(Split) SUSY

The Higgs
Whatever the Ultimate Theory

Relativity $\Rightarrow$ Quantum Mechanics

At “Long” distances, particles interacting as with spins $0, \frac{1}{2}, 1, \frac{3}{2}, 2$. Unique, “gravity”
Massless Particles

\[ p_{\alpha\bar{\alpha}} = (p_0 + p_3, p_1 - i p_2) = \lambda_{\alpha} \bar{\lambda}_{\bar{\alpha}} \]

Either

\[ \lambda_A < \lambda_B < \lambda_C \]

\[ \tilde{\lambda}_A < \tilde{\lambda}_B < \tilde{\lambda}_C \]

\[ g < \langle 12 \rangle, \langle 23 \rangle, \langle 31 \rangle \]

Completely determined by Poincaré
\[
(\langle 12 \rangle [34])^{2 \otimes 3} F(s, t, u)
\]

\[
\begin{align*}
\frac{1}{s} & \cdot \frac{g^2}{t^2} \\
\frac{1}{t} & \cdot \frac{g^2}{u^2} \\
\frac{1}{u} & \cdot \frac{g^2}{s^2}
\end{align*}
\]

\[
\implies \text{Only } \begin{cases} 
\nu = 0, & F = g^2 \left( \frac{1}{s} + \frac{1}{t} + \frac{1}{u} \right) \\
\nu = 2, & F = \frac{g^2}{s t u} \end{cases}
\]
$\text{Spin } 1$

$b \rightarrow c \ (g \ f^{abc})$

$a \rightarrow \Rightarrow f^{abc} \text{ satisfies Jacobi}$
Gauge “Symmetry” Does Not Exist

(Sometimes) convenient redundancy to describe physics in manifestly local way.
Spin of $X$:

$O \times \times \times \times \times \ldots$

MUST BE SPIN $O$

$X = \text{Higgs}$
At very high energies, $H$ and $W_L, Z_L$ are all united into $H$.

Usual Allowed Interactions
This was a Bold Proposal:

No Fundamental Spin 0 had ever been seen.
Triumph for experiment
Triumph for theory
Physics works
Belief in Principles Paid Off

0, $\frac{1}{2}$, 1, $\frac{3}{2}$, 2

Higgs is first “really new” particle we’ve seen
Why is there a Macroscopic Universe?
* Why are particles (nearly) massless relative to Planckian Scales?
But photon MUST stay massless, because

# massless helicities

2 ≠ 3

# massive spins

 photon

 photon
WHY ISN'T HIGGS ENORMOUSLY MASSIVE? PLANCKIAN?

Higgs

massless spin 0

1 = 1 massive spin 0

NO DIFFERENCE
Never seen before in "state of nature"

"fine-tuning"

Why are we all pointed in same direction?
An Obvious Gap!

\[ \{0, \frac{1}{2}, 1, \frac{3}{2}, 2\} \]

↑ Possible, Very Special!

Supersymmetry
All spin $\frac{1}{2}$ particles have spin $0$ partners.

All spin $1$ particles have spin $\frac{1}{2}$ partners.
Conserved Quantity
Energy + Momentum

Conserved Quantity
\[ Q_{1,2,3,4} \]
\[ Q_1 Q_2 = -Q_2 Q_1 \]
Supersymmetry

* Last Consistent Possibility
* Dramatic extension of Spacetime
Infinite Energy In Electric Field

\[ \frac{e^2}{4\pi a_{cl}} \sim m_e c^2 \Rightarrow a_{cl} \sim \frac{e^2}{4\pi m_e c^2} \]

\[ a_{\text{Compton}} \sim \frac{\hbar}{m_e c} \sim \left[ \frac{e^2}{4\pi \hbar c} \right]^{-1} \times a_{cl} \]
"Tension Driving BSM Physics For 30 yrs"

Naturalness

"Not Problems - Opportunities"
Natural SUSY
SUSY circa 1990

\[ \mathbf{E} \]

SPECTACULAR

+ D.M.
Why No SUSY @ LEP?

- $Z, h, \tilde{t}, \tilde{g}, \ldots$
- $\tilde{\ell}, \text{EW kinematics}$

“Natural” Spectrum

- $Z, h$

“Natural” spectrum
In the MSSM, a milder cousin of this problem is

\[ M_h \leq M_Z + M_{h, \text{tree,stop}} \]

With \( m_h \approx 125 \), this alone is a few \% tuning.
\[ W = \lambda S H_u H_d \rightarrow (\lambda^2 |H_u H_d|^2) \]

\[ M_{h^\sim}^2 = (M_h^2)_{\text{MSSM}} + \frac{4 \lambda^2 v^2}{\epsilon_\beta} \]

\[ (115 \text{ GeV})^2 \]

\[ (125 \text{ GeV})^2 \]

\[ M_{SSM} + U(1)_X \]

\[ M_{h^\sim}^2 = (M_h^2)_{\text{MSSM}} + \left( \frac{g_x}{g^2} \right) M_Z^2 \]

\[ (115 \text{ GeV})^2 \]

\[ (125 \text{ GeV})^2 \]
Unavoidable tunings: \( \left( \frac{400}{m_t} \right)^2, \left( \frac{4 m_{\tilde{g}}}{M_{\tilde{g}}} \right)^2 \)
Letting Go of Naturalness
\text{Naturality}
Plausible anthropic tuning for weak scale: existence of atoms other than hydrogen

\[
\begin{align*}
\nu & \leftrightarrow \nu \\
3\nu & \leftrightarrow \text{other nuclear binding energies}
\end{align*}
\]
**Split SUSY**

- **Reason for splitting:**
  - Fermions carry R-symmetry, scalars don’t.

- **100's → 1000's TeV**

- **10 TeV**

- ** Scalars → Unification ✓
  - Dark Matter ✓
  - **NO** Flavor, CP, moduli, ... problems

- **Fermions**
Indeed, a 1-loop splitting between gauginos + scalars was ubiquitous in simplest models of SUSY.

Modern guise: H.S. SUSY:

\[ m_\lambda \sim \frac{\alpha}{4\pi} m_{3/2} \]
\[ m_S \sim m_{3/2} \]

Unless you work!

["Not problem, opportunity"]
THIS SPECTRUM

~ $10^{-4}$
- $10^{-6}$
tuned

~ $100\text{ TeV}$ scalars
- 1000

~ $\text{TeV}$ fermions

IS WHAT SUSY MODELS "WANT TO DO." LET THEM!
Simplest Split SUSY

Also $\mu \sim m_5 \sim m_3^{1/2}$

So only gluino, wino, bino light
An Idea With a Long History

Early 80’s: 1-loop split spectrum common in SUSY models

1999: Giudice-Luty-Murayama-Rattazzi anom-med

Split Spectrum thought of as embarrassment

2003: J. Wells “PeV-scale SUSY”
2004: NAH + Savas; Giudice + Romanino “Split SUSY”
2006: NAH, Delgado, Giudice “Simplest Split SUSY”

Many Others
Higgs Mass

\[ \xi t_\beta = 4 \]

\[ \xi t_\beta = 2 \]
Unification a Bit Better than Natural SUSY

\[ \alpha_3(M_Z) = 0.108 \left( \mu \sim 10^2 \text{ TeV} \right) \]
\[ = 0.115 \left( \mu \sim 10^2 \text{ TeV} \right) \]
The Obvious Worry

"WIMP miracle" relic could mean $m_{\text{higgsino}} \sim 1\text{TeV}$ or $m_{\text{wino}} \sim 3\text{TeV}$.

Won't ever see even fermionic superpartners.
A) Could still be "well-tempered" relic, lighter OK.

B) Relic could constitute part of DM [rest, say, axions] → lower bottom of spectrum.

C) Moduli near ~100 TeV decay late, dilute initial abundance [† largely solve axion overclosure problem!], repopulate DM still favors light ~5 TeV LSP.
\[ \tilde{J} \quad 2100 \quad \text{GeV} \]
\[ \tilde{B} \quad 800 \quad \text{GeV} \]
\[ \tilde{W} \quad 350 \quad \text{GeV} \]
WITH EXTRA VECTOR-LIKE STATES
LHC Signals, Smoking Guns
Any observed deviation in Higgs properties KILLS ALL SUCH THEORIES
Vacuum Stability Disaster
Probing Higher Scale
With $\tilde{g}, \tilde{W}, \tilde{b}$ as only new particles - their decays can only proceed through higher-dimension operators!

Inside detector $\rightarrow$ scale $\lesssim 10^3 \text{TeV}$
If seen: experimental future for HEP on ~50 yr timescale

[WE CAN BUILD 100 TeV COLLIDERS]
Gluino Decays

\[ \frac{\tilde{g} \tilde{g} \tilde{b} \tilde{b}}{M^2} \]

\[ \frac{\tilde{g} \tilde{g} \tilde{W} \tilde{W}}{M^2} \]

\[ \sim \text{mm displ.} \]

\[ m_{\tilde{g}} \gtrsim (300 \text{ TeV}) \left( \frac{\Delta m}{\text{TeV}} \right)^{5/4} \]
Flavor-violation in gluino decays

Unless Operator is suppressed by

$\sim 100 - 1000 \text{ TeV}$
Here, EW breaking contributions to squark masses are tiny, \( \equiv \frac{3}{2} \frac{\text{param}}{m_{\tilde{q}_3, \tilde{u}_3, \tilde{d}_3}} \)

\[ \tilde{g} \rightarrow t\bar{t} \quad \tilde{b} \quad \tilde{b} \quad \tilde{w} \quad \tilde{t} \rightarrow t\bar{b} \tilde{W}^- \]

5 final states \( \equiv 4 \) ratios \( \rightarrow \) 1 relation
**Wino + Bino Decays**

\[
\begin{align*}
\tilde{h} \tilde{h} b & \overset{M}{\rightarrow} h h \tilde{b} \\
\tilde{h} \tilde{w} & \overset{\lambda}{\rightarrow} \tilde{h} h \tilde{w} \\
\tilde{b} & \rightarrow \tilde{w}^0 h \text{ only} \\
\tilde{b} & \rightarrow \tilde{w}^0 Z \times
\end{align*}
\]
\[ \text{Br} \left[ \tilde{\nu} \rightarrow bZ \right] \sim \left( \frac{m_\nu}{M} \right)^2 \text{ or } \left( \frac{\alpha}{4\pi} \right)^2 \]

\[ \downarrow \]

Probes heavy Higgsino, directly tuning
\[ \gtrsim 10 \text{ TeV} \]
Decaying To Other Sectors

$SM \times U(1)_Y, e^F_F$

$\epsilon \frac{\tilde{b_x} \tilde{b}^\dagger \tilde{h} \tilde{h}}{M}, \epsilon \frac{\tilde{h}^\dagger \tilde{W} \tilde{h} \tilde{b_x}}{M}$

$\tilde{b_x} \rightarrow \tilde{b} \rightarrow h$

Displaced!
\[ \tilde{g} \quad \text{2300} \]
\[ \tilde{b} \quad \text{800} \]
\[ \tilde{\tilde{W}} \quad \text{350} \]

\[ \tilde{g} \rightarrow \tilde{t} \quad \text{plausibly lightest squark} \]
\[ \tilde{t} \rightarrow \tilde{b} \quad \tilde{W}^0 \]

\[ \Rightarrow \quad 8 \ b's, \ 4 \ W's \quad [+ \text{perhaps displacement}] \]

in every event!
\[ \tilde{g} \quad \tilde{t} \quad \tilde{t}_R \quad \tilde{b} \quad \tilde{w} \quad \tilde{h} \quad x \ 2 \ \{ \begin{array}{l} 12 \text{ b's}, \ 4 \text{ W's}, \ \text{Displacement} \end{array} \} \]

\text{displaced} \leftarrow \text{displaced!
The Stakes Are Very High

$M_H \sim 125\text{ GeV}$

- 11th hour naturalness
  - Somewhat elaborate

- Un-natural
  - Simple
    - (Even minimal split is dramatic tuning)