Jet structures in Higgs and New Physics searches
Parts 1 & 2

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Focus Week on QCD in connection with BSM study at LHC
IPMU, Tokyo, 10 November 2009

Part based on work with
Jon Butterworth, Adam Davison (UCL), John Ellis (CERN),
Tilman Plehn (Heidelberg), Are Raklev (Stockholm)
Mathieu Rubin (LPTHE) and Michael Spannowsky (Oregon)
LHC searches for hadronically-decaying new particles are **challenging**:

- Huge QCD backgrounds
- Limited mass resolution (detector & QCD effects)
- Complications like combinatorics, e.g. too many jets
- Especially true for EW-scale new particles

New strategy emerging in past 2 years: **boosted particle searches**

- Heavy particles reveal themselves as jet substructure
- E.g. top/W/H from decay of high mass particle
- Or directly Higgs (etc.) production at high $p_t$

**This talk**

- 70% on one major search channel: $pp \rightarrow HV$ with $H \rightarrow b\bar{b}$
  Butterworth, Davison, Rubin & GPS '09
- 30% on other applications of these ideas many groups, including Butterworth, Ellis, Raklev & GPS '09; Plehn, GPS & Spannowsky '09
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Higgs production at LHC

Domestic Higgs production channels:

- **Gluon fusion**
  - \[ gg \rightarrow H \]
  - \[ gg, q\bar{q} \rightarrow Ht\bar{t} \]
  - \[ gg, q\bar{q} \rightarrow Hbb \]

- **Vector-boson fusion**
  - \[ qq \rightarrow Hq\bar{q} \]
  - \[ qq' \rightarrow HW \]

- **Associated production**
  - H radiated off top-quark
  - or W or Z boson

\[ \sigma(pp \rightarrow H + X) [pb] \]
\[ \sqrt{s} = 14 \text{ TeV} \]
\[ M_t = 174 \text{ GeV} \]

CTEQ6M
Higgs production at LHC

Dominant Higgs production channels:

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**Intro**

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CTEQ6M

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- q̅q'→HW
- q̅q→Hqq
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- gg,q̅q→Hbb
- q̅q→HZ

**0 200 400 600 800 1000**

10^-4

10^-3

10^-2

10^-1

10

10^2

10^3

10^4

M_H [GeV]
**Higgs production at LHC**

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CTEQ6M

$M_H$ [GeV]

$10^{-2}$ $10^{-1}$ $10^0$ $10^1$ $10^2$ $10^3$ $10^4$ $10^5$
Intro

Higgs decay

Higgs decay branching ratios

Dominant Higgs decay mode depends on mass.

- Low mass: $H \rightarrow b\bar{b}$
- High mass: $H \rightarrow WW/ZZ$
Higgs mass constraints

Mass constraints come from
- LEP exclusion
- Tevatron exclusion
- EW precision fits

Strong preference for low-mass Higgs, one that decays mainly to $b\bar{b}$
LHC search prospects

Low-mass Higgs search ($115 \lesssim m_h \lesssim 130$ GeV) complex because dominant decay channel, $H \rightarrow bb$, often swamped by backgrounds.

Various production & decay processes

- $gg \rightarrow H \rightarrow \gamma\gamma$ feasible
- $WW \rightarrow H \rightarrow \tau\tau$ feasible
- $gg \rightarrow H \rightarrow ZZ^* \rightarrow 4\ell$ feasible
- $gg \rightarrow t\bar{t}H, H \rightarrow b\bar{b}$ v. hard
- $q\bar{q} \rightarrow WH, ZH, H \rightarrow b\bar{b}$ v. hard
What does a “very hard” search channel look like?
WH/ZH search channel @ LHC

- **Signal is** $W \rightarrow \ell \nu$, $H \rightarrow b \bar{b}$.
- **Backgrounds include** $Wb\bar{b}$, $t\bar{t} \rightarrow \ell \nu b\bar{b}jj$, ...

**Difficulties, e.g.**

- Poor acceptance ($\sim 12\%$)
  - Easily lose 1 of 4 decay products
- $p_t$ cuts introduce intrinsic bkgd mass scale;
- $gg \rightarrow t\bar{t} \rightarrow \ell \nu b\bar{b}[jj]$ has similar scale
- small S/B
- Need exquisite control of bkgd shape
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Jets, G. Salam, LPTHE (p. 8)

WH/ZH search channel @ LHC

- Signal is $W \rightarrow \ell \nu$, $H \rightarrow b\bar{b}$.
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Studied e.g. in ATLAS TDR

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Conclusion (ATLAS TDR):

“The extraction of a signal from $H \rightarrow b\bar{b}$ decays in the WH channel will be very difficult at the LHC, even under the most optimistic assumptions [...]”
LHC will (should…) span two orders of magnitude in $p_t$:

\[
\frac{m_{EW}}{2} \leftrightarrow 50m_{EW}
\]

That’s why it’s being built

In much of that range, EW-scale particles are **light**

[a little like $b$-quarks at the Tevatron]

**Can large phase-space be used to our advantage?**

[At Tevatron, $p_t = 0$ is not easiest place to look for $B$-hadrons...]
Study subset of WH/ZH with high $p_t$

Take advantage of the fact that $\sqrt{s} \gg M_H, m_t, \ldots$

Go to high $p_t$:
- Higgs and W/Z more likely to be central
- high-$p_t$ $Z \rightarrow \nu\bar{\nu}$ becomes visible
- Fairly collimated decays: high-$p_t$ $\ell^\pm, \nu, b$
  - Good detector acceptance
- Backgrounds lose cut-induced scale
- $t\bar{t}$ kinematics cannot simulate bkgd
  - Gain clarity and S/B
- Cross section will drop dramatically
  - By a factor of 20 for $p_{tH} > 200$ GeV

Will the benefits outweigh this?
And how do we ID high-$p_t$ hadronic Higgs decays?
Boosted massive particles, e.g.: EW bosons

Hadronically decaying EW boson at high p\(_t\) ≠ two jets

\[
R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1 - z)}}
\]

Rules of thumb:

- \(R < \frac{2m}{p_t}\): always resolve two jets

- \(R \gtrsim \frac{3m}{p_t}\): resolve one jet in 75% of cases \((\frac{1}{8} < z < \frac{7}{8})\)

\(m = 100\) GeV, \(p_t = 500\) GeV

\(R < 0.4\)

\(R \gtrsim 0.6\)
Finding a boosted Higgs?

How do we find a boosted Higgs inside a single jet?
Special case of general (unanswered) question: how do we best do jet-finding?

Various people have looked at boosted objects over the years
- Seymour ’93 [heavy Higgs $\rightarrow WW \rightarrow \nu\ell$jets]
- Butterworth, Cox & Forshaw ’02 [$WW \rightarrow WW \rightarrow \nu\ell$jets]
- Agashe et al. ’06 [KK excitation of gluon $\rightarrow t\bar{t}$]
- Butterworth, Ellis & Raklev ’07 [SUSY decay chains $\rightarrow W, H$]
- Skiba & Tucker-Smith ’07 [vector quarks]
- Lillie, Randall & Wang ’07 [KK excitation of gluon $\rightarrow t\bar{t}$]
- ETC.

...
Boosted ID strategies

Select on the jet mass with one large (cone) jet

Can be subject to large bkgds [high-$p_t$ jets have significant masses]

Choose a small jet size ($R$) so as to resolve two jets

Easier to reject background if you actually see substructure

[NB: must manually put in “right” radius]

Take a large jet and split it in two

Let jet algorithm establish correct division
To understand what it means to split a jet, let’s take a detour, and look at how jets are built up
Sequential recombination

**kt algorithm:**

Find smallest of

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2 / R^2, \quad d_{iB} = k_{ti}^2$$

If $d_{ij}$ recombine; if $d_{iB}$, $i$ is a jet

Example clustering with $k_t$ algorithm, $R = 1.0$

$\phi$ assumed 0 for all towers
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**Graph:**

- \( p_t / \text{GeV} \)
- \( d_{\text{min}} \) is \( d_{ij} = 1.75968 \)

- Axis labels: 0, 1, 2, 3, 4

- Data points (0, 1, 2, 3, 4) with \( \phi \) assumed 0 for all towers
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\[
\begin{align*}
\text{p}_t/\text{GeV} & \quad \text{dmin is } d_{ij} = 24.4196 \\
0 & \quad 1 & \quad 2 & \quad 3 & \quad 4 & \quad y
\end{align*}
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Example clustering with \( k_t \) algorithm, \( R = 1.0 \)

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Past methods

Use \( k_t \) jet-algorithm’s hierarchy to split the jets

Use \( k_t \) alg.’s distance measure (rel. trans. mom.) to cut out QCD bkgd:

\[
d_{ij}^{k_t} = \min(p_{ti}^2, p_{tj}^2) \Delta R_{ij}^2
\]

Y-splitter only partially correlated with mass
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**Y-splitter** only partially correlated with mass

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**Fig. 2.** A hadronic W decay, as seen at calorimeter level, a without, and b with, particles from the underlying event. Box sizes are logarithmic in the cell energy, lines show the borders of the sub-jets for infinitely soft emission according to the cluster (solid) and cone (dashed) algorithms.
3 QCD principles help guide our analysis

- QCD radiation from a boosted Higgs decay is limited by angular ordering
- Higgs decay shares energy symmetrically, QCD background events with same mass share energy asymmetrically
- QCD radiation from Higgs decay products is point-like, noise (UE, pileup) is diffuse
The Cambridge/Aachen jet alg.

Dokshitzer et al '97
Wengler & Wobisch '98

Work out $\Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta \phi_{ij}^2$ between all pairs of objects $i, j$;
Recombine the closest pair;
Repeat until all objects separated by $\Delta R_{ij} > R$.

[in FastJet]

Gives “hierarchical” view of the event; work through it backwards to analyse jet
#1: Our tool

**The Cambridge/Aachen jet alg.**

Dokshitzer et al '97  
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\[ \Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta \phi_{ij}^2 \text{ between all pairs of objects } i, j; \]

Recombine the closest pair;

Repeat until all objects separated by \( \Delta R_{ij} > R \).

[in FastJet]

Gives “hierarchical” view of the event; work through it backwards to analyse jet

\( k_t \) algorithm

Cam/Aachen algorithm

Allows you to “dial” the correct \( R \) to keep perturbative radiation, but throw out UE
#2: The jet analysis

Start with high-$p_t$ jet

1. Undo last stage of clustering ($\equiv$ reduce $R$): $J \rightarrow J_1, J_2$

2. If $\max(m_1, m_2) \lesssim 0.67 m$, call this a mass drop

   Automatically detects correct $R \sim R_{bb}$ to catch angular-ordered radn.

   Require $y_{12} = \frac{\min(y_1, y_2)}{\max(y_1, y_2)} \Delta R_{12} \sim \frac{\min(p_{1t}, p_{2t})}{\max(p_{1t}, p_{2t})} \gtrsim 0.09$

   Dimensionless rejection of automatic OS branching

   Require each subjet to have $b$-tag

Correlate flavour & momentum structure
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2. If $\max(m_1, m_2) \lesssim 0.67m$, call this a mass drop \[\text{Automatically detects correct } R \sim R_{bb} \text{ to catch angular-ordered radn.}\] [else goto 1]

3. Require $y_{12} = \frac{\min(p_{12}, p_{12}^2)}{m_{12}^2} \Delta R_{12}^2 \sim \frac{\min(z_1, z_2)}{\max(z_1, z_2)} > 0.09$ \[\text{dimensionless rejection of asymmetric QCD branching}\] [else goto 1]

4. Require each subjet to have $b$-tag \[\text{Correlate flavour & momentum structure}\] [else reject event]
#2: The jet analysis

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2. If \(\max(m_1, m_2) \lesssim 0.67m\), call this a **mass drop**
   
   Automatically detects correct \(R \sim R_{bb}\) to catch angular-ordered radn.
   
   [else goto 1]

3. Require \(y_{12} = \frac{\min(p_{11}^2, p_{12}^2)}{m_{12}^2} \Delta R_{12}^2 \sim \frac{\min(z_1, z_2)}{\max(z_1, z_2)} > 0.09\)
   
   dimensionless rejection of asymmetric QCD branching
   
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   [else reject event]
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2. If $\max(m_1, m_2) \lesssim 0.67 m$, call this a **mass drop**
   
   Automatically detects correct $R \sim R_{bb}$ to catch angular-ordered radn.

3. Require $y_{12} = \frac{\min(p_{11}^2, p_{12}^2)}{m_{12}^2} \Delta R_{12}^2 \sim \frac{\min(z_1, z_2)}{\max(z_1, z_2)} > 0.09$
   
   dimensionless rejection of asymmetric QCD branching

4. Require each subjet to have $b$-tag
   
   Correlate flavour & momentum structure
Start with high-\(p_t\) jet

1. Undo last stage of clustering (\(\equiv\) reduce \(R\)): \(J \rightarrow J_1, J_2\)

2. If \(\text{max}(m_1, m_2) \lesssim 0.67 m\), call this a mass drop \[\text{else goto 1}\]

   Automatically detects correct \(R \sim R_{bb}\) to catch angular-ordered radn.

3. Require \(y_{12} = \frac{\min(p_{t1}^2, p_{t2}^2)}{m_{12}^2} \Delta R_{12}^2 \approx \frac{\min(z_1, z_2)}{\max(z_1, z_2)} > 0.09\) \[\text{else goto 1}\]

   dimensionless rejection of asymmetric QCD branching

4. Require each subjet to have \(b\)-tag \[\text{else reject event}\]

   Correlate flavour & momentum structure
#2: The jet analysis

Start with high-\(p_t\) jet

1. Undo last stage of clustering (\(\equiv\) reduce \(R\)): \(J \rightarrow J_1, J_2\)

2. If \(\max(m_1, m_2) \lesssim 0.67 m\), call this a mass drop

   Automatically detects correct \(R \sim R_{bb}\) to catch angular-ordered radn.

3. Require \(y_{12} = \frac{\min(p_{t1}^2, p_{t2}^2)}{m_{12}^2} \Delta R_{12}^2 \sim \frac{\min(z_1, z_2)}{\max(z_1, z_2)} > 0.09\)

   Dimensionless rejection of asymmetric QCD branching

4. Require each subjet to have \(b\)-tag

   Correlate flavour & momentum structure
#2: The jet analysis

Start with high-\(p_t\) jet

1. Undo last stage of clustering (\(\equiv\) reduce \(R\)): \(J \rightarrow J_1, J_2\)

2. If \(\max(m_1, m_2) \lesssim 0.67 m\), call this a **mass drop**
   
   Automatically detects correct \(R \sim R_{bb}\) to catch angular-ordered radn.

   [else goto 1]

3. Require \(y_{12} = \frac{\min(p_{t1}^2, p_{t2}^2)}{m_{12}^2} \Delta R^2_{12} \sim \frac{\min(z_1, z_2)}{\max(z_1, z_2)} > 0.09\)
   
   dimensionless rejection of asymmetric QCD branching

   [else goto 1]

4. Require each subjet to have \(b\)-tag
   
   Correlate flavour & momentum structure

   [else reject event]
At moderate $p_t$, $R_{bb}$ is quite large; \textit{UE} & pileup degrade mass resolution
\[ \delta M \sim R^4 \Lambda_{UE} \frac{p_t}{M} \] [Dasgupta, Magnea & GPS '07]

Filter the jet

- Reconsider region of interest at smaller $R_{filt} = \min(0.3, R_{bb}/2)$
- Take 3 hardest subjets $b, \bar{b}$ and leading order gluon radiation
At moderate $p_t$, $R_{bb}$ is quite large; $UE$ & pileup degrade mass resolution
\[ \delta M \sim R^4 \Lambda_{UE} \frac{p_t}{M} \] [Dasgupta, Magnea & GPS '07]

Filter the jet

- Reconsider region of interest at smaller $R_{filt} = \min(0.3, R_{bb}/2)$
- Take 3 hardest subjets $b$, $\bar{b}$ and leading order gluon radiation
$pp \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

**Herwig 6.510 + Jimmy 4.31 + FastJet 2.3**

Cluster event, C/A, R=1.2

**arbitrary norm.**
Jets, G. Salam, LPTHE (p. 21)

Boosted object finding

\[ pp \rightarrow ZH \rightarrow \nu \bar{\nu} b \bar{b}, \ @14 \text{TeV}, \ m_H = 115 \text{GeV} \]

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

Fill it in, \( \rightarrow \) show jets more clearly
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

Consider hardest jet, $m = 150$ GeV

SIGNAL

Zbb BACKGROUND

arbitrary norm.
Jets, G. Salam, LPTHE (p. 21)

Boosted object finding

$$pp \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}, \ @14 \text{ TeV, } m_H = 115 \text{ GeV}$$

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

$$m = 150 \text{ GeV, } \frac{\max(m_1, m_2)}{m} = 0.92 \rightarrow \text{ repeat}$$
Jets, G. Salam, LPTHE (p. 21)

Boosted object finding

\[ pp \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}, \odot 14 \text{ TeV}, \quad m_H = 115 \text{ GeV} \]

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

split: \( m = 139 \text{ GeV}, \quad \frac{\max(m_1, m_2)}{m} = 0.37 \rightarrow \text{mass drop} \)

SIGNAL

\[ 200 < p_{tZ} < 250 \text{ GeV} \]

Zbb BACKGROUND

\[ 200 < p_{tZ} < 250 \text{ GeV} \]

arbitrary norm.
$pp \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}$, $\sqrt{s} = 14$ TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

Check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \rightarrow$ OK + 2 $b$-tags (anti-QCD)
**Boosted object finding**

**SIGNAL**

\[ pp \rightarrow ZH \rightarrow \nu \bar{\nu} b \bar{b}, \ @14 \text{ TeV}, \ m_H = 115 \text{ GeV} \]

**Zbb BACKGROUND**

\[ 200 < p_{tZ} < 250 \text{ GeV} \]

**arbitrary norm.**
$pp \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

$R_{filt} = 0.3$: take 3 hardest, $m = 117$ GeV

SIGNAL

200 < ptZ < 250 GeV

m_H [GeV]

0.15

0.1

0.05

0.0

arbitrary norm.

Zbb BACKGROUND

200 < ptZ < 250 GeV

m_H [GeV]
Compare with “standard” algorithms

Check mass spectra in HZ channel, $H \rightarrow b\bar{b}$, $Z \rightarrow \ell^+\ell^-$

Cambridge/Aachen (C/A) with mass-drop and filtering (MD/F) works best
The full analysis (scaled to 30 fb$^{-1}$)

Consider $HW$ and $HZ$ signals: $H \rightarrow b\bar{b}$, $W \rightarrow 3\ell$, $Z \rightarrow \ell^+\ell^-$ and $Z \rightarrow \nu\bar{\nu}$.

### Common cuts

- $p_{tV}, p_{tH} > 200$ GeV
- $|\eta_{Higgs-jet}| < 2.5$
- $\ell = e, \mu$, $p_{t,\ell} > 30$ GeV, $|\eta_\ell| < 2.5$
- No extra $\ell$, $b$'s with $|\eta| < 2.5$

### Channel-specific cuts:

See next slides

### Assumptions

- Real/fake $b$-tag rates: 0.6/0.02 should be fairly safe
- $S/\sqrt{B}$ from 16 GeV window ATLAS jet-mass resln $\sim$ half this?

### Tools:

Herwig 6.510, Jimmy 4.31 (tuned), hadron-level $\rightarrow$ FastJet 2.3

### Backgrounds:

$VV$, $Vj$, $jj$, $t\bar{t}$, single-top, with $> 30$ fb$^{-1}$ (except $jj$)
The full analysis (scaled to 30 fb$^{-1}$)

Consider $HW$ and $HZ$ signals: $H \to b\bar{b}$, $W \to \ell \nu$ and $Z \to \ell^+ \ell^-$.

### Common cuts

- $p_{tV}$, $p_{tH} > 200$ GeV
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- $S/\sqrt{B}$ from 16 GeV window

### Tools:

Herwig 6.510, Jimmy 4.31 (tuned), hadron-level $\to$ FastJet 2.3

### Backgrounds:

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- $|\eta_{Higgs-Jet}| < 2.5$
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- $S/\sqrt{B}$ from 16 GeV window ATLAS jet-mass resln $\sim$ half this?

**Tools:** Herwig 6.510, Jimmy 4.31 (tuned), hadron-level $\rightarrow$ FastJet 2.3

**Backgrounds:** $VV, Vj, jj, t\bar{t}$, single-top, with $> 30$ fb$^{-1}$ (except $jj$)
The full analysis (scaled to 30 fb$^{-1}$)

Consider $HW$ and $HZ$ signals: $H \rightarrow b\bar{b}$, $W \rightarrow 3 \ell\ell$, $Z \rightarrow \ell^+\ell^- + E_T$, and $Z \rightarrow \nu\bar{\nu}$.

**Common cuts**

- $p_{tV}, p_{tH} > 200$ GeV
- $|\eta_{Higgs-jet}| < 2.5$
- $\ell = e, \mu, p_{t\ell} > 30$ GeV, $|\eta_\ell| < 2.5$
- No extra $\ell$, $b$'s with $|\eta| < 2.5$

**Channel-specific cuts:**

See next slides

**Assumptions**

- Real/fake $b$-tag rates: 0.6/0.02
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**Backgrounds:** $VV$, $Vj$, $jj$, $t\bar{t}$, single-top, with $> 30$ fb$^{-1}$ (except $jj$)
combine HZ and HW, $p_t > 200$ GeV

**Common cuts**

- $p_{tV}, p_{tH} > 200$ GeV
- $|\eta_H| < 2.5$
- $[p_{t,\ell} > 30$ GeV, $|\eta_\ell| < 2.5]$
- No extra $\ell, b'$s with $|\eta| < 2.5$
- Real/fake $b$-tag rates: $0.6/0.02$
- $S/\sqrt{B}$ from 16 GeV window

**Leptonic channel**

$Z \rightarrow \mu^+\mu^-, e^+e^-$

- $80 < m_{\ell^+\ell^-} < 100$ GeV

At $4.5\sigma$ for 30 fb$^{-1}$ this looks like a possible new channel for light Higgs discovery. Deserves serious exp. study!
combine HZ and HW, $p_t > 200$ GeV

**Common cuts**

- $p_{tV}, p_{tH} > 200$ GeV
- $|\eta_H| < 2.5$
- $[p_{t\ell} > 30$ GeV, $|\eta_{\ell}| < 2.5]$
- No extra $\ell, b$'s with $|\eta| < 2.5$
- Real/fake $b$-tag rates: 0.6/0.02
- $S/\sqrt{B}$ from 16 GeV window

**Missing-$E_T$ channel**

$Z \rightarrow \nu \bar{\nu}, W \rightarrow \nu [\ell]$

- $E_T > 200$ GeV

At $4.5\sigma$ for 30 fb$^{-1}$ this looks like a possible new channel for light Higgs discovery. Deserves serious exp. study!
combine HZ and HW, $p_t > 200$ GeV

Semi-leptonic channel

Common cuts

- $p_t V, p_t H > 200$ GeV
- $|\eta_H| < 2.5$
- $[p_t, \ell > 30$ GeV, $|\eta_\ell| < 2.5]$  
- No extra $\ell$, $b$'s with $|\eta| < 2.5$
- Real/fake $b$-tag rates: 0.6/0.02
- $S/\sqrt{B}$ from 16 GeV window

Semi-leptonic channel

$W \rightarrow \nu \ell$

- $E_T > 30$ GeV (\& consistent $W$.)
- no extra jets $|\eta| < 3$, $p_t > 30$

At $4.5\sigma$ for 30 fb$^{-1}$ this looks like a possible new channel for light Higgs discovery. Deserves serious exp. study!
**VH Results**

Combine HZ and HW, $p_t > 200$ GeV

### 3 channels combined

![Graph](image)

**Common cuts**

- $p_{tV}, p_{tH} > 200$ GeV
- $|\eta_H| < 2.5$
- $[p_{t,\ell} > 30$ GeV, $|\eta_\ell| < 2.5]$
- No extra $\ell$, $b$'s with $|\eta| < 2.5$
- Real/fake $b$-tag rates: 0.6/0.02
- $S/\sqrt{B}$ from 16 GeV window

**3 channels combined**

Note excellent VZ, $Z \rightarrow b\bar{b}$ peak for calibration

**NB:** $q\bar{q}$ is mostly $t\bar{t}$

At 4.5σ for 30 fb$^{-1}$ this looks like a possible new channel for light Higgs discovery. **Deserves serious exp. study!**
**Rough impact of going to high-$p_t$**

### How can we be doing so well despite losing factor 20 in X-sct?

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>Background</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eliminate $t\bar{t}$, etc.</td>
<td>—</td>
<td>$\times 1/3$</td>
<td>[very approx.]</td>
</tr>
<tr>
<td>$p_t &gt; 200$ GeV</td>
<td>$\times 1/20$</td>
<td>$\times 1/60$</td>
<td>[bkgds: $Wb\bar{b}$, $Zb\bar{b}$]</td>
</tr>
<tr>
<td>Improved acceptance</td>
<td>$\times 4$</td>
<td>$\times 4$</td>
<td></td>
</tr>
<tr>
<td>Twice better resolution</td>
<td>—</td>
<td>$\times 1/2$</td>
<td></td>
</tr>
<tr>
<td>Add $Z \rightarrow \nu\bar{\nu}$</td>
<td>$\times 1.5$</td>
<td>$\times 1.5$</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$\times 0.3$</td>
<td>$\times 0.017$</td>
<td></td>
</tr>
</tbody>
</table>

much better $S/B$; better $S/\sqrt{B}$

[exact numbers depend on analysis details]
Impact of $b$-tagging, Higgs mass

Most scenarios above $3\sigma$

For it to be a significant discovery channel requires decent $b$-tagging, lowish mass Higgs [and good experimental resolution]

In nearly all cases, suitable for extracting $b\bar{b}H$, $WWH$, $ZZH$ couplings
Impact of $b$-tagging, Higgs mass

Most scenarios above $3\sigma$

For it to be a significant discovery channel requires decent $b$-tagging, lowish mass Higgs [and good experimental resolution]

In nearly all cases, suitable for extracting $b\bar{b}H$, WWH, ZZH couplings
You only know it’s the SM Higgs if couplings agree with SM expectations. Detailed study of all observable LHC Higgs production/decay channels carried out by Lafaye, Plehn, Rauch, Zerwas, Duhrssen ’09

Without VH, $H \to b\bar{b}$

With VH, $H \to b\bar{b}$

Without direct $H \to b\bar{b}$ measurement, errors on couplings increase by $\sim 100\%$
Does any of this hold with a real detector?

ATLAS had $WW$ scattering studies with the $k_t$ algorithm that suggested that general techniques were realistic.

But kinematic region was different ($p_t > 500$ GeV). And Higgs also has $b$-tagging of subjets, . . .
As of August 2009: ATLAS have preliminary public analysis of this channel

ATL-PHYS-PUB-2009-088

What changes?

- Inclusion of detector simulation mixture of full and validated ATLFAST-II
- Study of triggers All OK
- New issue: *importance of fake b tags from charm quarks*
- But b-tagging itself reaches 70% eff, 1% fake-rate for light partons
- *New background: Wt production* with $t \rightarrow bW$, $W \rightarrow cs$, giving $bc$ as a Higgs candidate.
- Larger mass windows, 24 – 32 GeV rather than 16 GeV for signal, reflecting full detector resolution
- Various changes in details of cuts
- ATLAS numbers shown for $m_H = 120$ GeV (previous plots: $m_H = 115$ GeV)
Leptonic channel

What changes compared to particle-level analysis?

$\sim 1.5\sigma$ as compared to $2.1\sigma$

Expected given larger mass window
What changes compared to particle-level analysis?

\[ \sim 1.5\sigma \text{ as compared to } 3\sigma \]
Suffers: some events redistributed to semi-leptonic channel
ATLAS results

Semi-leptonic channel

What changes compared to particle-level analysis?

$\sim 3\sigma$ as compared to $3\sigma$

Benefits: some events redistributed from missing $E_T$ channel
Likelihood-based analysis of all three channels together gives signal significance of

\[ 3.7\sigma \text{ for } 30 \text{ fb}^{-1} \]

To be compared with \( 4.2\sigma \) in hadron-level analysis for \( m_H = 120 \text{ GeV} \)

K-factors not included: don’t affect significance (\( \sim 1.5 \) for VH, 2 – 2.5 for Vbb)

With 5\% (20\%) background uncertainty, ATLAS result becomes 3.5\( \sigma \) (2.8\( \sigma \))

Comparison to other channels at ATLAS (\( m_H = 120, 30 \text{ fb}^{-1} \)):

<table>
<thead>
<tr>
<th>Process</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>( gg \to H \to \gamma\gamma )</td>
<td>4.2( \sigma )</td>
</tr>
<tr>
<td>( WW \to H \to \tau\tau )</td>
<td>4.9( \sigma )</td>
</tr>
<tr>
<td>( gg \to H \to ZZ^* )</td>
<td>2.6( \sigma )</td>
</tr>
</tbody>
</table>

Extracted from 0901.0512
ATLAS: “Future improvements can be expected in this analysis:”

- b-tagging might be calibrated [for this] kinematic region
- jet calibration [...] hopefully improving the mass resolution
- background can be extracted directly from the data
- multivariate techniques

CMS is looking at this channel
- Biggest difference wrt ATLAS could be jet mass resolution
  But CMS have plenty of good ideas that might compensate for worse hadronic calorimeter

Combination of different kinematic regions
- E.g. in original analysis, $p_t > 300$ GeV (only 1% of VH, but very clear signal) was almost as good as $p_t > 300$ GeV (5% of VH).
- Treating different $p_t$ ranges independently may have benefits.
What about other boosted objects?

E.g. Boosted top

[hadronic decays]
$X \rightarrow t\bar{t}$ resonances of varying difficulty

RS KK resonances $\rightarrow t\bar{t}$, from Frederix & Maltoni, 0712.2355

NB: QCD dijet spectrum is $\sim 500$ times $t\bar{t}$
Tagging boosted top-quarks

High-$p_t$ top production often envisaged in New Physics processes.\[\sim\] high-$p_t$ EW boson, but: top has 3-body decay and is coloured.

7 papers on top tagging in ’08-’09 (at least): jet mass + something extra.

Questions

- What efficiency for tagging top?
- What rate of fake tags for normal jets?

<table>
<thead>
<tr>
<th>Rough results for top quark with $p_t \sim 1$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>“Extra”</strong></td>
</tr>
<tr>
<td>[from T&amp;W]</td>
</tr>
<tr>
<td>Brooijmans ’08</td>
</tr>
<tr>
<td>Thaler &amp; Wang ’08</td>
</tr>
<tr>
<td>Kaplan et al. ’08</td>
</tr>
<tr>
<td>Almeida et al. ’08</td>
</tr>
<tr>
<td>Ellis et al. ’09</td>
</tr>
<tr>
<td>ATLAS ’09</td>
</tr>
<tr>
<td>Plehn et al. ’09</td>
</tr>
</tbody>
</table>
Kaplan, Rehermann, Schwartz & Tweedie '08

Efficiency v. $p_T$

- $t\bar{t}$
- Boosted top

Tagging efficiency

- $\epsilon_t$
- $10\times\epsilon_g$
- $10\times\epsilon_q$

$p_T$ (GeV)
Efficiency v. $p_T$

Kaplan et al '08

without detector segmentation

$\epsilon_t$

$10 \times \epsilon_g$

$10 \times \epsilon_q$

Tagging efficiency

$p_T$ (GeV)

$600$ $800$ $1000$ $1200$ $1400$ $1600$ $1800$ $2000$
$t\bar{t}H$

boosted top and Higgs together?

(NB: inclusive $ttH$ deemed unviable in past years by ATLAS & CMS)
Resurrecting $t\bar{t}H$?

\[ pp \rightarrow t\bar{t}H \]

- $t \rightarrow b\ell(\not{E}_T)$
- $t \rightarrow \text{jet}_{jjj}$ (boosted)
- $H \rightarrow \text{jet}_{bb}$ (boosted)

Ask for just two boosted particles in order to maintain some cross-section

Plehn, GPS & Spannowsky '09

Main ingredients

- one lepton $p_T > 15 \text{ GeV}, |y| < 2.5$
- $\geq 2$ C/A ($R = 1.5$) jets with $p_T > 200 \text{ GeV}, |y| < 2.5$
- Mass-drop based substructure ID for top
  - With filtering to reduce UE
  - Allow for extraneous subjets since busy environment
  - require $65 < m_W < 95 \text{ GeV}, 150 < m_t < 200 \text{ GeV}$

Similar substructure on procedure on other hard jets: any pair of
  - b-tagged subjets within the same hard jet is a Higgs candidate
After eliminating constituents from tagged hadronic top and H, require one extra b-jet (C/A, $R=0.6$, $p_T > 40 \text{ GeV}$).
Resurrecting $t\bar{t}H$?

$$pp \to t\bar{t}H$$

$$t \to b\ell(\not{E_T})$$

$$t \to \text{jet}_{jjj} \quad \text{(boosted)}$$

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Plehn, GPS & Spannowsky '09

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\[ pp \rightarrow t\bar{t}H \]

\[ t \rightarrow b\ell(\not{E}_T) \]

\[ t \rightarrow \text{jet}_{jjj} \quad \text{(boosted)} \]

\[ H \rightarrow \text{jet}_{bb} \quad \text{(boosted)} \]

Ask for just two boosted particles in order to maintain some cross-section

\[ \text{Plehn, GPS & Spannowsky '09} \]

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With filtering to reduce UE

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$$t \rightarrow b\ell(\not{E_T})$$

$$t \rightarrow \text{jet}_{jjj} \quad \text{(boosted)}$$

$$H \rightarrow \text{jet}_{bb} \quad \text{(boosted)}$$

Ask for just two boosted particles in order to maintain some cross-section

Plehn, GPS & Spannowsky '09

Main ingredients

- one lepton $p_t > 15$ GeV, $|y| < 2.5$
- $\geq 2$ C/A ($R = 1.5$) jets with $p_T > 200$ GeV, $|y| < 2.5$
- Mass-drop based substructure ID for top
  - With filtering to reduce UE
  - Allow for extraneous subjets since busy environment
  - require $65 < m_W < 95$ GeV, $150 < m_t < 200$ GeV
- Similar substructure on procedure on other hard jets: any pair of b-tagged subjets within the same hard jet is a Higgs candidate
- After eliminating constituents from tagged hadronic top and $H$, require one extra b-jet (C/A, $R=0.6$, $p_t > 40$ GeV).
Signal, backgrounds, tools

\textit{ttH}: Madgraph + Herwig++ 2.3.1; Herwig 6.510

\textit{ttbb}: Madgraph + Herwig++; Alpgen + Herwig 6.5

\textit{ttj}(j): Herwig 6.5 $t\bar{t}$ events (jets from shower)
   
   But we check that its \textit{ttbb} component is consistent with the ME \textit{ttbb} simulation
   
   And for final result it’s negligible anyway

\textit{Wjj}: Madgraph (\textit{Wjj}) + Herwig++ (for internal structure in j’s)
   
   turns out to be negligible

\textit{ttZ}: Madgraph + Herwig++

NLO K-factors: 1.3 for \textit{ttH}, 2.2 for \textit{ttbb}; we don't know what to do for \textit{ttj}(j)

\textit{ttH}: Madgraph + Herwig++

UE: Herwig++ default; Jimmy 4.31 for Herwig (quite noisy old ATLAS tune)

Particle-level analysis; $b$-tagging: 0.7/0.01 in subjets (cf ATLAS note), 0.6/0.02 otherwise. Checked 10% fake rate from charm (small effect).

Jet clustering: FastJet 2.4
ttH subjet analysis

Decomposition of jet into subjets

- Break $j$ into $j_1, j_2$, $m_{j_1} > m_{j_2}$
- If mass drop, i.e. $\max(m_{j_1}, m_{j_2}) < 0.9m_j$ (or 0.8), recurse on $j_1, j_2$, otherwise recurse just on $j_1$
- Stop when $m_j < 30$ GeV

Top tagging

- Look for all pairs of subjets consistent with $m_W$ and an additional third subjet consistent with $m_t$ + cut on helicity angle, $\theta_h$
  
  \[ \theta_h \text{ cut as in Kaplan et al '08} \]
- Take solution most consistent with $m_W$ and $m_t$

Higgs tagging

- Take all pairs of b-tagged subjets

Filtering

- Apply to $W$, top and $H$ mass reconstructions
Cross sections in fb (including NLO K-factors for signal, $t\bar{t}b\bar{b}$ & $t\bar{t}Z$)

<table>
<thead>
<tr>
<th>Stage of Analysis</th>
<th>signal</th>
<th>$t\bar{t}Z$</th>
<th>$t\bar{t}b\bar{b}$</th>
<th>$t\bar{t}+$jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events after acceptance $\ell+2j$ cuts</td>
<td>24.9</td>
<td>7.3</td>
<td>229</td>
<td>5200</td>
</tr>
<tr>
<td>Events with one top tag</td>
<td>10.6</td>
<td>3.1</td>
<td>84.2</td>
<td>1821</td>
</tr>
<tr>
<td>Events with $m_{jj} = 110 - 130$ GeV corresponding to subjet pairings</td>
<td>3.0</td>
<td>0.47</td>
<td>15.1</td>
<td>145</td>
</tr>
<tr>
<td>Subjet pairings two subjet $b$ tags</td>
<td>3.3</td>
<td>0.50</td>
<td>16.5</td>
<td>151</td>
</tr>
<tr>
<td>Subjet pairings two subjet $b$ tags including a third $b$ tag</td>
<td>1.0</td>
<td>0.08</td>
<td>2.7</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>0.48</td>
<td>0.03</td>
<td>1.26</td>
<td>0.07</td>
</tr>
</tbody>
</table>
**$t\bar{t}H$ results**

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>$S$ (fb)</th>
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<tr>
<td>115</td>
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Numbers of events in 20 GeV window centred on Higgs mass, including $K$-factors

Using 0.7/0.01 for $b$-tag rate/fake within subjet (cf. ATLAS '09)
and 0.6/0.02 for $b$-tag rate/fake in “normal” jet
**$t\bar{t}H$ results**

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and 0.6/0.02 for $b$-tag rate/fake in “normal” jet

Doesn’t recover $t\bar{t}H$ as a discovery channel, but promising for coupling measurements

Next step: see what ATLAS & CMS say
Boosted new-physics objects?
As a final example, a search for neutralinos in R-parity violating supersymmetry.

Normal SPS1A type SUSY scenario, except that neutralino is not LSP, but instead decays, $\tilde{\chi}_1^0 \rightarrow qqq$.

Jet combinatorics makes this a tough channel for discovery.

- Produce pairs of squarks, $m_{\tilde{q}} \sim 500$ GeV.
- Each squark decays to quark + neutralino, $m_{\tilde{\chi}_1^0} \sim 100$ GeV
- Neutralino is somewhat boosted → jet with substructure

Butterworth, Ellis, Raklev & GPS ’09
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- Neutralino is somewhat boosted \( \rightarrow \) jet with substructure

Butterworth, Ellis, Raklev & GPS ’09
Subjet decomposition procedures are not just trial and error.

Mass distribution for undecomposed jet:

\[
\frac{1}{N} \frac{dN}{dm} \sim \frac{2C\alpha_s \ln Rp_t/m}{m} e^{-C\alpha_s \ln^2 Rp_t/m + \cdots}
\]

Strongly shaped, with Sudakov peak, etc.

Mass distribution for hardest (largest Jade distance) substructure within C/A jet that satisfies a symmetry cut (\(z > z_{min}\)):

\[
\frac{1}{N} \frac{dN}{dm} \sim \frac{C'\alpha_s(m)}{m} e^{-C'\alpha_s \ln Rp_t/m + \cdots}
\]

\[
\sim \frac{C'\alpha_s(Rp_t)}{m} \left[ 1 + (2b_0 - C') \alpha_s \ln Rp_t/m + \mathcal{O}(\alpha_s^2 \ln^2) \right]
\]

Procedure gives nearly flat distribution in \(mdN/dm\)

Neutralino procedure involves 2 hard substructures, but ideas are similar
Knock it simple:

**Look at mass of leading jet**

- Plot $\frac{m_{100 \text{ GeV}} \frac{dN}{dm}}{\text{dN/dbin per fb}^{-1}}$ for hardest jet ($p_t > 500 \text{ GeV}$)
- Require 3-pronged substructure
- And third jet
- And fourth central jet

99% background rejection

scale-invariant procedure so remaining bkgd is flat

Once you’ve found neutralino:

- Look at $m_{14}$ using events with $m_1$ in neutralino peak and in sidebands

Out comes the squark!
Keep it simple:

**Look at mass of leading jet**

- Plot \( \frac{m}{100 \text{ GeV}} \frac{dN}{dm} \) for hardest jet (\( p_t > 500 \text{ GeV} \))
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Neutralinos

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Neutralinos

RPV SUSY, SPS1a, 1 fb$^{-1}$

Keep it simple:

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- And fourth central jet

99% background rejection using scale-invariant procedure so remaining bkgd is flat

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Out comes the squark!
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- Plot $\frac{m}{100\,\text{GeV}} \frac{dN}{dm}$ for hardest jet ($p_t > 500$ GeV)
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- And third central jet
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so remaining bkgd is flat

Once you’ve found neutralino:

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Out comes the squark!
Neutralinos

\[ \frac{m}{100 \text{ GeV}} \frac{dN}{dm} \text{ per fb}^{-1} \]

Keep it simple:

**Look at mass of leading jet**

- Plot \( \frac{m}{100 \text{ GeV}} \frac{dN}{dm} \) for hardest jet (\( p_t > 500 \text{ GeV} \))
- Require 3-pronged substructure
- And third **central jet**
- And fourth central jet

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**Once you’ve found neutralino:**

- Look at \( m_{14} \) using events with \( m_1 \) in neutralino peak and in sidebands

Out comes the squark!
Conclusions
Higgs discovery

- High-$p_t$ limit recovers WH and ZH ($H \rightarrow b\bar{b}$) channel at LHC
- So far, only viable channel that can see $H \rightarrow b\bar{b}$ decay
- First in-depth experimental study from ATLAS has promising results
  Work continues in ATLAS. Also being examined by CMS
- Related methods look promising for observation of $t\bar{t}H$, $H \rightarrow b\bar{b}$

New Physics searches

- Can be used for ID of high-$p_t$ top from decaying multi-TeV resonances
  Kaplan et al. 40%/1% eff./fake rate $\sim$ moderate-$p_t$ $b$-tag performance!
- Can be used for ID of EW-scale new particles, e.g. neutralino

General

- Boosted EW-scale particles can be found in jets
- Cambridge/Aachen alg. is very powerful (flexible, etc.) tool for this
  Being used in many different ways
- QCD resummation formulae help tell you why certain methods work well
Cross section for signal and the $Z$+jets background in the leptonic $Z$ channel for $200 < p_{TZ}/\text{GeV} < 600$ and $110 < m_J/\text{GeV} < 125$, with perfect $b$-tagging; shown for our jet definition (C/A MD-F), and other standard ones close to their optimal $R$ values.

<table>
<thead>
<tr>
<th>Jet definition</th>
<th>$\sigma_S/\text{fb}$</th>
<th>$\sigma_B/\text{fb}$</th>
<th>$S/\sqrt{B}\cdot\text{fb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/A, $R = 1.2$, MD-F</td>
<td>0.57</td>
<td>0.51</td>
<td>0.80</td>
</tr>
<tr>
<td>$k_t$, $R = 1.0$, $y_{cut}$</td>
<td>0.19</td>
<td>0.74</td>
<td>0.22</td>
</tr>
<tr>
<td>SISCone, $R = 0.8$</td>
<td>0.49</td>
<td>1.33</td>
<td>0.42</td>
</tr>
<tr>
<td>anti-$k_t$, $R = 0.8$</td>
<td>0.22</td>
<td>1.06</td>
<td>0.21</td>
</tr>
</tbody>
</table>
Analysis shown without $K$ factors. What impact do they have?

- **Signal:** $K \sim 1.6$
- **$Vbb$ backgrounds:** $K \sim 2 - 2.5$
- **$t\bar{t}$ backgrounds:** $K \sim 2$ for total; not checked for high-$p_t$ part

Conclusion: $S/\sqrt{B}$ should not be severely affected by NLO contributions
Raise $p_t$ cut to 300 GeV (70%/1% $b$-tagging).

NB: kills $t\bar{t}$ background.
Boosted top extras
If you want to use the tagged top (e.g. for $t\bar{t}$ invariant mass) QCD tells you:

\[
\text{the jet you use to tag a top quark} \neq \text{the jet you use to get its } p_t
\]

Within inner cone $\sim \frac{2m_t}{p_t}$ (dead cone) you have the top-quark decay products, but no radiation from top ideal for reconstructing top mass

Outside dead cone, you have radiation from top quark essential for top $p_t$

Cacciari, Rojo, GPS & Soyez '08
Impact of using small cone angle

**Use small cone**

qq, M = 4000 GeV

Cam/Aachen, R=0.4
Q^W_f=0.24 = 416.2 GeV

**Use large cone**

qq, M = 4000 GeV

C/A-filt, R=1.2
Q^W_f=0.24 = 162.5 GeV

Figure actually from 0810.1304 (Cacciari, Rojo, GPS & Soyez)
for light $q\bar{q}$ resonance — but $t\bar{t}$ will be similar

How you look at your event matters: http://quality.fastjet.fr/
Neutralino extras
RPV SUSY: significance v. mass scale

- All points use $1\text{ fb}^{-1}$
- as $m_\chi$ increases, $m_\tilde{q}$ goes from 530 GeV to 815 GeV
- Same cuts as for main SPS1A analysis
  
  no particular optimisation