Searching for 
Supersymmetric Higgs Bosons 
at the LHC

Tilman Plehn
CERN

- Light neutral Higgs: no-lose-theorem
- Charged Higgs: bottom induced processes
- Heavy neutral Higgs: decay to two light Higgses
MSSM Higgs Sector

- Softly broken supersymmetric anomaly–free theory
- two doublets, coupling to up and down type fermions
  → five physical states $h^0, H^0, A^0, H^\pm$
  → mixing of scalars to mass eigenstates (mixing angle $\alpha$)
  → more predictive than Standard Model (upper $h^0$ mass limit)
- conveniently expressed as function of $m_A$ and $\tan \beta \equiv v_2/v_1$
- Yukawa couplings to $H, A, H^\pm$: $m_b \tan \beta, m_t/\tan \beta$ (large $m_A$)
- typically one light, many heavy scalars [Heinemeyer, Weiglein]

Find first Higgs boson

- complete coverage by WBF $h \rightarrow \tau \tau$ [TP, Rainwater, Zeppenfeld]
- problem: mass degeneracy [Boos, Djouadi, Mühlleitner, Nikitenko]
  $\Delta m_h/m_h \sim \sigma/\sqrt{N}$ ($\sigma \sim 1.5$ GeV for $\mu\mu, \gamma\gamma$ and $\sigma \sim 15$ GeV for $\tau\tau$)

Tell it is 2HDM (MSSM?) ⇒ look for heavy Higgs bosons

- $H^0, A^0 \rightarrow \tau\tau, \mu\mu$ inclusive $gg \rightarrow H$ and $gg \rightarrow b\bar{b}H$
- $H^\pm \rightarrow \nu\tau, tb$ in $pp \rightarrow tH^-, W^+H^-, H^+H^-$
  (n.b. SUSY loops) [Hollik et al, Kniehl et al]
- appearance in SUSY cascades [Datta, Djouadi, Guchait, Moortgat]
- no other conclusive way but to find these particles
\[ M_{\text{Higgs}} \text{ [GeV]} \]

\[ M_A \text{ [GeV]} \]

\[ m_h^{\text{max scen.}, \tan \beta = 5} \]

- \( h \)
- \( H \)
- \( A \)
- \( H^+ \)
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- no other conclusive way but to find these particles
$m_A = 200 \ \text{GeV/c}^2$, $M_2 = 200 \ \text{GeV/c}^2$

$A_t = \sqrt{6} \ \text{TeV/c}^2$, $M_{\text{SUSY}} = 1 \ \text{TeV/c}^2$

Excluded by LEP
1. Light Neutral Higgs

MSSM Higgs bosons in weak boson fusion [TP, Rainwater, Zeppenfeld]

- SM cross section $> 3$ pb for light Higgs in $qq \to qqH$
  (tagging jet signature, central decay products, minijet veto)

- approximate 12 GeV $\tau\tau$ mass reconstruction at high $p_{T,h}$ [K.Ellis]

- MSSM decoupling region:
  (a) Higgs mass range after LEP2: $m_Z \ll m_h < 135$ GeV
  (b) production cross section: $g_{WWH} = \sin(\beta - \alpha) \sim 1$
  (c) branching fraction: $BR(h \to \tau\tau) > BR(H_{SM} \to \tau\tau)$

→ enhancement of rate: $pp \to qqh \to qq\tau\tau$

→ heavy Higgs production at low $m_A$

→ no–lose theorem for MSSM Higgs scalars

Attempts to escape this channel

- low $\tan\beta$: forbidden by LEP2

- $m_A = 91$ GeV and $m_h = 95$ GeV: wide open channel for $H$

- super–large mixing $A_t > 6$ TeV: enhanced WBF $WW$ and $\gamma\gamma$ rate

- CP phases in $A_t$: coverage solid [Carena, Ellis, Wagner,...]

- funny couplings of all kind: again solid [Schumacher]

- many multiplets: go for WBF $WW$ channel [Alves, Eboli, TP, Rainwater]
$m_h[GeV]$

$h^0$

$H^0$

$\tan \beta$

$m_A$

$\sin^2(\beta-\alpha)$

$\cos^2(\beta-\alpha)$

$(\sigma.B)_{h}[fb]$

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$M_{SUSY}=1 \, \text{TeV}$, maximal mixing
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\[ \tan \beta \]

LHC(40 fb^{-1}):

- \( VV \rightarrow H \rightarrow \tau \tau \)
- \( VV \rightarrow h \rightarrow \tau \tau \)

LEP2: \( e^+ e^- \rightarrow Zh \)
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2. (Heavy) Charged Higgs

Most promising channel

- associated production $pp \rightarrow tH^- + X$ for large $\tan \beta$
- decay $H^\pm \rightarrow \nu \tau$ most promising  [Assamagan, Coadou]

Exclusive production $gg \rightarrow \bar{b}tH^-$

- collinear bottom jets from gluon splitting, regularized by $m_b$
  → experiment: forward jets, $p_{T;b}$ peaked at $m_b$  (factor 1/6 for each tagged $b$)
  → use bottom–inclusive cross section
  → check asymptotic cross section behavior  $d\sigma/dp_{T;b} \propto p_{T;b}/m_{T,b}^2$
  → inclusive total rate  $\sigma \propto \log(p_{T,b}^{\text{max}}/p_{T,b}^{\text{min}}) = \log(p_{T,b}^{\text{max}}/m_b)$
  → how large logarithms? resum?

Inclusive process $bg \rightarrow tH^-$

- resum large logarithms $\log(p_{T;b}/m_b)$ in exclusive process $gg \rightarrow \bar{b}tH^-$
  → equivalent to bottom parton density and inclusive process $bg \rightarrow tH^-
  → \mu_{F,b} \text{ ‘transverse momentum size’ of bottom parton}
    $(\mu_{F,b} \equiv p_{T,b}^{\text{max}} ; \text{usually hard scale } \mu_{F,b} = M)$
  → numerical improvement or overestimate?
  → (1) check bottom–inclusive total rate
    (2) check bottom–inclusive $t, H$ distributions
\[ \frac{1}{\sigma_{\text{tot}}} \frac{d\sigma}{dy_{b\bar{b}}} (gg \rightarrow b\bar{t}H^-) \]

- \( m_b = 4.6 \text{ GeV} \)
- \( m_b = 0.46 \text{ GeV} \)
- \( m_H = 1000 \text{ GeV} \)
- \( m_H = 500 \text{ GeV} \)
- \( m_H = 250 \text{ GeV} \)

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$p_{T,b} \frac{d\sigma}{dp_{T,b}} (gg \rightarrow btH^-)$

$m_H = 1000$ GeV

$m_H = 500$ GeV

$m_H = 250$ GeV

$m_b = 4.6$ GeV

$m_b = 0.46$ GeV

$p_{T,b}$ [GeV]
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Perturbative bottom factorization scale from exclusive process  [Boos, TP]

- two steps: first bottom virtuality $Q_b^{\text{max}}$
- general exclusive process: $gg \rightarrow \bar{b}X_M$
  approximate gluon density $\mathcal{L} = \mathcal{L}_0/x^2$
  asymptotic behavior $|\mathcal{M}|^2 = S^2\sigma_0/Q_b^2$

$$\sigma = \frac{2\sigma_0\mathcal{L}_0}{16\pi} \int_0^{S-M^2} \frac{dQ_b}{Q_b} F(Q_b)$$

→ $F(Q_b)$ known correction to asymptotic behavior  $d\sigma/dQ_b \sim 1/Q_b$

→ define $Q_b^{\text{max}}$ at turning point $d^2F(Q_b)/d(\log Q_b)^2 = 0$

→ $Q_b^{\text{max}} \sim M/2$  (hard scale argument $Q_b^{\text{max}} \propto M$, not more than that!)

Second step: transverse momentum $p_{T,b}^{\text{max}}$

- check explicitly: $Q_b \sim Q_b^{\text{max}}$  also yields  $p_{T,b} \sim p_{T,b}^{\text{max}}$

→ translate $Q_b$ into $p_{T,b}$ point by point

→ $p_{T,b}^{\text{max}}/Q_b^{\text{max}} \sim Q_b^{\text{max}}/M$  yields  $p_{T,b}^{\text{max}} \sim Q_b^{\text{max}}/2 \sim M/4$
  (numerical study of $gg \rightarrow \bar{b}tH^-$:  $\mu_{F,b} \sim M/5$)

So what did we learn from exclusive process?

- $\log(p_{T,b}/m_b)$ after integrating over bottom jet
  but ‘large’ logs at maximum $\log(M/(5m_b))$  [TP; Maltoni, Willenbrock]
- hard scale for inclusive process:  $\mu_{F,b} \propto M$
- $gg$ and $bg$ processes:  $\mu_{F,b} \sim M/5$ from partonic phase space

$\Rightarrow$ Total cross section with bottom partons understood
LHC: $gg \rightarrow b\bar{t}H$

$$Q_b \frac{d\sigma}{dQ_b} = \frac{Q_b}{(m_t + m_H)}$$

$m_H = 250, 500, 1000$ GeV

$p_T,b \frac{d\sigma}{dp_{T,b}}$

$m_H = 250$ GeV

$m_H = 500$ GeV

$m_H = 1000$ GeV

LHC: $gg \rightarrow b\bar{t}H$ with $P_g (x) = 1$

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$\Rightarrow$ Total cross section with bottom partons understood
Next-to-leading Order QCD Calculation [TP]

- leading order uncertainty large for $bg \rightarrow tH^-$
- complete set of virtual and real SUSY corrections
- running Yukawa couplings, everything else misleading

$\rightarrow$ NLO correction $+30\% \cdots 40\%$ perturbatively stable [Zhu]

Scale Dependence

- renormalization scale dependence numerically dominant
  $\mu_R \sim (m_t + m_H)/2$ natural choice [c.f. Higgs decays, Melnikov]
- factorization scale dependene critical only for small $\mu_F$
  $\mu_F \sim (m_t + m_H)/5$ from exclusive process
- problem at small scales: bottom induced process not dominant

$\rightarrow$ NLO scale dependence $\pm 20\%$

$\rightarrow$ well defined limit $\mu_F \rightarrow m_b$ returns exclusive process $gg \rightarrow \bar{b}tH^-$

Matching at threshold

- $m_H < m_t - m_b$: top pair production and Breit–Wigner propagator
  $m_H > m_t - m_b$: resummed off-shell process
- double counting of $pp \rightarrow t\bar{t}^* \rightarrow t(\bar{b}H^-)$
- subtract on-shell top pairs from NLO $bg \rightarrow tH^-$ process
  (unique in small width approximation, see SUSY-pairs)

$\rightarrow$ consistent matching by simply adding channels
\[ \sigma_{\text{tot}} \ (pp \to tH^- + X) \ [\text{pb}] \]

\( (m_b \text{ running mass}) \)

\[ m_b \text{ pole mass} \]

- NLO: \( gb \to tH^- \)
- LO: \( gb \to tH^- \)
- LO: \( gg \to b tH^- \)

\[ m_H \, [\text{GeV}] \]

\[ \mu = 4m_{\text{av}} \]
\[ \mu = m_{\text{av}} \]
\[ \mu = m_{\text{av}} / 4 \]

\[ \tan \beta = 30 \]

\[ K \ (pp \to tH^- + X) \]

\[ m_H \, [\text{GeV}] \]
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\[ m_t = m_H + m_b \pm 2 \Gamma_t \]
On to the distributions [Berger, Han, Jiang, TP]

- bottom parton description appropriate for total rate

→ Higgs and top distributions?

→ bottom partons established for exclusive cross sections?

(1) Test zero transverse momentum approximation

- bottom partons assuming small $p_{T,b} \ll p_{z,b}$

→ compare inclusive process and (massless) exclusive $(2 \rightarrow 3)$ process

(as it is part of NLO rate)

→ run bottom factorization scale $\mu_F \rightarrow m_b$

switch on/off incoming bottoms, left with $gg \rightarrow \bar{b}tH^-$

→ slightly harder distributions (due to $x$ dependence of bottom PDF)

(2) Test zero bottom mass approximation

- agreement exclusive vs. inclusive cross section established

→ check with bottom mass dependent $pp \rightarrow \bar{b}tH^-$

→ perfect agreement with exclusive process for small $m_b$

very good agreement with physical bottom mass case

→ bottom parton picture altogether appropriate
\[
\frac{1}{\sigma} \frac{d\sigma}{dp_{T,H}} \quad m_H = 250 \text{GeV} \quad \tan\beta = 30
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\frac{1}{\sigma} \frac{d\sigma}{dm_{tH}} \quad m_H = 250 \text{GeV} \quad \tan\beta = 30
\]

\[
\frac{1}{\sigma} \frac{d\sigma}{dm_{tH}} \quad \frac{p_{g}(\mu_{F})^2}{P_{g}((M/5)^2)} \quad x_{PDF} = m_{tH}/E_{coll}
\]

LO: \( \mu_F = M/5 \)
NLO: \( \mu_F = 10,20 \text{GeV} \)
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$1/\sigma \, d\sigma/dp_{T,t}$

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$tan\beta=30$

$\sigma_{incl,NLO}$

$\sigma_{excl,0.46}$

$\sigma_{excl}$

$\sigma_{excl,qq}$

$1/\sigma \, d\sigma/dm_{tH}$
**Distributions for Inclusive Process**

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SUSY-QCD Corrections

SUSY-QCD Loop Contributions  [TP; Berger, Han, Jiang, TP]

- infrared finite but ultraviolet divergent SUSY loop contributions

- (1) universal corrections $y_b/(1 + \Delta_b)$

[Carena, Garcia, Nierste, Wagner; Guasch, Häflinger, Spira]

(2) remaining explicit SUSY loop diagrams

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<th>$m_H$</th>
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<td>10</td>
<td>633</td>
<td>719</td>
<td>-8.8%</td>
<td>3.0%</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>300</td>
<td>50</td>
<td>389</td>
<td>357</td>
<td>-32.0%</td>
<td>-0.4%</td>
</tr>
<tr>
<td>5</td>
<td>150</td>
<td>300</td>
<td>5</td>
<td>637</td>
<td>697</td>
<td>-7.7%</td>
<td>10.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$m_0$</th>
<th>$m_{1/2}$</th>
<th>$\tan \beta$</th>
<th>$\mu$</th>
<th>$m_H$</th>
<th>$M_1$</th>
<th>$M_{2,3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>150</td>
<td>300</td>
<td>10</td>
<td>402</td>
<td>476</td>
<td>480</td>
<td>300</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\Lambda$</th>
<th>$M_{\text{mes}}$</th>
<th>$N_{\text{mes}}$</th>
<th>$\tan \beta$</th>
<th>$\mu$</th>
<th>$m_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>$40 \times 10^3$</td>
<td>$80 \times 10^3$</td>
<td>3</td>
<td>15</td>
<td>316</td>
<td>476</td>
</tr>
<tr>
<td>8</td>
<td>$100 \times 10^3$</td>
<td>$200 \times 10^3$</td>
<td>1</td>
<td>15</td>
<td>421</td>
<td>538</td>
</tr>
</tbody>
</table>

$\rightarrow \Delta m_b$ corrections dominant for $\tan \beta \gtrsim 10$ (dependent on sign of $\mu$)

$\rightarrow$ explicit loop corrections negligible $\lesssim 10\%$ for generic mSUGRA
3. (Heavy) Neutral Higgs

Bottom induced production of neutral Higgses

- rate enhanced by \( \tan^2 \beta \)

- \( gg \rightarrow b\bar{b}H \) exclusive versus \( bg \rightarrow bH \) inclusive
- \( bg \rightarrow bh \) exclusive versus \( b\bar{b} \rightarrow H \) inclusive

- appropriate factorization scale \( \mu_{F,b} \sim M/5 = m_h/5 \)

- check: \( b\bar{b} \rightarrow H \) NNLO scale dependence  
  [Harlander & Kilgore]
  \( \mu_{R,b} \) variation for fixed \( \mu_{F,b} \sim m_h/4 \) well under control
  \( \mu_{F,b} \) variation for fixed \( \mu_{R,b} \sim m_h \) almost fixed point

- check: exclusive vs. inclusive total rate  
  [Dittmaier, Spira, Krämer]

<table>
<thead>
<tr>
<th>( M_H )</th>
<th>( \sigma(q\bar{q}, gg \rightarrow b\bar{b}H + X) ) [fb]</th>
<th>( \sigma(b\bar{b} \rightarrow H + X) ) [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LO</td>
<td>NLO</td>
</tr>
<tr>
<td>Tevatron</td>
<td>120</td>
<td>( 3.9^{+3.5}_{-1.7} ) 0.22 ( +0.19^{--0.09} )</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>( 4.3^{+2.4}<em>{-1.4} ) ( (5.3^{+2.7}</em>{-1.7}) \times 10^2 )</td>
</tr>
<tr>
<td>LHC</td>
<td>120</td>
<td>( (5.3^{+2.7}<em>{-1.7}) \times 10^2 ) ( (7.3^{+2.0}</em>{-1.6}) \times 10^2 )</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>( 4.3^{+2.4}_{-1.4} )</td>
</tr>
</tbody>
</table>

Side remark: single top production \( qg \rightarrow b\bar{t}q' \)  
[Willenbrock et al]

- less steep quark densities, \( x_1 \neq x_2 \)

- production above threshold

\( Q_{b}^{\text{max}} \sim m_t \)

- generally \( p_{T,b}^{\text{max}} \sim Q_{b}^{\text{max}}/2 \)

\( \mu_{F,b} \sim m_t/2 \) covered by quoted theoretical uncertainty
$\sigma(pp \rightarrow (b\bar{b})H+X)$

LHC
$M_H=120$ GeV

$\mu_R=M_H$

$\mu_F/M_H$

Harlander, Kilgore
HEAVY HIGGS DECAY TO LIGHT HIGGSES

SM Higgs pair production at the LHC  [Baur, TP, Rainwater]

- $HH \rightarrow 4W$: believable detector simulation needed, not hopeless
  (use $m_{\text{vis}}$ to determine $\lambda_{HHH}$)
- $HH \rightarrow b\bar{b}\tau\tau$: miracle required
- $HH \rightarrow 4b$: several major miracles mandatory
  TESLA in better shape [Castanier, Gay,...; Lafaye, Mühlleitner,...]
- $HH \rightarrow b\bar{b}\mu\mu$: at least small miracle would be helpful
  (might come out of $\mu\mu$ mass resolution)
- $HH \rightarrow b\bar{b}\gamma\gamma$: some enhancement needed

MSSM pair production $gg \rightarrow hh$  [Djouadi, Haber, Zerwas]

- only way to access $\tan\beta < 10$ beyond no-lose theorem
- factor 20 enhancement of cross section
- $HH \rightarrow b\bar{b}\gamma\gamma$ best shot
- backgrounds hard to compute but under control
- $5\sigma$ with 300 fb$^{-1}$ possible for $\tan\beta = 3$
$\Delta \lambda_{H} = (\lambda - \lambda_{SM}) / \lambda_{SM}$

$pp \rightarrow t^{+}t^{-} + 4j$

$\sqrt{s} = 14$ TeV

95% C.L. limits

$m_{H}$ (GeV)
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\[ \tan \beta = 3 \]

\[ m_h = 117.5 \text{ GeV} = m_H / 2 \]
Conclusions

1. One MSSM Higgs guaranteed to be seen stable to variations of MSSM
2. heavy Higgs bosons necessary to tell it might be the MSSM charged Higgs production with bottom jets understood

2'. NLO rate for charged Higgs production known:
   NLO₁: inclusive process well defined
   NLO₂: remaining scale uncertainty ≲ 20%
   NLO₃: $\Delta m_b$ corrections dominant in MSSM for large $\tan\beta$
   NLO₄: non-factorizable corrections negligible in MSSM

3. neutral Higgs production with $b\bar{b} \rightarrow H$ understood

4. signal $H^* \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$ for small $\tan\beta$
$x^n P^{(p)}(x)$

$Q_F = 100$ GeV

$Q_F = 1000$ GeV
\[ \sigma_{\text{tot}} (pp \to tH^- + X) \ [\text{pb}] \]

- \( m_H = 250 \text{ GeV} \)
- \( m_H = 500 \text{ GeV} \)

\[ \mu_F/\mu_{F,0} = \mu_R/\mu_{R,0} \]
\[ \mu_F = \mu_{F,0} \]
\[ \mu_R = \mu_{R,0} \]

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\[ \mu_R = \mu_{R,0} \]
LHC: $gg \rightarrow bbH$

$m_H = 130, 250, 500, 1000$ GeV

$m_t = 175, 500, 1000$ GeV