SUSY —
What's Left?

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SUSY — What's Left? or What's Right?

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IS SUSY DEAD?
IS SUSY DEAD?

NO, BUT SOMewhat HUMBLED...
When SUSY was young...

Beautiful, minimal, maximally visible

Hierarchy Problem...

\[ E \] \[ M_{\text{Pl}} \] \[ H^t \] \[ H_w \]

radiative corrections
When SUSY was young...

... solved by weak scale SUSY

\[ \mathcal{E} \]

\[ M_{\text{pl}} \]

\[ H_\text{W} \]

\[ H_\text{t} \]

Sparticle corrections
ZOOMING IN MORE

\[ E \uparrow \quad TeV \]

\[ \tilde{t} \quad \tilde{H} \quad \tilde{g} \quad \tilde{t} \quad t \]

\[ \Rightarrow \quad \sigma \quad \text{colored, sub-TeV} \]
FCNCs

\[ M_{\text{squark}}^2 \]

\[ \bar{s} \rightarrow \bar{d} \leftrightarrow \bar{d} \rightarrow \bar{s} \]

Evaded if \( M_{\text{squark}}^2 \propto I_{\text{generations}} \) as in GMSB, AMSSB, \( \tilde{g} \) MSB, ...

\[ \Rightarrow \text{sub-TeV} \]

"Valence squarks"

Flavor-degenerate mechanisms favored by p.d.f.s
GUTs

\[ \frac{1}{\alpha} \]

\[ \begin{align*}
S & \quad U(1) \\
SU(2) & \quad \text{GUT} \\
SU(3) & \quad \text{RG7 tendency (but model dependent)}
\end{align*} \]

\[ \begin{align*}
\text{TeV} & \quad 10^{16} \text{GeV} \\
E & \quad M_{\text{Pl}} \\
\end{align*} \]

\[ \Rightarrow \text{Interesting Cascades} \]

\[ \begin{align*}
\text{colored sparticles} & \quad \text{EW sparticles}
\end{align*} \]
Proton Stability

\[ \text{Baryon No., GUT symmetry} \neq 0 \]

\[ \Rightarrow \text{Baryon No. not fundamental symmetry} \]

(Lepton No.)

but \[ \text{R-parity, GUT symmetry} \neq 0 \]

\[ \Rightarrow \text{R-parity can be fundamental symmetry} \]

\[ E \uparrow \]

colored sparticles

EW sparticles

stable LSP (WIMP dark matter)

\[ \begin{array}{c}
\text{\underline{\text{\scriptsize 9/9}}}\\
\text{\underline{\text{\scriptsize 9/9}}}\\
\text{\underline{\text{\scriptsize 9}}}
\end{array} \]

\[ \text{\underline{\text{\scriptsize E_T}}} \]
LHC has

v. strongly constrained this picture.

But is it all these ingredients or nothing?

How hard & long should we persist searching for SUSY?
SUSY's Pedigree

SUSY connects to deepest ideas of quantum gravity — strings, supergravity

It would be as fundamental a structure of spacetime as Lorentz invariance

But SUSY, like EW, can arise from a (super-)Higgs mechanism possibly related by hierarchy problem

Warrants all-out effort to test broadly
Trouble on the Horizon

The other naturalness problem

Cosmological Constant Problem

Must get $\Rightarrow$ galaxies

$\Rightarrow$ radius of curvature of spacetime

not $\Rightarrow$ atom

relates to vacuum energy $\equiv$ Susy order param.

\[ \text{may } \Rightarrow \text{ tension with EW-scale Susy} \]

reviews Kachru, Douglas '07; Kachru, Denef, Douglas '07
NATURE'S OPTIONS:

PLACE YOUR BETS

Sparticles

don't (alone) protect EW hierarchy

LHC

Higgs

fully solves EW hierarchy problem fully

"meso-tuned"

SPLIT SUSY

inos

protected by R-symmetry

Arkani-Hamed, Dimopoulos '04
Giudice, Romanino '04
Wells '04
COMPATIBILITY WITH STANDARD PRECISION SUSY GAUGE COUPLING UNIFICATION

Sparticles

don't (alone) protect EW hierarchy

LHC

H

E

M_{Pl}

SPLIT SUSY

"mesotuned"

inos protected by R-symmetry

but may be some other plot for "perfecting" non-SUSY SM unification
COMPATIBILITY WITH

$$m_H = 125 \text{ GeV}$$

LARGE SUSY RADIATIVE CORRECTION OR NEW LOWISH RICH THRESHOLD

SParticles
don't (alone) protect EW hierarchy

Eg. Harnik, Kribs, Larson, Murayama '04

SPLIT SUSY

LHC

solves EW hierarchy problem fully

"meso-tuned"

-inos protected by R-symmetry

✓

tension, no compelling untuned model, but possible

✓

Bottom-up: Barbieri, Hall, Nomura, Rychkov '06
General discussion: Hall, Pinner, Ruderman '11
NATURE'S OPTIONS:

PLACE YOUR BETS

- Sparticles
  - don't (alone) protect EW hierarchy

- Split SUSY
  - inos protected by R-symmetry
  - displaced vertices
  - CHAMPS R-hadrons $E_T$ (DM?)

- Fully solves EW hierarchy problem
  - EMERGENT (accidental) SUSY!

- “meso-tuned”
  - EW extra Higgs scalars
  - higher mass colored sparticles
  - $\rightarrow$ Luty '02; DeWolfe Giddings '02; Strassler '03; Gherghetta, Pomarol '03; Groh, Luty, Ng '03; Sundrum '09
NATURE’S OPTIONS:
PLACE YOUR BETS

- sparticles
  - don’t (alone) protect EW hierarchy

- split SUSY
  - “meso-tuned”

- LHC
  - solves EW hierarchy problem fully

- “inos protected by R-symmetry”

COMPLEMENTARY:
DM detection, proton decay, flavor physics, dark forces, precision Higgs tests, EDMs, $g-2$, ...
R-PARITY VIOLATION (RPV)

Modern GUT variants, e.g. Orbifold, String Unification are compatible with alternate proton stability mechanisms, e.g. baryon no., lepton no.

Stable LSP dark matter no longer "sings" alternative DM symmetries considered in modern SUSY theories. E.g., Arkani-Hamed, Weiner '08

RPV flavor problem/predictivity has elegant solutions. Nikolidakis, Smith '07; Gripaios, Giudice, Sundrum; Brust, Lawrence, Katz, Sundrum '11; Csaki, Grossman, Heidenreich '11; Keren-Zur, Lodone, Nardecchia, PapPoddopulo, Rattazzi, Vecchi '12
Still Viable Example: Lepton no. preserving RPV

Keren-Zur, Lodone, Nardecchia, Pappadopulo, Rattazzi, Vecchi '12

"partially composite" flavor structure
“NATURAL” ("EFFECTIVE") SUSY

E

--- other sparticles

\( g \)

\( \tilde{g} \)

\( \tilde{t} \)

\( \tilde{t} \)

\( \tilde{H} \)

\( H \)

\( H \)

---

H

sflavor non-degenerate solution to excessive FCNCs, EDMs

Dimopoulos, Giudice '95; Pomarol, Tommasini '96; Barbieri, Dvali, Hall '96; Cohen, Kaplan, Nelson '96 .... model-building

Flavor/CP constraints: Giudice, Nardocchia, Romanino '09; Brust, Katz, Lawrence, Sundrum '11
"NATURAL" ("EFFECTIVE") SUSY
still viable

\[ \tilde{g} \leftarrow \text{volatile pheno} \]
@ 7-8 TeV (due to PDFs)

R-Parity: $\tilde{H}^0$ LSP say.

Major background!
"NATURAL" ("EFFECTIVE") SUSY

Baryon (lepton-no. preserving) RPV
Kilic, Thomas 'll; Brust, Katz, Lawrence, Sundrum 'll;
volatile pheno
@ 7-8 TeV (due to pdfs)

\[ \tilde{g} \]

\[ \tilde{t}_1, \text{LSP say:} \]

dib-j Allanach, Griparais' 12
pair-dijet resonances multi-\( \ell \)
dijet resonances + \( \ell_\ell + E_T \)

\[ \tilde{t}_1, \tilde{b}_1 \]

\[ \tilde{H}_1^0, \tilde{H}_2^0 \]

major background

\[ \tilde{e}_L, \tilde{b}_L \]

\[ \tilde{e}_R \]

\[ E_\gamma \]

\[ \tilde{t}_2 \]
PAIR OF DIJET RESONANCES WITH LEPTONS

without $b$-veto, for $\bar{t} \rightarrow b + j$

with $b$-veto, for $\bar{t} \rightarrow jj$

Pairing up leading jets: $|M_{jj}^{(1)} - M_{jj}^{(2)}| < 10 \text{ GeV}$

Require hard event with "soft" leptons, $E_T$

Brust, Katz, Sundrum, '12
Analogous cut & count strategy (no bump hunt)
DIRAC GLUINO RPV

\[ m_{\tilde{t}} < m_t + m_{\tilde{H}_0} \]

\[ t\bar{t} \gg t\bar{t} \]

Dirac gauginos not their own anti-particle:

Hall, Randall '91; Randall, Rius '92; Fox, Nelson, Weiner '02
IT AIN'T OVER TILL I SAY VENN

where we must act, now

Robust
Bottom-up
effective
(simplified)
models

Experimental
Visibility

Model-builders, field theorists need to further understand

Robust top-down mechanisms, models