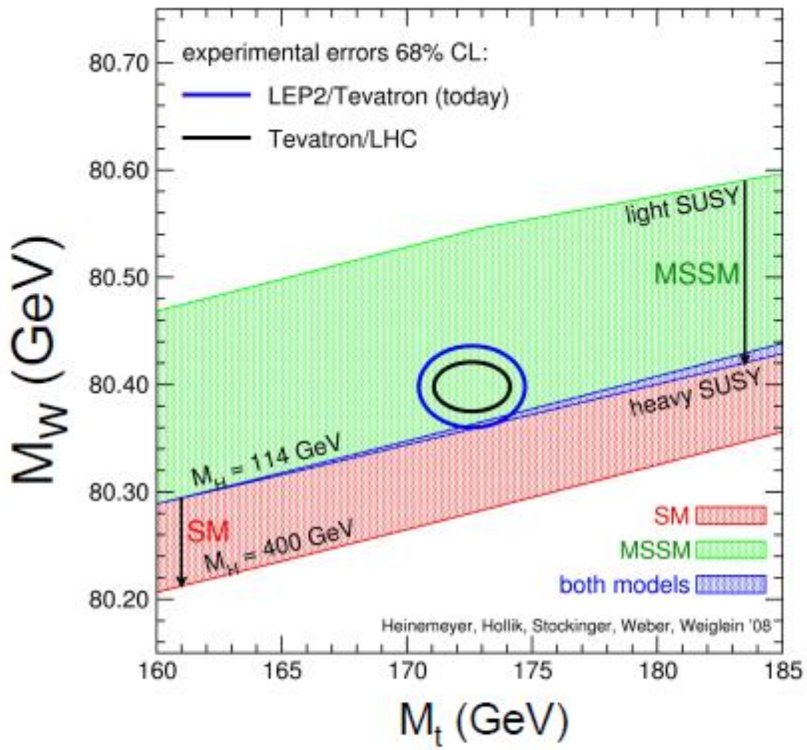




UNIVERSITY OF Southampton

Supersymmetry (MSSM version)

- Good agreement with electroweak measurements if SUSY masses are 1-2 TeV



Two Higgs Doublet Models

- 8 degrees of freedom
- 3 form $W_L^{\pm}$, Z_L
- 5 physical Higgs bosons
  - h^0, H^0, A^0, $H^{\pm}$

Higgs potential is predicted in SUSY:

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

Gauge Couplings

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

Gives up quark mass

Gives down quark mass

- Supersymmetric models always have at least ***two Higgs doublets*** with opposite hypercharge in order to give mass to up and down quarks

EWSB and SUSY Models

- Electroweak symmetry broken by vevs

$$\langle H_1 \rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix} \qquad \langle H_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

- 5 Physical Higgs bosons, h^0, H^0, $H^\pm$, A^0
- W gets mass, $M_W^2 = g^2(v_1^2 + v_2^2)/2$
- 2 free parameters, typically pick

M_A, $\tan\beta = v_2/v_1$

- ***Predict M_h, M_H, $M_{H\pm}$***

$$M_A^2 = m_{12}^2(\tan\beta + \cot\beta)$$

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

Neutral Higgs Masses

$$M^2_{h,H} = \frac{1}{2}\left[M^2_A + M^2_Z \pm \sqrt{\left(M^2_A + M^2_Z\right)^2 - 4M^2_Z M^2_A \cos^2 2\beta}\right]$$

- $M_h < M_Z \cos 2\beta$
- Theory implies light Higgs boson!
- Neutral Higgs mass matrix diagonalized with mixing angle α

$$\cos 2\alpha = -\cos 2\beta \left(\frac{M^2_A - M^2_Z}{M^2_H - M^2_h}\right)$$

Theoretical Upper Bound on M_h

At tree level, $M_h < M_Z$

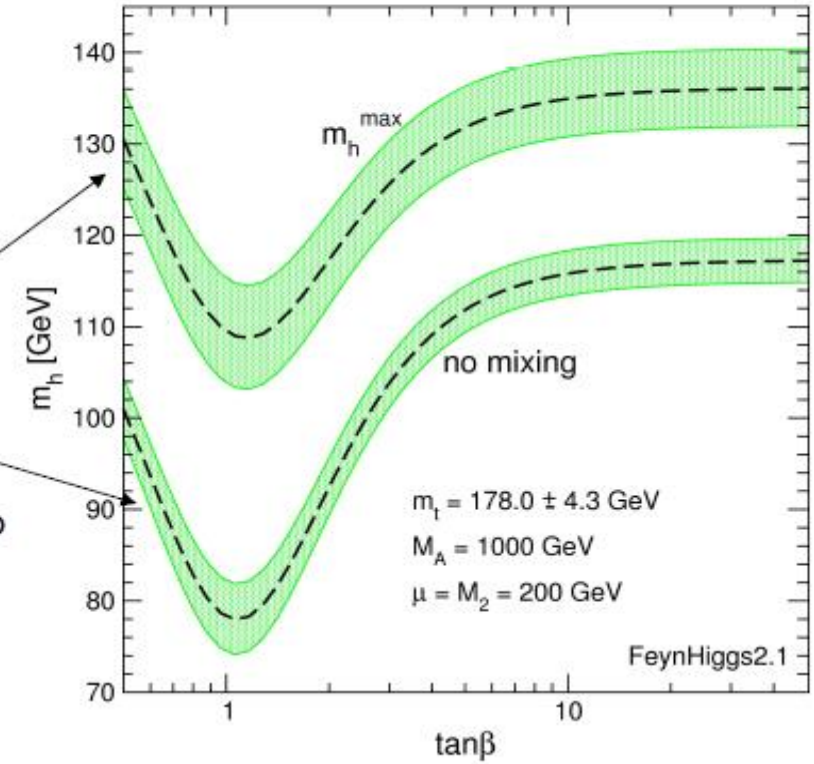
- Large corrections $O(G_F m_t^2)$
  - Predominantly from stop squark loop

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

- Stop mass should be TeV scale for naturalness

MSSM predicts a light Higgs boson!!!

Theoretical Upper Bound on M_h



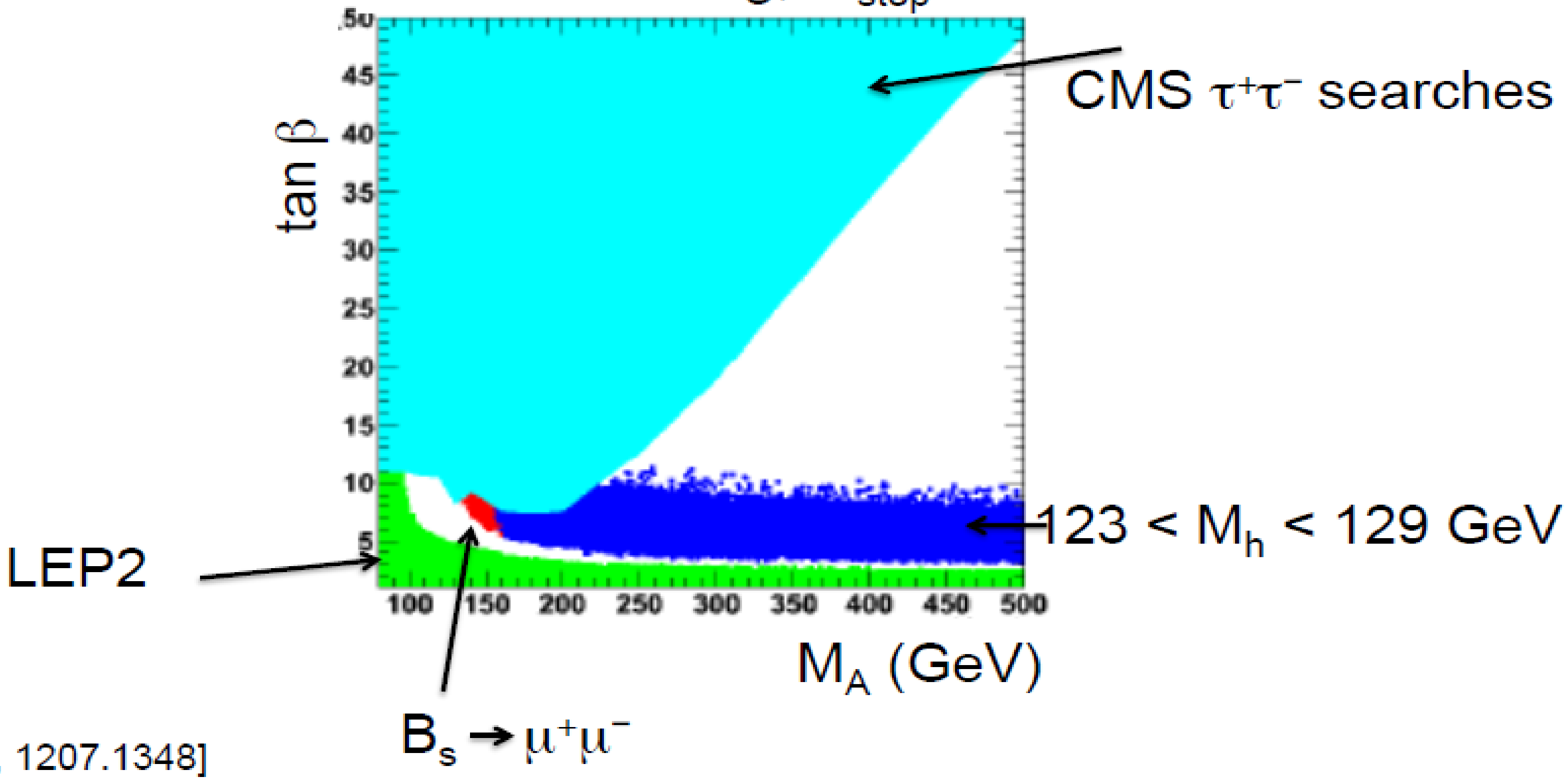
Upper bound on lightest neutral Higgs boson mass with m_{stop} = 1 TeV

- M_t^4 enhancement
- Logarithmic dependence on stop mass

Now that we've found M_h=125 GeV….

- Maybe very heavy stops?
- Parameter space becomes quite restricted

Maximal Mixing, M_{stop} = 2 TeV



[Arbey, 1207.1348]

SUSY is being Squeezed

- Need large stop masses or large SUSY breaking trilinear couplings to get M_h=125 GeV