Higgs and Jet Color-Connections
Jet Superstructure and Event Kinematics

Jason Gallicchio

UC Davis

27 September 2011
Higgs Status and \( H \rightarrow b\bar{b} \) Motivation
Higgs Status and $H \to b\bar{b}$ Motivation

Jets beyond $(E, \eta, \phi)$: Color Superstructure
  - Color Connection Primer
  - QCD radiation *between* and *within* jets
  - DØ Data on Higgs and Top and ATLAS work
Outline

- Higgs Status and $H \rightarrow b\bar{b}$ Motivation
- Jets beyond $(E, \eta, \phi)$: Color Superstructure
  - Color Connection Primer
  - QCD radiation between and within jets
  - DØ Data on Higgs and Top and ATLAS work
- Multivariate Kinematics+Color
  - New kinematic observables
  - Ranking observables
  - Combining observables (multivariate Boosted Decision Trees)
LEP Precision Electroweak

\[ \Delta \chi^2 \]

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

Excluded

Preliminary

\[ \Delta \alpha_{\text{had}}^{(5)} = 0.02761 \pm 0.00036 \]

0.02747 \pm 0.00012

incl. low Q^2 data

LHC Possibilities 2011

\[ \int L dt = 1.0 - 2.3 \text{ fb}^{-1} \]

\[ \sqrt{s} = 7 \text{ TeV} \]

90%

95%

99%

ATLAS Preliminary

Observed

Expected
Production at LHC

\[ \sigma(pp \rightarrow H + X) [\text{pb}] \]

\[ \sqrt{s} = 14 \text{ TeV} \]

MRST/NLO

\[ m_t = 178 \text{ GeV} \]

Decay Branching Ratios

\[ \text{BR}(H) \]
Improve search for $H \rightarrow b\bar{b}$ associated with a $Z/W$ for $m_H \approx 120$ GeV.
Kinematic variables to distinguish **signal** from **background** somewhat...

Good ones are $p_T^H$, $\Delta \eta_{bb}$, $\Delta \phi_{bb}$, ...

Full multivariate treatment after a long interlude...
Long History: ‘String Effect’ or ‘Drag Effect’ on planar events:

\[ e^+ e^- \rightarrow \]

Gluons are treated as a colinear \( q\bar{q} \) pair with \textit{different} colors...

... equivalent up to \( 1/N_C^2 \) corrections
An Unexploited Handle for Higgs

bs form color singlet

Higgs Signal
An Unexploited Handle for Higgs

Higgs Signal

- $bs$ form color singlet

$Z + b\bar{b}$ QCD Background

- $bs$ color connected to beams
Showering Same Hard Event Millions of Times
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Higgs example:

\[ \Delta \eta_{b\bar{b}} = 1 \]
\[ \Delta \phi_{b\bar{b}} = 2 \]

Add up \( p_T \) in each cell:
But event-by-event?
Higgs+Z Signal Event Example
$Z + b\bar{b}$ Background Event Example
Probability that a GeV of $p_T$ somewhere is from Higgs

Higgs:

Background:
Probability that a GeV of $p_T$ somewhere is from Higgs

Higgs:

![Higgs distribution plot]

Background:

![Background distribution plot]

Important discrimination isn’t at jet center — it’s $\Delta R \approx 0.5 - 1.5$ away.
Focus on Jets Themselves — Pull

Signal Accumulated $p_t$

Background Accumulated $p_t$
Add up particles or calorimeter energy deposits within a jet:

Pull Vector \( \vec{m} = \sum_{i \in \text{jet}} \frac{p_T^i |r_i|}{p_T^{\text{jet}}} \vec{r}_i \) where \( \vec{r}_i \equiv (y_i - y_{\text{jet}}, \phi_i - \phi_{\text{jet}}) \)
Add up particles or calorimeter energy deposits *within* a jet:

\[
Pull Vector \quad \vec{m} = \sum_{i \in jet} \frac{p_T^i |r_i|}{p_T^{jet}} \vec{r}_i\quad \text{where} \quad \vec{r}_i \equiv (y_i - y_{jet}, \phi_i - \phi_{jet})
\]

- Angle of moment $\vec{m}$ gives “pointing” direction of teardrop
- Length of moment $|\vec{m}|$ doesn’t help much
Distribution of the pull angle (one $b$-jet) with $\Delta y_{b\bar{b}} = 1$ and $\Delta \phi_{b\bar{b}} = 2$
Signal Accumulated $p_t$

Signal pull: $\alpha = \sqrt{\alpha_1^2 + \alpha_2^2}$

Background Accumulated $p_t$

Background pull: $\beta = \sqrt{\beta_1^2 + \beta_2^2}$
Pull Distributions for Full Z+Higgs Search

- Pull of high-$p_T$ b jet: $\alpha_1$
- Pull of low-$p_T$ b jet: $\alpha_2$
- Pull signal-distance: $\alpha$

- Pull of high-$p_T$ b jet: $\beta_1$
- Pull of low-$p_T$ b jet: $\beta_2$
- Pull background-distance: $\beta$
Pull in DØ Data for (background to) $ZH \to b\bar{b}\nu\bar{\nu}$!

$\alpha_1$

pull of high-$p_T$ b jet: $\alpha_1$

DØ Note 6087-CONF Aug 2010, Andy Haas: $ZH \to b\bar{b}\nu\bar{\nu}$ (data consistent with flat background)

Andy claims 5% improvement in multivariate search
- The two $b$ jets are color-connected to the beam (like $Z + b\bar{b}$ background earlier)

- The two light quark jets from $W$ are color-connected to each other
Validating Pull through Semileptonic $t\bar{t}$

- The two $b$ jets are color-connected to the beam (like $Z + b\bar{b}$ background earlier)
- The two light quark jets from $W$ are color-connected to each other

Test QCD and the Monte Carlos: Given $b$ tags and clean top sample, what do the pulls look like?
Event Example 1

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$t\bar{t}$ Pull in DØ Data!

\textbf{\ttbar Pull in DØ Data!}

\textbf{\ttbar Jets:}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{ttbar_pull}
\end{figure}
**t\bar{t} Pull in DØ Data!**

**t\bar{t}Jets:**

![Graph 1](image1.png)  
**DØ, L=5.3 fb⁻¹**  
Data $\chi^2/ndf: 0.95$  
- t\bar{t}  
- Other  
- W+jets  
- Multijets

![Graph 2](image2.png)  
**DØ, L=5.3 fb⁻¹**  
Data $\chi^2/ndf: 0.95$  
- t\bar{t}  
- Other  
- W+jets  
- Multijets

![Graph 3](image3.png)  
**DØ, L=5.3 fb⁻¹**  
Data $\chi^2/ndf: 1.08$  
- t\bar{t}  
- Other  
- W+jets  
- Multijets

**W + 2jets** (no b tags, so not from top):
$W$ looks like a color singlet, not octet
$W$ looks like a color singlet, not octet

\[
f_{\text{Singlet}} = 0.56 \pm 0.36\text{(stat)} \pm 0.22\text{(syst)}
\]

... or exclude $f_{\text{Singlet}} = 0$ to three standard deviations
Measure $W$’s $f_{\text{Singlet}}$ to 10% at ATLAS (DØ got 40%)
\begin{itemize}
\item Measure $W$'s $f_{\text{Singlet}}$ to 10\% at ATLAS (DØ got 40\%)
\item $t\bar{t}$ cross section $\times$ acceptance at ATLAS is 25x to 80x Tevatron
\end{itemize}
- Measure $W$’s $f_{\text{Singlet}}$ to 10% at ATLAS (DØ got 40%)
- $t\bar{t}$ cross section $\times$ acceptance at ATLAS is 25x to 80x Tevatron
- Better calorimeter, tracking, and calo/track matching
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Improvements and ATLAS Plans

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- Use pull in $ZH$ and in $t\bar{t}H$ searches

(This is a way to measure color of new particles!)
Improving the $H \rightarrow b\bar{b}$ search

Higgs Window

Higgs Invariant Mass $m_{b\bar{b}}$ using anti-$k_T$ $R=0.5$ jets

$ZH$ signal (solid blue) and $Zb\bar{b}$ background. Normalized to same area (or you couldn’t even see signal.)

Pick initial window: $90$ GeV $< m_{b\bar{b}} < 124$ GeV (justified later)
## LHC and TVT cross sections for $ZH$ and QCD

<table>
<thead>
<tr>
<th>Integrated Luminosity, $\int L$</th>
<th>LHC (14 TeV)</th>
<th>Tevatron (1.96 TeV)</th>
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<tbody>
<tr>
<td></td>
<td>$30 \ fb^{-1}$</td>
<td>$10 \ fb^{-1}$</td>
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<tr>
<td>Xsec times Branching Ratio</td>
<td>$pp \rightarrow ZH$</td>
<td>$pp \rightarrow Zbb$</td>
</tr>
<tr>
<td></td>
<td>$33.4 \ fb$</td>
<td>$57,200 \ fb$</td>
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<tr>
<td>After Generator-Level Cuts</td>
<td>$31.5 \ fb$</td>
<td>$26,000 \ fb$</td>
</tr>
<tr>
<td>Two $b$ Tags % (of Gen-Level)</td>
<td>$57%$</td>
<td>$25%$</td>
</tr>
<tr>
<td>Higgs Window % (of Gen-Level)</td>
<td>$40%$</td>
<td>$4%$</td>
</tr>
<tr>
<td>Initiated by $gg$</td>
<td>$0%$</td>
<td>$90%$</td>
</tr>
<tr>
<td>Xsec (in Higgs Window)</td>
<td>$12.3 \ fb$</td>
<td>$1100 \ fb$</td>
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<tr>
<td>Events ($Xsec \times \int L$)</td>
<td>$370$</td>
<td>$33,700$</td>
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<tr>
<td>Starting $B/S$</td>
<td>$91.1$</td>
<td>$8.2$</td>
</tr>
<tr>
<td>Starting $S/\sqrt{B}$</td>
<td>$2.02$</td>
<td>$1.47$</td>
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</table>

### Hard-parton level cuts
- $p_T^b > 7 \ GeV$
- $p_T^\mu > 3 \ GeV$
- $p_T^e > 3 \ GeV$
- $|\eta_b| < 5$ and $|\eta_e| < 5$

### Detector level cuts
- $p_T^b > 15 \ GeV$
- $p_T^\mu > 6 \ GeV$
- $p_T^e > 20 \ GeV$ (LHC), $10 \ GeV$ (Tevatron)
- $|\eta_b| < 2.5$ and $|\eta_e| < 2.5$
Standard Kinematic Variables

![Graphs showing distributions for Standard Kinematic Variables](image)

All In Higgs Mass-Window: $90 \text{GeV} < m_{b\bar{b}} < 124 \text{GeV}$ (and equal area)
Twist $\tau = \pi/2$

Higgs-Like

Beam

$\tau = \frac{\pi}{2}$

Twist $\tau = 0$

QCD-Like

Beam

$\tau = 0$
Twist Distributions

Parton level with no cuts

Jet level with detector cuts

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Higgs Rest Frame: Helicity and Azilicity

- $b$ direction
- $\bar{b}$ direction
- $H$ boost direction
- $\theta_h$
- $\phi_a$
- $Z$ direction
- Beam direction

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Madgraph hard partons with no cuts:

**H Frame** \( \cos(\theta_h) \) helicity angle

**H Frame** \( \phi_\alpha \) azilicity angle

Showered and reconstructed, with detector cuts:

**H Frame** \( \cos(\theta_h) \) helicity angle

**H Frame** \( \phi_\alpha \) azilicity angle
Menu-Method Variables: ‘One from Column A…’
How to Evaluate a Variable?

How do we pick the most useful variables?

We want to find clean variables that can be used for separation.

![Sliding Cut](image-url)
Background vs Signal Efficiency "ROC Curve"

LHC HZ: Signal and Background Efficiencies

- $\Delta \eta_{bb}$
- $\Delta y_{H,b2}$
- $\Delta y_{H,b1}$
- $p_{T}^{b1}$
- $p_{T}^{b2}$
- $CM \cos(\theta_{b2})$
- $\tau_{bb}$
- $\Delta R_{bb}$
- $\Delta \phi_{\ell^{+}\ell^{-}}$
- $p_{T}^{Z}$
\[
\frac{S}{B} \xrightarrow{\text{cut}} \frac{\varepsilon_S S}{\varepsilon_S B} = \left( \frac{\varepsilon_S}{\varepsilon_B} \right) \frac{S}{B}
\]

**LHC HZ : Signal over Background**

- $\Delta \eta_{b\bar{b}}$
- $\Delta y_{H,b2}$
- $\Delta y_{H,b1}$
- $p_T^{b1}$
- $p_T^{b2}$
- $CM \cos(\theta_{b2})$
- $\tau_{b\bar{b}}$
- $\Delta R_{b\bar{b}}$
- $\Delta \phi_{\ell^+\ell^-}$
- $p_T^Z$
\[ \sigma \equiv \frac{S}{\sqrt{B}} \rightarrow \frac{\varepsilon S S}{\sqrt{\varepsilon_B B}} = \left( \frac{\varepsilon S}{\sqrt{\varepsilon_B}} \right) \sigma \]

**LHC HZ : Significance**

![Graph showing significance improvement with Higgs signal efficiency \( \varepsilon_S \)]
2D Likelihood

Signal

Background

\[ \Delta \eta_{b2}, \ell_1 \]

\[ \Delta \theta_{b1}, \ell_1 \]
Boosted Decision Trees

![Decision Tree Diagram]

- Root node
- \( x_i > c_1 \) node
  - \( x_j > c_2 \) node
    - \( B \)
  - \( x_j < c_2 \) node
    - \( S \)
- \( x_i < c_1 \) node
  - \( x_j > c_3 \) node
    - \( S \)
  - \( x_j < c_3 \) node
    - \( x_k > c_4 \) node
      - \( B \)
    - \( x_k < c_4 \) node
      - \( S \)
Boosted Decision Trees

BDT 2

BDT 8

BDT 32

BDT 64

BDT 256

Likelihood

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Tevatron $ZH$ improvements, up to 10 variables

TVT HZ : Significance

Higgs Signal Efficiency $\varepsilon_S$
### Linear Correlation Sig

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### Linear Correlation Bkg

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</table>
Tevatron Improvement

**TVT HZ : Significance**

- 11: TVT HZ best
- 9: D0 HZ
- 7: CDF HZ

**TVT HW : Significance**

- 11: TVT HW best
- 8: CDF HW
- 13: D0 HW
Results:

- Tevatron Searches can be Improved 10% to 20%
- LHC’s current “boosted Higgs” can be improved as much as 200%
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Thank You
## CDF and DØ Variables

<table>
<thead>
<tr>
<th>CDF ZH</th>
<th>DØ ZH</th>
<th>CDF WH</th>
<th>DØ WH</th>
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<td>$p_T^{b1}$</td>
<td>$p_T^{imbalance}$</td>
<td>$p_T^{b1}$</td>
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<tr>
<td>$p_T^{b2}$</td>
<td>$p_T^{b2}$</td>
<td>$m_{W,b1}$</td>
<td>$p_T$</td>
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<tr>
<td>$\Delta R_{b\bar{b}}$</td>
<td>$\Delta R_{b\bar{b}}$</td>
<td>$m_{W,b2}$</td>
<td>$E_{b2}$</td>
</tr>
<tr>
<td>$\Delta R_{e+e-}$</td>
<td>$\Delta R_{e+e-}$</td>
<td>$\eta_{\ell}$</td>
<td>$\Delta R_{b\bar{b}}$</td>
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<tr>
<td>$\Delta R_{ZH}$</td>
<td>$\Delta R_{ZH}$</td>
<td>$\Sigma p_T^{b\bar{b}}$</td>
<td>$\Delta \phi_{b\bar{b}}$</td>
</tr>
<tr>
<td>CM $\cos \theta_H$</td>
<td>CM $\cos \theta_H$</td>
<td>$p_T^{H}$</td>
<td>$\Delta \phi_{b1,\ell}$</td>
</tr>
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<td>$P_T^{H}$</td>
<td>$P_T^{H}$</td>
<td>$p_T^{W}$</td>
<td>$p_T^{H}$</td>
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<td>$H_T$</td>
<td>$H_T$</td>
<td>$H_T$</td>
<td>$p_T^{W}$</td>
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<td>Sphericity^{obj.}</td>
<td>Sphericity^{obj.}</td>
<td>$\hat{s}$</td>
<td>$\hat{s}$</td>
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<td>$\Delta R_{W,H}$</td>
<td>$\Delta R_{W,H}$</td>
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<td></td>
<td></td>
<td>$H_{z}$</td>
<td>$H_{z}$</td>
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<td>CM $\cos \theta_H$</td>
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Our Top Variables: (GROUP LENGTH IN - GROUP LENGTH OUT)

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<thead>
<tr>
<th>LHC ZH</th>
<th>LHC WH</th>
<th>TVT ZH</th>
<th>TVT WH</th>
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<tr>
<td>1-10 $</td>
<td>\vec{p}_T^{b1}</td>
<td>+</td>
<td>\vec{p}_T^{b2}</td>
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<td>1-3 $\Delta \eta_{b\bar{b}}$</td>
<td>1-10 $\Delta y_{WH}$</td>
<td>1-10 $\Delta \eta_{b\bar{b}}$</td>
<td>1-10 $\Delta y_{WH}$</td>
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<tr>
<td>1-2 $\Delta y_{H,b2}$</td>
<td>2-10 $</td>
<td>\vec{p}_T^{b1}</td>
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<tr>
<td>2-4 $</td>
<td>\vec{p}_T^H</td>
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<td>\vec{p}_T^{b2}</td>
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<td>3-5 $\Delta y_{H,\ell1}$</td>
<td>1-2 CM cos $\theta_H$</td>
<td>2-10 Centrality</td>
<td>3-10 $H_T^{\text{prim.}}$</td>
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<tr>
<td>3-4 $\Delta y_{ZH}$</td>
<td>2-4 $\Delta \phi_{\ell+\ell-}$</td>
<td>2-7 $\text{Twist } \tau_{b\bar{b}}$</td>
<td>4-10 $\Delta \eta_{b\bar{b}}$</td>
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<td>4-10 $m_{H,\ell1}$</td>
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<td>\vec{p}_T^{b1}</td>
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<td>4-9 Sphericity</td>
<td>3-10 pull $\beta$</td>
<td>3-10 $m_{H,\ell2}$</td>
<td>4-10 pull $\alpha$</td>
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<td>5-9 $\Sigma y_{Z,b1}$</td>
<td>4-10 $\text{pull } \beta$</td>
<td>3-5 $\cos \theta_{\ell2}$</td>
<td>4-10 pull $\beta$</td>
</tr>
<tr>
<td>5-9 $\Sigma y_{Z,b1}$</td>
<td>4-6 $\Delta \phi_{W,\ell 2}$</td>
<td>(Z Frame)</td>
<td>7-10 avg. subj. $p_T$</td>
</tr>
<tr>
<td>5-9 $\Sigma y_{Z,b1}$</td>
<td>5-10 $m_{W,b1}$</td>
<td>5-8 girth $g_{b2}$</td>
<td>7-10 $m_{b2}/p_T^{b2}$</td>
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<tr>
<td>5-10 $E_{\text{vis}}^{\text{obj.}}$</td>
<td>6-10 $\Delta R_{H,b2}$</td>
<td>6-10 angul. $A_{b2}^{-0.1}$</td>
<td>8-9 $m_T^{bb}$</td>
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<td>5-10 angul. $A_{b1}^{0.90}$</td>
<td>7-9 $m_{b2}/p_T^{b2}$</td>
<td>8-10 $m_{W,b1}$</td>
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<td>8-9 pull $\alpha$</td>
<td>9-10 $\Delta \phi_{b\bar{b}}$</td>
<td>9-10 $m_{W,b1}$</td>
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