Where Do We Stand With SUSY?

Lawrence Hall
UC Berkeley & LBNL
The Prime Goal of LHC

Our theoretical knowledge

![Diagram with particles and mass labeling]
The Prime Goal of LHC

Our observed knowledge

\begin{align*}
\text{Mass} & \quad \text{Strong} & \quad \text{Weak} \\
& & \\
\text{u} & \quad \text{d} & \quad \text{e} & \quad \nu & \quad \gamma, g \\
& & & & & \quad W, Z
\end{align*}
The Prime Goal of LHC

Our observed knowledge

Strong

Weak

EM

A Physical Understanding of Vacuum and Mass Scale, $\nu$
The Contenders

Dynamical

\[ v = (\ldots) \Lambda_{\text{new}} \]

Susy

\[ v = (\ldots) \tilde{m} \]
The Contenders

**Dynamical**

\[ v = (...) \Lambda_{\text{new}} \]

**Large Extra Dim**

\[ v = (...) M_{\text{Fund}} \]

**Susy**

\[ v = (...) \tilde{m} \]

**Multiverse**

\[ v_{\text{obs}} \text{ near } v_c \]

\[ \nabla f \]

\[ \tilde{p} \]

\[ \tilde{m} \]

\[ p \]

\[ g_{\text{new}} \]
The Contenders

Dynamical

\[ v = (...) \Lambda_{\text{new}} \]

[Graph showing a function \( g_{\text{new}} \) against \( E \) in GeV]

Large Extra Dim

\[ v = (...) M_{\text{Fund}} \]

[Diagram showing \( M_{\text{Fund}} \) and \( v \) on vertical axes]

Susy

\[ v = (...) \tilde{m} \]

[Diagram showing \( \tilde{p} \), \( \tilde{m} \), and \( p \) with \( v_{\text{obs}} \) near \( v_c \)]

Multiverse

[Diagram showing \( v_{\text{obs}} \) near \( v_c \)]
Motivation for Supersymmetry

SUSY

Gauge coupling unification

Beauty/String

Dark Matter

Natural EWSB
Motivation for Supersymmetry

- Beauty/String
- Dark Matter
- Natural EWSB
- Motivation that susy will be found at LHC

- Gauge coupling unification
- Natural EWSB
  - Motivation that susy will be found at LHC
Motivation for Supersymmetry

Gauge coupling unification

Natural EWSB

Beauty/String

Dark Matter

 Cannot avoid naturalness/fine-tuning

Motivation that susy will be found at LHC
Problems for Weak Scale SUSY

- Baryon and Lepton Conservation not automatic
- Suppression of FCNC not automatic
Problems for Weak Scale SUSY

* Baryon and Lepton Conservation not automatic

* Suppression of FCNC not automatic

* Vector-Like Higgs Supermultiplet $\mu H_u H_d$
  
  $\mu$ problem
  
  no matter-Higgs unification
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* Higgs not discovered at LEP2
Problems for Weak Scale SUSY

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* Suppression of FCNC not automatic

* Vector-Like Higgs Supermultiplet \( \mu H_u H_d \)
  * \( \mu \) problem
  * no matter-Higgs unification

* Higgs not discovered at LEP2

Give up on susy? The other contenders also problematic!!
The Bottom Line

Dynamical

Large Extra Dim

I really don’t know. That’s the excitement of the LHC.

Susy

Multiverse

Fundamental

$v$

$\frac{1}{R}$
High-Scale Mediation

(No decays within detector to gravitinos)
Key Missing Energy Search

Jets + missing $E_T$

$\tilde{g} \rightarrow \bar{q}q\tilde{\chi}$

$\tilde{q} \rightarrow q\tilde{\chi}$
Jets + missing $E_T$

$\tilde{g} \rightarrow \bar{q}q\tilde{\chi}$

$\tilde{q} \rightarrow q\tilde{\chi}$

Important result:

* Some simple theories are now much less interesting

* Other theories are not yet probed
Jets + missing $E_T$

$\tilde{g} \rightarrow \bar{q}q \tilde{\chi}$

$\tilde{q} \rightarrow q \tilde{\chi}$

Important result:

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Dependence on LSP mass

No limit for \( m_{LSP} \geq 350 \text{ GeV} \)

\[ \mu \geq 350 \text{ GeV} \]
\[ \alpha_i \propto \alpha_i \]
Mín SUGRA

High-scale boundary condition: \( m_0, M_{1/2}, A, B, \mu \)

Radiative EWSB
Mín SUGRA

High-scale boundary condition: \( m_0, M_{1/2}, A, B, \mu \)

Radiative EWSB
Mín SUGRA

High-scale boundary condition: $m_0, M_{1/2}, A, B, \mu$

Radiative EWSB
Min SUGRA: Fine-tuning

$\frac{M_Z^2}{2} \approx -|\mu|^2 + |m_{H_u}^2|$

Cancellation
Min SUGRA: Fine-tuning

\[ \frac{M_Z^2}{2} \approx -|\mu|^2 + |m_{H_u}^2| \]

Worse than 1 in 100
$\textbf{SUGRA: non-universal scalar masses}$

High-scale boundary condition:

\[
M_{1/2}, A, B, \mu \\
\]

\[
m_0 \rightarrow m_{H_u}, m_{H_d}, m_{1,2}, m_3
\]

\[
m_t = (m_{Q_3}^2 m_{L_3}^2)^{1/4} \approx 250 \text{ GeV}
\]

Kitano, Nomura hep-ph/0602096
A Natural Spectrum

General “bottom-up” viewpoint

M

1 TeV

500 GeV

Closeness to Higgs
A Natural Spectrum

General “bottom-up” viewpoint

M

1 TeV

500 GeV

μ

\tilde{h}_2^0
\tilde{h}_+^0
\tilde{h}_1^0

Closeness to Higgs
A Natural Spectrum

General “bottom-up” viewpoint

\[ \tilde{t}_1, \tilde{t}_2, \tilde{b}_L, \tilde{h}_1, \tilde{h}_2, \tilde{h}_1^0, \tilde{h}_2^0, \tilde{h}_1^+ \]

M

1 TeV

500 GeV

Closeness to Higgs

\[ \tilde{h}_1, \tilde{h}_2, \tilde{h}_2^0, \tilde{h}_1^+ \]
A Natural Spectrum

General “bottom-up” viewpoint

The “Nuclear Family”

of the Higgs

\[ \tilde{h}_1, \tilde{h}_2, \tilde{t}_1, \tilde{b}_L \]

Closeness to Higgs
A Natural Spectrum

General “bottom-up” viewpoint

The “Nuclear Family” of the Higgs

Closeness to Higgs

\[ 
\begin{align*}
\tilde{g} & \\
\tilde{t}_2 & \\
\tilde{b}_L & \\
\tilde{t}_1 & \\
\tilde{h}_0^0 & \\
\tilde{h}_2 & \\
\tilde{h}_1^+ & \\
\tilde{h}_1^0 & \\
\end{align*} 
\]
The "Nuclear Family" of the Higgs

Closeness to Higgs

M

1 TeV

500 GeV

μ

A Natural Spectrum

General "bottom-up" viewpoint
**A Natural Spectrum**

General “bottom-up” viewpoint

- The “Nuclear Family” of the Higgs
  - $\tilde{h}^0_2$, $\tilde{h}^+_2$, $\tilde{h}^0_1$

- $\tilde{t}_2$
- $\tilde{b}_L$
- $\tilde{t}_1$

- Closeness to Higgs

- $\tilde{g}$

- $\tilde{q}_{1,2}$, $\tilde{b}_R$, $\tilde{\ell}$

“Distant Cousins”
Would I prefer a factor of 3 lower?
A Natural Spectrum

General “bottom-up” viewpoint

The “Nuclear Family” of the Higgs

The “Nuclear Family” of the Higgs

Key Search

Closeness to Higgs

Would I prefer a factor of 3 lower?
A Natural Spectrum

General “bottom-up” viewpoint

The “Nuclear Family” of the Higgs

Key Search

Closeness to Higgs

Would I prefer a factor of 3 lower?
A Common Scalar Mass $m_0$?

So long as we are careful to break the supersymmetry by adding a common mass to all the matter bosons with the same quantum numbers, this diagram is suppressed by a super-GIM mechanism.

\[ V_{\text{eff}} = \sum_{\alpha} \left| \frac{\partial f_{\text{eff}}}{\partial z^{\alpha}} \right|^2 + 2 \text{Re}(m_g^* f^{(3)}) + 4 \text{Re}(m_g^* f^{(2)}) + m_0^2 \sum_{\alpha} |z^{\alpha}|^2 + V_0 + \text{gauge terms} \]

Softly Broken Supersymmetry and SU(5).
Dimopoulos, Georgi

Supergravity as the Messenger of Supersymmetry Breaking.
Hall, Lykken, Weinberg
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$m_0$

Simplest assumption to avoid FCNC

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\]

$m_0$

Simplest assumption to avoid FCNC

\[
m_{\tilde{H}_1} H_1^* H_1 + m_{\tilde{H}_2} H_2^* H_2 + m_{\tilde{Q}} \tilde{Q}^* (I + c_6 \lambda_U^+ \lambda_U + c_7 \lambda_D^+ \lambda_D + \cdots) \tilde{Q} +
\]

The top squarks may be heavier or lighter than the up and charm squarks.

On the other hand, bounds on the masses of the first two generations of sleptons and squarks range between 2 and 5 TeV.
A Common Scalar Mass $m_0$?

So long as we are careful to break the supersymmetry by adding a common mass to all the matter bosons with the same quantum numbers, this diagram is suppressed by a super-GIM mechanism.

\[
V_{\text{eff}} = \sum \left| \frac{\partial f_{\text{eff}}}{\partial z^\alpha} \right|^2 + 2 \text{Re}(m_g^* f^{(3)}) + 4 \text{Re}(m_g^* f^{(2)}) + |m_g|^2 \sum \left| z^\alpha \right|^2 + V_0 + \text{gauge terms}.
\]

$V_0$

Simplest assumption to avoid FCNC

\[
m_{H_1}^2 H_1^* H_1 + m_{H_2}^2 H_2^* H_2 + m_{\tilde{Q}}^2 \tilde{Q}^* (I + c_6 \lambda_U^+ \lambda_U + c_7 \lambda_D^+ \lambda_D + \cdots) \tilde{Q} +
\]

The top squarks may be heavier or lighter than the up and charm squarks.

On the other hand, bounds on the masses of the first two generations of sleptons and squarks range between 2 and 5 TeV.

“Natural Spectrum” is 15-20 years old

Softly Broken Supersymmetry and SU(5).
Dimopoulos, Georgi

Supergravity as the Messenger of Supersymmetry Breaking.
Hall, Lykken, Weinberg

Weak Scale Effective Supersymmetry.
Hall, Randall

Naturalness Constraints in Supersymmetric theories with Nonuniversal Soft Terms.
Dimopoulos, Giudice
Jets + MET

Jets + missing $E_T$

$\tilde{g} \rightarrow \bar{q}q \tilde{\chi}$

$\tilde{q} \rightarrow q \tilde{\chi}$

Probes $\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}$

not $\tilde{t}, \tilde{b}$

$\tilde{\chi}_1 < 200$ GeV
Search in b Jets

$0 \ell, b$-jets, $E_{T\text{miss}}$

\begin{align*}
\tilde{g} & \rightarrow b \tilde{\chi}^- \\
\tilde{b} & \rightarrow \tilde{\chi}^0 \tilde{\chi}^- \\
\tilde{\chi}^0 & \rightarrow \tilde{\chi}^- 
\end{align*}
\( \tilde{g} \rightarrow \bar{b}b\tilde{\chi} \) is sub-dominant

Nuclear family decay dominantly via \( y_t \)

Dominant modes

\[
\tilde{g} \rightarrow \bar{t}t\tilde{\chi}^0 \\
\tilde{g} \rightarrow \bar{b}b\tilde{\chi}^+ 
\]
Search for Light $\tilde{t}$

$\tilde{g} \rightarrow \bar{t}b\tilde{\chi}^+$

Low values of $m_{\tilde{g}}, m_{\tilde{t}}$ allowed

$g + \tilde{t} \tilde{\tau}^+ \rightarrow \tilde{t}_1 \tilde{\tau}_1 \rightarrow \tilde{t}_1 \tilde{\tau}_1 \rightarrow b \bar{b} \bar{\chi}^+$

$\sqrt{s} = 7\,\text{TeV}$

$\Delta m = 1.03\,\text{fb}^{-1}$

$\Delta m_{\text{expected limit}} \pm 1\sigma$

Observed ATLAS (35 pb$^{-1}$)

Expected ATLAS (35 pb$^{-1}$)
Search for Light $\tilde{t}$

$\tilde{g} \rightarrow \overline{t}b\tilde{\chi}^+$

Low values of $m_{\tilde{g}}, m_{\tilde{t}}$ allowed

Further searches are underway & eagerly awaited.
Bottom-Up Viewpoint

We already bought something like this after LEP
This natural spectrum has not been excluded, and may take 5+ years to probe.

We already bought something like this after LEP.
What if (Light Stop + MET) Absent?

Reduced Missing Energy

Stops are Naturally Heavy

\[ \tilde{t}_1 \, \tilde{b}_L \, \tilde{t}_2 \]

\[ \text{TeV} \]

\[ \text{GeV} \]
What if (Light Stop + MET) Absent?

Reduced Missing Energy

- R Parity Violation
- $\chi \rightarrow tbs, \nu\bar{b}b, \tau\bar{b}t, \tau W, \nu Z$

- Squashed susy spectrum

Stops are Naturally Heavy

- $\tilde{t}_2, \tilde{b}_L, \tilde{t}_1$

$1$ TeV

$500$ GeV

$\tilde{g}, \tilde{q}$

LSP
What if (Light Stop + MET) Absent?

Reduced Missing Energy

- R Parity Violation
  - eg: \( \tilde{t}_2 \), \( \tilde{b}_L \), \( \tilde{t}_1 \)
  - \( \chi \rightarrow tbs \), \( \nu \bar{b}b \), \( \tau \bar{b}t \), \( \tau W \), \( \nu Z \)

- Squashed susy spectrum
  - \( \tilde{g}, \tilde{q} \)
  - LSP

Stops are Naturally Heavy

- Focus Points
  - \( \tilde{t}_2 \), \( \tilde{b}_L \), \( \tilde{t}_1 \)

- Heavier Higgs
  - Fat Higgs
  - \( \lambda \)-SUSY
What if (Light Stop + MET) Absent?

Reduced Missing Energy

R Parity Violation

eg

χ → 

\( tbs \)
\( νbb \)
\( τbt \)
\( τW \)
\( νZ \)

*Squashed susy spectrum

\( \tilde{t}_2 \)
\( \tilde{b}_L \)
\( \tilde{t}_1 \)

Stops are Naturally Heavy

Focus Points

*Heavier Higgs
Fat Higgs
\( λ \)-SUSY

Plenty to explore for the coming decade

\( \tilde{g}, \tilde{q} \)
\( \tilde{g}, \tilde{q} \)
\( \text{LSP} \)

1 TeV

500 GeV

1 TeV

500 GeV
II

Low-Scale Mediation
Naturalness

Generically a factor 10 more natural

\[ m_t^2 \lesssim (450 \text{ GeV})^2 \left( \frac{1}{1 + \frac{x^2}{2}} \right) \left( \frac{20\%}{\Delta^{-1}} \right) \left( \ln \frac{3}{\frac{M_{\text{mess}}}{m_t}} \right) \]

Plenty of room for Gravitino LSP
Naturalness

Generically a factor 10 more natural

\[ m_t^2 \lesssim (450 \text{ GeV})^2 \frac{1}{1 + \frac{x^2}{2}} \left( \frac{20\%}{\Delta^{-1}} \right) \left( \frac{3}{\ln \frac{M_{\text{mess}}}{m_t}} \right) \]

Plenty of room for Gravitino LSP

But not in minimal gauge mediation models (a theorists problem)

Kitano, Nomura
hep-ph/0602096
Key Missing Energy Searches

\[ \gamma \gamma + \text{missing } E_T \]

\[ \tilde{g} \rightarrow \bar{q}q \tilde{B} \]

\[ \tilde{G}_{3/2} + \gamma \]

Minimal gauge-mediated models: no worse

Natural models: no problem with stop at 300 GeV
III

SUSY Higgs
SUSY Higgs

\[ h_{SM} \rightarrow h, H, A, H^+ \]

\[ m_{h_{SM}} \rightarrow \tan \beta, m_A \]
SUSY Higgs

\[ h_{SM} \rightarrow h, H, A, H^+ \]

\[ m_{h_{SM}} \rightarrow \tan \beta, m_A \]

\[ m_h^2 = M_Z^2 \cos^2 2\beta + \delta_{\text{top}} \]

Need heavy \( \tilde{t} \)!
SUSY Higgs

$h_{SM} \rightarrow h, H, A, H^+$

$m_{h_{SM}} \rightarrow \tan \beta, m_A$

\[ m_h^2 = M_Z^2 \cos^2 2\beta + \delta_{top} \]

Need heavy $\tilde{t}$!

\[ m_h = 115 \text{ GeV} \]

FeynHiggs 2.5

Large $A$

Kitano, Nomura
hep-ph/0602096
**SUSY Higgs**

\[ h_{SM} \rightarrow h, H, A, H^+ \]

\[ m_{h_{SM}} \rightarrow \tan \beta, m_A \]

\[ m_h^2 = M_Z^2 \cos^2 2\beta + \delta_{top} \]

Need heavy \( \tilde{t} \)!

\[ m_h = 115 \text{ GeV} \]

Large \( A \)

Or \( \mu \rightarrow S \)

Kitano, Nomura
hep-ph/0602096
Search for $H,A$ of MSSM

$H,A$ couplings to $b, \tau$
enhanced at large $\tan \beta$

$H, A \rightarrow \tau^+ \tau^-$
Search for $h$

$m_{h_{SM}} \rightarrow \tan \beta, m_A$

$h_{SM} \rightarrow h, H, A, H^+$
Search for $h$

$m_{h_{SM}} \to \tan \beta, m_A$

$h_{SM} \to h, H, A, H^+$

Should show up here “soon”!!
Search for $h$

$m_{h_{SM}} \rightarrow \tan \beta, m_A$

$h_{SM} \rightarrow h, H, A, H^+$

Should show up here “soon” !!

What if it doesn’t?
Not In Decoupled Region
Effect of Light $\tilde{t}$ on $h \rightarrow \gamma\gamma$ Signal Rate

modifies rate by $B \sigma$
Effect of Light $\tilde{t}$ on $h \rightarrow \gamma\gamma$ Signal Rate

modifies rate by $B\sigma$
Effect of Light $\tilde{t}$ on $h \rightarrow \gamma \gamma$ Signal Rate

modifies rate by $B \sigma$

Large $A$
Effect of Light $\tilde{t}$ on $h \rightarrow \gamma \gamma$ Signal Rate

 modifies rate by $B \sigma$

Shaded regions from varying $\mu$
Natural Spectrum and Dark Matter

\[ \tilde{g}, \tilde{t}_1, \tilde{t}_2, \tilde{b}_L, \tilde{\mu}, \tilde{\nu}_1, \tilde{\nu}_2, \tilde{\nu}_R, \tilde{l} \]

- \( \tilde{h}_2 \)  (Higgsino-like)
- \( \tilde{h}_2^0 \)  (neutralino-like)
- 500 GeV
- 1 TeV
- Closeness to Higgs

\[ \tilde{g} \]
Natural Spectrum and Dark Matter

\[ M \]

1 TeV

500 GeV

\[ \tilde{h}^0_2 \quad \tilde{h}^0_1 \quad \tilde{h}^+_1 \]

\[ \tilde{t}_1 \quad \tilde{b}_L \]

\[ (\quad) \quad \tilde{w} \quad (\quad) \quad \tilde{B} \]

\[ \tilde{g} \]

\[ \tilde{q}_{1,2} \quad \tilde{b}_R \quad \tilde{l} \]

Dark Matter likely \( \tilde{B}/\tilde{h} \) mixture

Closeness to Higgs
Higgs Decays to Neutralino Dark Matter

\[ \tan\beta = 3 \]

\[ \tan\beta = 10 \]

Farina, Kadastik, Pappadopulo, Pata, Raidal, Strumia 1104.3572
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1104.3572
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Farina, Kadastik, Pappadopulo, Pata, Raidal, Strumia
1104.3572

\[ \tan \beta = 10 \]

Gilly Elor, Lawrence Hall, David Pinner, Josh Ruderman
Is $h$ in Light Window?

[Graph showing ATLAS Preliminary CLs Limits for $m_h$ at 95% CL Limit on $\sigma/\sigma_{SM}$ with observed and expected data points and limits.]

$\int Ldt = 1.0-2.3$ fb$^{-1}$

$s = 7$ TeV

??
Is $h$ in Light Window?
**Is $h$ in Light Window?**

Our Field Is Approaching a Defining Moment
Is h in Light Window?

Our Field Is Approaching a Defining Moment

### Table

<table>
<thead>
<tr>
<th>SM (1 Higgs)</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excluded</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SUSY</th>
<th>Look for deviations from $h_{SM}$</th>
<th>$H \tilde{t} \tilde{\chi}$ light</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\lambda S H_u H_d$ large</td>
</tr>
</tbody>
</table>

### Graphs

- **ATLAS Preliminary CLs Limits**
- **CMS Preliminary: Oct 2010**
  - Projected 95% CL Limit on $\sigma/\sigma_{SM}$
  - Significance of Observation ($\sigma$)
  - Limit?
  - Hint?

- **CMS Preliminary, $\sqrt{s} = 7$ TeV**
  - Higgs boson mass ($m_H$ [GeV/c²])
  - CL limit on $\sigma/\sigma_{SM}$

---

---
CONCLUDE:

The Excitement of the LHC

Origin and scale of EW Symmetry Breaking
CONCLUDE:

**The Excitement of the LHC**

Contenders:

- Weak scale supersymmetry
- New strong dynamics
- Multiverse
- Large Extra Dimensions

Origin and scale of EW Symmetry Breaking

We really don’t know!
The Excitement of the LHC

Supersymmetry will be probed deeply in the coming months and years. It may take a while.

CONTENDERS:

Weak scale supersymmetry
New strong dynamics
Multiverse
Large Extra Dimensions

We really don’t know!

Origin and scale of EW Symmetry Breaking
$\textbf{IV}$

$\textbf{Multiverse}$

$v$

$v_c \rightarrow v_{\text{obs}}$

$\nabla f$

$v_{\text{obs}}$ near $v_c$
Motivation for Supersymmetry

- Beauty/String
- Gauge coupling unification
- Natural Weak Scale
- Dark Matter
Motivation for Supersymmetry

A fine-tuned weak scale is evidence for multiverse

\[ \tilde{m} \gg v \]
The Higgs Mass Prediction

$\tilde{m} \gg v$

Some superpartners at weak scale?

Yes (fermionic): Split Supersymmetry
Arkani-Hamed, Dimopoulos, hep-th/0405159

WIMP DM

No: High-Scale Supersymmetry
Hall. Nomura arXiv:0910.2235

Axion DM
The Higgs Mass Prediction

$\tilde{m} \gg v$

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Hall. Nomura arXiv:0910.2235

WIMP DM

Axion DM

Giudice, Strumia 1108.6077
The Higgs Mass Prediction

The Higgs is hard to hide:
- no h/H mixing
- no h production from squark loop

Some superpartners at weak scale?

Yes (fermionic): Split Supersymmetry
Arkani-Hamed, Dimopoulos, hep-th/0405159

No: High-Scale Supersymmetry
Hall. Nomura arXiv:0910.2235

WIMP DM

Axion DM

\[ \tilde{m} \gg v \]
Long-Lived Gluinos In Split SUSY
Long-Lived Gluinos In Split SUSY

\[ \tilde{g} \rightarrow q \tilde{q}, \quad \tilde{m} \gg v \]

- \[ \tilde{g} \rightarrow \tilde{q} \tilde{b} \]

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

Graphical representation:
- Scatter plot showing long-lived gluinos in split SUSY, with a line indicating the stop point as a function of the stop mass and lifetime.
- Diagram with jets indicating the decay of split SUSY particles.
Long-Lived Gluinos In Split SUSY
Long-Lived Gluinos In Split SUSY

\[ \tilde{g} \rightarrow q \tilde{q} \tilde{b} \]

Excluded

\[ m_{\tilde{g}} < 500 \text{ GeV} \]
Gluino R Hadron Charged Tracks

$\tilde{g}$ → $\tilde{q} \rightarrow q + \tilde{\bar{q}}$  
$\tilde{b}$  

$\tilde{m} \gg v$

Heavy Stable Charged Particle Tracks
Gluino R Hadron Charged Tracks

\[ \tilde{g} \rightarrow q \tilde{q} \tilde{b} \quad \tilde{m} \gg v \]

Heavy Stable Charged Particle Tracks

Excluded

\[ m_{\tilde{g}} < 850 \text{ GeV} \]
Gluino $R$ Hadron Charged Tracks

Excluded

$m_{\tilde{g}} < 850$ GeV

Problem:

$m_{\tilde{g}}$ not constrained by naturalness