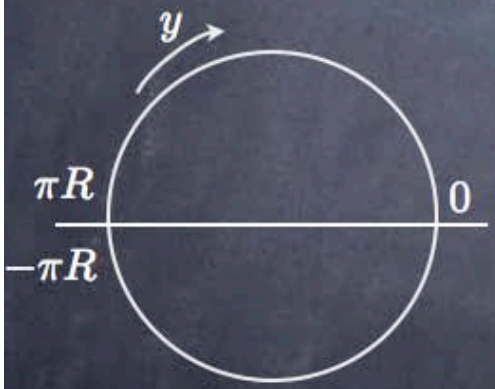
The LHC Roulette Wheel

Extra dimensions

Particle Spectrum in Simplest Model with Extra Dimensions



circle: $y \sim y + 2\pi R$

$$\phi(y + 2\pi R) = \phi(y)$$

$$\phi(x,y) = \sum_n \frac{1}{\sqrt{2^{\delta_{n0}}\pi R}} \left(\cos\left(\frac{ny}{R}\right) \phi_n^+(x) + \sin\left(\frac{ny}{R}\right) \phi_n^-(x) \right)$$

5D field

wavefunction = localization of KK mode along the xdim

4D Kaluza-Klein modes

$$m_n = p_y^n = \frac{n}{R}$$

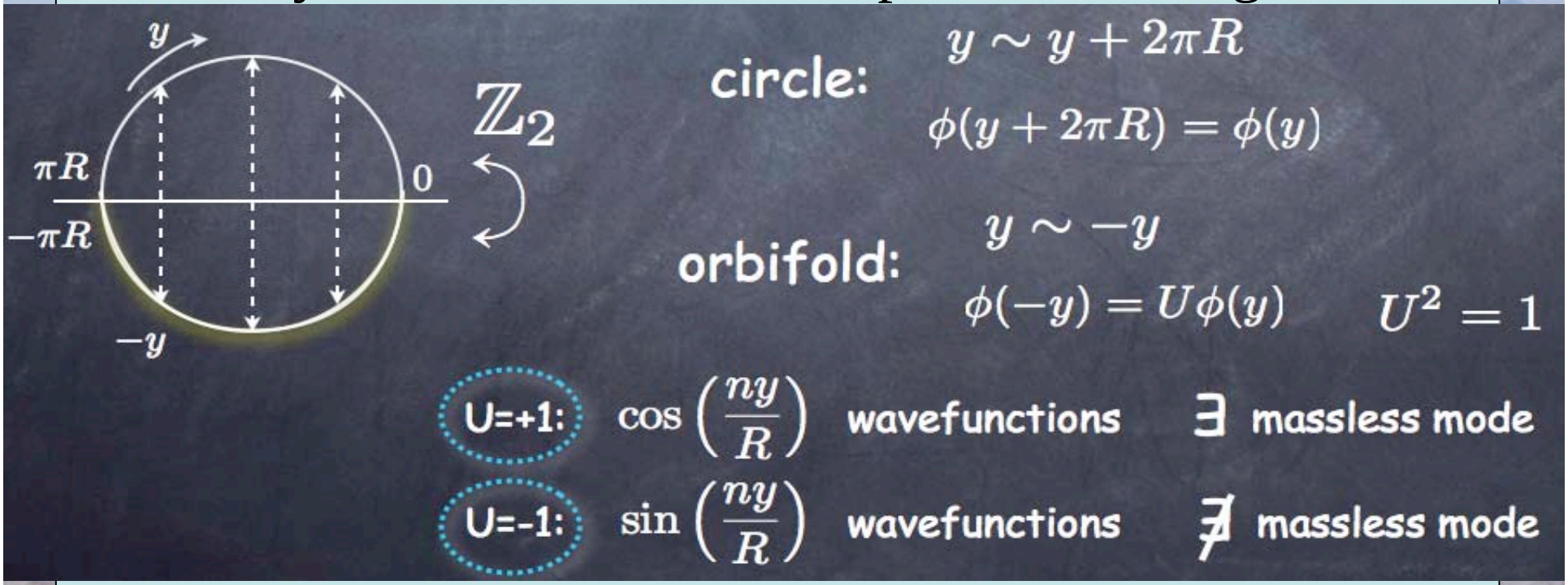
Lowest-lying states have flat wave functions (n = 0)

Excitations (Kaluza-Klein) have nodes (n > 0):

Mass ∝ n/R (R = radius of circle)

‘Fold’ Circle: Orbifold

- Identify two halves of circle: up to a minus sign



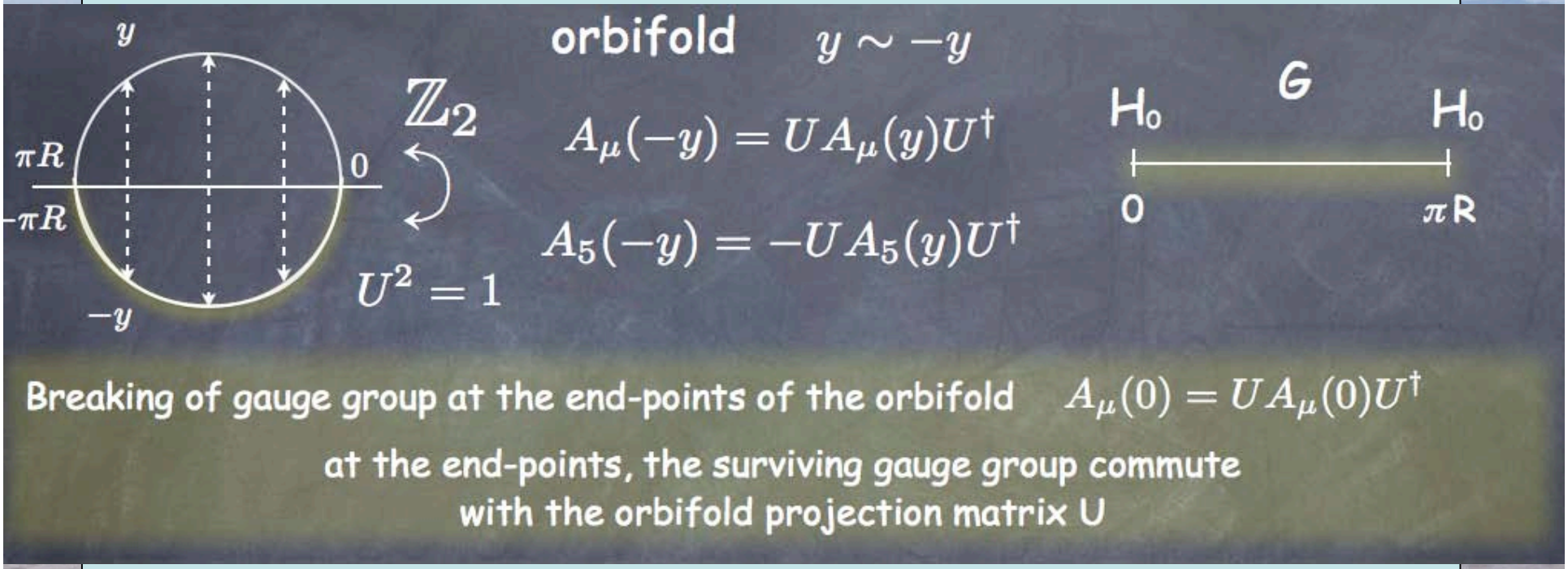
- ‘Even’ particles include massless: odd ones all massive
- A way to give masses to particles that are asymmetric

The LHC Roulette Wheel

Higgsless model

Mechanism to break Gauge Symmetry

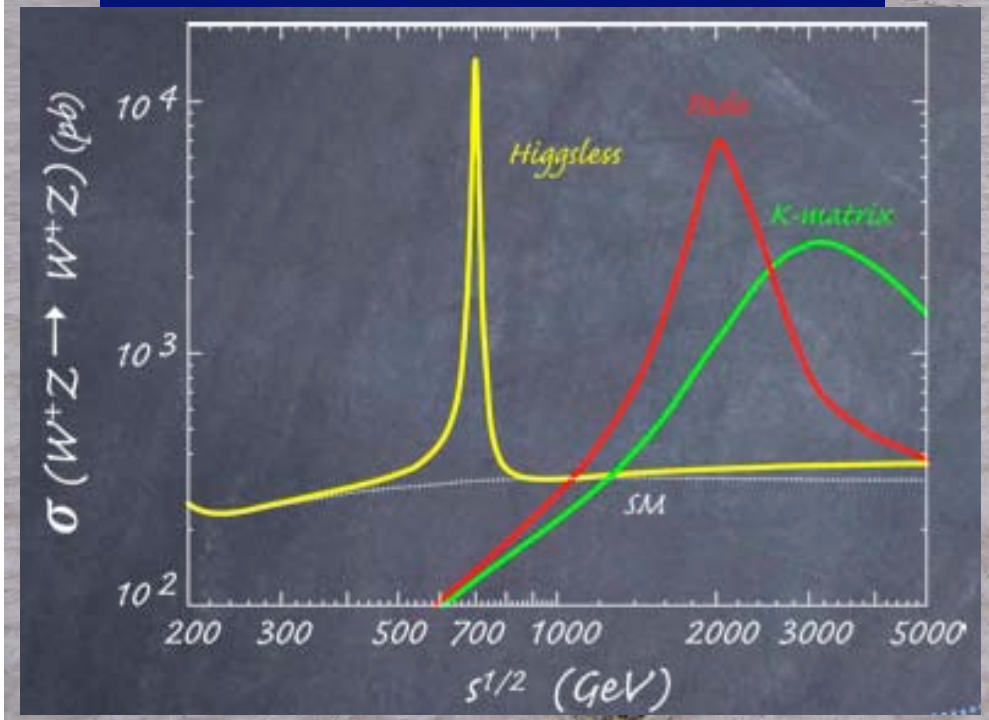
- Identify two halves up to a group transformation U



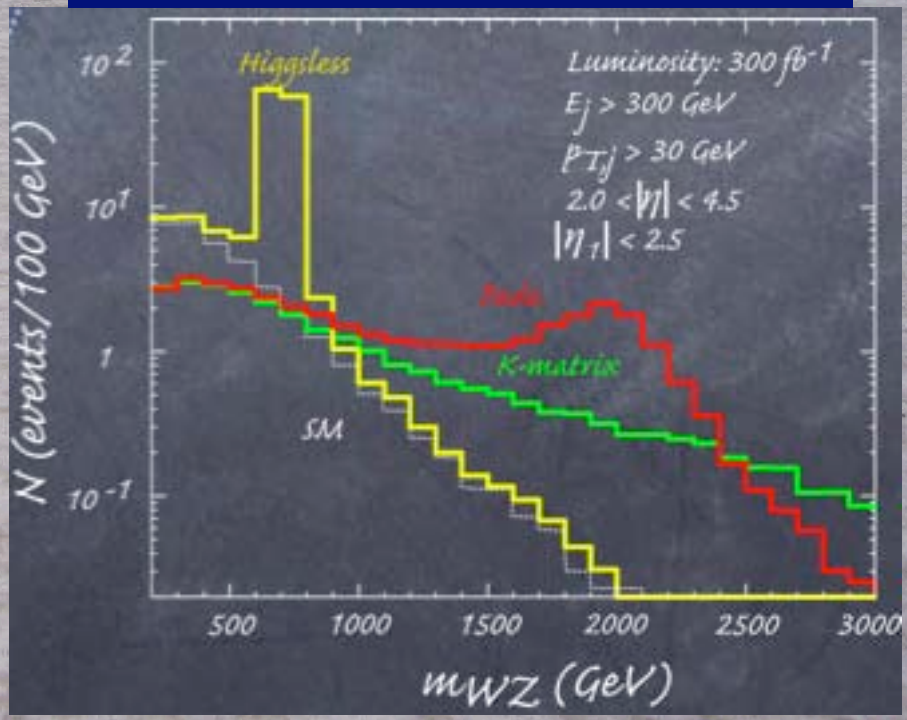
- Unbroken part of gauge group commutes with U
- Masses for asymmetric particles:
  - e.g., SU(2) × U(1) → U(1)

Search for Vector Resonance in Higgsless Model

Vector resonance structure in WZ scattering



Simulation of resonance structure in m_{WZ} @ LHC



The LHC Roulette Wheel

Supersymmetry

Supersymmetry?

- Would unify matter particles and force particles
- Related particles spinning at different rates

  0 - ½ - 1 - 3/2 - 2

  Higgs - Electron - Photon - Gravitino - Graviton

  (Every particle is a ‘ballet dancer’)
- Would help fix particle masses
- Would help unify forces
- Predicts light Higgs boson
- **Could provide dark matter for the astrophysicists and cosmologists**

A Bitino of Shistory

- 1967: Impossible to combine internal and external (Lorentz) symmetry – Coleman & Mandula
- 1971: Extend Poincaré symmetry using fernionic charges – Gol'fand & Likhtman
- 1971: Supersymmetry in 2 dimensions (for baryons in strings) – Neveu & Schwarz; Ramond
- 1973: First supersymmetric field theories in 4 dimensions: nonlinear for ν – Volkov & Akulov

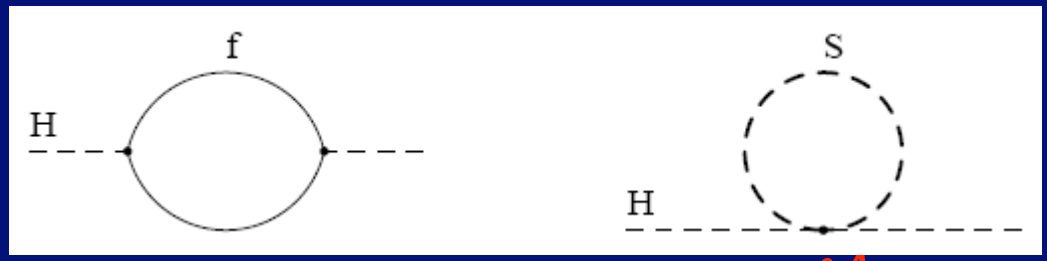
renormalizable theories – Wess & Zumino

Why Supersymmetry (Susy)?

- Hierarchy problem: why is $m_W << m_P$?
  ($m_P \sim 10^{19}$ GeV is scale of gravity)
- Alternatively, why is
  $G_F = 1/ m_W^2 >> G_N = 1/m_P^2$?
- Or, why is
  $V_{Coulomb} >> V_{Newton}$? $e^2 >> G\, m^2 = m^2 / m_P^2$
- Set by hand? What about loop corrections?
  $\delta m_{H,W}^2 = O(\alpha/\pi)\, \Lambda^2$
- Cancel boson loops ⇔ fermions
- Need $| m_B^2 - m_F^2 | < 1$ TeV^2

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

- Leading divergence cancelled if

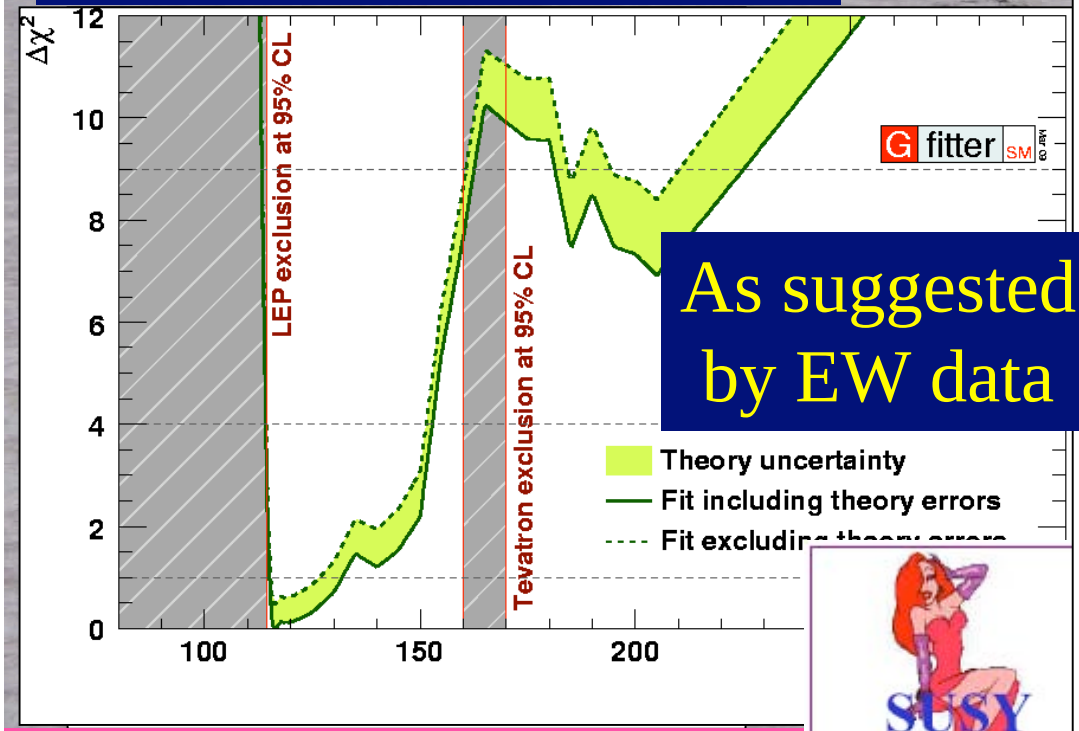
$$\lambda_S = y_f^2 \text{ x } 2$$

Supersymmetry!

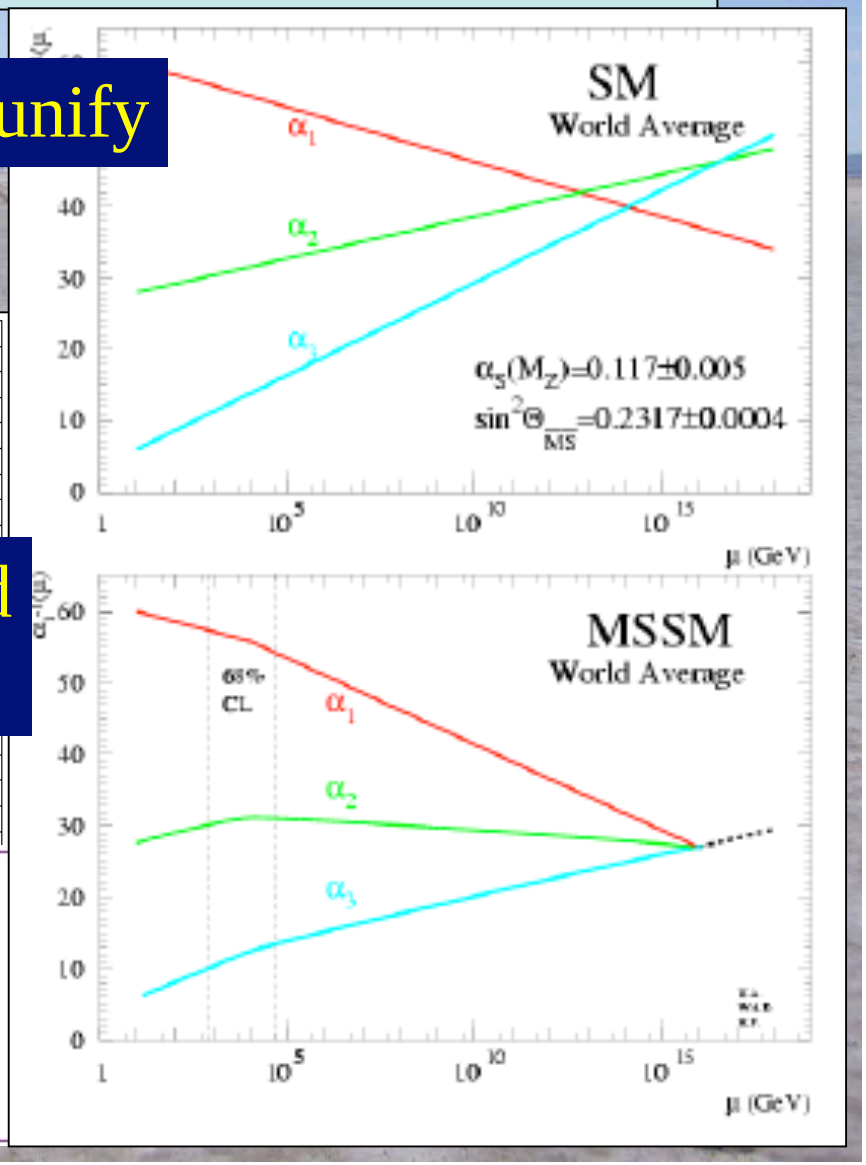
Other Reasons to like Susy

It enables the gauge couplings to unify

It predicts $m_H < 150$ GeV



As suggested by EW data



Provided by Fabiola Gianotti

Dark Matter in the Universe

Astronomers say that most of the matter in the Universe is invisible Dark Matter

‘Supersymmetric’ particles ?

We shall look for them with the LHC

More Shistory

- 1974: No-renormalization theorems –
  Ferrara, Iliopoulos, Wess & Zumino
- 1976: Discovery of supergravity –
  Freedman, van Nieuwenhuizen & Ferrara; Deser & Zumino
- 1979/1981: Relevance to hierarchy problem –
  Maiani, Witten
- 1983: Source of astrophysical dark matter –
  Goldberg; JE, Hagelin, Nanopoulos, Olive & Nanopoulos
- 1990: Superunification of gauge couplings –
  JE, Kelley & Nanopoulos; Langacker & Luo
- 1995: LEP data favour light Higgs boson

Minimal Supersymmetric Extension of Standard Model (MSSM)

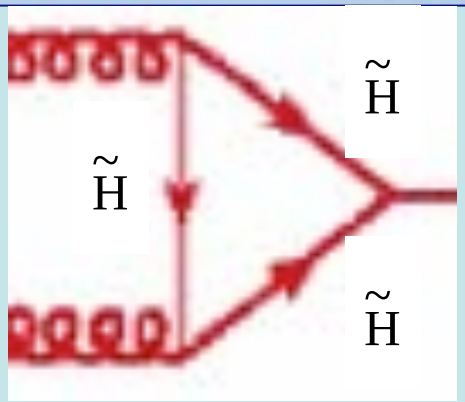
- Particles + spartners

$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} e.g., \begin{pmatrix} \ell\,(lepton) \\ \tilde{\ell}\,(slepton) \end{pmatrix} or \begin{pmatrix} q\,(quark) \\ \tilde{q}\,(squark) \end{pmatrix} \begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} e.g., \begin{pmatrix} \gamma\,(photon) \\ \tilde{\gamma}\,(photino) \end{pmatrix} or \begin{pmatrix} g\,(gluon) \\ \tilde{g}\,(gluino) \end{pmatrix}$$

- 2 Higgs doublets, coupling μ, ratio of v.e.v.'s = $\tan\beta$
- Unknown supersymmetry-breaking parameters:
  Scalar masses m_0, gaugino masses $m_{1/2}$,
  trilinear soft couplings $A_{\lambda,}$ bilinear soft coupling B_μ
- Often assume universality:
  Single m_0, single $m_{1/2}$, single A_λ, B_μ: not string?
- Called constrained MSSM = CMSSM
- Minimal supergravity also predicts gravitino mass
  $m_{3/2} = m_0$, $B_\mu = A_\lambda - m_0$

Why 2 Higgs Doublets?

- Cancel anomalous Higgsino triangle diagrams



- Superpotential must be analytic function of superfields:

$$W = \frac{\lambda}{3}\phi^3 + \frac{m}{2}\phi^2$$

  - Cannot use QU^cH, QD^cH^*
  - Must use QU^cH_u, QD^cH_d
- Two Higgs fields →
  - Coupling between them: $\mu H_u H_d$
  - Two different vev's, ratio tan β

Non-Universal Scalar Masses

- Different sfermions with same quantum #s?

  e.g., d, s squarks?

  disfavoured by upper limits on flavour-changing neutral interactions

- Squarks with different #s, squarks and sleptons?

  disfavoured in various GUT models

  e.g., $d_R = e_L$, $d_L = u_L = u_R = e_R$ in SU(5), all in SO(10)

- Non-universal susy-breaking masses for Higgses?

  No reason why not! NUHM