Boosting BSM Higgs discovery with jet substructure

Adam Martin (aomartin@fnal.gov) with G. Kribs, T. Roy and M. Spannowsky (U. Oregon)

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$$h \rightarrow \bar{b}b$$

will be difficult to find
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will be difficult to find
for the lightest mass range the most sensitive channel is $h \rightarrow \gamma\gamma$

- reconstruct the diphoton invariant mass peak, on top of continuum diphoton background
- ATLAS: inclusive diphoton and exclusive $\gamma\gamma + \text{jets}$ searches

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

$S/\sqrt{B} = 1.8$

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source (ATL-PHYS-2008-258)
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$hW(\ell\nu)/hZ(\ell\ell, \nu\nu)$

$h \rightarrow \tau\tau$

also contribute, but small
Going beyond the SM... light Higgs still hard

ex.) MSSM

conventional MSSM light higgs search

some enhancement, but only when $m_A$ is small and $\tan \beta$ is large

flavor problems?
Recently, a new technique for light Higgses

(Butterworth, Davison, Rubin, Salam ’08)

In associated production of Higgs + Z,W: \( W(\ell\nu)/Z(\ell\ell) + h(\bar{b}b) \)

significance \( \sim 4.5 \) for \( L = 30 \text{ fb}^{-1} \) \( (\sim 2.6 \) for \( L = 10 \text{ fb}^{-1} ) \)

obtained by focusing on

boosted Higgses, \( p_{T,h} > 200 \text{ GeV} \)
Recently, a new technique for light Higgses

**Basic Idea:**

**signal:** high $m_{b\bar{b}}$, $R_{b\bar{b}}$ depends on boost

**background:** high $m_{b\bar{b}}$ at large $R_{b\bar{b}}$

$$m^2_{ij} \sim 2p_T^i p_T^j (R_{ij})^2$$

**boosted regime:** high $m_{b\bar{b}}$ smaller $R_{b\bar{b}}$

Boosted objects appear as a single ‘fat jet’ in the detector...

to dig out the b-jets from a ‘fat jet’ use recently developed jet substructure techniques
Other Applications of Boosted analysis

- **two-pronged decays (SM Higgs):**
  
  Butterworth, Davison, Rubin, Salam (2008)

- **three-pronged decays (boosted top):**
  
  Kaplan, Rehermann, Schwartz, Tweedie (2007)
  Brooijmans (2008)
  Thaler and Wang (2008)
  Butterworth, Ellis, Rakhlev, Salam (2009)

- **jet pruning/trimming:**
  
  Ellis, Vermilion, Walsh (2009)
Boosted Higgses

interesting new approach

\textbf{BUT a bit limited in SM}

* boosted Higgs are rare in the \textbf{SM}: \( \sim 5\% \) in \( H + W/Z \)

* need to trigger & suppress SM backgrounds: limited to \( W/Z \) leptonic decay modes

\textbf{What about jet substructure analysis + BSM?}
Higgs from BSM

BSM particles can decay to Higgses

new colored stuff

= a new source of Higgses

initial (colored) states are heavy (∼ TeV)

while Higgs can be light

higher fraction of boosted Higgses
Higgs from BSM

If BSM contains new colored states, production at LHC is easily in the \( \sim \) few pb range comparable to or greater than SM EW Higgs production

BSM production often comes with new, effective handles for suppressing SM backgrounds

\[ E_T, \text{ high } - p_T \text{ jets, } \ell, \gamma, H_T, \cdots \]

Higgses from BSM have all of the important ingredients for a successful substructure analysis
the plan:

Substructure Techniques + BSM = an opportunity for light Higgs discovery

1. Pick a new physics scenario with gives us a source of boosted Higgses

2. Use substructure techniques in these scenarios to combat backgrounds, both from the SM and from new physics

3. Adapt substructure to work in hectic, crowded BSM environments
Part I: SUSY sources of boosted Higgs

Though our techniques apply to a wide array of BSM scenarios, we’ll look at (weak scale) SUSY

why SUSY?

• **MSSM** Higgs has to be light $m_h \lesssim 130$ GeV, decays dominantly to $b\bar{b}$
• it has new colored particles (squarks, gluinos), which can be produced with large cross sections
• all events include $E_T$
• Higgs via various decays:

\[
\begin{align*}
\tilde{\chi}_2^0 & \rightarrow \tilde{\chi}_1^0 + h \\
\tilde{\chi}_2^\pm & \rightarrow \tilde{\chi}_1^\pm + h \\
\tilde{t}_{L,R} & \rightarrow \tilde{t}_{R,L} + h \\
\tilde{\chi}_1^0 & \rightarrow \tilde{G} + h
\end{align*}
\]
Neutralino Decays to Gravitinos

- happens when the scale of SUSY breaking is low (GMSB)
- decays of neutralinos governed by $M_1, M_2, \mu, \tan \beta$
- can get appreciable BR to Higgses when the lightest neutralino is primarily Higgsino $|\mu| \ll M_1, M_2$

(Matchev, Thomas '99)
(Meade, Reece, Shih '09)
Why start with $\tilde{\chi}_1^0 \rightarrow \tilde{G} + h$?

- The mixed decay $\tilde{\chi}^0 \tilde{\chi}^0 \rightarrow h + \gamma + E_T$

  has a smaller rate, but many advantages

  - hard, isolated photon plus large $E_T$
  - kills off much of the SM background

  - heavier, colored sparticles control LHC production

- simplest BSM scenario we could think of to test jet substructure techniques on
Higgses source comparison

how we want to look for the MSSM Higgs

- Higgses from sparticle decays
- big cross-section (inclusive SUSY prod.)
- all events have $E_T$, lots of extra jets
- SM and BSM backgrounds

Higgs produced in association with SM particles

- smaller cross section (set by $y_b$)
- no (BSM) $E_T$
- only SM backgrounds

how people usually look for the MSSM Higgs
with so much going on in inclusive SUSY events... how can we do better than traditional search?

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JET SUBSTRUCTURE!
Remember

* focus on the subset of new physics events with boosted characteristics

  specifically, demand one or more ‘fat’ jets:

  \[ p_{T,j} > 200 \text{ GeV} \]

  this limits the kinematic regime, costing us events, but we greatly reduce combinatorial background

* Our goal is to discover the Higgs, not the new physics!

* also, going to high-\( p_T \) \( \rightarrow \) better detector resolution:

  \[ \left( \frac{\delta E}{E} \right)_{\text{jets}} \approx \frac{0.6}{\sqrt{E/\text{GeV}}} + 0.03 \]

  (ATLAS TDR, cone jets.)

  so boosted analysis are also cleaner
Part II: Jet Substructure Analysis

- Combining particles
- Unraveling jets/searching for substructure
- Benefits of substructure
Making and breaking jets

to be able to better use the information contained in jets, we have to know how they are created

starting from a list of final particles, calculate:

\[ d_{ij} = \min(p_{T_i}^{2n}, p_{T_j}^{2n}) \frac{\Delta R_{ij}^2}{R^2} \]

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

\[ n = \begin{cases} 
  n = 1 & k_T \\
  n = 0 & C/A \\
  n = -1 & \text{anti-}k_T
\end{cases} \]

we use the C/A (angle ordered shower) throughout
Making and breaking jets

find the minimum: \( \min (d_{ij}, d_i) \)

if min is one of the \( d_{ij} \), replace \( \text{particle}_j \) and \( \text{particle}_i \) with \( \vec{k} = \vec{i} + \vec{j} \)

and repeat...
Making and breaking jets

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Making and breaking jets

If \( \min(d_{ij}, d_i) \) is one of the \( d_i \)

promote particle\(_i\) to a jet, and remove it from the list

repeat the procedure until the list is empty
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if $\min (d_{ij}, d_i)$ is one of the $d_i$

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Making and breaking jets

\[ \text{if} \quad \min(d_{ij}, d_i) \quad \text{is one of the} \quad d_i \]

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Jet Substructure #1

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For each jet \( R = 1.2 \) in the event:

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so only keep events with significant mass-drop: \( m_i < \mu m_J \)
Jet Substructure #2

For each jet ($R = 1.2$) in the event:

1. Undo the last stage of clustering $J \rightarrow i + j$, calling the more massive daughter $i$.

For a heavy particle decay, expect $m_i \ll m_J$ so only keep events with significant mass-drop: $m_i < \mu m_J$

But rates for QCD jets/BSM jets are so high, we need another handle:

$$\text{demand: } \frac{\min(p_{T_i}^2, p_{T_j}^2)}{m_J^2} \Delta R_{ij}^2 > (0.3)^2$$
for massless daughter particles:

\[
\min \left( \frac{p_{T_i}^2, p_{T_j}^2}{m_j^2} \Delta R_{ij}^2 \right)
\]

\[
\frac{m_i^2}{E_j} \min \left( E_i, E_j \right) \equiv z
\]

... in soft, collinear limit

\[
df_{M \rightarrow ij}^{QCD} \sim dQ_M^2 dz \frac{1}{Q_M^2} P_{M \rightarrow ij}(z)
\]

blows up as \( z \rightarrow 0 \)

\[
df_{M \rightarrow ij}^{res} \sim dQ_M^2 dz \frac{\Gamma_{M \rightarrow ij}}{\Gamma_{M,tot}} \delta (Q_M^2 - m_{res}^2)
\]

nonsingular in \( z \)
Jet Substructure #3

for massless daughter particles:

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\frac{\min(p_{T_i}^2, p_{T_j}^2)}{m_J^2} \Delta R_{ij}^2 \quad \rightarrow \quad \frac{\min(E_i, E_j)}{E_J} \equiv z
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\]

nonsingular in \( z \)

\[
\text{cut} \quad \frac{\min(p_{T_i}^2, p_{T_j}^2)}{m_J^2} \Delta R_{ij}^2 > (0.3)^2 \quad \text{suppresses QCD contamination}
\]
Jet Substructure #4

2. If conditions not met, continue unclustering using more massive daughter jet as new parent

BUT if both conditions met, stop unclustering

Identity $\Delta R_{ij}$ as the substructure scale $R_{sub}$

3. For jets with substructure, resolve at scale $\approx R_{sub}/2$

this captures the perturbative, angle-ordered radiation associated with the subjets, while filtering out diffuse radiation like the underlying event
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Jet Substructure: in pictures

4. retain the \textbf{three} hardest subjets ...

if two of the three hardest subjets are tagged as b-jets:

\begin{itemize}
  \item candidate Higgs
\end{itemize}
4. retain the **three** hardest subjets ...

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(candidate Higgs)
Jet Substructure: in pictures

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`h` \rightarrow \{ \text{"b"}, \text{"\bar{b}"}, R_{\text{sub}} \}

**candidate Higgs**
Jet Substructure: in pictures

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Thursday, February 18, 2010
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(candidate Higgs)
Why substructure?

• Seems like we are doing a lot of work. Isn’t there an easier way, such as:

Why not just start with a smaller cone?

BUT

QCD radiated jets can carry much of the ‘mother’ particle’s mass...

Small cones miss this mass, degrading the $jj$ invariant mass resolution

(Seymour, ‘94)
Why substructure?

Why not a big cone, with multiple $b$ tags?

The bigger the cone, the more extraneous jets we allow in, either from radiation/underlying event... leading to worse resolution on $m_{jj}$
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... leading to worse resolution on $m_{jj}$
Improved jet substructure

The large number of $b$ quarks, especially when 3rd generation squarks are important in SUSY production, becomes a problem (similar to $t$-$\bar{t}$-h in SM)

(Plehn, Salam, Spannowsky '09)

identifying a pair of heavy particles is no longer enough

extra $b$'s can end up in the 'higgs jet' disrupting the substructure algorithm
Improved jet substructure

• add another handle: \(p_T\) similarity

rather than stop at a mass drop, calculate

\[
S_i = \frac{\min(p_{Tj_1}^2, p_{Tj_2}^2)}{(p_{Tj_1} + p_{Tj_2})^2} \Delta R_{j_1j_2}
\]

and continue undoing the original jet

at each subsequent mass drop, record \(S_i\)

(Kribs, AM, Roy, Spannowsky)
Improved jet substructure

- Identify the splitting with maximum $S_i$ and two daughter b-jets as the Higgs candidate

extraneous
Improved jet substructure

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Improved jet substructure

- Identify the splitting with maximum $S_i$ and two daughter b-jets as the Higgs candidate

but

by selecting the splitting with the more even distribution of subjet $\rho_T$

extraneous

we can reduce contamination
Improved Jet Substructure on BSM:

1. cluster particles into jets, $R = 1.2$

2. for each fat jet, undo clustering step by step, looking for mass drop and even splitting of energy between daughters. If conditions met, record $\Delta R_{sub,i}$ and $S_i$. Keep unclustering until no more parent jets

3. Determine which splitting $\mathcal{R}$ has most even $p_T$ splitting

4. Resolve the fat jet into subjets at the scale $\approx \Delta R_{sub,n}/2$

5. if two of the three hardest subjets are tagged as b-jets

candidate Higgs jet
Part III

**Higgs from neutralino decays**

+ **Jet substructure results**
Results: Point #1

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

![Graph showing candidate Higgs-jet mass distribution](image)

**cuts:**

substructure $+ \quad \sum E_T > 100 \text{ GeV} \quad p_T \gamma > 80 \text{ GeV}$

**boosted fraction $\sim 38\%$**

(Kribs, AM, Roy, Spannowsky)

**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\%**

Light squarks dominate SUSY production.
Results: 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%
**Results: Point #2**

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

- \( m\tilde{Q}_{1,2} \) \( \sim 1 \text{ TeV} \)
- \( m\tilde{Q}_3 \) \( \sim 750 \text{ GeV} \)
- \( M_2 \) \( \sim 600 \text{ GeV} \)
- \( M_1 \) \( \sim 300 \text{ GeV} \)
- \( |\mu| \) \( \sim -250 \text{ GeV} \)

3rd generation squarks and gluinos play a bigger role in SUSY production, more b/t quarks in the events.

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

same ino spectrum as previous, but light squarks now 1 TeV
Results: Point #3

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

**Candidate Higgs-jet mass**

- **boosted fraction** \( \sim 47\% \)

- **BR(\tilde{\chi}^0 \rightarrow \gamma + \tilde{G}) \sim 82.6\%**
- **BR(\tilde{\chi}^0 \rightarrow Z + \tilde{G}) \sim 16\%**
- **BR(\tilde{\chi}^0 \rightarrow h + \tilde{G}) \sim 1.3\%**

**much trickier region of parameter space**

\[ M_1 \]

\[ |\mu| \]

\[ m_{\tilde{Q}_3} \]

\[ m_{\tilde{Q}_{1,2}} \]

\[ 1 \text{ TeV} \]

\[ 750 \text{ GeV} \]

\[ 200 \text{ GeV} \]
Results: Point #3

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

- **Candidate Higgs-jet mass**
- **Number of Events/6.0 GeV**
- **boosted fraction $\sim 47\%$**

**BR($\tilde{\chi}^0 \rightarrow \gamma + \tilde{G}$) $\sim 82.6\%$**
**BR($\tilde{\chi}^0 \rightarrow Z + \tilde{G}$) $\sim 16\%$**
**BR($\tilde{\chi}^0 \rightarrow h + \tilde{G}$) $\sim 1.3\%$**

**much trickier region of parameter space**
boosted analysis finds the Higgs peak even where conventional analysis fails completely or leads to confusing features

\[ M_{b\ell} \]

Comparison of boosted and conventional searches

Results: Point #3

(PGS cone jets \( M_{bb} \))
We’ve used SUSY with gravitino LSP as an example source of Higgses from BSM, but the technique is by no means limited to this.

**Ingredients:**

- new, heavy particles whose decays include Higgses
- Higgs which decays primarily to $b\bar{b}$
- some handle to suppress SM backgrounds (high-$p_T$ particles, $E_T$)

Ex. SUSY w/ $\tilde{\chi}_0$ LSP
UED
Little Higgs
4th Generation
...

* cleanliness of substructure analysis
  better extraction of underlying parameters
Higgses from other BSM sources

moving beyond SUSY with gravitino LSP ...
Example: SUSY with neutralino LSP

• as before, squarks dominate LHC production

• squarks decay into charginos/neutralinos
  
  decays to winos/binos, set by gauge couplings, dominate
  (at least for first/second generation squarks)

• provided $M_2, M_1 \gg |\mu|$, winos/binos are heavier than
  higgsinos, and subsequent decays:

  $\tilde{W}_3 \rightarrow \tilde{H}_0 + h,$  
  $\tilde{W}^{\pm} \rightarrow \tilde{H}^{\pm} + h$

  $\tilde{B} \rightarrow \tilde{H}_0 + h$

  all give Higgses!
Example: SUSY with neutralino LSP

fewer handles than \( \tilde{\chi}_0 \rightarrow h / \gamma + \tilde{G} \)

require large \( H_T, \not{E}_T \) to suppress SM background

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

\[ \begin{align*}
\text{Number of Events/7.0 GeV} \\
\text{candidate Higgs jet mass (GeV)}
\end{align*} \]

\[ \text{tf + jets, SUSY} \]

\[ m_{\tilde{Q}} \]

\[ \begin{align*}
M_1 & \rightarrow 450 \text{ GeV} \\
M_2 & \rightarrow 350 \text{ GeV} \\
|\mu| & \rightarrow 150 \text{ GeV}
\end{align*} \]

\[ H_T > 1.5 \text{ TeV}, \not{E}_T > 150 \text{ GeV} \]

\[ 2^+ \text{ high-}\not{p}_T \text{ jets + substructure} \]

\[ \begin{align*}
BR(\tilde{u}_L, \tilde{d}_L \rightarrow h + X) & \sim 16\% \\
BR(\tilde{u}_R, \tilde{d}_R \rightarrow h + X) & \sim 31\%
\end{align*} \]

careful treatment of background is needed, but looks possible
Conclusions

Light Higgses are hard to find at the LHC ...

* the decays of BSM particles offer a new source of Higgses at the LHC, especially boosted Higgses

* The rate is smaller, but BSM often comes with handles to suppress SM backgrounds

* Using jet substructure analysis to fight combinatorial BSM backgrounds, result is new channels to discover $h \rightarrow \bar{b}b$

  improved substructure extends this to ‘b-rich’ environments

* Complementary to conventional Higgs searches, smaller jet-resolution effects

* These new Higgs discovery channels can easily be as significant (or more so !) than conventional $h \rightarrow \gamma\gamma$