The Supersymmetric Limit of Electroweak Symmetry Breaking

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Columbia University
The SM Higgs ruled out at 170 GeV!

Tevatron Run II Preliminary, L=3 fb^{-1}

- Solid line: Observed
- Dotted line: Expected
- Green: ±1σ
- Yellow: ±2σ

SM

m_H(GeV/c^2)

July 30, 2008
The MSSM Scalar Sector

- First choice for non-SM Higgs searches

  2 parameters \((m_A, t_\beta)\) \rightarrow\quad\text{Physics of 4 fields}\quad\\(h^0, H^0, H^\pm, A^0\)

  a generic theory has 7 more parameters.

- Expectation:

  Looking for the **MSSM** Higgs Boson is just like looking for the **SM** Higgs Boson.
**MSSM (CP-even) Higgs properties**

- Very Light SM-like Higgs mass

\[ m_{h^0} < M_Z \] at tree-level

\[ m_{h^0} \leq 130 \text{ GeV} \] with %-ish tuning

\( (\chi^0, \chi^+) \)
MSSM (CP-even) Higgs properties

- LEP 2b bounds \( (m_{H^0} \geq m_{h^0}) \)

\[ M_{\tilde{t}} \sim m_t \]
MSSM (CP-even) Higgs properties

- LEP 2b bounds

\[ m_{H^0} \geq m_{h^0} \]

\[ M_{\tilde{t}} \sim m_t \]

\[ M_{\tilde{t}} \sim 400 \text{ GeV} \]
MSSM (CP-even) Higgs properties

- LEP 2b bounds \((m_{H^0} \geq m_{h^0})\)

\[
M_{\tilde{t}} \sim m_t \quad M_{\tilde{t}} \sim 400 \text{ GeV}
\]

\[
m_A^2 < M_Z^2 \rightarrow \frac{b}{m_Z^2} \ll \frac{1}{20} \quad \& \quad \frac{b}{|m_u^2 - m_d^2|} \ll \frac{1}{30}
\]
MSSM (CP-even) Higgs properties

- LEP 2b bounds

\[ m_{H^0} \geq m_{h^0} \]

- \[ M_{\tilde{t}} \sim m_t \]
- \[ M_{\tilde{t}} \sim 400 \text{ GeV} \]
- \[ M_{\tilde{t}} \sim 600 \text{ GeV} \]

\[
m_A \simeq m_H \simeq m_{H^\pm} \left[ \pm \mathcal{O} \left( \frac{m_Z^2}{m_A} \right) \right] \quad g_{H^0 ZZ} \sim 0 + \mathcal{O} \left( \frac{m_Z^2 s_\beta^4}{4m_A^2} \right)
\]

Decoupling limit \(~h^0\) is SM-like
Beyond The MSSM Scalar Sector

• Can use strong-coupling to increase $m_{h^0}$

$m_{h^0} \sim 300$ GeV

Haber-Sher, Espinosa-Quiros, Randall, P.B. et al., “The Fat Higgs”, ...
Beyond The MSSM Scalar Sector

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• Generalized Analyses

Brignole et al., Dine, Seiberg, Thomas

• Can evade LEP bounds via singlet production

NMSSM, Dermisek-Gunion, Chang-Fox-Weiner

qualitative shift in Higgs physics!

\[ h^0 \rightarrow 2a \rightarrow 4b, 4\tau, 2b2\tau, \ldots \]
Outline

1. Supersymmetric-EWSB (sEWSB)
   Defined; Qualitative structure; LEP-motivated; UV complete example;

2. An Effective Field Theory approach to sEWSB
   MSSM degrees of freedom only; simple, surprisingly under control; very rich vacuum structure; moving away from the SUSY-breaking limit

3. Higgs searches in sEWSB
   The heavier higgs, $H^0$, is naturally SM-like;
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   NLSP Chargino
The MSSM

No SUSY-breaking $\implies$ No EWSB

\[ W = \mu H_u H_d \rightarrow |\mu|^2 |H|^2 \]
Radiative EWSB

\[ t_\beta \equiv \frac{\langle H_u \rangle}{\langle H_d \rangle} \]

\[ \text{Tr} = -\frac{1}{2} M_Z^2 - \frac{2 \sec^2(2\beta)}{M_Z^2} \text{Det} \]

\[ m_{H_u}^2 \]

No EWSB w/o SUSY breaking driven negative by top loops

\[ \text{MSSM all } \beta \]

\[ \beta = 0, \pi/2, \pi \]

stable origin no EWSB

unstable potential

unstable potential

\[ (--) \]

\[ (++) \]

\[ \langle -- \rangle \]

\[ \langle ++ \rangle \]
Supersymmetric EWSB (sEWSB)

SUSY-breaking --> 0, EWSB still occurs
Supersymmetric EWSB (sEWSB)

SUSY-breaking $\rightarrow 0$, EWSB still occurs

**general features**

--In the SM, massive vector fields ‘eat’ a real scalar

$$H = e^{iX^\theta} \tilde{H}$$

--With sEWSB, massive vector superfields ‘eat’ an entire chiral superfield.

$$H_i = e^{iX^\Theta} \tilde{H}_i \quad \Theta \supset (\theta + i\theta', \psi_\theta)$$

$$M_{H^\pm} = M_{\chi^\pm} = M_{W^\pm} \quad M_{h^0} = M_{\chi^0} = M_Z$$
Supersymmetric EWSB (sEWSB)

SUSY-breaking $\rightarrow 0$, EWSB still occurs

---In the SM, a real ‘radial’ mode remains which contains the SM-like Higgs.

$$\tilde{H} = H_{SM}$$

---With sEWSB, a ‘super-radial’ mode remains (an entire chiral superfield) which contains the SM-like Higgs, a CP-odd Higgs, and a neutralino

$$\tilde{H} = (H_{SM}, A^0, \chi'^0)$$
Supersymmetric EWSB (sEWSB)

SUSY-breaking $\rightarrow$ 0, EWSB still occurs

**general features**

--In the SM, the Higgs mass is determined by the curvature of the potential.

--With sEWSB, the superfield Higgs mass is determined by the superpotential.

The Kahler potential: $g^2 D^2 \sim \left( \tilde{H}_i^\dagger T^a \tilde{H}_i \right)^2$

does not contain a mass term for $\tilde{H}$
Supersymmetric EWSB (sEWSB)

Summary:

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No real decoupling limit (strong coupling limit)
Supersymmetric EWSB (sEWSB)

Example of a Twisted Custodial Symmetry

\[ \Sigma_1 = \begin{pmatrix} v + H_{SM} & 0 \\ 0 & v + H_{SM} \end{pmatrix} \rightarrow U_L \Sigma_1 U_R^\dagger \]

Preserves an SU(2) Custodial, but

\[ \Sigma_2 = \begin{pmatrix} h^0 - iA^0 & H^+ \\ H^- & h^0 + iA^0 \end{pmatrix} \rightarrow U_L \Sigma_2 \left( X^\dagger U_R^\dagger X \right) \]

Custodital triplet

\[ X = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \text{ or } \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad \left( H^\pm, A^0 \right) \text{ or } \left( H^\pm, h^0 \right) \]
Supersymmetric EWSB (sEWSB)

Two theoretical motivations for study, but don’t forget:
Supersymmetric EWSB (sEWSB)

Two theoretical motivations for study, but don’t forget:

Unlike the MSSM, the SM-like Higgs mass is NOT determined by gauge couplings ($g_w$).

Should expect the SM-like Higgs mass to be related to $M_Z$ as it is in the Standard Model (unitarity).

Very straightforward resolution to the SUSY hierarchy problem in sEWSB vacua.
Concrete example: Fat Higgs

Solves the SUSY-hierarchy problem

Harnik, Kribs, Larson, Murayama

\[ W \supset \lambda N \left( H_u H_d - \nu_0^2 \right) \]
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   NLSP Chargino
An effective field theory of sEWSB

The simplest SUSY extension of the MSSM has sEWSB!

\[ W \supset \mu H_u H_d + \frac{1}{2\mu_s} (H_u H_d)^2 \]

-- \( \mu_s \) is the scale of unknown (SUSY) UV physics

\( \mu \ll \mu_s \)

-- one (but not the only) example is a SUSY singlet

\[ W \supset \lambda S H_u H_d + \mu_S S^2 \]
An effective field theory of sEWSB

\[ W \supset \mu H_u H_d + \frac{1}{2\mu_s} (H_u H_d)^2 \]

\[ V = (|H_u^0|^2 + |H_d^0|^2) \left| \mu - \frac{1}{\mu_s} H_u^0 H_d^0 \right|^2 \]

\[ \tan \beta = 1 \]

\[ \langle H_u^0 H_d^0 \rangle = \mu \mu_s \]

D-terms give mass to \( H^\pm, h^0 \)
**Mass of the super-radial mode**

\[ H^0_u = \frac{e^{-iT\Theta}}{\sqrt{2}} \left( \tilde{H} + v \right) \quad H^0_d = \frac{e^{iT\Theta}}{\sqrt{2}} \left( \tilde{H} + v \right) \]

\[ W \supset \mu H_u H_d + \frac{1}{2\mu_s} (H_u H_d)^2 = \frac{1}{2} (2\mu) \tilde{H}^2 \]

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Mass of the super-radial mode

\[ 2|\mu| > M_Z \rightarrow H_{SM} = H^0 \]

Inverted scalar hierarchy
Validity of the Effective Field Theory

Already a surprising result:

a ‘non-renormalizable’ VEV!

--Consider a the SM-Higgs potential

\[ V \sim -m^2 H^2 + \lambda H^4 \quad \langle H^2 \rangle \sim \frac{m^2}{\lambda} \]

--Consider a dim-6 potential

\[ V \sim -\lambda H^4 + \frac{H^6}{M^2} \quad \langle H^2 \rangle \sim \lambda M^2 \]

If \( \lambda \sim 1 \), the VEV is not reliable.
Validity of the Effective Field Theory

Ironically, the LEP paradox exists precisely because no large quartic ($\lambda$) can be written down with just the MSSM d.o.f !!!

\[
W \supset \mu H_u H_d + \frac{1}{2\mu_s} (H_u H_d)^2
\]

\[
V = (|H_u^0|^2 + |H_d^0|^2) \left| \mu - \frac{1}{\mu_s} H_u^0 H_d^0 \right|^2
\]

\[
\lambda = \frac{\mu}{\mu_s} \ll 1 \quad (\mu \ll \mu_s)
\]

\[
\langle H^2 \rangle \sim \lambda M^2 \sim \mu \mu_s
\]
Ignored operators?

Ignored superpotential operators:

\[ W = \mu H_u H_d + \frac{\omega_1}{2\mu_S} (H_u H_d)^2 + \frac{\omega_2}{3\mu_S^3} (H_u H_d)^3 + \cdots , \]

higher-order effects are suppressed by \( \frac{\mu}{\mu_S} \)

Note, the importance of an operator can only be assessed after expanding around the right minimum.
Ignored operators?

Ignored Kahler terms:

\[ K \supset H_u^\dagger e^V H_u \left(1 + \frac{1}{\mu_S^2} H_u^\dagger e^V H_u \right) + \ldots \]

higher-order effects are suppressed by \( \frac{\mu}{\mu_S} \)

Nevertheless, leading corrections to

\[ \tan \beta = 1 + \mathcal{O} \left( \frac{\mu}{\mu_S} \right), \quad g_{H_{SM}ZZ} \]
Away from the SUSY-limit

SUSY-breaking is required to lift slepton/squark masses

-- sEWSB defined as SUSY is restored

-- Benefit of the EFT: only one new soft-term in the Higgs sector

\[ V_{SB} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + \left[ b H_u H_d - \xi \left( \frac{\omega_1}{2\mu_s} \right) (H_u H_d)^2 + h.c. \right] \]
Much larger region of EWSB

\[ \begin{align*}
\text{signs matter,} & \quad \beta \in \left[ -\frac{\pi}{2}, \frac{\pi}{2} \right] \\
\tan(\beta) & < 0!
\end{align*} \]

\[ |\mu|/\mu_s = 1/10 \]
\[ \omega_1 = 2, \xi = 0 \]
\[ \tan \beta = 1 \]
Away from the SUSY-limit

Some tension between making $m_{H^0}$ large, but keeping the EFT under control.

\[
2\mu \quad \text{vs.} \quad v^2 = \mu \mu_S \quad \text{vs.} \quad \frac{\mu}{\mu_S} \ll 1
\]

SUSY-breaking eases this tension

• lifts the masses of $\chi^\pm$, $\chi^0$, $H^\pm$ above LEP bounds
• introduces MSSM-like vacua
• ensures that sEWSB vacua are global minima
Rich Vacuum Structure

Figure 2: An illustration showing the equipotential lines in the $v_u$–$v_d$ plane for a case with two nontrivial minima. The nature of these minima can be determined by exploring how the physics depends on the UV scale $\mu_S$: the MSSM-like VEV remains near the origin as $\mu_S \to \infty$ while the "sEWSB" VEV scales like $\sqrt{\mu_S}$ as indicated by the arrow for large $\mu_S$. The limit is taken with all other microscopic parameters fixed.

New minima can be described as those that are "brought in from infinity" when the higher-dimensional operators are turned on. It is important to notice that, as argued by an operator analysis in Subsection 2, the EFT gives a good control of the physics of such nonsupersymmetric vacua provided $v^2 - \mu^2_S \sim 2\rho \omega_1 \mu \mu_S \ll -\mu_S$.

This approximation becomes even better in the limit described above and leads to the interesting situation in which, although the physics at $\mu_S$ is crucial in triggering EWSB, the details of that physics actually become unimportant. With a slight abuse of notation we will continue referring to vacua that obey the scaling $v \sim \sqrt{\mu_S}$ in the large $\mu_S$ limit as sEWSB vacua even when SUSY breaking is not negligible.

The important property is that they exist only due to the presence of the higher-dimensional operators while being describable within the EFT framework.

Decoupling of sEWSB vacua as new physics becomes massive.
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   NLSP Chargino
Inverted Hierarchy in the MSSM

- Inverted Hierarchy: $H^0$ is SM-like ($m_{h^0} < m_{H^0}$)

$M_{\tilde{t}} \sim m_t$  
$M_{\tilde{t}} \sim 400$ GeV  
$M_{\tilde{t}} \sim 600$ GeV
Inverted Hierarchy in sEWSB vacua

Inverted hierarchy in roughly ‘half’ of parameter space
# Example Inverted Spectra

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## Point 2

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## Example Inverted Spectra

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Extreme Inverted Spectra

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<td>0.70</td>
<td>-1.0</td>
<td>.86</td>
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<th>$\rho$</th>
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Orientation at low $\tan \beta$

- Inverted Hierarchy: $H^0$ is SM-like ($c_{\beta-\alpha} \sim 1$)
Orientation at low $\tan \beta$

- Inverted Hierarchy: $H^0$ is SM-like ($c_{\beta-\alpha} \sim 1$)

- Gauge Boson couplings:

$$\frac{h^0 ZZ}{h_{SM} ZZ} = s_{\beta-\alpha} \to 0$$

$$\frac{H^0 ZZ}{h_{SM} ZZ} = c_{\beta-\alpha} \to 1$$
Orientation at low $\tan \beta$

- Inverted Hierarchy: $H^0$ is SM-like ($c_{\beta-\alpha} \sim 1$)

- Gauge Boson couplings:
  \[
  \frac{h^0 ZZ}{h_{SM} ZZ} = s_{\beta-\alpha} \to 0 \quad \frac{H^0 ZZ}{h_{SM} ZZ} = c_{\beta-\alpha} \to 1
  \]

- down-type couplings:
  \[
  \frac{h^0 b\bar{b}}{h_{SM} b\bar{b}} = s_{\beta-\alpha} - t_\beta c_{\beta-\alpha} \to 1 \quad \frac{H^0 b\bar{b}}{h_{SM} b\bar{b}} = c_{\beta-\alpha} + t_\beta s_{\beta-\alpha} \to 1
  \]
Orientation at low $\tan \beta$

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  \]

- up-type couplings:
  \[
  \frac{h^0 t\bar{t}}{h_{SM} t\bar{t}} = s_{\beta-\alpha} + \cot \beta c_{\beta-\alpha} \to 1 \quad \frac{H^0 t\bar{t}}{h_{SM} t\bar{t}} = c_{\beta-\alpha} - \cot \beta s_{\beta-\alpha} \to 1
  \]
Orientation at low $\tan \beta$

- Inverted Hierarchy: $H^0$ is SM-like ($c_{\beta-\alpha} \sim 1$)

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- down-type couplings:
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  \frac{h^0 b\bar{b}}{h_{SM} b\bar{b}} = s_{\beta-\alpha} - t_\beta c_{\beta-\alpha} \to 1 \quad \quad \frac{H^0 b\bar{b}}{h_{SM} b\bar{b}} = c_{\beta-\alpha} + t_\beta s_{\beta-\alpha} \to 1
  \]

- gluon fusion unchanged, important contrib. to $h^0 \to \gamma\gamma$
  \[
  \frac{h^0 t\bar{t}}{h_{SM} t\bar{t}} = s_{\beta-\alpha} + \cot_\beta c_{\beta-\alpha} \to 1 \quad \quad \frac{H^0 t\bar{t}}{h_{SM} t\bar{t}} = c_{\beta-\alpha} - \cot_\beta s_{\beta-\alpha} \to 1
  \]
Enhanced Scalar Decays

Low mass, $H \rightarrow b\bar{b}$ dominates

High mass, $H \rightarrow W^+W^- (ZZ)$ dominates
Enhanced Scalar Decays

\[ H^0 \rightarrow \Gamma (H^0 \rightarrow ZZ) \sim \frac{m_{H^0}^3}{v^2} \]

\[ \lambda v \sim \frac{m_{H^0}^2}{v} \]
Enhanced Scalar Decays

\[
\lambda v \sim \frac{m_{H^0}^2}{v}
\]

\[
\Gamma (H^0 \to ZZ) \sim \frac{m_{H^0}^3}{v^2}
\]

- Consider

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Enhanced Scalar Decays

\[ \lambda v \sim \frac{m_{H^0}^2}{v} \]

\[ \Gamma (H^0 \rightarrow h^0 h^0) \sim \frac{m_{H^0}^3}{v^2} \]

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## Enhanced Scalar Decays

\[ \lambda v \sim \frac{m^2_{H^0}}{v} \]

\[ \Gamma (H^0 \rightarrow h^0 h^0) \sim \frac{m^3_{H^0}}{v^2} \]

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- \[ \frac{Br (H^0 \rightarrow 2h^0, H^\pm)}{Br (H^0 \rightarrow VV)} \sim \frac{1}{5} \]
Enhanced Scalar Decays

\[ H^0 \rightarrow G^0, h^0 \]

\[ \lambda v \sim \frac{m_{H^0}^2}{v} \]

\[ \Gamma (H^0 \rightarrow h^0 h^0) \sim \frac{m_{H^0}^3}{v^2} \]

Toy model:

\[ \mathcal{L} \supset -m_H^2 |H|^2 + \lambda |H|^4 + \lambda |H|^2 |S|^2 - m_S^2 |S|^2 \]

cancel to 20% in our model
**Inverted Phenomenology**

**Higgs to SUSY decay modes**

\[ H^0 \rightarrow \chi^0 + \chi^0 \]

\[ \Gamma \propto g^2 m_H \]

\[ (\Gamma \propto y_b^2 m_H) \]

Haber, Dicus, Dress & Tata; Gunion & Haber, ...

\[ \tilde{\ell} \rightarrow \ell \tilde{N}_1 \]

\[ \tilde{\nu} \rightarrow \nu \tilde{N}_1 \]
Invisible Higgs Decays

Higgs to SUSY decay modes

Eboli, Zeppenfeld

Godbole et al., Davoudiasl, Han, Logan
Invisible Higgs Decays

Higgs to SUSY decay modes

LHC:

<table>
<thead>
<tr>
<th>$M_H$ (GeV)</th>
<th>110</th>
<th>120</th>
<th>130</th>
<th>150</th>
<th>200</th>
<th>300</th>
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<tr>
<td>100 fb$^{-1}$</td>
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<td>4.9%</td>
<td>5.1%</td>
<td>5.3%</td>
<td>6.2%</td>
<td>8.5%</td>
<td>11.7%</td>
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Eboli, Zeppenfeld
Invisible Higgs Decays

Higgs to SUSY decay modes

Godbole et al., Davoudiasl, Han, Logan

LHC:

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<th>$p_T$ cut</th>
<th>$m_h = 120$ GeV</th>
<th>$m_h = 140$ GeV</th>
<th>$m_h = 160$ GeV</th>
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<tbody>
<tr>
<td></td>
<td>$S/B$</td>
<td>$S/(\sqrt{B} \ (10 \text{ fb}^{-1}))$</td>
<td>$S/(\sqrt{B} \ (30 \text{ fb}^{-1}))$</td>
</tr>
<tr>
<td>65 GeV</td>
<td>0.22 (0.16)</td>
<td>5.6 (4.9)</td>
<td>9.8 (8.5)</td>
</tr>
<tr>
<td>75 GeV</td>
<td>0.25 (0.22)</td>
<td>5.7 (5.3)</td>
<td>9.9 (9.1)</td>
</tr>
<tr>
<td>85 GeV</td>
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Chargino NLSP?

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Every SUSY event has $W^+W^- + \text{MET}$

Chargino decay may be prompt, displaced, or outside the detector.
Inverted Phenomenology

Charged Higgs constraints

- direct constraints from LEP, $m_{H^+} > 80$ GeV
- indirect constraints from B factories
  $b \rightarrow s\gamma : m_{H^+} > 300$ GeV
vanishes in the SUSY-limit

Ferrara & Remiddi, Barbieri & Giudice

- direct constraints from Tevatron, when $t \rightarrow H^+b$
Inverted Phenomenology

Charged Higgs constraints

-- direct constraints from Tevatron, when \( t \rightarrow H^+ b \)

![Graph showing charged Higgs constraints](image)

**Table 2. Standard Model (SM) expected and observed number of events...**

**Excluded LEP**

**LEP (ALEPH, DELPHI, L3 and OPAL)**

Assuming \( H^\pm \rightarrow \tau V \) or \( H^\pm \rightarrow c \bar{s} \) only

**Theoretical inaccessible**

\( M_{H^+} \) (GeV/c^2)

- SM Expected
- SM \( \pm 1 \sigma \) Expected
- Excluded CDF Run II
- Excluded LEP

**CDF Run II Preliminary**

\( m_t = 175 \text{ GeV/c}^2 \)

\( \int L \ dt = 192 \text{ pb}^{-1} \)

**t \rightarrow H^\pm b \) search

Excluded 95 \% CL

**\( M_{\text{SUSY}} = 1000 \text{ GeV/c}^2 \), \( \mu = -500 \text{ GeV/c}^2 \), \( A_t = A_b = 2000 \text{ GeV/c}^2 \), \( A_\tau = 500 \text{ GeV/c}^2 \)**

**\( M_1 = 0.498 \times M_2 \), \( M_2 = M_3 = M_Q = M_U = M_D = M_E = M_L = M_{\text{SUSY}} \)**
Inverted Phenomenology

Charged Higgs constraints

-- direct constraints from Tevatron, when $t \rightarrow H^+ b$

\[ H^+ \rightarrow \chi^+ \chi^0 \]

$\Gamma \propto g^2 m_H$

$(\Gamma \propto y_b^2 m_H)$

--unexplored top decay channel!
Conclusions

• Post-LEP, it is worth reconsidering what the most likely BSM Higgs sector looks like:

\[ h^0 \rightarrow 2a \rightarrow 4b \quad m_{h^0} < m_{H^0}, \quad H^0 \text{ SM-like} \]

• Supersymmetric EWSB is a qualitatively new starting point---EFT approach is very powerful!

  Easy to UV complete into a theory with \[ W \supset \lambda S H_u H_d \]

• Light Higgs \(
\rightarrow \) enhanced scalar decays, Light charginos, charged Higgs = new phenomenology!

  Rich Vacuum Structure---cosmological applications?

  Uniquely Identifiable?
• supplements
Figure 5: Higgs signal (double-hatched) on top of the sum of the backgrounds at the LHC in the 4b decay channel together with a leptonically decaying W. The invariant mass of four (left) and two (right) b-jets are shown. Constraints of $60 \text{ GeV} < m(4b) < 160 \text{ GeV}$ and $10 \text{ GeV} < m(2b) < 70 \text{ GeV}$ are implemented in both plots. $C_{4b}^2 = 0.50$, $m_h = 120 \text{ GeV}$ and $m_a = 30 \text{ GeV}$ are understood. From bottom to top, the background histograms indicate the accumulative sum of $2b2cW$, $2b2cW + 2b2jW$, $2b2cW + 2b2jW + 3b1jW$, and $2b2cW + 2b2jW + 3b1jW + 4bW$, respectively.
CP conservation:

\[ b/|\mu|^2 \geq 0 \text{ or } \xi \mu^2 > 0, \]

No Charge-Breaking

\[ \left\{ 4m_{H_d}^2 + v^2 (g^2 + g'^2 c_{2\beta}) + 4|\mu|^2 (\rho s_{2\beta} - 1)^2 \right\} \geq 0 \]
FIG. 1. Missing transverse momentum spectra within the cuts (1) and (3). Results are shown separately for the EW $Z_{jj}$ (blue dashed line) and $W_{jj}$ (blue dotted line) backgrounds, as well as the QCD processes $Z_{jj}$ (black dashed line), $W_{jj}$ (black dotted line), and $jjj$ (magenta histogram) production. We exhibit the invisible Higgs contribution for $M_H = 120$ (red solid line) and 300 GeV (red dot-dashed line).

FIG. 2. Dijet invariant mass distributions when applying the cuts of Eqs. (1,2). The lines follow
FIG. 3. Distributions of the azimuthal angle separation between the two tagging jets for the various background processes and the Higgs signal at $M_H = 120$ and 300 GeV. Results are shown after applying the cuts (1-3) and including the effect of a central jet veto with the survival probabilities of Table I. The lines follow the same convention as in Fig. 1.
FIG. 1: Missing $p_T$ distribution for $Z(\rightarrow e^+e^-) + h_{inv}$ signal (solid lines, with $m_h = 120, 140$ and $160$ GeV top to bottom) and backgrounds from $WW$ and $ZZ$ (dotted lines) at the LHC, after applying the cuts in Eqs. (3), (5) and (6).
Just CDF bounds

CDF Run II Preliminary, L=2.0-3.0 fb$^{-1}$

LEP Excl.

95% CL Limit/SM

m$_H$ (GeV/c$^2$)

WWW 2.7 fb$^{-1}$ Obs
WWW 2.7 fb$^{-1}$ Exp
H→ττ 2.0 fb$^{-1}$ Obs
H→ττ 2.0 fb$^{-1}$ Exp
ZH→llbb 2.7 fb$^{-1}$ Obs
ZH→llbb 2.7 fb$^{-1}$ Exp
WH+ZH→bbMET 2.1 fb$^{-1}$ Obs
WH+ZH→bbMET 2.1 fb$^{-1}$ Exp
WH→llbb 2.7 fb$^{-1}$ Obs
WH→llbb 2.7 fb$^{-1}$ Exp
H→WW 3.0 fb$^{-1}$ Obs
H→WW 3.0 fb$^{-1}$ Exp
Combined Obs
Combined Exp

LEP Excl.

SM

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Minimization Relations

\[
\begin{align*}
 s_{2\beta} &= \frac{2b - 4|\mu|^2 \rho (\rho s_{2\beta} - 1)}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2 (\rho s_{2\beta} - 1)^2 - 2\xi \mu^2 \rho} , \\
m_Z^2 &= \frac{m_{H_u}^2 - m_{H_d}^2}{c_{2\beta}} - \left[ m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2 (\rho s_{2\beta} - 1)^2 \right] , \\
v^2 &\equiv \rho \left( \frac{2\mu \mu_S}{\omega_1} \right) .
\end{align*}
\]
Near SUSY limit

\[ V \approx (m_{H_u}^2 + m_{H_d}^2 + 2b) \frac{v^2}{2}, \quad \text{(small SUSY breaking)} \]
\[
\rho_\epsilon = \frac{1}{2} \xi \pm 2 \sqrt{\frac{3}{3}} \left\{ 1 + \epsilon \sqrt{1 - \frac{3}{(\frac{1}{2} \xi \pm 2)^2} \left( 1 + \frac{m^2_{H_u} + m^2_{H_d}}{2 \mu^2} \right)} \right\},
\]

\[
\delta \beta = \pm \frac{m^2_{H_d} - m^2_{H_u}}{2 \left( m^2_Z + m^2_{H_u} + m^2_{H_d} + 2 \mu^2 (1 \mp \rho_\epsilon)^2 \right)},
\]

\[
m^2_{A_0} = 4(\pm 1 + \xi) \rho \mu^2 \pm 2b + O(\delta \beta^2),
\]

\[
m^2_{H^0} = \frac{1}{2} \left[ m^2_Z + m^2_{A_0} + 8 \mu^2 \rho (\rho \mp 1 - \xi/2) + |D| \right] + O(\delta \beta^2),
\]

\[
m^2_{h^0} = \frac{1}{2} \left[ m^2_Z + m^2_{A_0} + 8 \mu^2 \rho (\rho \mp 1 - \xi/2) - |D| \right] + O(\delta \beta^2),
\]

\[
D \equiv m^2_Z + m^2_{A_0} - 8 \mu^2 \rho (2 \rho \mp 1).
\]

\[
c^2_{\beta-\alpha} = \begin{cases} 0 + O(\delta \beta^2) & D > 0 \\ 1 + O(\delta \beta^2) & D < 0 \end{cases}.
\]
\[ m_{H^+}^2 = \begin{cases} 
   m_{H^0}^2 + (m_W^2 - m_Z^2) + \mathcal{O}(\delta \beta^2) & D > 0 \\
   m_{h^0}^2 + (m_W^2 - m_Z^2) + \mathcal{O}(\delta \beta^2) & D < 0 
\end{cases} \]