Higgs at 125 GeV and SUSY

Lawrence Hall
UC Berkeley
SUSY Spectrum, 1984

SPECTRUM

is constrained:

$M_W$

"Squark mass"

m

"Gluino mass"

$\tilde{g}$

$\tilde{t}$

$\tilde{t}$

$\tilde{W}_H$

$\tilde{W}_L$

THREE PARAMS!
Over 3 decades of susy: seismic shifts!
Assume Higgs is near 125 GeV

Reasonable
Assume Higgs is near 125 GeV

Could go away!

Reasonable
Is SUSY Natural?

Natural
\( \tilde{m} \sim v \)

Unnatural
\( \tilde{m} \gg v \)
Is SUSY Natural?

Natural

$\tilde{m} \sim v$

Unnatural

$\tilde{m} \gg v$

We simply don’t know
Is SUSY Natural?

Natural

\[ \tilde{m} \sim v \]

Unnatural

\[ \tilde{m} \gg v \]

We simply don’t know

Savas was at the beginning of both!

SUSY

SU(5)

Dimopoulos, Georgi, 1981

SPLIT

SUSY

Arkani-Hamed, Dimopoulos, 2004
Fine-Tuning in the MSSM: 2012

$m_h = 124 - 126 \text{ GeV}$

$\Delta = \frac{\partial \ln m_h}{\partial \ln \rho}$

Minimize $\Delta$

$\tan \beta > 10$

$m_{Q_3} = m_{U_3} = m_{\tilde{t}}$

messenger scale of 10 TeV
Fine-Tuning in the MSSM: 2012

David Pinner, Josh Ruderman, LJH 1112.2703

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$m_{Q_3} = m_{U_3} = m_{\tilde{t}}$

Messenger scale of 10 TeV

$\Delta > 100$ The MSSM is fine-tuned
Adding a Singlet: \( \lambda S H_u H_d \)

\( \lambda < 0.7 \)
Adding a Singlet: \( \lambda \, S \, H_u \, H_d \)

\( \lambda < 0.7 \)

\( 1 < \lambda < 2 \)
Adding a Singlet: $\lambda SH_u H_d$

$\lambda < 0.7$

$1 < \lambda < 2$

$\Delta < 10$
Adding a Singlet: $\lambda S H_u H_d$

$\lambda < 0.7$

$1 < \lambda < 2$

$\Delta < 10$

Explains why we haven’t seen superpartners yet
R Parity Violation, Jan 88

**New Signatures for Supersymmetry**

- AT
  - $e^+e^-$ and Hadron Colliders.

- Four Minimal Models

- Spectacular Sign for $\Delta L \neq 0$ Model.

- $\Delta B \neq 0$ Model: Weak Scale Baryogenesis
  - $B$ Viol. AT $e^+e^-$ Colliders

With Savas Dimopoulos

**$\Delta L \neq 0$ Collider Signatures.**

- $l (e\gamma e)$
- $l \rightarrow e\gamma f$ (decays inside detector)
- $l \rightarrow e\gamma f$
- $e^+\gamma \rightarrow e^-$
- $(no\ need\ for\ f)$

**$(\text{events}) \sim 100 \left( \frac{100 \, \text{GeV}}{m_e} \right)^4 \frac{s}{(40 \, \text{GeV})^2} \left( \frac{Z}{100 \, \text{pb}^{-1}} \right) \beta^2$**

Present data $\Rightarrow m_\gamma \geq 25 \, \text{GeV}$ (or $m_\gamma$ heavy)

At higher $\Delta S^*$ as we get above $88$ threshold should watch out for eg:

- $e^+e^- \mu^+\mu^- + \text{missing}$
- $e^+e^- \mu^-\mu^+ + \text{missing}$
If SUSY is Split, By How Much?
If SUSY is Split, By How Much?

This needs some “Deep Thought”
If SUSY is Split, By How Much?

This needs some “Deep Thought”

I   Top Down
II  Bottom Up
High scale messengers couple directly only to scalar masses

\[ \tilde{q}, \tilde{\ell}, H^0, A \]

\[ \tilde{G} \]

\[ \tilde{g}, \tilde{B}, \tilde{W} \]

Anomaly Mediation with unsuppressed scalar masses
I  Split SUSY from Anomaly Mediation

**Higgsino LSP**

Yasunori Nomura, LJH  1111.4519

- High scale messengers couple directly only to scalar masses

- Two versions depending on $\mu$

- Anomaly Mediation with unsuppressed scalar masses

**Spread SUSY**

- $\tilde{q}, \tilde{\ell}, H^{0,\pm}, A$

**Wino LSP**

- Giudice, Luty, Murayama, Rattazzi
  hep-ph/9810442

- Wells
  hep-ph/0411041

- $\tilde{q}, \tilde{\ell}, H^{0,\pm}, A$

- $\tilde{\eta}, \tilde{G}$

- $\tilde{g}$

- $\tilde{B}

- $\tilde{W}$
I Split SUSY from Anomaly Mediation

Higgsino LSP

Spread SUSY
Yasunori Nomura, LJH 1111.4519

Wino LSP

High scale messengers couple directly only to scalar masses

Two versions depending on $\mu$

Anomaly Mediation with unsuppressed scalar masses

Normalization set Environmentally by Dark Matter
I Split SUSY from Anomaly Mediation

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High scale messengers couple directly only to scalar masses

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Anomaly Mediation with unsuppressed scalar masses

Normalization set Environmentally by Dark Matter

A 125 GeV Higgs is good for both
II  A Bottom-Up Approach

Revisit Motivation for SUSY

Natural

- Natural weak scale
- Gauge coupling unification
- WIMP LSP Dark Matter

Unnatural
II A Bottom-Up Approach

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- What sets the scale of the squark mass?
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Gilly Elor, David Pinner, Josh Ruderman, LJH
Fermion Masses 1992

Predictions for Fermion Masses and Mixing

Lawrence J. Hall: Aspen Jan '92

(1) Introduction to Ideas
(2) Framework
(3) The Predictions

Most predictive model to date

S. Dinopoulos
S. Raby

Conclusions

- Precise measurements of \(\sin^2 \theta\)
- Successful predictions in gauge sector
- Successful mass relations

- Theory of quark and lepton masses

- Flavor sector with few interactions
- Super symmetry
- Grand unified symmetry

- Precise measurements
  - \(V_{cb}\)
  - \(\sin 2\alpha, \sin 2\beta\)
Superpartners at 2 TeV
2 loop RGE
No susy thresholds
± 2σ

\[ \frac{b}{\tau} \text{ in 2012} \]
Superpartners at 2 TeV
2 loop RGE
No susy thresholds
$\pm 2\sigma$

Yukawas span 6 decades: $b/\tau$ in 2012

Is $b/\tau$ a hint?
Superpartners at 2 TeV
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Yukawas span 6 decades: Is $b/\tau$ a hint?

In 2012

Yukawa ratios

- $y_d/y_e$
- $y_b/y_\tau$
- $y_s/y_\mu$

$\mu$ [GeV]

$tan \beta = 50$
$\delta_b^{finite} = 0.12$
$m_{susy} = 2$ TeV

Georgi-Jarlskog Clebsch 1979!

Includes 12% susy threshold
Thresholds for $b/\tau$

Susy thresholds: $\delta_b, \delta_3$

Unified threshold: $\epsilon$

Precision $b/\tau$:

$$\epsilon = \epsilon(\delta_b, \delta_3, \tan \beta)$$
Thresholds for $\frac{b}{\tau}$

Susy thresholds: $\delta_b, \delta_3$

Unified threshold: $\epsilon$

Precision $\frac{b}{\tau}$: $\epsilon = \epsilon(\delta_b, \delta_3, \tan \beta)$

$\tan \beta = 50$
Thresholds for $b/\tau$

Susy thresholds: $\delta_b, \delta_3$  

Unified threshold: $\epsilon$

Precision $b/\tau$: $\epsilon = \epsilon(\delta_b, \delta_3, \tan \beta)$

$\tan \beta = 50$
Thresholds for $b/\tau$

Susy thresholds: $\delta_b, \delta_3$

Unified threshold: $\epsilon$

Precision $b/\tau$: $\epsilon = \epsilon(\delta_b, \delta_3, \tan \beta)$

$tan \beta = 50$

Varying $\tan \beta$
Thresholds for $b/\tau$

Susy thresholds: $\delta_b, \delta_3$

Unified threshold: $\epsilon$

Precision $b/\tau$: $\epsilon = \epsilon(\delta_b, \delta_3, \tan \beta)$

$\tan \beta = 50$

- Varying $\tan \beta$
- $\delta_{b}^{fin}$ or $\epsilon$
The Finite SUSY Threshold

\[ \delta_{b}^{f_{in}} \propto \frac{\mu}{m_{\tilde{q}}} \tan \beta \]
The Finite SUSY Threshold

\[ \delta_{\text{fin}}^b \propto \mu \tan \beta \]

\[ \delta_{\text{fin}}^b = -\frac{g_3^2}{12\pi^2} \frac{\mu M_3}{m_b^2} \tan \beta - \frac{y_t^2}{32\pi^2} \frac{\mu A_t}{m_t^2} \tan \beta \]

bino/Higgsino LSP
dark matter

Cannot decouple squarks
The Finite SUSY Threshold

\[ \delta_{\text{fin}}^b \propto \mu m_{\tilde{q}} \tan \beta \]

Cannot decouple squarks

Need large \( \tan \beta \)

bino/Higgsino LSP dark matter

\[ \delta_{\text{fin}}^b = -\frac{g_3^2 \mu M_3}{12\pi^2 m_b^2} \tan \beta - \frac{y_t^2 \mu A_t}{32\pi^2 m_t^2} \tan \beta \]
SUSY $b/\tau$ with a 125 GeV Higgs

Parameter space

$M_3, X_t, \mu, \tan \beta$

$m_{Q_3} = m_{U_3} = m_{D_3} = m_{\tilde{t}}$
SUSY $b/\tau$ with a 125 GeV Higgs

Parameter space

$M_3, X_t, \mu, \tan \beta$

$m_{Q_3} = m_{U_3} = m_{D_3} = m_{\tilde{t}}$

RGE prefer right lobe
SUSY $b/\tau$ with a 125 GeV Higgs
Rare B decays
Rare B decays
Rare B decays

\[ \delta_{32}^{LL} \]

\[ V_{ts} \]

\[ \langle H_u^* \rangle \]

\[ B_s \rightarrow \mu^+ \mu^- \]

Look at

\[ X_t < 0 \]
Rare B decays

Look at $B_s \rightarrow \mu^+ \mu^-$
Green: $\Omega h^2 \leq 0.1$

$log_{10}(\sigma_{DD}/\text{cm}^2)$

$tan \beta = 50$

Gaugino mass unification
125 GeV Higgs: Is SUSY Natural?

**SUSY at TeV Scale**
- **MSSM:** $\Delta > 100$
- Adding S helps
- ...

**SUSY at Higher Scales**
- Moderately Split Spectra like 125 GeV
- $b/\tau$ suggests SUSY at 1-10 TeV
- High Scale SUSY OK?
Savas

New Ideas

New Signals
Savas Unifies 3 Generations
High Scale SUSY

SM up to $\tilde{m} = 10^{14}$ GeV ($\sim M_u$)

$$\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8} \cos^2 2\beta$$

$\beta$-dependence of Higgs mass $M_h$ for $\tilde{m} = 10^{14}$ GeV

$m_t = (173.1 \pm 1.3)$ GeV

$\alpha_s = 0.1176$
High Scale SUSY

SM up to \( \tilde{m} = 10^{14} \text{ GeV} \sim M_u \)

\[
\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8} \cos^2 2\beta
\]

Uncertainties from

\( \alpha_s, m_t \)

\( m_h \)

unified thresholds

Hall, Nomura 0910.2235

\( m_t = (173.1 \pm 1.3) \text{ GeV} \)

\( \alpha_s = 0.1176 \)

\( \tilde{m} = 10^{14} \text{ GeV} \)
SM up to $\tilde{m} = 10^{14}$ GeV ($\sim M_u$)

$$\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8}\cos^22\beta$$

Uncertainties from $\alpha_s, m_t, m_h$

unified thresholds

An Alarming Possibility!!
Close to zero
Close to catastrophic vacuum tunneling
$b/\tau$ at low $\tan \beta$

Sample running

$\tan \beta = 20, 1$
$\delta_b^{\text{finite}} = 0.23$

$m_{\text{susy}} = 2 \text{ TeV}, 1 \text{ PeV}$

low $\tan \beta$

$\epsilon$

$\frac{y_t^2 (M_{\text{GUT}})}{(4 \pi)^2}$
Baryogenesis at the MeV to GeV Era, 1987

**Baryogenesis and Weak Scale Physics**

S. Dimopoulos

(I) **Cosmological Baryon Asymmetry.**

(II) **A Model (MeV – GeV era).**

(III) **Tests of the Model.**

**New Signatures**

Many possibilities. Dare to be optimistic:

1. \( e^+ e^- \rightarrow Z \rightarrow e^+ e^- \rightarrow (e^+ \bar{\nu}) (e^- \bar{\nu}) \)

\[
\begin{align*}
  e^+ & \rightarrow j_1 \\
  e^- & \rightarrow j_2 \\
  M_{e^+} & = M_{e^-} \\
  \text{Suppose } & \ m_\gamma \sim 10 \text{ GeV} \\
  \gamma & \rightarrow c \bar{b} s \\
  \Rightarrow j & \sim \text{large strangeness} \\
  \text{Search for } & \ e^+ e^- j(\Lambda) j(\Lambda) \\
  1 \text{ event useless} \\
  \text{Expect } \sim 1 \text{ event per } 10^3 \Gamma.
\end{align*}
\]
BBN at the KeV Era; 1987

The Hot Big Bang at a KeV

Is There a Second Era of Primordial Nucleosynthesis?

S. Dimopoulos
R. Esmailzadeh
G. Starkman
BARYOGENESIS

AT THE

GeV ERA

Lawrence Hall.
Sams Dimopoulos.

(1) SUSY, BARYOGENESIS, GRAVITINOS

(2) A MODEL.

CONCLUDE,

- Standard SUSY + \( U^c D^c D^c \)
- INFLATION: \( I \rightarrow \bar{q} \rightarrow q \bar{q} B \)
  \( \text{CP: } d_n \)
  \( B: \tau_n \)
- \( T_R \sim \text{GeV} \) : no gravitino problem.
- Lightest superpartner unstable
  - No dark matter candidate
  - No missing energy signature in superpartner searches.