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

Gavin P. Salam
LPTHE, UPMC Paris 6 & CNRS

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: $pp \to HV$ with $H \to b\bar{b}$

  Butterworth, Davison, Rubin & GPS '09

- 30% on other applications of these ideas — many groups, including

  Butterworth, Ellis, Raklev & GPS '09; Plehn, GPS & Spannowsky '09

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: $pp \to HV$ with $H \to b\bar{b}$

  Butterworth, Davison, Rubin & GPS '09

- 30% on other applications of these ideas — many groups, including

  Butterworth, Ellis, Raklev & GPS '09; Plehn, GPS & Spannowsky '09

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

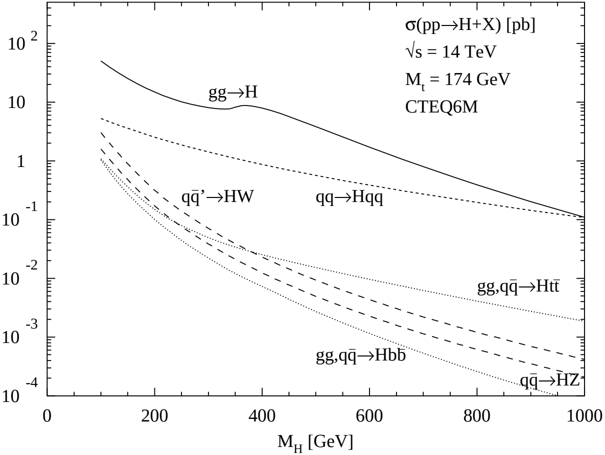
New strategy emerging in past 2 years: **boosted particle searches**

- 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: $pp \to HV$ with $H \to b\bar{b}$
  Butterworth, Davison, Rubin & GPS '09
- 30% on other applications of these ideas — many groups, including
  Butterworth, Ellis, Raklev & GPS '09; Plehn, GPS & Spannowsky '09

Higgs production at LHC



Dominant Higgs production channels:

- Gluon fusion

  via top loop

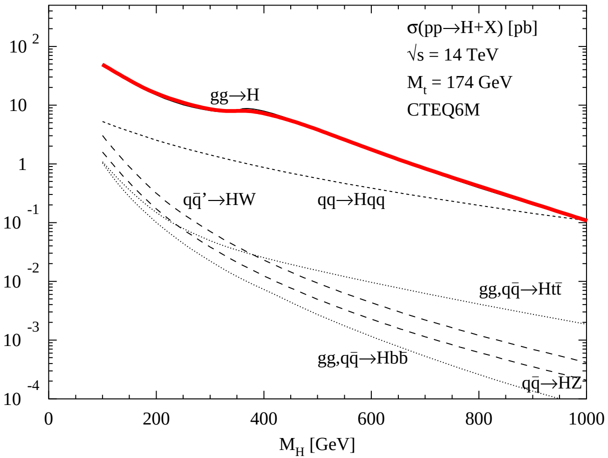
- Vector-boson fusion

  with two forward jets

- Associated production

  H radiated off top-quark or W or Z boson

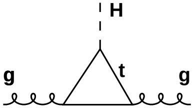
Higgs production at LHC



Dominant Higgs production channels:

- Gluon fusion

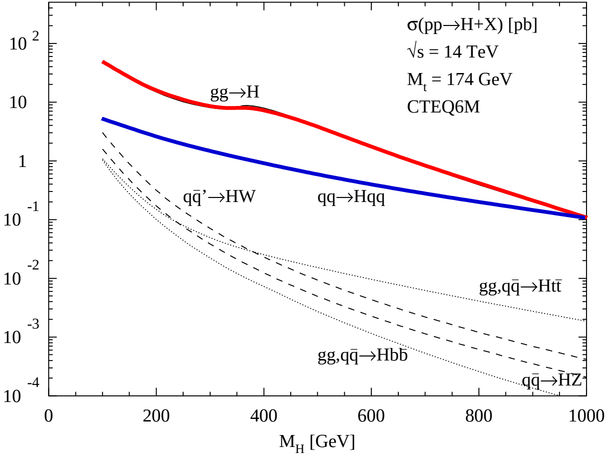
via top loop



- Vector-boson fusion
  with two forward jets

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

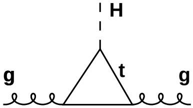
Higgs production at LHC



Dominant Higgs production channels:

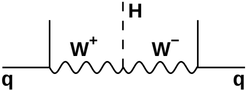
- Gluon fusion

  via top loop



- Vector-boson fusion

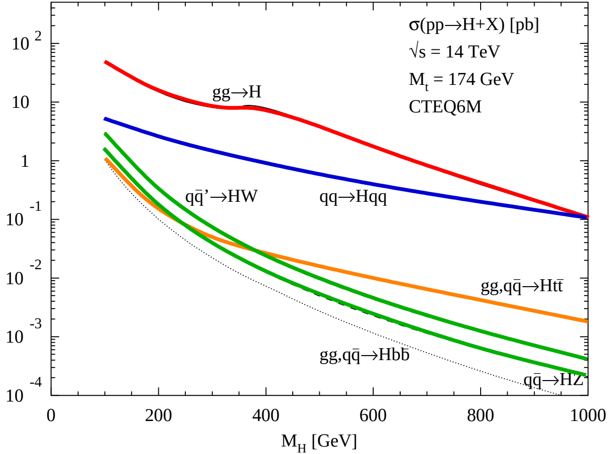
  with two forward jets



- Associated production

  H radiated off top-quark or W or Z boson

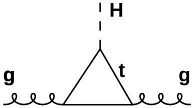
Higgs production at LHC



Dominant Higgs production channels:

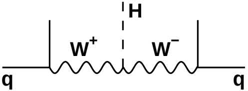
- Gluon fusion

via top loop



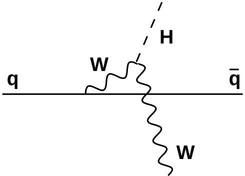
- Vector-boson fusion

with two forward jets

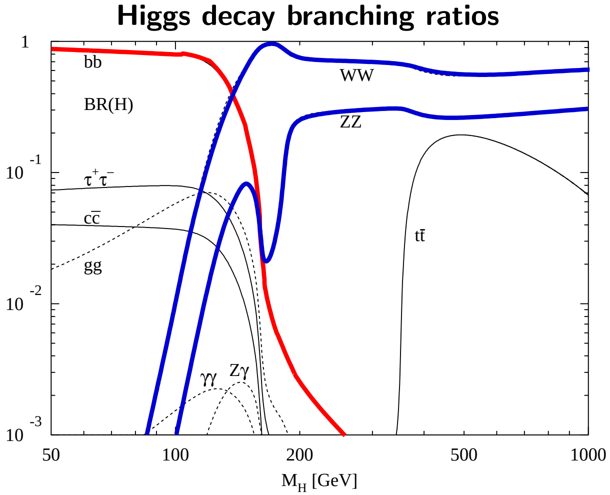


- Associated production

H radiated off top-quark or W or Z boson



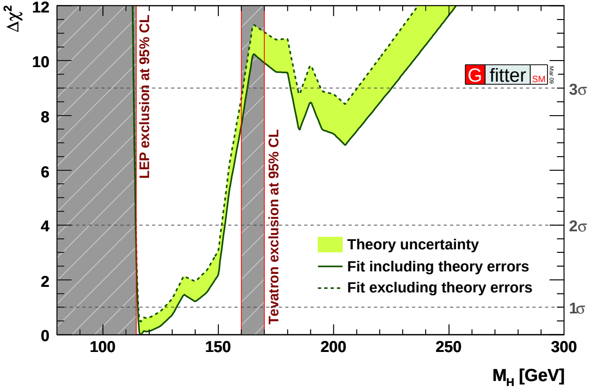
Higgs decay



Dominant Higgs decay mode depends on mass.

- Low mass: $H \to b\bar{b}$
- High mass: $H \to WW/ZZ$

Higgs mass constraints

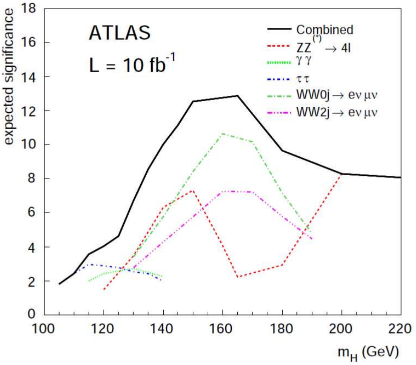


Mass constraints come from

- LEP exclusion
- Tevatron exclusion
- EW precision fits

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

LHC search propspects



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

Various production & decay processes

- $gg \to H \to \gamma\gamma$ feasible
- $WW \to H \to \tau\tau$ feasible
- $gg \to H \to ZZ^* \to 4\ell$ feasible
- $gg \to t\bar{t}H, H \to b\bar{b}$ v. hard
- $q\bar{q} \to WH, ZH, H \to b\bar{b}$ v. hard

What does a “very hard” search channel look like?

WH/ZH search channel @ LHC

- Signal is $W \to \ell\nu$, $H \to b\bar{b}$.

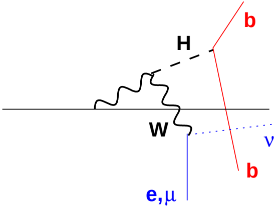
Studied e.g. in ATLAS TDR

- Backgrounds include $Wb\bar{b}$, $t\bar{t} \to \ell\nu b\bar{b}jj$, ...

Difficulties, e.g.

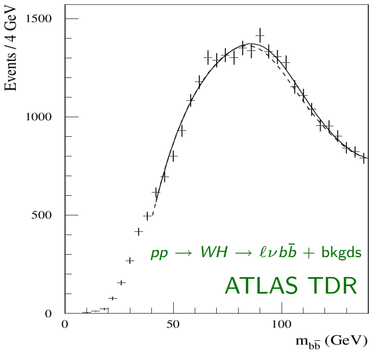
- Poor acceptance ($\sim 12\%$)

  Easily lose 1 of 4 decay products
- p_t cuts introduce intrinsic bkgd mass scale;
- $gg \to t\bar{t} \to \ell\nu b\bar{b}[jj]$ has similar scale
- small S/B
- Need exquisite control of bkgd shape



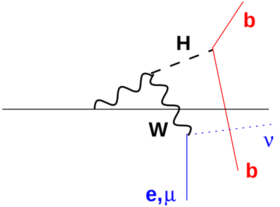
WH/ZH search channel @ LHC

- Signal is $W \to \ell\nu$, $H \to b\bar{b}$. Studied e.g. in ATLAS TDR
- Backgrounds include $Wb\bar{b}$, $t\bar{t} \to \ell\nu b\bar{b}jj$, ...



Difficulties, e.g.

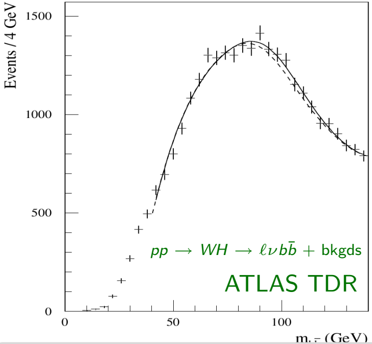
- Poor acceptance ($\sim$ 12%)
  Easily lose 1 of 4 decay products
- p_t cuts introduce intrinsic bkgd mass scale;
- $gg \to t\bar{t} \to \ell\nu b\bar{b}[jj]$ has similar scale
- small S/B
- Need exquisite control of bkgd shape



WH/ZH search channel @ LHC

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

Studied e.g. in ATLAS TDR

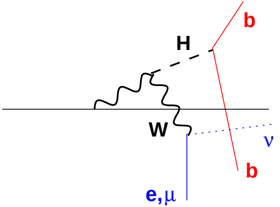


Difficulties, e.g.

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

Conclusion (ATLAS TDR):

"The extraction of a signal from $H \to b\bar{b}$ 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:

$$\frac{m_{EW}}{2} \longleftrightarrow 50 m_{EW}$$

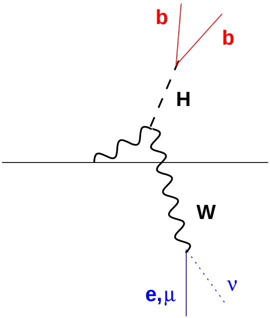
That's why it's being built

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 $Z \to \nu\bar{\nu}$ 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

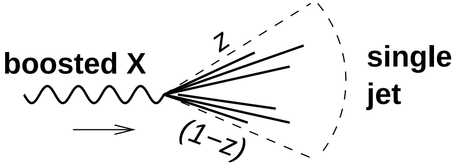
By a factor of 20 for $p_{tH} > 200$ GeV

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 $\mathbf{p_t} \neq$ two jets



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

<u>Rules of thumb:</u>

$m = 100$ GeV, $p_t = 500$ GeV

- $R < \dfrac{2m}{p_t}$: always resolve **two** jets — $R < 0.4$
- $R \gtrsim \dfrac{3m}{p_t}$: resolve **one** jet in 75% of cases $(\frac{1}{8} < z < \frac{7}{8})$ — $R \gtrsim 0.6$

Finding a boosted Higgs?

How do we find a boosted Higgs inside a single jet?

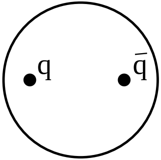
Special case of general (unanswered) question: how do we best do jet-finding?

Various people have looked at boosted objects over the years

- Seymour '93 [heavy Higgs $\to WW \to \nu\ell$jets]
- Butterworth, Cox & Forshaw '02 [$WW \to WW \to \nu\ell$jets]
- Agashe et al. '06 [KK excitation of gluon $\to t\bar{t}$]
- Butterworth, Ellis & Raklev '07 [SUSY decay chains $\to W, H$]
- Skiba & Tucker-Smith '07 [vector quarks]
- Lillie, Randall & Wang '07 [KK excitation of gluon $\to t\bar{t}$]
- ...

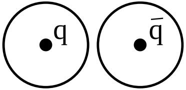
ETC.

Boosted ID strategies



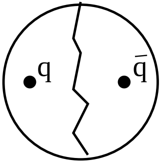
Select on the jet mass with one large (cone) jet

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

$\mathbf{k_t}$ algorithm:

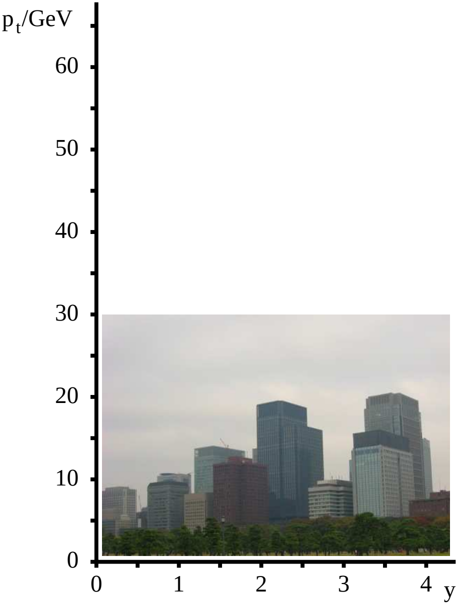
Find smallest of

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

If d_{ij} recombine; if d_{iB}, i is a jet
Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

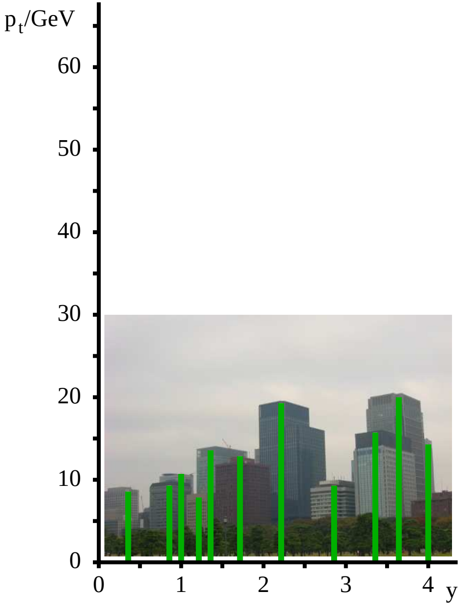
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

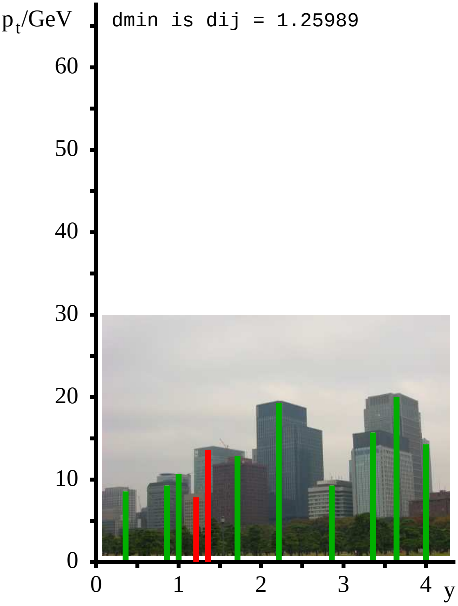
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

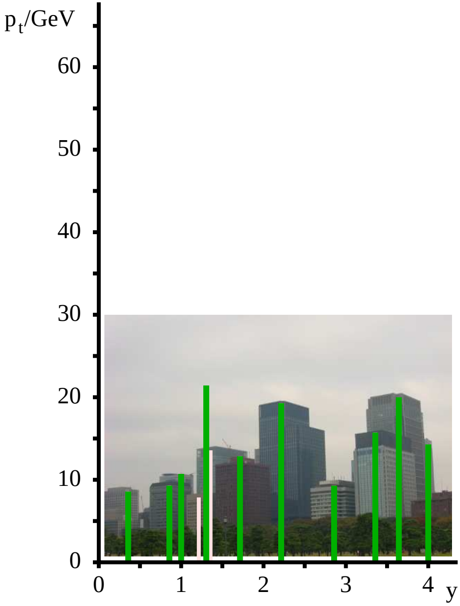
Find smallest of

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

If d_{ij} recombine; if d_{iB}, i is a jet
Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

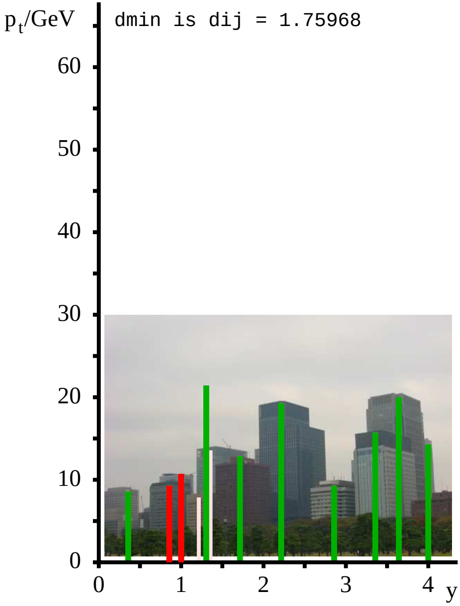
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

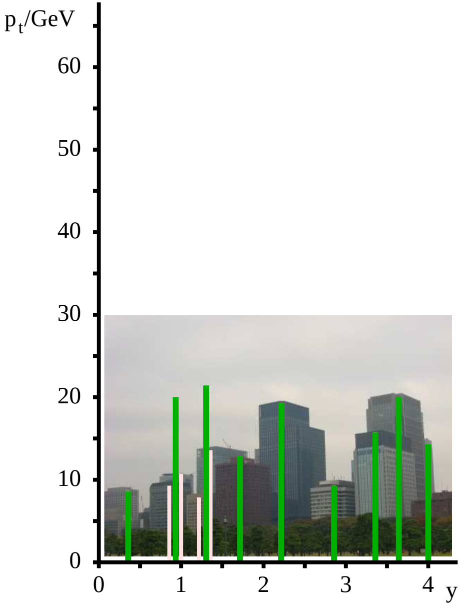
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

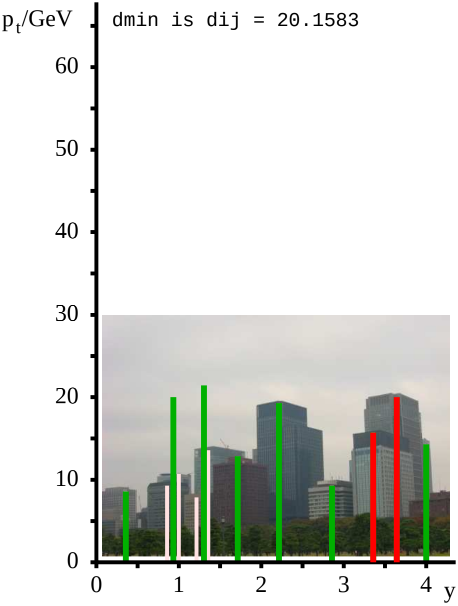
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

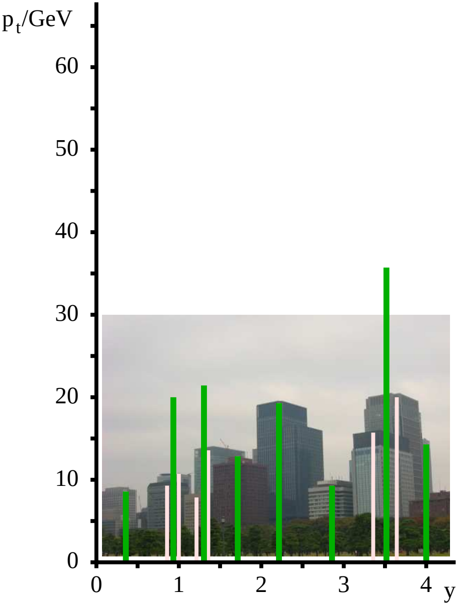
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

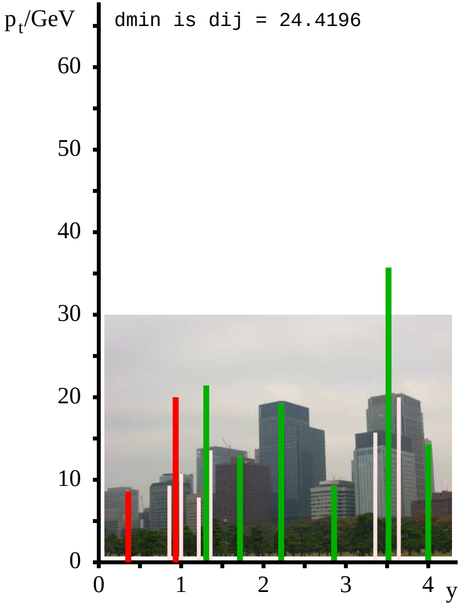
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

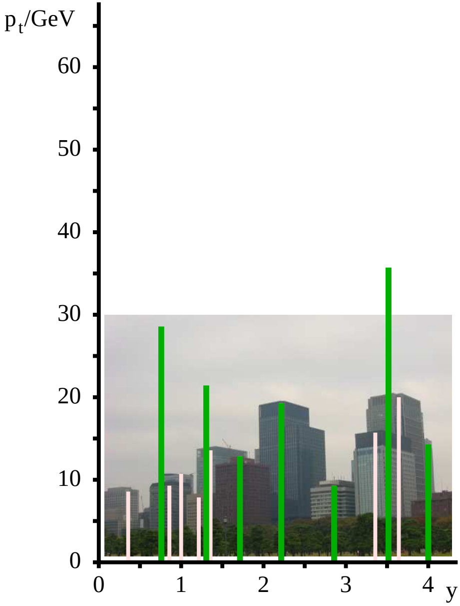
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

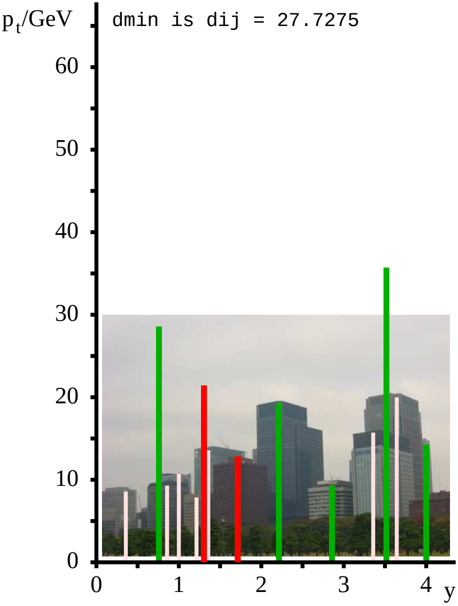
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

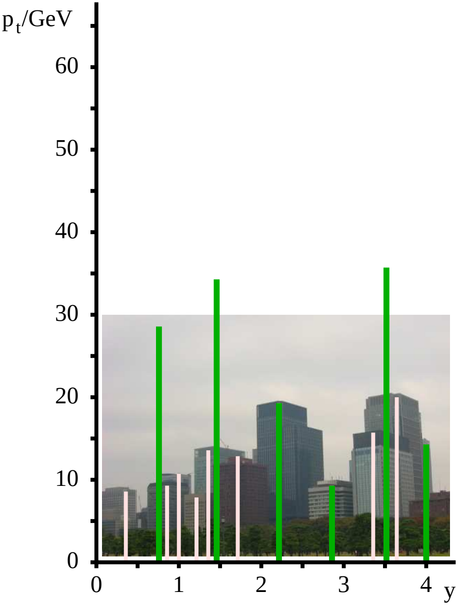
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

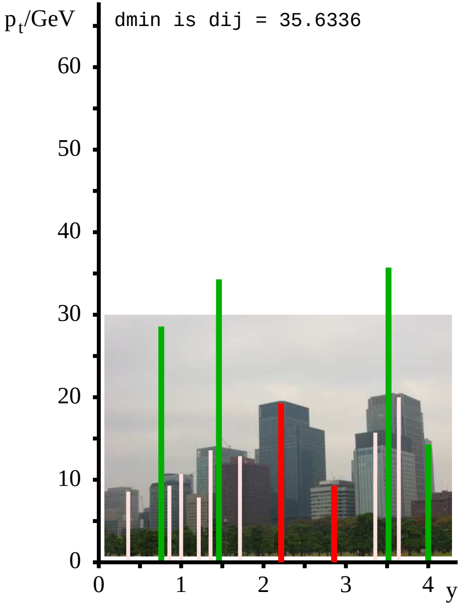
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



$\mathbf{k_t}$ algorithm:

Find smallest of

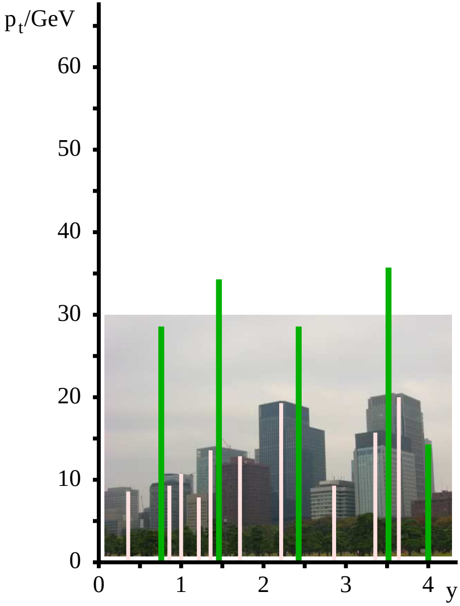
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

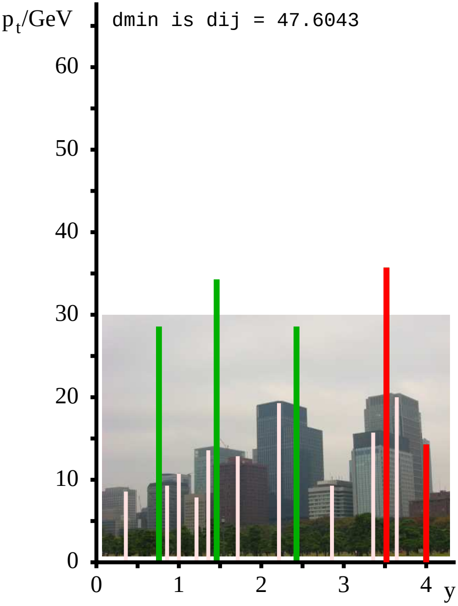
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

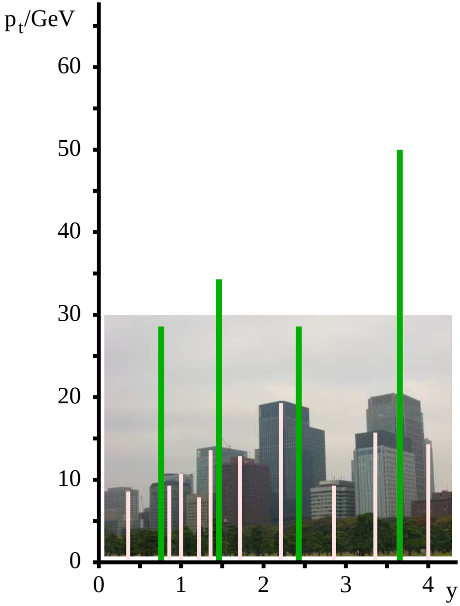
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

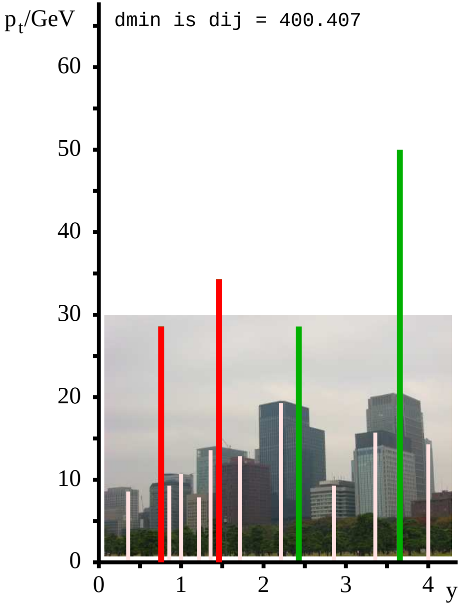
Find smallest of

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

If d_{ij} recombine; if d_{iB}, i is a jet
Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

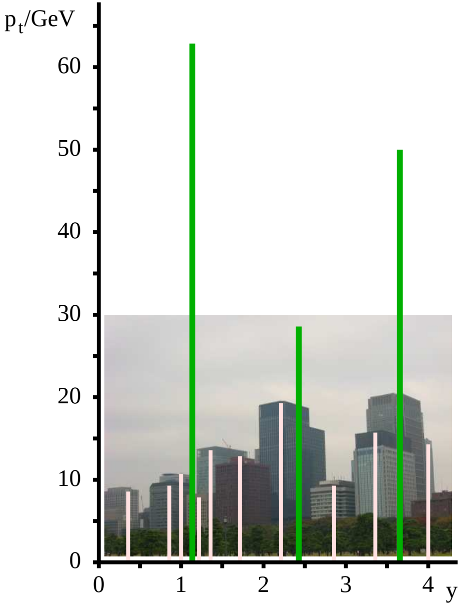
Find smallest of

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

If d_{ij} recombine; if d_{iB}, i is a jet
Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

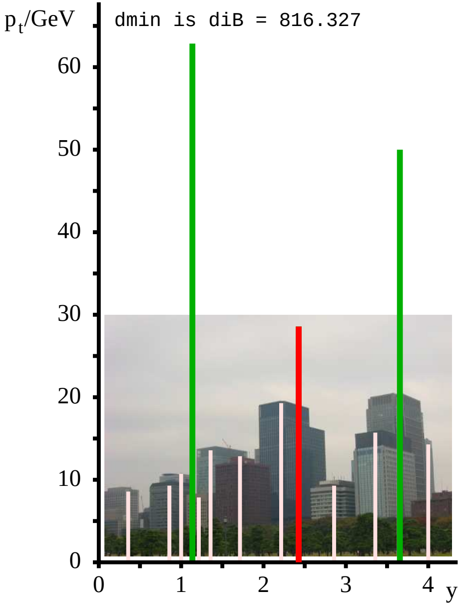
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

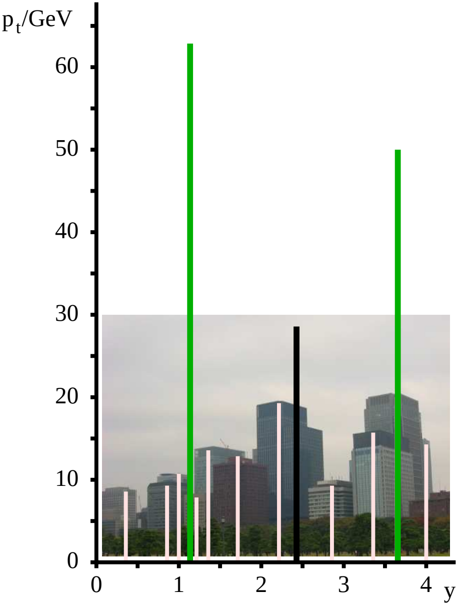
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

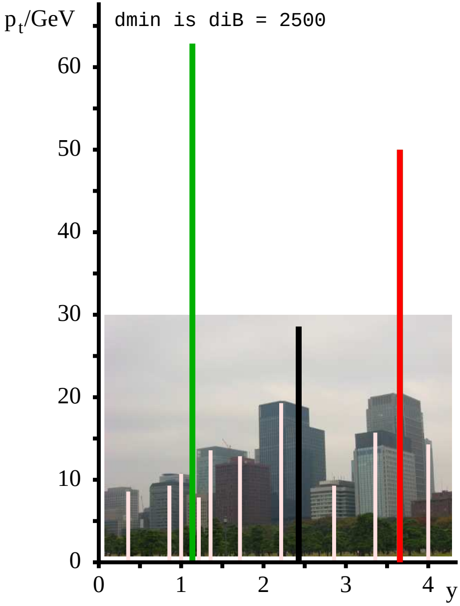
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

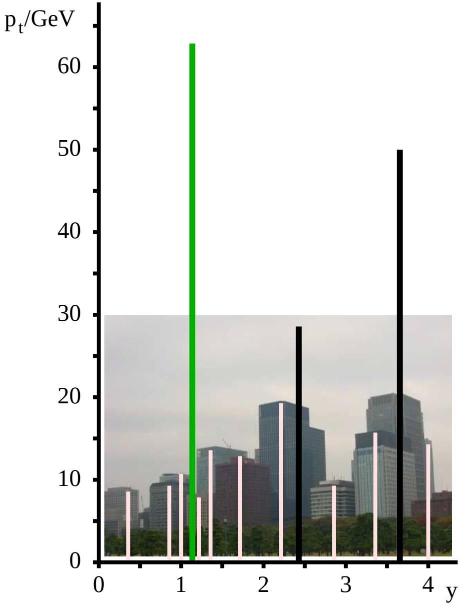
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

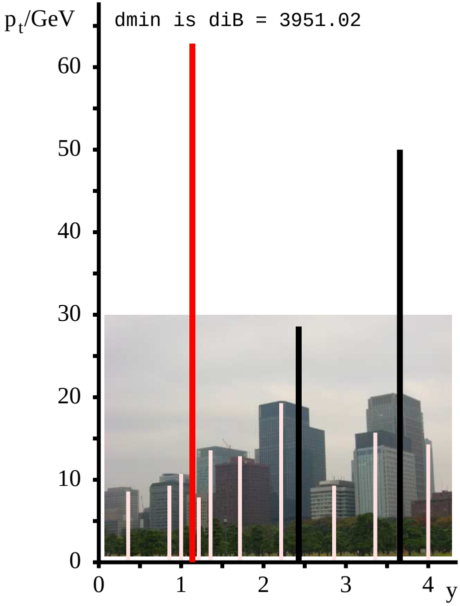
Find smallest of

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

If d_{ij} recombine; if d_{iB}, i is a jet
Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t algorithm:

Find smallest of

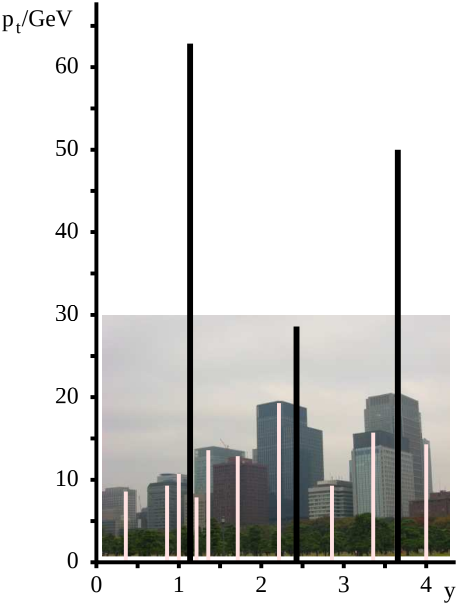
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

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

Example clustering with k_t algorithm, $R = 1.0$

ϕ assumed 0 for all towers

Sequential recombination



k_t 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, $R = 1.0$

ϕ assumed 0 for all towers

Past methods

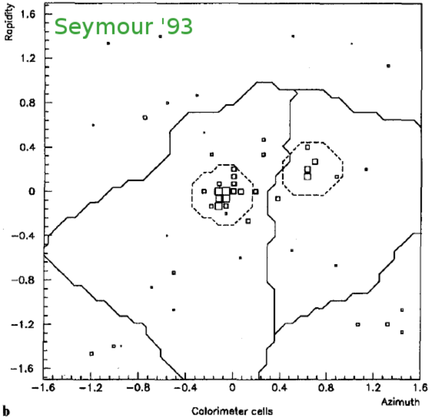
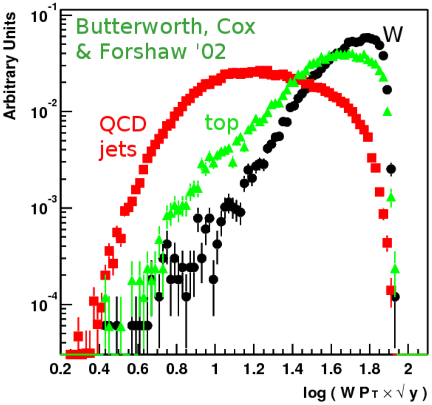


Fig. 2. A hadronic W decay, as seen at calorimeter level, **a** without, and **b** with, particles from the underlying event. Box sizes are logarithmic in the cell energy, lines show the borders of the sub-jets for infinitely soft emission according to the cluster (solid) and cone (dashed) algorithms

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

Past methods

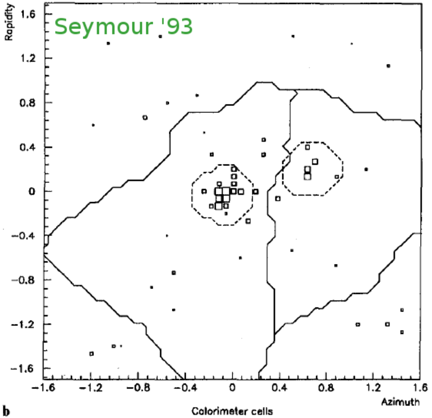
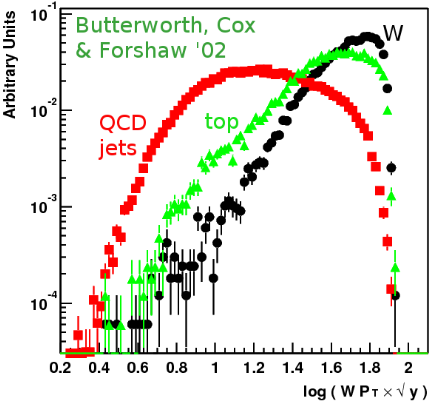


Fig. 2. A hadronic W decay, as seen at calorimeter level, **a** without, and **b** with, particles from the underlying event. Box sizes are logarithmic in the cell energy, lines show the borders of the sub-jets for infinitely soft emission according to the cluster (solid) and cone (dashed) algorithms

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

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

#1: Our tool

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

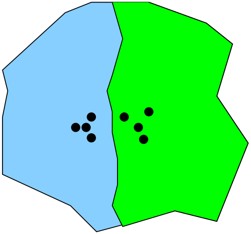
The Cambridge/Aachen jet alg.

Dokshitzer et al '97
Wengler & Wobisch '98

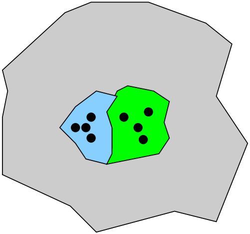
Work out $\Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta\phi_{ij}^2$ between all pairs of objects i, j;
Recombine the closest pair;
Repeat until all objects separated by $\Delta R_{ij} > R$. [in FastJet]

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

k_t algorithm

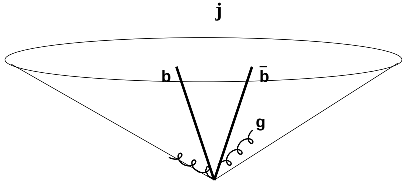


Cam/Aachen algorithm



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): $J \to J_1, J_2$

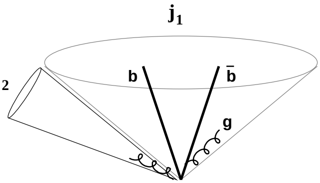
2. If $\max(m_1, m_2) \lesssim 0.67m$, call this a **mass drop** [else goto 1]

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

   Require $y_{12} = \frac{\min(p_{t1}^2, p_{t2}^2)}{m_{12}^2} \Delta R_{12}^2 \simeq \frac{\min(p_{t1}, p_{t2})}{\max(p_{t1}, p_{t2})} > 0.09$ [else goto 1]

   Require each subjet to have b-tag [else reject event]

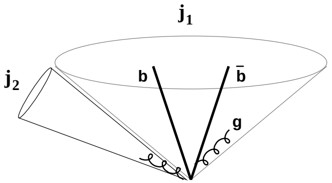
#2: The jet analysis



Start with high-p_t jet

1. Undo last stage of clustering ($\equiv$ reduce R): $J \to J_1, J_2$
2. If $\max(m_1, m_2) \lesssim 0.67m$, call this a **mass drop** [else goto 1]
   Automatically detects correct $R \sim R_{bb}$ to catch angular-ordered radn.
3. Require $y_{12} = \frac{\min(p_{t1}^2, p_{t2}^2)}{m_{12}^2} \Delta R_{12}^2 \simeq \frac{\min(z_1, z_2)}{\max(z_1, z_2)} > 0.09$ [else goto 1]
   dimensionless rejection of asymmetric QCD branching
4. Require each subjet to have b-tag [else reject event]
   Correlate flavour & momentum structure

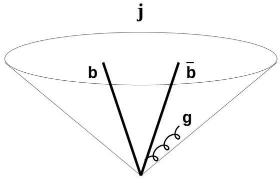
#2: The jet analysis



Start with high-p_t jet

1. Undo last stage of clustering ($\equiv$ reduce R): $J \to J_1, J_2$
2. If $\max(m_1, m_2) \lesssim 0.67m$, call this a **mass drop** [else goto 1]
   Automatically detects correct $R \sim R_{bb}$ to catch angular-ordered radn.
3. Require $y_{12} = \frac{\min(p_{t1}^2, p_{t2}^2)}{m_{12}^2}\Delta R_{12}^2 \simeq \frac{\min(z_1,z_2)}{\max(z_1,z_2)} > 0.09$ [else goto 1]
   dimensionless rejection of asymmetric QCD branching
4. Require each subjet to have b-tag [else reject event]
   Correlate flavour & momentum structure

#2: The jet analysis



Start with high-p_t jet

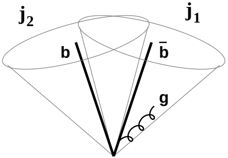
1. Undo last stage of clustering ($\equiv$ reduce R): $J \to J_1, J_2$
2. If $\max(m_1, m_2) \lesssim 0.67m$, call this a **mass drop** [else goto 1]

   Automatically detects correct $R \sim R_{bb}$ to catch angular-ordered radn.
3. Require $y_{12} = \frac{\min(p_{t1}^2, p_{t2}^2)}{m_{12}^2} \Delta R_{12}^2 \simeq \frac{\min(z_1, z_2)}{\max(z_1, z_2)} > 0.09$ [else goto 1]

   dimensionless rejection of asymmetric QCD branching
4. Require each subjet to have b-tag [else reject event]

   Correlate flavour & momentum structure

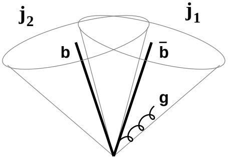
#2: The jet analysis



Start with high-p_t jet

1. Undo last stage of clustering ($\equiv$ reduce R): $J \to J_1, J_2$
2. If $\max(m_1, m_2) \lesssim 0.67m$, call this a **mass drop** [else goto 1]
   Automatically detects correct $R \sim R_{bb}$ to catch angular-ordered radn.
3. Require $y_{12} = \frac{\min(p_{t1}^2, p_{t2}^2)}{m_{12}^2} \Delta R_{12}^2 \simeq \frac{\min(z_1, z_2)}{\max(z_1, z_2)} > 0.09$ [else goto 1]
   dimensionless rejection of asymmetric QCD branching
4. Require each subjet to have b-tag [else reject event]
   Correlate flavour & momentum structure

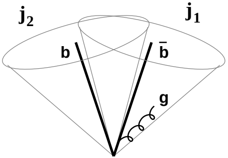
#2: The jet analysis



Start with high-p_t jet

1. Undo last stage of clustering ($\equiv$ reduce R): $J \to J_1, J_2$
2. If $\max(m_1, m_2) \lesssim 0.67m$, call this a **mass drop** [else goto 1]
   Automatically detects correct $R \sim R_{bb}$ to catch angular-ordered radn.
3. Require $y_{12} = \frac{\min(p_{t1}^2, p_{t2}^2)}{m_{12}^2} \Delta R_{12}^2 \simeq \frac{\min(z_1, z_2)}{\max(z_1, z_2)} > 0.09$ [else goto 1]
   dimensionless rejection of asymmetric QCD branching
4. Require each subjet to have b-tag [else reject event]
   Correlate flavour & momentum structure

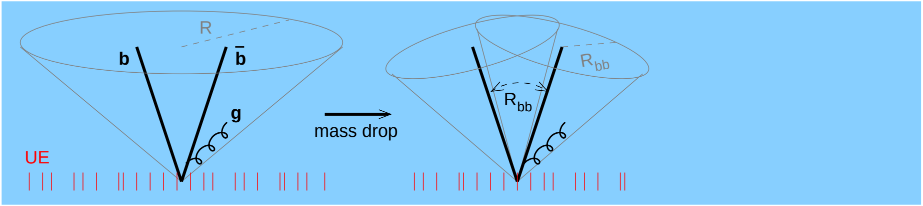
#2: The jet analysis



Start with high-p_t jet

1. Undo last stage of clustering ($\equiv$ reduce R): $J \to J_1, J_2$
2. If $\max(m_1, m_2) \lesssim 0.67m$, call this a **mass drop** [else goto 1]
   Automatically detects correct $R \sim R_{bb}$ to catch angular-ordered radn.
3. Require $y_{12} = \frac{\min(p_{t1}^2, p_{t2}^2)}{m_{12}^2} \Delta R_{12}^2 \simeq \frac{\min(z_1, z_2)}{\max(z_1, z_2)} > 0.09$ [else goto 1]
   dimensionless rejection of asymmetric QCD branching
4. Require each subjet to have b-tag [else reject event]
   Correlate flavour & momentum structure

#3: jet filtering



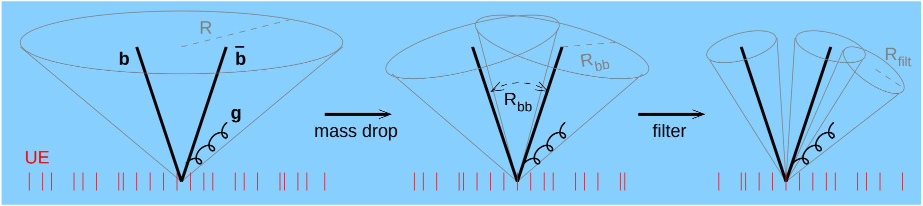
At moderate p_t, R_{bb} is quite large; *UE & pileup degrade mass resolution*

$\delta M \sim R^4 \Lambda_{UE} \frac{p_t}{M}$ [Dasgupta, Magnea & GPS '07]

Filter the jet

- Reconsider region of interest at smaller $R_{filt} = \min(0.3, R_{b\bar{b}}/2)$
- Take **3** hardest subjets — b, $\bar{b}$ and leading order gluon radiation

#3: jet filtering



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]

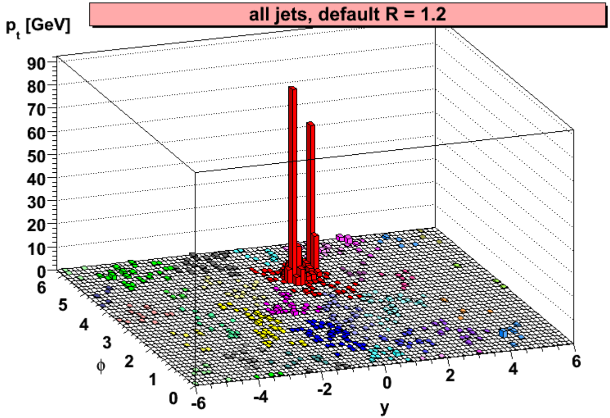
Filter the jet

- Reconsider region of interest at smaller $R_{filt} = \min(0.3, R_{b\bar{b}}/2)$
- Take **3** hardest subjets — b, $\bar{b}$ and leading order gluon radiation

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

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

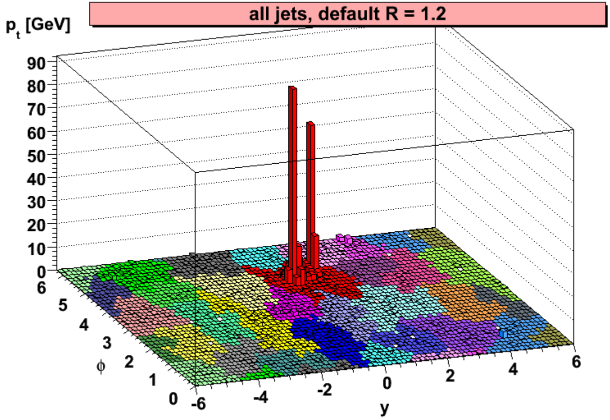
Cluster event, C/A, R=1.2

arbitrary norm.

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

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



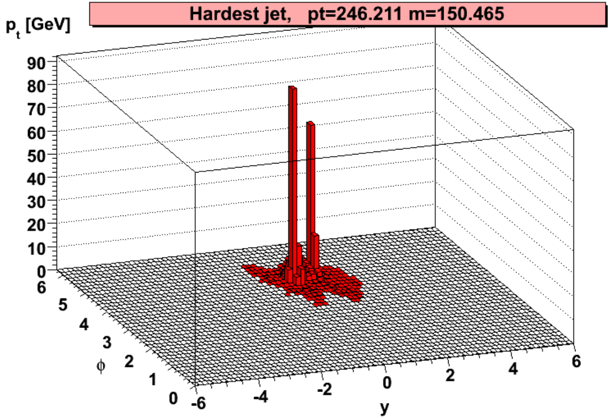
Zbb BACKGROUND

Fill it in, → show jets more clearly

arbitrary norm.

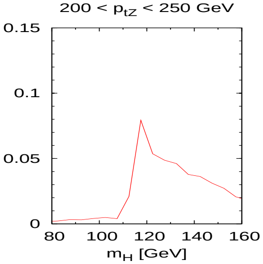
$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

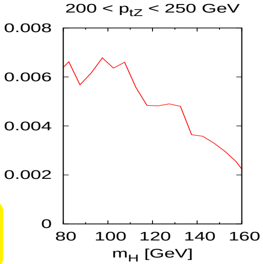


Consider hardest jet, $m = 150$ GeV

SIGNAL



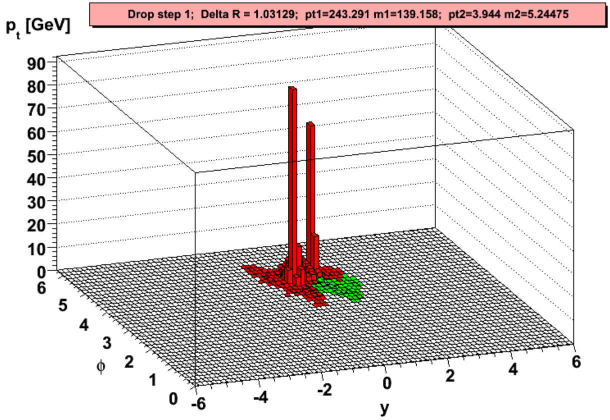
Zbb BACKGROUND



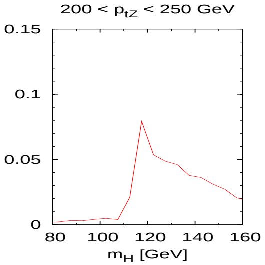
arbitrary norm.

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

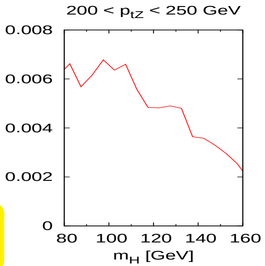
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



Zbb BACKGROUND

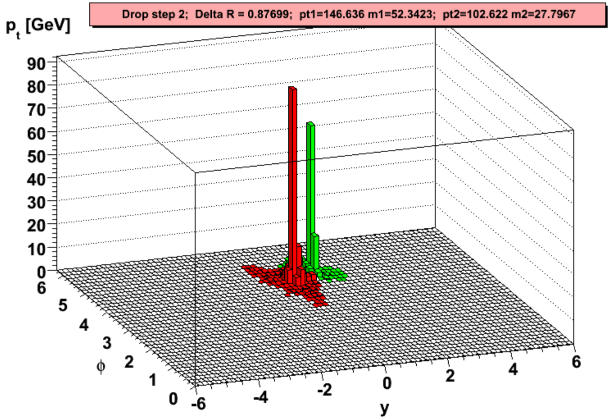


split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

arbitrary norm.

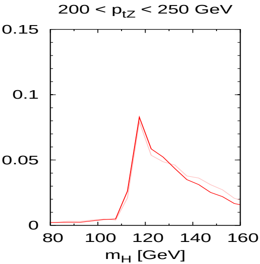
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

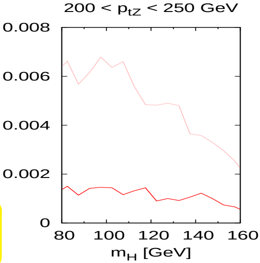


split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

SIGNAL



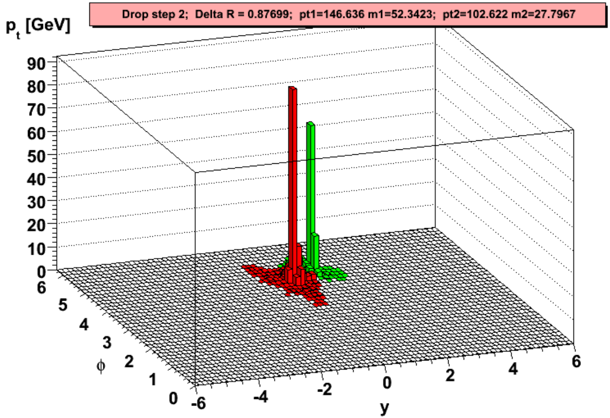
Zbb BACKGROUND

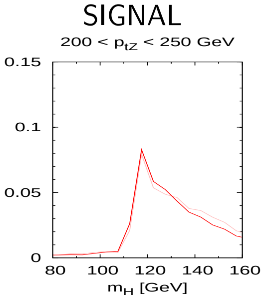


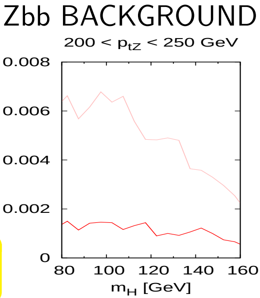
arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3





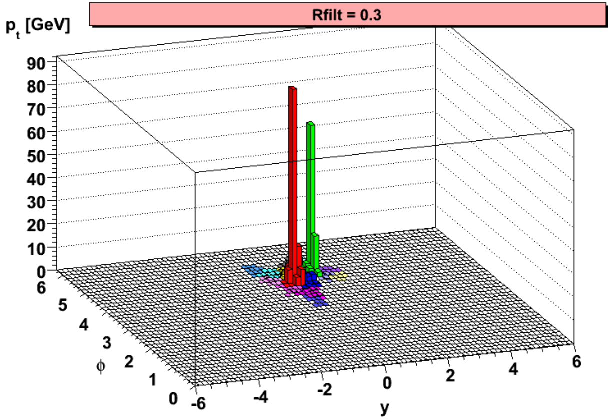


check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

arbitrary norm.

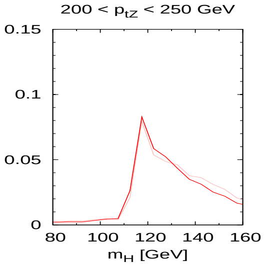
$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

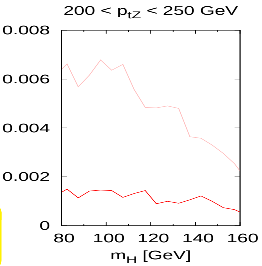


$R_{filt} = 0.3$

SIGNAL



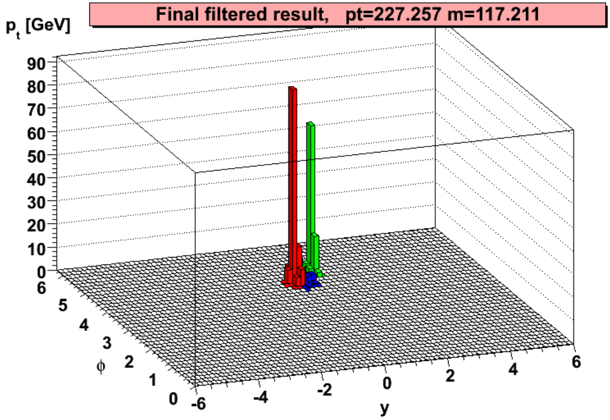
Zbb BACKGROUND



arbitrary norm.

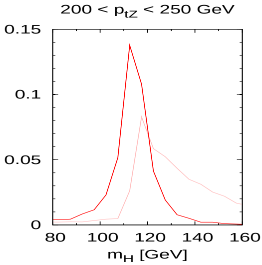
$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

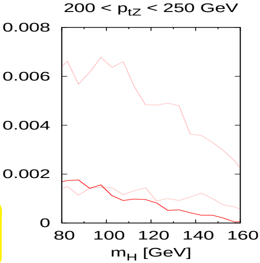


$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

SIGNAL



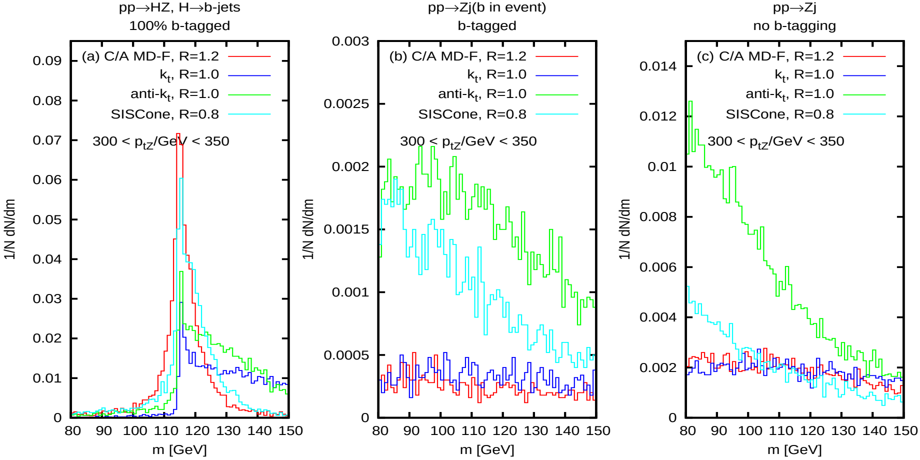
Zbb BACKGROUND



arbitrary norm.

Compare with "standard" algorithms

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



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: $H \to b\bar{b}$, $W \to \ell\nu$, $Z \to \ell^+\ell^-$ and $Z \to \nu\bar{\nu}$,

3 channels: $\ell + \not{E}_T$; $\ell^+\ell^-$; $\not{E}_T$

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 ℓ, 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 ∼ half this?

Tools: Herwig 6.510, Jimmy 4.31 (tuned), *hadron-level* → FastJet 2.3
Backgrounds: VV, Vj, jj, $t\bar{t}$, single-top, with $> 30\ \text{fb}^{-1}$ (except jj)

The full analysis (scaled to 30 fb^{-1})

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

3 channels: $\ell\nu + \not\!\!E_T$; $\ell^+\ell^-$; $\not\!\!E_T$

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 ℓ, 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* $\to$ 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: $H \to b\bar{b}$, $W \to \ell\nu$, $Z \to \ell^+\ell^-$ and $Z \to \nu\bar{\nu}$,

3 channels: $\ell + \not{E}_T$; $\ell^+\ell^-$; $\not{E}_T$

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 ℓ, 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* $\to$ 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: $H \to b\bar{b}$, $W \to \ell\nu$, $Z \to \ell^+\ell^-$ and $Z \to \nu\bar{\nu}$,

3 channels: $\ell + \not{E}_T$; $\ell^+\ell^-$; $\not{E}_T$

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 ℓ, b's with $|\eta| < 2.5$

Channel-specific cuts:

See next slides

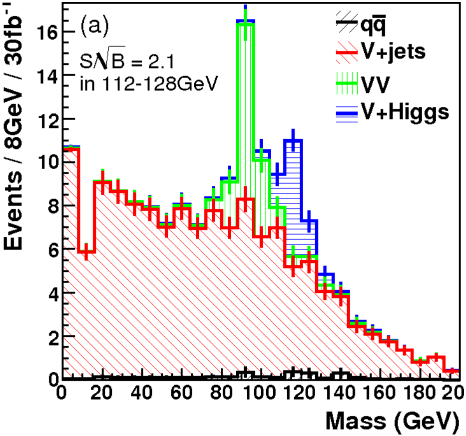
Assumptions

- 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* $\to$ FastJet 2.3
Backgrounds: VV, Vj, jj, $t\bar{t}$, single-top, with > 30 fb^{-1} (except jj)

combine HZ and HW, $p_t > 200$ GeV

Leptonic channel



Common cuts

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

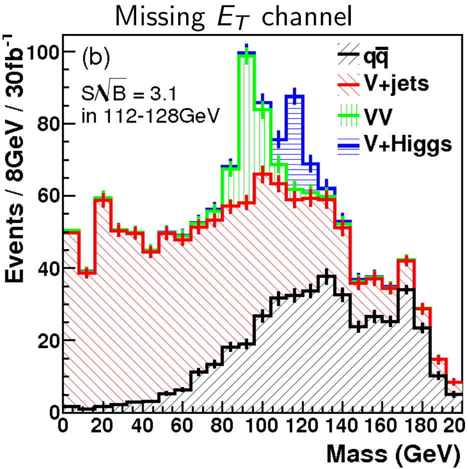
Leptonic channel

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

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

At 4.5σ 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 ℓ, 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

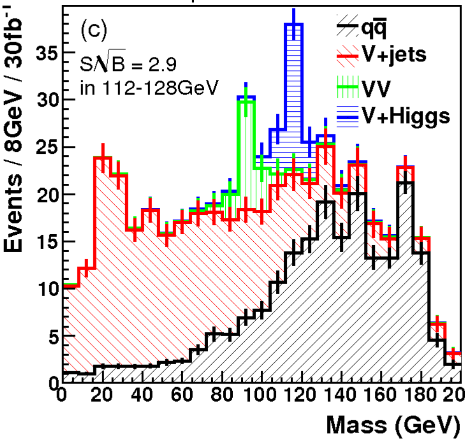
$Z \to \nu\bar{\nu}$, $W \to \nu[\ell]$

- $\not{E}_T > 200$ GeV

At 4.5σ 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

- $p_{tV}, p_{tH} > 200$ GeV
- $|\eta_H| < 2.5$
- $[p_{t,\ell} > 30$ GeV, $|\eta_\ell| < 2.5]$
- No extra ℓ, 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

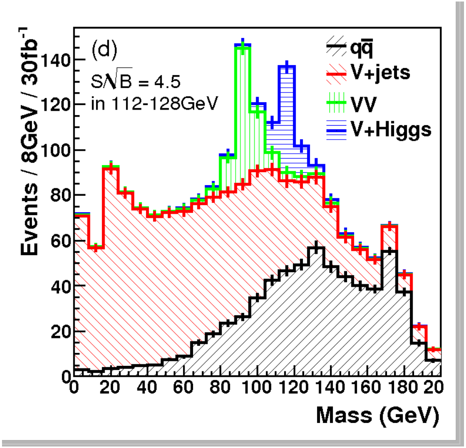
$W \to \nu\ell$

- $\not{E}_T > 30$ GeV (& consistent W.)
- no extra jets $|\eta| < 3, p_t > 30$

At 4.5σ 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

3 channels combined



Common cuts

- $p_{tV}, p_{tH} > 200$ GeV
- $|\eta_H| < 2.5$
- $[p_{t,\ell} > 30$ GeV, $|\eta_\ell| < 2.5]$
- No extra ℓ, 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, $Z \to b\bar{b}$ 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

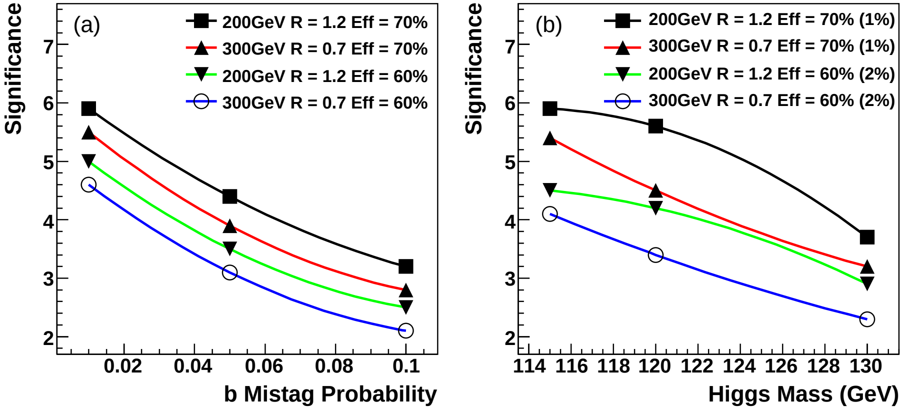
How can we be doing so well despite losing factor 20 in X-sct?

	Signal	Background	
Eliminate $t\bar{t}$, etc.	–	$\times 1/3$	[very approx.]
$p_t > 200$ GeV	$\times 1/20$	$\times 1/60$	[bkgds: $Wb\bar{b}$, $Zb\bar{b}$]
improved acceptance	$\times 4$	$\times 4$	
twice better resolution	–	$\times 1/2$	
add $Z \to \nu\bar{\nu}$	$\times 1.5$	$\times 1.5$	
total	$\times 0.3$	$\times 0.017$	

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

[exact numbers depend on analysis details]

Impact of *b*-tagging, Higgs mass

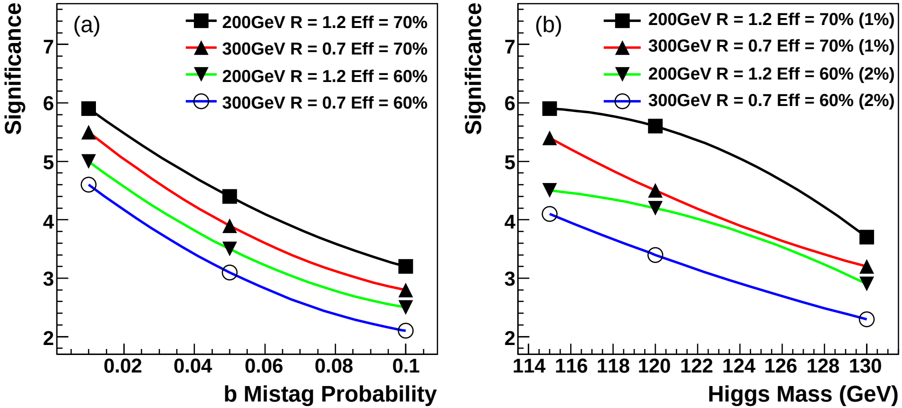


Most scenarios above 3σ

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 3σ

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

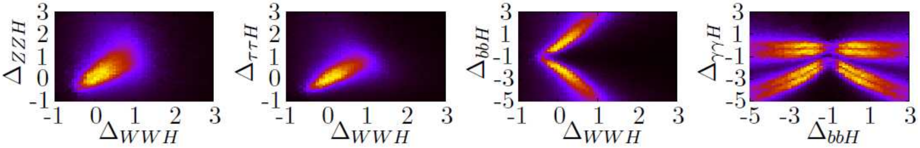
In nearly all cases, suitable for extracting $b\bar{b}H$, WWH, ZZH couplings

Higgs coupling measurements

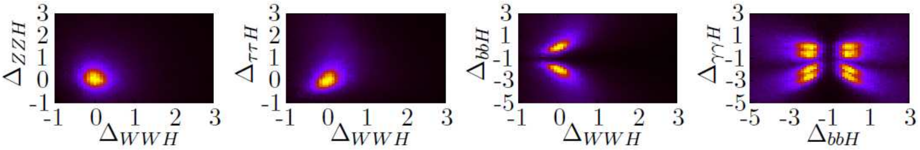
You only know it's the SM Higgs if couplings agree with SM expectations.

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, ...

ATLAS analysis

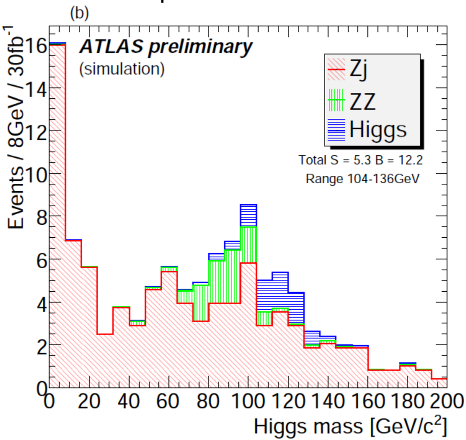
As of August 2009: ATLAS have preliminary public analysis of this channel
ATL-PHYS-PUB-2009-088

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 $t \to bW$, $W \to cs$, 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)

ATLAS results

Leptonic channel



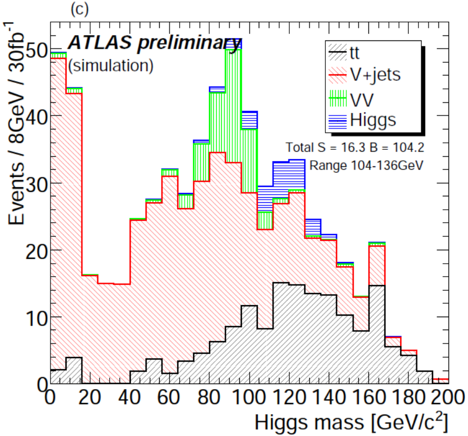
What changes compared to particle-level analysis?

$\sim 1.5\sigma$ as compared to 2.1σ

Expected given larger mass window

ATLAS results

Missing E_T channel



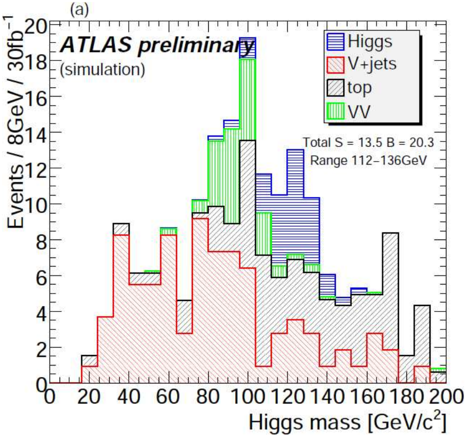
What changes compared to particle-level analysis?

$\sim 1.5\sigma$ as compared to 3σ

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 3σ

Benefits: some events redistributed from missing E_T channel

ATLAS combined results

Likelihood-based analysis of all three channels together gives signal significance of

3.7σ for 30 fb^{-1}

To be compared with 4.2σ in hadron-level analysis for $m_H = 120$ GeV

K-factors not included: don't affect significance (~ 1.5 for VH, $2 - 2.5$ for Vbb)

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

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

$gg \to H \to \gamma\gamma$	$WW \to H \to \tau\tau$	$gg \to H \to ZZ^*$
4.2σ	4.9σ	2.6σ

Extracted from 0901.0512

Prospects?

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

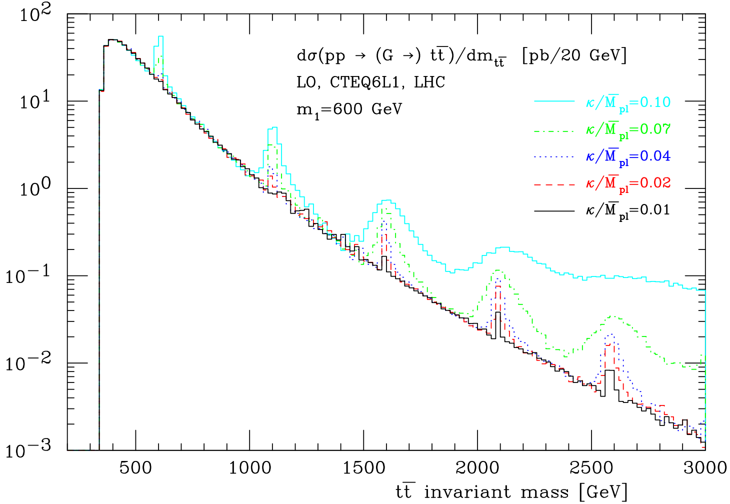
Combination of different kinematic regions

- 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]

$X \to t\bar{t}$ resonances of varying difficulty



RS KK resonances $\to t\bar{t}$, 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.

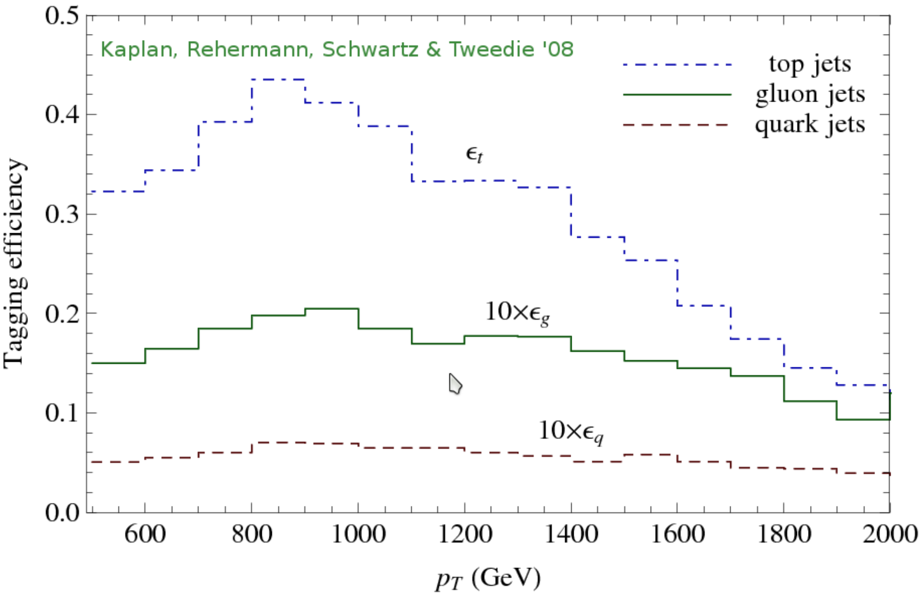
Questions

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

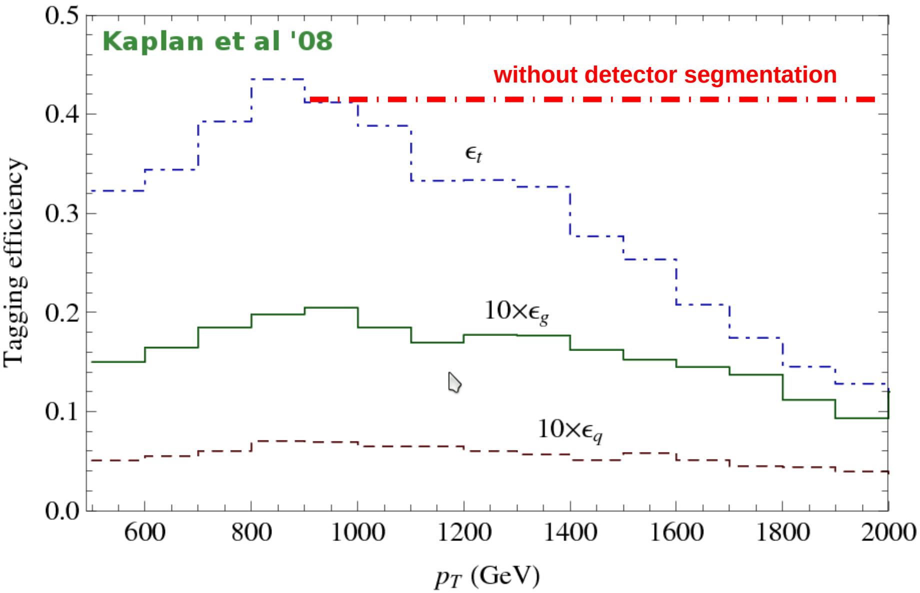
Rough results for top quark with $p_t \sim 1$ TeV

	"Extra"	eff.	fake
[from T&W]	just jet mass	50%	10%
Brooijmans '08	3,4 k_t subjets, d_{cut}	45%	5%
Thaler & Wang '08	2,3 k_t subjets, z_{cut} + various	40%	5%
Kaplan et al. '08	3,4 C/A subjets, $z_{cut} + \theta_h$	40%	1%
Almeida et al. '08	predict mass dist^n, use jet-shape	–	–
Ellis et al. '09	C/A pruning	10%	0.05%
ATLAS '09	3,4 k_t subjets, d_{cut} MC likelihood	90%	15%
Plehn et al. '09	C/A mass drops, θ_h [busy evs, $p_t \sim 250$]	40%	2.5%

Efficiency v. p_t



Efficiency v. p_t



$t\bar{t}H$

boosted top and Higgs together?

(NB: inclusive ttH deemed unviable in past years by ATLAS & CMS)

Resurrecting $t\bar{t}H$?

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

$t \to b\ell(\not{E}_T)$

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

$H \to \text{jet}_{b\bar{b}}$ (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, $|y| < 2.5$
- ≥ 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).

Resurrecting $t\bar{t}H$?

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

$t \;\to b\ell(\not\!\!E_T)$

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

$H \to \text{jet}_{b\bar{b}}$ (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, $|y| < 2.5$
- ≥ 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).

Resurrecting $t\bar{t}H$?

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

$t \to b\ell(\not{E}_T)$

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

$H \to$ jet$_{b\bar{b}}$ (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, $|y| < 2.5$
- ≥ 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).

Resurrecting $t\bar{t}H$?

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

$t \to b\ell(\not{E}_T)$

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

$H \to \text{jet}_{b\bar{b}}$ (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, $|y| < 2.5$
- ≥ 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).

Resurrecting $t\bar{t}H$?

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

$t \to b\ell(\not{E}_T)$

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

$H \to \text{jet}_{b\bar{b}}$ (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, $|y| < 2.5$
- ≥ 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).

Resurrecting $t\bar{t}H$?

$$pp \to t\bar{t}H$$
$$t \to b\ell(\not{E}_T)$$
$$t \to \text{jet}_{jjj} \quad \text{(boosted)}$$
$$H \to \text{jet}_{b\bar{b}} \quad \text{(boosted)}$$

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, $|y| < 2.5$
- ≥ 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

ttH: Madgraph + Herwig++ 2.3.1 ; Herwig 6.510

$ttbb$: Madgraph + Herwig++; Alpgen + Herwig 6.5

$ttj(j)$: Herwig 6.5 $t\bar{t}$ events (jets from shower)

But we check that its $ttbb$ component is consistent with the ME $ttbb$ simulation

And for final result it's negligible anyway

Wjj: Madgraph (Wjj) + Herwig++ (for internal structure in j's)

turns out to be negligible

ttZ: Madgraph + Herwig++

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

Beenakker et al '01; Dawson et al '03

Bredenstein et al '09; Bevilacqua et al '09

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, $m_{j1} > m_{j2}$
- If mass drop, i.e. $\max(m_{j1}, m_{j2}) < 0.9 m_j$ (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, θ_h

θ_h 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

Different stages of analysis

Cross sections in fb (including NLO K-factors for signal, $t\bar{t}b\bar{b}$ & $t\bar{t}Z$)

	signal	$t\bar{t}Z$	$t\bar{t}b\bar{b}$	$t\bar{t}$+jets
events after acceptance ℓ+2j cuts	24.9	7.3	229	5200
events with one top tag	10.6	3.1	84.2	1821
events with $m_{jj} = 110 - 130$ GeV	3.0	0.47	15.1	145
corresponding to subjet pairings	3.3	0.50	16.5	151
subjet pairings two subjet b tags	1.0	0.08	2.7	1.7
including a third b tag	0.48	0.03	1.26	0.07

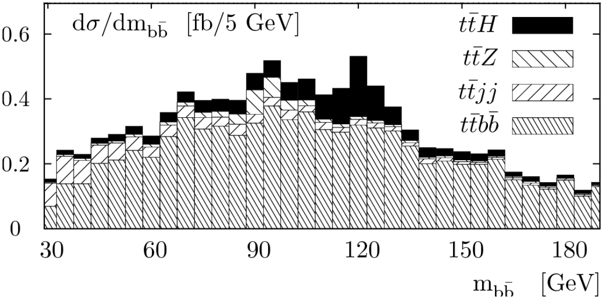
$t\bar{t}H$ results

	S[fb]	B[fb]	S/B	$S/\sqrt{B}$ (100 fb^{-1})
m_H = 115 GeV	0.57	1.39	1/2.4	4.8
120 GeV	0.48	1.36	1/2.8	4.1
130 GeV	0.29	1.21	1/4.2	2.6

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



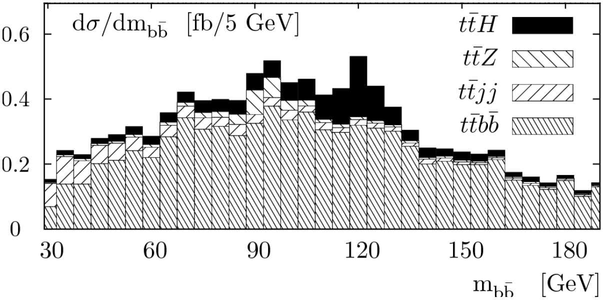
$t\bar{t}H$ results

	S[fb]	B[fb]	S/B	$S/\sqrt{B}$ (100 fb^{-1})
m_H = 115 GeV	0.57	1.39	1/2.4	4.8
120 GeV	0.48	1.36	1/2.8	4.1
130 GeV	0.29	1.21	1/4.2	2.6

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



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?

R-parity violating SUSY

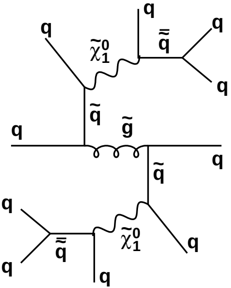
As a final example, a search for neutralinos in R-parity violating supersymmetry.

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

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



R-parity violating SUSY

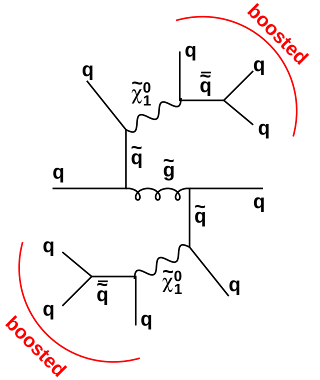
As a final example, a search for neutralinos in R-parity violating supersymmetry.

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

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



Analytics (back-of-the-enveolope)

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 ($z > z_{min}$):

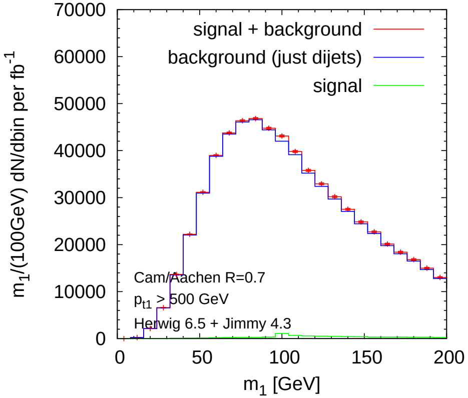
$$\frac{1}{N}\frac{dN}{dm} \sim \frac{C'\alpha_s(m)}{m} e^{-C'\alpha_s \ln Rp_t/m + \cdots}$$

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

Procedure gives nearly flat distribution in mdN/dm

Neutralino procedure involves 2 hard substructures, but ideas are similar

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



Keep it simple:

Look at mass of leading jet

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

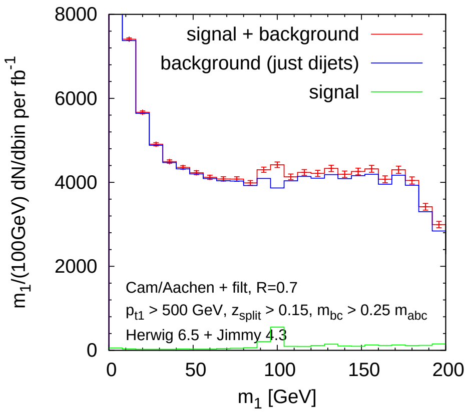
99% background rejection
scale-invariant procedure
so remaining bkgd is flat

Once you've found neutralino:

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

Out comes the squark!

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



Keep it simple:

Look at mass of leading jet

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

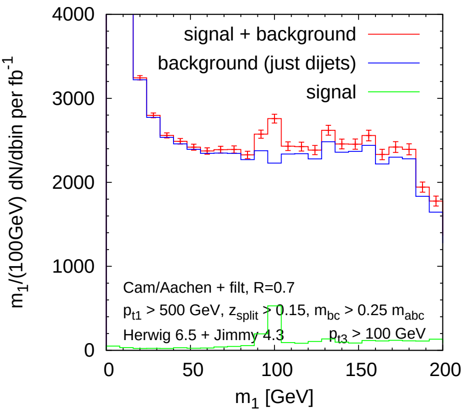
99% background rejection
scale-invariant procedure
so remaining bkgd is flat

Once you've found neutralino:

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

Out comes the squark!

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



Keep it simple:

Look at mass of leading jet

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

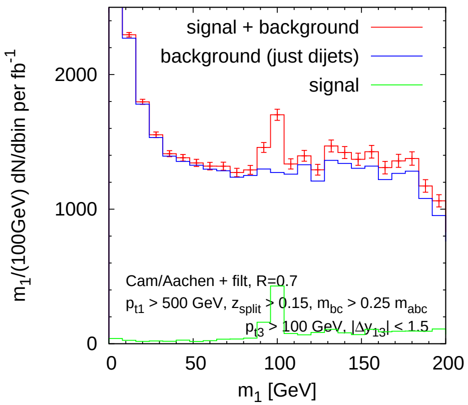
99% background rejection
scale-invariant procedure
so remaining bkgd is flat

Once you've found neutralino:

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

Out comes the squark!

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



Keep it simple:

Look at mass of leading jet

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

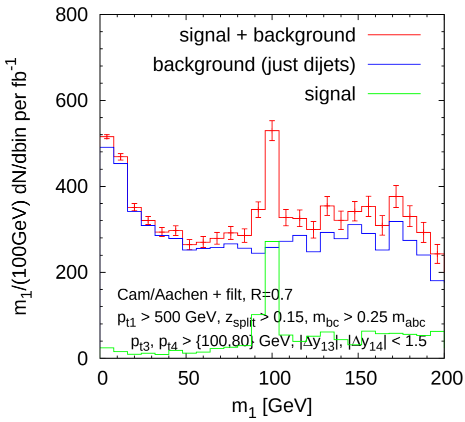
99% background rejection
scale-invariant procedure
so remaining bkgd is flat

Once you've found neutralino:

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

Out comes the squark!

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



Keep it simple:

Look at mass of leading jet

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

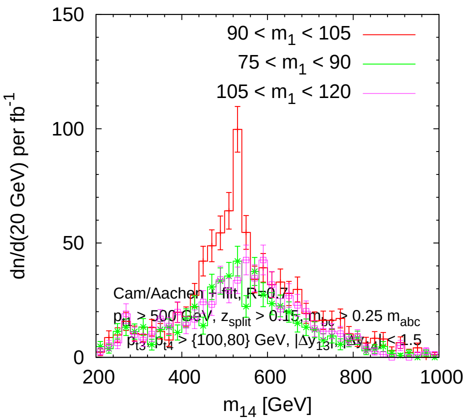
99% background rejection
scale-invariant procedure
so remaining bkgd is flat

Once you've found neutralino:

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

Out comes the squark!

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



Keep it simple:

Look at mass of leading jet

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

Conclusions

Conclusions

Higgs discovery

- High-p_t limit recovers WH and ZH ($H \to b\bar{b}$) channel at LHC
- So far, only viable channel that can see $H \to b\bar{b}$ 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 $t\bar{t}H$, $H \to b\bar{b}$

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

EXTRAS

Jet-alg comparison

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.

Jet definition	σ_S/fb	σ_B/fb	$S/\sqrt{B\cdot \text{fb}}$
C/A, $R = 1.2$, MD-F	0.57	0.51	0.80
k_t, $R = 1.0$, y_{cut}	0.19	0.74	0.22
SISCone, $R = 0.8$	0.49	1.33	0.42
anti-k_t, $R = 0.8$	0.22	1.06	0.21

K-factors

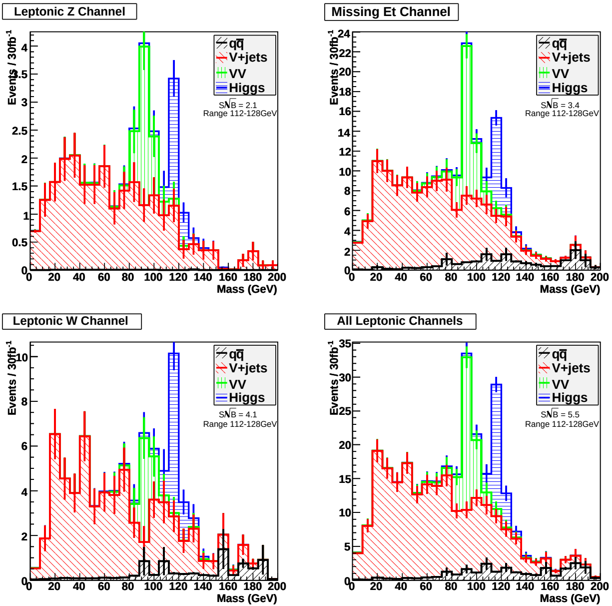
Analysis shown without K factors. What impact do they have?

Determined with MCFM, MC@NLO

- 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



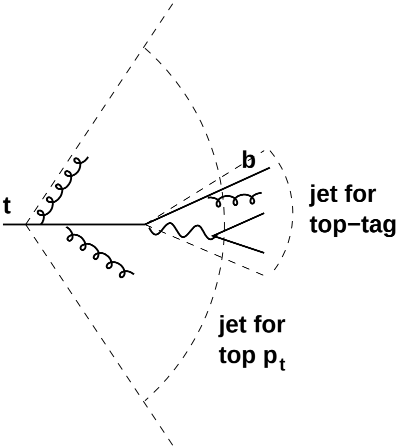
NB: kills $t\bar{t}$ background

Boosted top extras

Using (coloured!) boosted top-quarks

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

the jet you use to tag a top quark $\neq$ 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

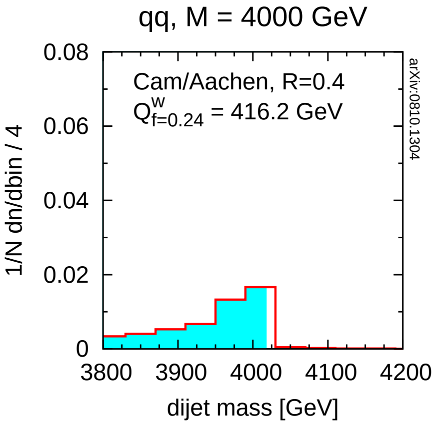
Outside dead cone, you have radiation from top quark

essential for top p_t

Cacciari, Rojo, GPS & Soyez '08

Impact of using small cone angle

Use small cone



Use large cone

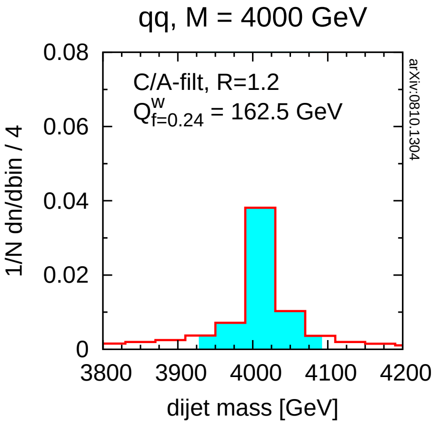
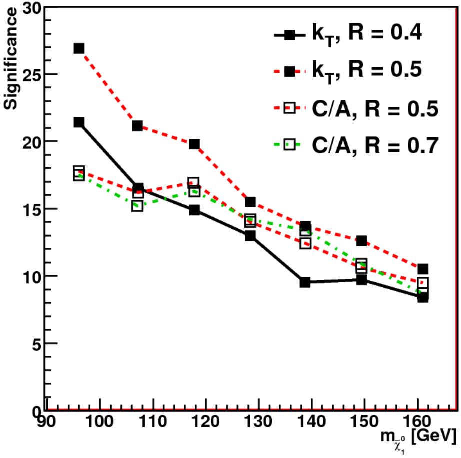


Figure actually from 0810.1304 (Cacciari, Rojo, GPS & Soyez)
for light $q\bar{q}$ resonance — but $t\bar{t}$ will be similar

How you look at your event matters: `http://quality.fastjet.fr/`

Neutralino extras

RPV SUSY: significance v. mass scale



- All points use 1 fb^{-1}
- as m_χ increases, $m_{\tilde{q}}$ goes from 530 GeV to 815 GeV
- Same cuts as for main SPS1A analysis

no particular optimisation