Boosting Higgs Discovery

Graham Kribs
Fermilab & U Oregon

Wine & Cheese 4 Feb 2011
Ben Lee

1935–1977

- First paper with “Higgs phenomena” in title (1971)
- Upper bound on Higgs mass from unitarity “Lee-Quigg-Thacker bound”
- Classic “Lee-Weinberg” bound on neutral lepton masses
- Series on renormalizability of gauge theories

“I, personally, know of no one who claimed to understand the details of ‘t Hooft’s paper. Rather we all learned it from Ben Lee, who combined insights from his own work”

Politzer Nobel Lecture
Outline

• Higgs in Standard Model

• Jet Substructure applied to $h \rightarrow b\bar{b}$ @ LHC

• Higgs in new physics:
  i) SUSY
  ii) top-partners

• Discovery of Higgs in new physics events

• Summary
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Higgs boson mass, are assumed. We choose to use the intersections of piecewise linear interpolations of our observed and expected rate limits in order to quote ranges of Higgs boson masses that are excluded and that are expected to be excluded. The sensitivities of our searches to Higgs bosons are smooth functions of the Higgs boson mass and depend most strongly on the predicted cross sections and the decay branching ratios (the decay $H \rightarrow W^+W^-$ is the dominant decay for the region of highest sensitivity). The mass resolution of the channels is poor due to the presence of two highly energetic neutrinos in signal events. We therefore use the linear interpolations to extend the results from the $5 \text{ GeV}/c^2$ mass grid investigated to points in between. This procedure yields higher expected and observed interpolated limits than if the full dependence of the cross section and branching ratio were included as well, since the latter produces limit curves that are concave upwards. The regions of Higgs boson masses excluded at the 95% C.L. thus obtained are $158 < m_H < 175 \text{ GeV}/c^2$ and $100 < m_H < 109 \text{ GeV}/c^2$. The expected exclusion region, given the current sensitivity, is $156 < m_H < 173 \text{ GeV}/c^2$. The excluded region obtained by finding the intersections of the line ar interpolations of $m_H (\text{GeV}/c^2)$
“Almost” discovery (or rule out) within 1–2 years

Except!
EW Precision $\Rightarrow$ SM Higgs is Light

$\Delta \chi^2$ vs $m_H [\text{GeV}]$

- $\Delta \alpha_{\text{had}}^{(5)} = 0.02758 \pm 0.00035$
- $0.02749 \pm 0.00012$
- incl. low $Q^2$ data

$m_{\text{Limit}} = 157 \text{ GeV}$

August 2009
Figure 3: Branching ratios of the dominant decay modes of the Standard Model Higgs boson as a function of Higgs mass for $m_{h_{SM}} \leq 200$ GeV, taken from ref. [32]. These results have been obtained with the program HDECAY[27], and include QCD corrections beyond the leading order [29]. The shaded bands represent the variations due to the uncertainties in the input parameters: $\alpha_s(M_Z) = 0.120 \pm 0.003$, $m_b(M_b) = 4.22 \pm 0.05$ GeV, $m_c(M_c) = 1.22 \pm 0.06$ GeV, and $M_t = 174 \pm 5$ GeV.

The running quark mass, $m_Q(m_{h_{SM}})$, so obtained from the MS mass, $m_Q(M_Q)$, by renormalization group evolution. The MS quark masses are obtained from fits to experimental data [33]. Note that the large decrease in the charm quark mass due to QCD running is responsible for suppressing BR($c \bar{c}$) relative to BR($\tau^+\tau^-$), in spite of the color enhancement of the former, thereby reversing the naively expected hierarchy. Below the corresponding two-body thresholds, the $WW$($\gamma\gamma$), $ZZ$($\gamma\gamma$), and $t\bar{t}$ decay modes (where the asterisk indicates an off-shell particle) are still relevant as shown in fig. 4.

The $h_{SM}gg$, $h_{SM}\gamma\gamma$ and $h_{SM}Z\gamma$ vertices are generated at one-loop. The partial width for $h_{SM} \rightarrow gg$ is primarily of interest because it determines the $gg \rightarrow h_{SM}$ production cross-section. The $h_{SM}\gamma\gamma$ vertex is especially relevant both for the $h_{SM} \rightarrow \gamma\gamma$ discovery mode at the LHC and for the $\gamma\gamma \rightarrow h_{SM}$ production mode at the LC operating as a $\gamma\gamma$ collider.
Pesky region is $115 < m_h < 125$ GeV
The median discovery significance as a function of the integrated luminosity and Higgs mass is shown. The validation exercises carried out indicate that the methods used should be valid or in some cases conservative for an integrated luminosity of at least 10 fb⁻¹. For a luminosity of 10 fb⁻¹, the expected number of events is low, and therefore the results should be taken as indications only. In most cases, however, the approximations tend to underestimate the true median significance.

For (a) the lower mass range (b) for masses up to 600 GeV, the distributions could be recovered. It is convenient to introduce a new parameter denoted by ξ which is finite and has values between 0 and 1. To study deviations from the Standard Model, both approaches were validated to be valid for an integrated luminosity of at least 10 fb⁻¹.

The Higgs boson. In the present analysis a simplified version of above results can be found in article [4].

The median discovery significance for the various channels and the combination with an integrated luminosity for the different Higgs boson production and decay channels is the combined median likelihood ratio: For this the distributions are conservative for an integrated luminosity of at least 10 fb⁻¹.
Search Channels $115 < m_h < 125$ GeV

$\text{BR}(h \rightarrow \gamma\gamma) \approx 1-2 \times 10^{-3}$

loop suppressed

$\text{BR}(h \rightarrow \tau\tau) \approx 5-7 \times 10^{-2}$

$y_{\tau} \approx 0.01$ suppressed

Until 2008, was thought that

$\text{BR}(h \rightarrow bb) \approx 0.7-0.9$

lost in the QCD background.
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Jet Substructure

Much activity in past 2–3 years...

Joint Theoretical-Experimental Workshop on Jets and Jet Substructure at the LHC

University of Washington
January 11-15, 2010

The joint workshop is on the topic of jets at the LHC. The special focus concerns strategies to use jet substructure to both revalidate the Standard Model (e.g., can we find top quarks as single jets in the first LHC data, or at Fermilab?) and to search for new physics. The workshop will also include a discussion of the challenging issue of calibrating the measurements of jet substructure (e.g., masses) on the experimental side, and better formalisms for describing jet substructure on the theory side.

Boost 2011

University of Oregon
31 January - 4 February 2011

The Boost 2011 conference will be held in May (5/23/11 - 5/27/11) at Princeton University, hosted by the Princeton Center for Theoretical Science. As with prior conferences in the Boost series, the weeklong event will focus on bringing together theorists and experimentalists for in-depth discussions of jets, jet substructure, and jets in more exotic contexts (e.g., lepton jets).
Jet Substructure

Extract more information out of jets.

Enhance $S/\sqrt{B}$ for massive objects decaying to jets over QCD background. (the boosted advantage)
No Boost versus Boost

\[ \Delta R \approx \frac{2 \, m_h}{p_T} \]

\[ R = \sqrt{\Delta y^2 + \Delta \phi^2} \]
Boosted Higgs Decay

Consider $m_h = 120$ GeV;

$p_T > 200$–$300$ GeV

$\Rightarrow \Delta R \approx 1.2$–$0.8$

Jet areas begin to overlap!

$\Delta R \approx \frac{2 \ m_h}{p_T}$

$R = \sqrt{\Delta y^2 + \Delta \phi^2}$
Advantage over Backgrounds

"Fat Jet" contains multiple hard partons with distinguishable kinematic properties
Jet Substructure and Filtering

Butterworth, Davison, Rubin, Salam [BDRS: 0802.2470] proposed a set of techniques to find $h \rightarrow b\bar{b}$ by precisely exploiting the $S/\sqrt{B}$ advantages of “fat jets”.

The basis of their techniques involves using an iterative jet clustering algorithm ($C/A$), examining subjet kinematics step-by-step, and finally choosing the “best” subjets from which to form the fat jet mass.
Fat Jets

Given $\Delta R \approx \frac{2 \ m_h}{p_T} = 1.2 \ \frac{m_h}{120 \ \text{GeV}} \ \frac{200 \ \text{GeV}}{p_T}$

Let C/A clustering algorithm proceed up to $R = 1.2$, to capture both $b$ jets into one fat jet, requiring $p_T > 200$ GeV.
Jet Decomposition Cartoon

fat jet

with jet mass: $m_j$

$R = 1.2$
In C/A, this came from two jets with jet masses $m_{j_1} > m_{j_2}$
repeat unclustering:

four jets with masses: \( m_{j_{11}} > m_{j_{12}} , m_{j_{21}} > m_{j_{22}} \)
Higgs Jet Identification

1) check for "mass drop"

\[ m_{j1} < 0.68 \, m_j? \]

2) check "asymmetry"

\[
y = \frac{\min(p_{t,j1}^2, p_{t,j2}^2)}{m_j^2} \Delta R_{j1,j2}^2 \quad y_{\text{cut}} \quad > \quad y_{\text{cut}} = (0.3)^2
\]

Tends to reject soft/collinear
QCD contamination

3) require both subjets b-tagged
4) **Filter** the subjets to reduce underlying event contamination:

- take 3 highest pT subjets ("third" captures leading parton shower gluon)
- recluster subjets with $R_{j_1,j_2,j_3} = \min(R_{bb}/2,0.3)$

**Higgs Candidate Mass formed from 3 highest pT subjets**
Production: Higgs-strahlung

Require Higgs is boosted
\[ p_T(h) > 200 \text{ GeV} \]
(only 5\% of Zh/Wh cross section @ 14 TeV)

Leptonic decay of W/Z into \( llbb, lvbb, vvbb \).
BDRS Result

- LHC 14 TeV; 30 fb\(^{-1}\); mh = 115 GeV
- HERWIG/JIMMY cross-checked with PYTHIA with “ATLAS tune”
- 60% b-tag; 2% mistag
- no smearing
**ATLAS Simulation**

The WH ($W \rightarrow l \nu, H \rightarrow bb$) analysis: cut flow (main signal and backgrounds samples)

<table>
<thead>
<tr>
<th>Mass cuts</th>
<th>$W\nu$</th>
<th>$WZ$</th>
<th>$W$s</th>
<th>$W$ jets</th>
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<tr>
<td>$M_{T} &gt; 400$ GeV</td>
<td>152.2 ± 7.8</td>
<td>9381</td>
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<tr>
<td>$p_{T}(\text{additional b}) &gt; 15$ GeV</td>
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<td>7485</td>
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<tr>
<td>Add. jets on $W$ side $p_{T} &lt; 20$ GeV</td>
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**Giacinto Piacquadio**

**ATLAS Simulation**

Loose jet veto and loose b-tagging (to be used as input to likelihood fit):

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Tight jet veto and tight b-tagging at $e^{-} > 3.3$ and $|\eta| < 0.2$ (for counting based analysis)

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Signal events ($m_{H}$ = 120 GeV): $-13.5$

Background events: $-20.3$

$$\frac{S}{B} = 3.0 \pm 0.3$$
Strongly Motivating!

- background uncertainty

<table>
<thead>
<tr>
<th>Channel</th>
<th>signal</th>
<th>$t_i$</th>
<th>$w_i$</th>
<th>$z_i$</th>
<th>$S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$llbb$</td>
<td>5.34</td>
<td>0.98</td>
<td>0.0</td>
<td>11.2</td>
<td>1.5</td>
</tr>
<tr>
<td>$l\nu bb$</td>
<td>13.5</td>
<td>7.02</td>
<td>12.5</td>
<td>0.78</td>
<td>3.0</td>
</tr>
<tr>
<td>$\nu\nu bb$</td>
<td>16.3</td>
<td>45.2</td>
<td>27.4</td>
<td>31.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Combined</td>
<td></td>
<td></td>
<td></td>
<td></td>
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- $b$-tagging efficiency (better for subjets!)

- underlying event

- pile-up; at $10^{34}$ cm$^{-2}$s$^{-1}$ mass resolution of Higgs degraded with C/A; more elaborate techniques?

- 10/15 % uncertainty considered as realistic:

- Median discovery significance: **3.0-3.2**
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Weak Scale Supersymmetry

“Minimal Supersymmetric Standard Model (MSSM)”
Higgs Sector of MSSM

quartic coupling \( \lambda \)

determined! \( g^2 + (g')^2 \)

up to radiative corrections

\[
m_h^2 = M_Z^2 \left( \frac{\tan^2 \beta - 1}{\tan^2 \beta + 1} \right)^2 + y_t^4 \log \frac{m_{st}}{m_t} \text{ (schematic)}
\]
Figure 12: The radiatively corrected light CP-even Higgs mass is plotted (a) as a function of $X_t$, where $X_t \equiv A_t - \mu \cot \beta$, for $M_t = 174.3$ GeV and choices of $\beta = 3$ and 30, and (b) a surface function of $\beta$, for the maximal mixing [upper band] and minimal mixing [lower band] benchmark cases. In (b), the central value of the shaded bands corresponds to $M_t = 175$ GeV, while the upper [lower] edge of the band corresponds to increasing [decreasing] $M_t$ by 5 GeV. In both (a) and (b), $m_A = 1$ TeV and the diagonals of the squarks squared-masses are assumed to be degenerate: $M_{\text{SUSY}} \equiv M_Q = M_U = M_D = 1$ TeV. The prediction for $m_h$ corresponds to its theoretical upper bound, $m_h = m_Z$. Including radiative corrections, the theoretical upper bound is increased. The dominant effects arise from incomplete cancellation of the top-quark and top-squark loops (these effects cancel in the exact supersymmetric limit). The qualitative behavior of the radiative corrections can be most easily seen in the large top squark mass limit, where in addition, the splitting of the two diagonal entries and the off-diagonal entry of the top-squark squared-mass matrix are both small in comparison to the average of the two top-squark squared-masses: $M^2_{\tilde{S}} \equiv \frac{1}{2} (M^2_{\tilde{t}_1} + M^2_{\tilde{t}_2})$.

In this case, the upper bound on the lightest CP-even Higgs mass is approximately given by

$$m_h^2 < \frac{3 g^2 m^4_t}{8 \pi^2 m^2_W} \left[ \ln \left( \frac{M^2_{\text{SUSY}} m^2_t}{12 M^2_{\tilde{S}}} \right) + X_t^2 M^2_{\text{SUSY}} \left( 1 - X_t^2 X_t^2 \right) \right]^{1/2}.$$  \(\text{(38)}\)

In certain regions of parameter space (corresponding to large $\tan \beta$ and large values of $\mu$), the incomplete cancellation of the bottom-quark and bottom-squark loops can be as important as the corresponding top sector contributions. For simplicity, we ignore this contribution in eq. (39).
Superpartner Decay to Higgs

SUSY with a gravitino LSP and Higgsino NLSP:

\[ \tilde{H} \rightarrow \tilde{G} + h \]

BR up to 50%

Kinematical requirement

\[ \mu > m_{\tilde{\chi}} + m_h \]
\[ > 120 \text{ GeV} \]

SUSY with a Higgsino LSP:

\[ \tilde{H}^{+-0} \rightarrow B, \tilde{W}^{+-0} + h, z, w^{+-} \]

BR \approx 25%

Kinematical requirement

\[ m_{Wino} > \mu + m_h \]
\[ > 100 + 120 = 220 \text{ GeV} \]
Squark Production to Gauginos

(which then decay to Higgs)

typical $\sigma(\text{squarks})_{14\,\text{TeV}} \approx \text{several pb}!!$
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Top Partners

little Higgs models, top color, ...

Vector-like pair of quarks $T(3,1,2/3), \bar{T}(\bar{3},1,-2/3)$

Kinematical requirement

$$m_{t'} > m_t + m_h$$

$$> 175 + 120 = 295 \text{ GeV}$$
Key Advantages of New Physics Source

- Production source can be QCD (enhanced!)

- Cascade decays from heavy new particles leads to significant boost for a large fraction of events

- In MSSM, Higgs is always light

  (in other models, lighter Higgs consistent with EW precision data)
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New Physics Production -- Busy Events!

New physics events tend to be “busy” with a lot of hadronic activity from squark/gluino/top-partner decay and associated parton showers.

Can have extra hard subjets in “fat jet” cone!

Similar problem also with t,tbar,h!

Plehn, Salam, Spannowsky
Our New Step
Search Jet Daughters for Maximal “Similarity”

At each stage of unclustering, calculate “similarity”:

\[ S_i = \frac{\min \left( p_{tj_1}^2, p_{tj_2}^2 \right)}{(p_{tj_1} + p_{tj_2})^2} \Delta R_{j_1j_2} \]

Choose 3 highest pT jets from stage which maximizes “S”

This helps improve the efficiency of finding the Higgs by \( \approx 10-20\% \) by not rejecting fat jets with stray b-tagged jet.
Simulation details...

**Background:** ALPGEN $\rightarrow$ PYTHIA6.4

**Signal:** SUSPECT2 $\rightarrow$ PYTHIA6.4

underlying event: ATLAS tune

- All final-state hadrons grouped into cells of size $(\Delta \eta \times \Delta \phi) = (0.1 \times 0.1)$
- Each cell is rescaled to be massless this models detector response (Thaler, Wang '08)

jet gymnastics performed using FastJet (hep-ph/0512210)

**b-tagging:** 60% efficiency, 2% fake rate

jet-photon fake rate: .1%
Example 1: MSSM with Higgsino LSP

10 fb\(^{-1}\) @ 14 TeV

GK, Martin, Roy, Spannowsky; 1006.1656

**MET > 300 GeV, H\(T\) > 1 TeV, 3+ jets, no lepton, + 1 “tagged” Higgs**

\[ BR(\tilde{u}_L, \tilde{d}_L \rightarrow h + X) \sim 23\% \]
\[ BR(\tilde{u}_R, \tilde{d}_R \rightarrow h + X) \sim 16\% \]
“What good is that fancy substructure?”

Comparison*: with substructure analysis vs. with PGS

$H_T > 1$ TeV, $\not{E}_T > 300$ GeV
3+ high-$p_T$ jets, no leptons
1 candidate Higgs

$(Stolen\ from\ A.\ Martin\ slides)$

$H_T > 1$ TeV, $\not{E}_T > 300$ GeV
4+ high − $p_T$ jets, no leptons
2+ b-tags

*not totally fair
Example 2: MSSM with $m_A = 200$ GeV

$10 \text{ fb}^{-1} @ 14 \text{ TeV}$

Could discover heavier A,H states!

GK, Martin, Roy, Spannowsky; 1006.1656
Example 3: Higgs from Top-Partners

always one top quark

short cascade:
Higgs $p_T \sim M_T/2$
(vs. $\sim M_T/4$ for MSSM)

+ additional gauge boson/top

4+ bs, many jets!

Unlike SUSY, require multiple “tags” involving
the varied final states, including
boosted top and boosted W tagging.
Example 3: Higgs from Top-Partners

![Flow diagram to summarize our selection procedures]

The flow has been devised so that no event can be counted more than once. In the figure, $v_T > v_T$ and $v_T > v_T$ for top-partner masses of $800$ GeV and $600$ GeV respectively.

The branching fraction of $Z \rightarrow \bar{b}b$ is $\sim r$, so the $Z$ feature is small. Hadronic $W$s are also produced in top-decay, however, the majority of them are removed by cuts preceding the Higgs tagger.

The measure we use for how well a particular analysis or subchannel performs is the significance, which we define simply as $S/\sqrt{B_p}$.

In addition to the SM background, we also include the new physics background—hadronically decaying $W$s and $Z$s from top-decay mentioned above. To account for this new physics background, we define the total background to be the average of the number of events in the bins $\pm t$ from the putative Higgs peak. This is a crude and somewhat conservative estimate for the significance.

The significance in each channel as well as the significance of all channels combined is summarized below in Table II.

As Table II shows, the most significant channels vary with the mass of the top-partner. When the top-partner is light, the cross section is large, but the boost of a Higgs or top from top-decay is smaller. Consequently, channels which require several substructure tags (Ch, w, z) are inefficient, while the high cross section makes up for small branching ratios in the multilepton channels (Ch, t, w).

At high mass, the channels swap roles; the multilepton channels don't receive enough events, while the efficiency of substructure taggers improves greatly. For the intermediate point, $m_{T'} = 1200$ GeV, all channels are equally efficient.

### Table II

<table>
<thead>
<tr>
<th>Channel</th>
<th>Lepton</th>
<th>Bins</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ch 1</td>
<td>1 lepton</td>
<td>$1^+ \text{ tagged W/Z}$, $2^+ \text{ b-jets}$</td>
<td>$S/\sqrt{B}$</td>
</tr>
<tr>
<td>Ch 2</td>
<td>2$^+$ lepton</td>
<td>$1^+ \text{ b-jets}$</td>
<td>$S/\sqrt{B}$</td>
</tr>
<tr>
<td>Ch 3</td>
<td>1 lepton</td>
<td>$1^+ \text{ b-jet}$</td>
<td>$S/\sqrt{B}$</td>
</tr>
<tr>
<td>Ch 4</td>
<td>2$^+$ lepton</td>
<td>$1^+ \text{ b-jet}$</td>
<td>$S/\sqrt{B}$</td>
</tr>
<tr>
<td>Ch 5</td>
<td>1$^+$ lepton</td>
<td>$1^+ \text{ b-jet}$</td>
<td>$S/\sqrt{B}$</td>
</tr>
</tbody>
</table>

The starred entries have significance less than $\sim 1$ and are not included in the summed significances. The double-starred entries have fewer than $\sim 5$ events in the signal and are also not included in the total significances.

Different pathways better for different $t'$ masses.
Top partner production & decay:

10 fb⁻¹ @ 14 TeV

GK, Martin, Roy; 1012.2866
Summary

• **Jet substructure** techniques are revolutionizing search for complicated hadronic final states

• MSSM h ideal candidate; large rate from squark production; large boost from cascade decay. Could **discover** h faster than SM!

  Rethink $m_A - \tan(b)$ plane!!

• Top-partners produced with large rate; large boost; large decay fraction into Higgs; can also help discover and measure top-partner properties.

• Remarkable opportunities -- requires validation
“We”

Adam Martin  Fermilab postdoc
Tuhin Roy  UW postdoc
Michael Spannowsky  UO->SLAC postdoc

“Discovering the Higgs Boson in New Physics Events using Jet Substructure”
0912.4731 [PRD 2010]

“Discovering Higgs Bosons of the MSSM using Jet Substructure”
1006.1656 [PRD 2010]

“Higgs Discovery through Top-Partners using Jet Substructure”
1012.2866