Boosting BSM-Higgs discovery with jet-substructure

Tuhin S. Roy

Martin, Kribs, TR, Spannowsky

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in preparation
LHC higgs reach

115-120 GeV higgs search is challenging
10.3. Discovery reach

Significance

| Significance | 1 | 10 | 100 | 200 | 300 | 400 | 500 | 600 |

cuts

| H \ (opt) |

| H \ (4l) |

| H \ (ZZ \ \rightarrow \ 2l2v) |

| H \ (WW \ \rightarrow \ l+jet) |

| H \ (\gamma\gamma \ \text{cuts}) |

| H \ (\gamma\gamma \ \text{opt}) |

| H \ (\tau\tau \ \rightarrow \ l+jet) |

| qqH, H \ (\gamma\gamma) |

| qqH, H \ (WW \ \rightarrow \ l+jet) |

| qqH, H \ (WW \ \rightarrow \ l+jet) |

| qqH, H \ (\tau\tau \ \rightarrow \ l+jet) |

The signal significance as a function of the Higgs boson mass for 30 fb⁻¹ of the integrated luminosity for the different Higgs boson production and decay channels.

10.3.3 Study of CP properties of the Higgs boson using angle correlation in the \( \Phi \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^- \) process

The most general \( \Phi VV \) coupling is \( V = W^{\pm}, Z_0^{\pm} \) for spin 0, Higgs boson \( \Phi \) means the Higgs particle with unspecified CP parity, while \( H^4 \) and \( A^4 \) mean the scalar and pseudoscalar Higgs particles, respectively. The decay width for the \( \Phi \rightarrow ZZ \rightarrow (\bar{\nu}_1 \nu_1 \bar{\nu}_2 \nu_2) \) process consists now of three terms: a scalar one denoted by \( H^4 \), a pseudoscalar one \( \sim \eta_2^4 \) denoted by \( A^4 \) and the interference term violating CP \( \sim \eta_3^4 \) denoted by \( I^4 \):

\[
\Gamma(\eta) \sim H^4 + \eta I^4 + \eta_2^4 A^4.
\]

This way the Standard Model scalar \( \eta = 0^4 \) and the pseudoscalar \( \eta = \pm 1 \) contributions could be recovered. It is convenient to introduce a new parameter \( \xi \) defined by \( \tan \xi = \eta \), which is finite and has values between \( -\pi/2 \) and \( \pi/2 \). Expressions for \( H^4 \) and \( A^4 \) can be found in article [4].

In study of the CP parity of the Higgs boson two angular distributions were used. The first one is a distribution of the angle \( \phi^3 \) called plane or azimuthal angle between the planes of two decaying Zs in the Higgs boson rest frame. The negatively charged leptons were used to fix plane orientations. The second one is a distribution of the polar angle \( \theta^9 \) in the \( Z \) plane.
this is unfortunate

MSSM higgs is most likely to be found in
115-130 GeV window
there will be plenty of Higgs at LHC

SM cross-section

source (ATL-PHYS-2008-258)
MSSM cross-section

source (ATL-PHYS-2008-258)
Most significant decay channel.

Reconstructed mass peak on top of continuum di-photon bkg.

Atlas: inclusive $\gamma\gamma$ and exclusive $\gamma\gamma$ +jets searches.

$S/\sqrt{B} = 1.8$

$S/\sqrt{B} = 2.6$

$S/\sqrt{B} = 1.9$

$\mathcal{L} = 10 \text{ fb}^{-1}$

source (ATL-PHYS-2008-258)
LHC higgs search in 115-120 GeV

$pp \rightarrow V h$

significance of 4.2 for $\mathcal{L} = 30$ fb$^{-1}$
using jet-substructure for jets with $p_{T,h} > 200$ GeV

Butterworth, Davison, Rubin, Salam (2008)
substructure

two-pronged decays

Butterworth, Davison, Rubin, Salam (2008)

Plehn, Salam, Spannowsky (2009)

three-pronged decays

Thaler and Wang (2008)

Brooijmans (2008)

Kaplan, Rehermann, Schwartz and Tweedie (2008)

Butterworth, Ellis, Rakhlev, Salam (2009)

pruning/trimming

Ellis, Vermilion, Walsh (2009)

Search for boosted Higgs

interesting new concept
but a bit limited in the SM

there are few boosted Higgses in SM:
only ~ 5% of boosted Higgs in $h + W/Z$

need to trigger & suppress SM backgrounds
search is limited to leptonic decay of $W/Z$
Higgs in the BSM

new colored stuff

initial colored states are heavy while Higgs is light

new sources of Higgs

much higher fraction of boosted Higgs
If BSM contains new colored states, production at LHC is easily in the ~few pb range comparable to or greater than SM EW production of Higgses

BSM production often comes with new effective handles for suppressing SM background

\[ \mathcal{E}_T, \text{high } p_T \text{ jets, } \ell, \gamma, H_T, \cdots \]

Higgses from decays of BSM particles are naturally boosted

**BSM-Higgses have all ingredients for a successful substructure analysis**
The plan for the talk

Pick new physics scenarios as sources of boosted Higgs.

- MSSM with a gravitino LSP (low scale mediation)
- MSSM with a neutralino LSP (high scale mediation)

Review of jet substructure technicalities:

- briefly discuss clustering
- simple substructure analysis as proposed by Butterworth et.al.
- our algorithm that works in hectic, crowded BSM environments

Results
**SUSY sources of boosted Higgs**

**Why SUSY?**

- **MSSM Higgs is light** ($m_h \lesssim 130$ GeV)
- **it has new colored particles (squarks, gluinos)**
- **all events include** $E_T$
- **Higgs via various decays**

\[
\tilde{\chi}_3^0, \tilde{\chi}_4^0 \rightarrow \tilde{\chi}_{1,2}^0 + h \\
\tilde{\chi}_2^\pm \rightarrow \tilde{\chi}_1^\pm + h \\
\tilde{\chi}_1^0 \rightarrow \tilde{G} + h \\
\tilde{t}_2 \rightarrow \tilde{t}_1 + h
\]
MSSM with neutralino LSP + gravitino LSP

everything super decays to the NLSP

gravitino + γ or Z or h

new source of Higgs
neutralino branching ratio:

\[ \text{Br}(\tilde{\chi}^0_1 \rightarrow \tilde{\chi}^0_1 + \gamma, h, Z) \]

as a function of the neutralino mixing angle \( \tan^{-1}(\mu/M_1) \), for a fixed mass
\( M_{\tilde{\chi}^0_1} = 160 \text{ GeV} \) and \( m_h = 105 \text{ GeV} \) for (a) \( \tan \beta = 3 \) and (b) \( \tan \beta = 40 \).

For definiteness the Higgs decoupling limit in which decays to the heavy scalar and pseudoscalar Higgs bosons, \( H \) and \( A \), are kinematically blocked is employed throughout. For gaugino-like \( \tilde{\chi}^0_1 \) the \( \gamma \) mode dominates, but for Higgsino-like \( \tilde{\chi}^0_1 \) the \( h \) and \( Z \) modes become important. The dependence on \( \text{sgn}(\mu) \) and \( \tan \beta \) apparent in Fig. 1 can be understood in terms of the \( \tilde{\chi}^0_1 \) quantum numbers and couplings and will be presented elsewhere.

You can almost make a Higgs factory out of LHC.
additional handles to get rid of SM backgrounds

1 isolated photon + large missing Et
**MSSM Higgs source comparison**

**how we want to look for**

- Higgses from sparticle decay
  - big cross-section (inclusive susy prod.)
  - all events have $E_T$
  - SM and BSM bkg

**how people usually look for**

- Higgses produced in association with SM particles
  - smaller cross-section (set by $Y_b$)
  - no BSM $E_T$
  - only SM bkg

with so much is going on in inclusive SUSY events.. how can we do better than traditional search
**MSSM Higgs source comparison**

**how we want to look for**

- Higgses from sparticle decay
- Big cross-section (inclusive SUSY prod.)
- All events have $E_T$
- SM and BSM bkg

**how people usually look for**

- Higgses produced in association with SM particles
- Smaller cross-section (set by $y_b$
- No BSM, $E_T$
- Only SM bkg

*use Jet substructure*
substructure

1. Briefly discuss clustering
2. Discuss simple substructure analysis
3. Describe our algorithm
First:

clustering

(I will talk about recombination scheme)
Recombination jet algorithm

\[ d_{ij} = \min(p_{2n}^{t_i}, p_{2n}^{t_j}) \Delta R_{ij}^2 / R^2 \]

\[ d_i = p_{2n}^{t_i} \]

\[ \Delta R_{ij} = \sqrt{\delta \eta_{ij}^2 + (\delta \phi_{ij})^2} \]

\[ \begin{cases} n = 1 & k_t \\ n = 0 & C/A \\ n = -1 & \text{anti } k_t \end{cases} \]
Recombination jet algorithm

calculate

\[ d_{ij} = \min \left( p_{ti}^{2n}, p_{tj}^{2n} \right) \Delta R_{ij}^2 / R^2 \]

\[ d_i = p_{ti}^{2n} \]

find \[ \min (d_{ij}, d_i) \]
Recombination jet algorithm

example:

\[ \min (d_{ij}, d_i) = d_{1\ 6} \]

combine 1 and 6 into 7
and remove 1 and 6
Recombination jet algorithm

\[ \text{calculate again} \quad \min (d_{ij}, d_i) \]
Recombination jet algorithm

\[ \min (d_{ij}, d_i) = d_5 \]
Recombination jet algorithm

\[
\min (d_{ij}, d_i) = d_5 \quad \text{promote 5 to jet and remove}
\]
Recombination jet algorithm

repeat until the list is empty
Next: 

de-clustering and finding heavy particle threshold
break a C/A b-jet $J$ into two parents by undoing its last stage of clustering

$m_{J_1} > m_{J_2}$
is J a suspect?

check if

\[ m_{J_1} < 0.68 \, m_J \]

\[ \min (p_{t1}^2, p_{t2}^2) \frac{\Delta R_{12}^2}{m_J^2} > (0.3)^2 \]
is J a suspect?

check if

\[ m_{J_1} < 0.68 \, m_J \]

\[ \min \left( p_{t1}^2, p_{t2}^2 \right) \frac{\Delta R_{12}^2}{m_J^2} > (0.3)^2 \]

if yes

J is at heavy particle threshold

exit
is $J$ a suspect?

check if

$$m_{J_1} < 0.68 m_J$$

$$\min(p_{t1}^2, p_{t2}^2) \frac{\Delta R^2_{12}}{m_j^2} > (0.3)^2$$

if no

replace $J$ by $J_1$

repeat
extra hard jet may enter the Higgs cone

simplest substructure algorithm does not work so well
break a C/A b-jet \( J \) into two parents by undoing its last stage of clustering

\[ m_{J_1} > m_{J_2} \]

parent-1

parent-2

parent-1

parent-2

daughter
is J a suspect?

check if

\[ m_{J_1} < 0.68 \ m_J \]

\[ \min(p_{t1}^2, p_{t2}^2) \ \frac{\Delta R_{12}^2}{m_J^2} > (0.3)^2 \]
is J a suspect?

check if

\[ m_{J_1} < 0.68 \, m_J \]

\[ \min\left( p_{t1}^2, p_{t2}^2 \right) \frac{\Delta R_{12}^2}{m_J^2} > (0.3)^2 \]

if yes

record \[ Z = \frac{\min\left( p_{tJ1}^2, p_{tJ2}^2 \right)}{p_{tj}^2} \Delta R_{J1J2} \]

replace J by J1

repeat as long as J has parents
is $J$ a suspect?

$J^n$ is a Higgs candidate

if

$Z$ is the largest

and

both parents are $b$-tagged
Filtering

\[ J^n \] is a Higgs candidate

For each jet (\( J^1 \)) in the event:

\[ R = 1.2 \]

(Butterworth et al, 0802.2470)

For a heavy particle decay, expect a significant mass-drop:

\[ m_i > m_J \]

\[ m_i < \mu_m J \]

\[ 22 \]

Thursday, February 18, 2010

Tuesday, April 13, 2010
Filtering

$J^n$ is a Higgs candidate

record $\Delta R_{J_1^n, J_2^n}$
Filtering

\( J^n \) is a Higgs candidate

\( J^n \) record \( \Delta R_{J_1^n, J_2^n} \)
Filtering

$J^n$ is a Higgs candidate

de-cluster $J^n$ completely
Filtering

re-cluster using

\[
R_{\text{filt}} = \min \left( \frac{\Delta R_{J_1^n, J_2^n}}{2}, 0.3 \right)
\]

Pt order the jets
Filtering

- retain only three hardest component and combine. call it Higgs Jet
Results
For example: take the spectrum

\[ m_{\tilde{Q}} \quad 750 \text{ GeV} \]
\[ M_2 \quad 600 \text{ GeV} \]
\[ M_1 \quad |\mu| \quad 300 \text{ GeV} \quad -250 \text{ GeV} \]

\[ \text{BR}(\tilde{\chi}^0 \rightarrow \tilde{G} + \gamma) \approx 43\% \]
\[ \text{BR}(\tilde{\chi}^0 \rightarrow \tilde{G} + Z^0) \approx 29\% \]
\[ \text{BR}(\tilde{\chi}^0 \rightarrow \tilde{G} + h) \approx 28\% \]

substructure + \( E_T > 100 \text{ GeV} \)
\[ p_T \gamma > 80 \text{ GeV} \]

\[ L = 10 \text{ fb}^{-1}, \sqrt{s} = 14 \text{ TeV} \]
For example: this one is harder

\begin{align*}
m_{\tilde{Q}_{1,2}} & \quad 1 \text{ TeV} \\
m_{\tilde{Q}_3} & \quad 750 \text{ GeV} \\
M_2 & \quad 600 \text{ GeV} \\
M_1 & \quad 300 \text{ GeV} \\
|\mu| & \quad -250 \text{ GeV}
\end{align*}

\[ BR(\tilde{\chi}^0 \rightarrow \tilde{G} + \gamma) \sim 43\% \]
\[ BR(\tilde{\chi}^0 \rightarrow \tilde{G} + Z^0) \sim 29\% \]
\[ BR(\tilde{\chi}^0 \rightarrow \tilde{G} + h) \sim 28\% \]

substructure $+ \quad p_T > 100 \text{ GeV}$

\[ p_T > 80 \text{ GeV} \]

L = 10 fb$^{-1}$, $\sqrt{s} = 14 \text{ TeV}$

\[ \begin{cases}
tt + \text{jets} \\ W + \bar{b}b \\ Z + \bar{b}b \\ W + \text{jets} \\ Z + \text{jets} \\ \text{SUSY}
\end{cases} \]

Number of Events/6.0 GeV

Candidate Higgs-jet mass
For example: this one is almost impossible

\[ m_{\tilde{Q}_3} \]
\[ M_2 \]
\[ m_{\tilde{Q}_{1,2}} \]
\[ M_1 \]
\[ |\mu| \]

\[ 1 \text{ TeV} \]
\[ 750 \text{ GeV} \]
\[ 200 \text{ GeV} \]

\[ \text{BR}(\tilde{\chi}^0 \rightarrow \gamma + \tilde{G}) \approx 82.6\% \]
\[ \text{BR}(\tilde{\chi}^0 \rightarrow Z + \tilde{G}) \approx 16\% \]
\[ \text{BR}(\tilde{\chi}^0 \rightarrow h + \tilde{G}) \approx 1.3\% \]

substructure + \( p_T > 100 \text{ GeV} \)
\( p_T \gamma > 80 \text{ GeV} \)

\[ L = 10 \text{ fb}^{-1}, \sqrt{s} = 14 \text{ TeV} \]

Results: Point #3

47% SUSY
Z + jets
W + jets
Z + W + jets
tt + jets

47% SUSY
Z + jets
W + jets
Z + W + jets
tt + jets

36%
33%
28%
29%
43%
38%
16%
82.6%
1.3%
boosted analysis finds Higgs peak even when conventional search completely fails
Higgses from other BSM scenarios

work in progress
Higgses from other BSM scenarios

Example: MSSM with neutralino LSP

work in progress

should appear in 1 week
Results: MSSM with neutralino LSP

\[ \chi_4 \rightarrow h + \ldots \]
\[ \chi_2^\pm \rightarrow h + \ldots \]
\[ \chi_3 \rightarrow h + \ldots \]

\[ p_T(h) > 200 \text{ GeV} \]
\[ p_T(h) > 300 \text{ GeV} \]

\[ \tilde{q}_L \rightarrow h + \ldots \]
\[ \tilde{q}_R \rightarrow h + \ldots \]

Tuesday, April 13, 2010
Results: **MSSM with neutralino LSP**

\[ m_{\tilde{Q}} \]
\[ M_2 \]
\[ M_1 \]
\[ |\mu| \]

<table>
<thead>
<tr>
<th>1 TeV</th>
<th>600 GeV</th>
</tr>
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</table>
\[ \chi_3 \rightarrow h + \chi_1 \sim 16\% \]
\[ \chi_4 \rightarrow h + \chi_1 \sim 16\% \]
\[ \chi_{2}^{\pm} \rightarrow h + \chi_{1}^{\pm} \sim 25\% \]

\[ H_T > 1.5 \text{ TeV}, \not{E}_T > 150 \text{ GeV} \]
\[ 2^+ \text{ high}-p_T \text{ jets} + \text{ substructure} \]

\[ L = 10 \text{ fb}^{-1}, \sqrt{s} = 14 \text{ TeV} \]
Results: MSSM with neutralino LSP

$E_T > 300$ GeV, $H_T > 1.0$ TeV

Number of Events/9.0 GeV

$\sim$ 28%

$m_{\tilde{q}_{1,2}}$ 1 TeV

$M_2$ 600 GeV

$M_1$ 300 GeV

$|\mu|$ 150 GeV
Results: MSSM with neutralino LSP

$\not{E}_T > 300 \text{ GeV}, H_T > 1.0 \text{ TeV}$

Can even discover heavier $A,H$ states!

$\tan \beta = 6.5$

$m_{\tilde{q}_{1,2}}$

$M_2$

$m(A) \vert \mu \vert$

$M_1$

$1 \text{ TeV}$

400 GeV

200 GeV

150 GeV
conclusions

light Higgs are hard to find at the LHC

decays of BSM particles provide a new and natural source of boosted Higgs at the LHC

- rate is smaller but BSM provides additional tools to suppress background

Substructure opens up the dominant channel \( h \to \bar{b}b \)

- our algorithm extends it to busier environment
- complimentary to conventional search
- these new Higgs discovery channels can easily be as significant (or more so !) than conventional \( h \to \gamma \gamma \)
Offering seems important enough to have a full detector simulation.