Jet structures in Higgs and New Physics searches

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Séminaire du LAL
Orsay, 8 September 2009

Part based on work with
Jon Butterworth, Adam Davison (UCL) & Mathieu Rubin (LPTHE)

This seminar is about two things:

- A new Higgs search channel at LHC

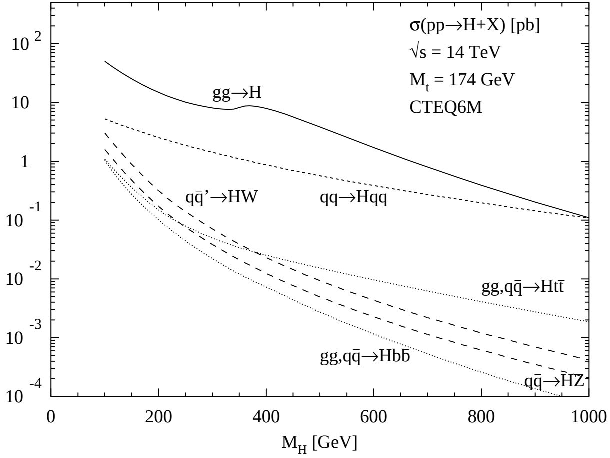
  Work with Butterworth, Davison & Rubin

- Which overlaps with the question of how to get the best out of jets at LHC

  A broader body of work
  centred on the FastJet program with Cacciari & Soyez
  and work also with: Dasgupta, Ellis, Magnea, Raklev, Rojo

The Higgs search will provide the backbone of the talk.

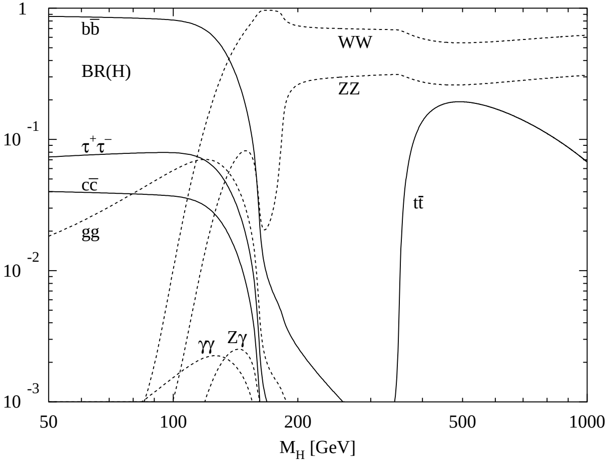
Higgs production at LHC



Dominant Higgs production channels are

- gluon fusion
  via top loop
- WW fusion
  with two forward jets
- H radiated off top-quark, or W or Z boson
  "associated production"

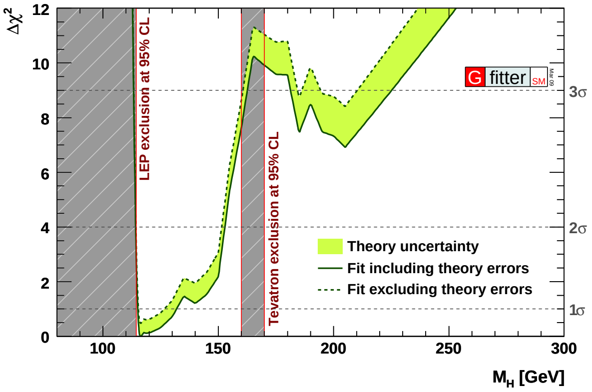
Higgs decay



Dominant Higgs decay mode depends on mass.

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

Higgs mass constraints

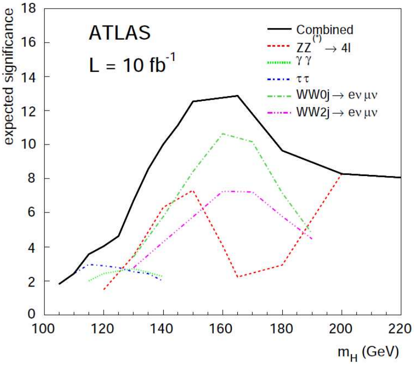


Mass constraints come from

- 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

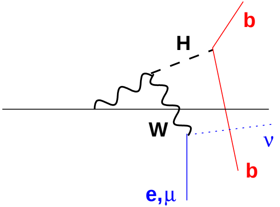
- Backgrounds include $Wb\bar{b}$, $t\bar{t} \to \ell\nu b\bar{b}jj$, ...

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



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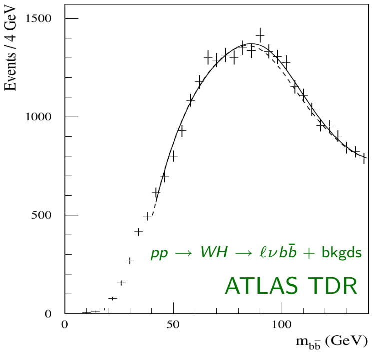

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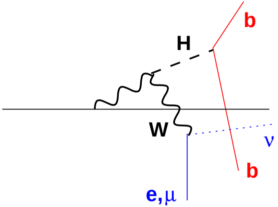

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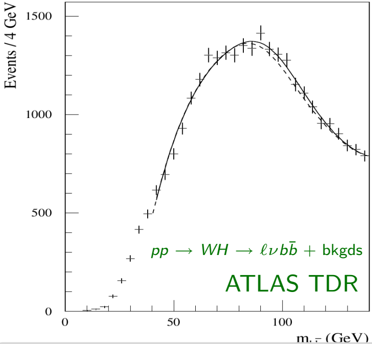

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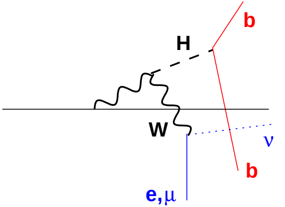
Conclusion (ATLAS TDR):

"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:

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

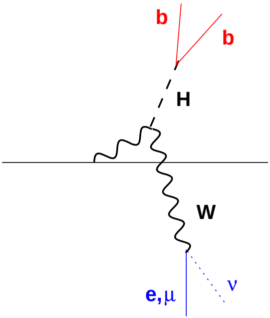
That's why it's being built

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 you don't look for B-hadrons at zero p_t. . .]

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

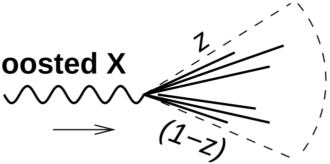
By a factor of 20 for $p_{tH} > 200$ GeV

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 $p_t \neq$ two jets



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

Rules of thumb:

$m = 100$ 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?

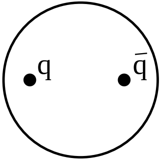
Special case of general (unanswered) question: how do we best do jet-finding?

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 $\to t\bar{t}$]
- . . .

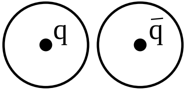
ETC.

Boosted ID strategies



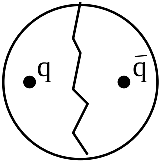
Select on the jet mass with one large (cone) jet

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

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, $R = 0.7$

ϕ assumed 0 for all towers

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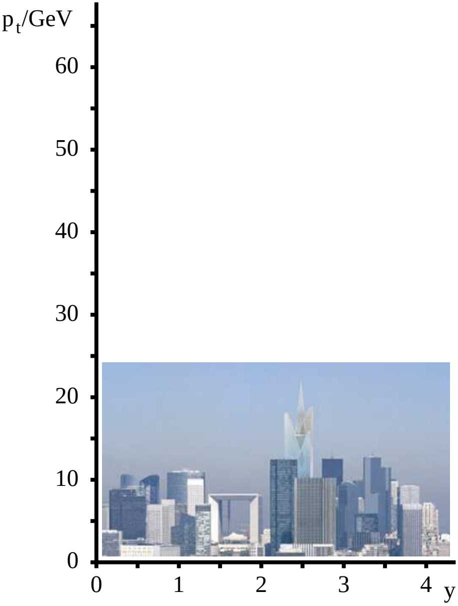

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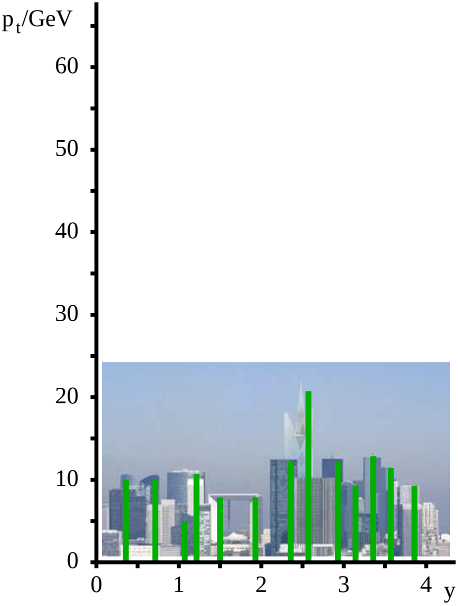

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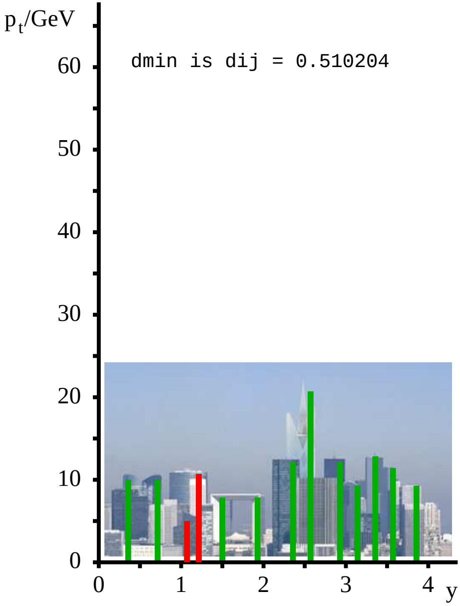

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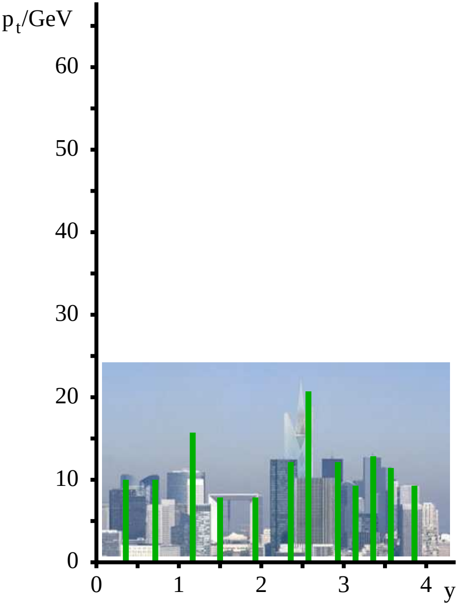

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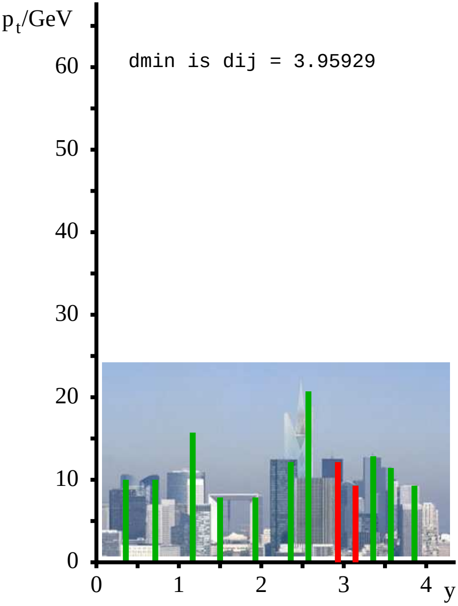

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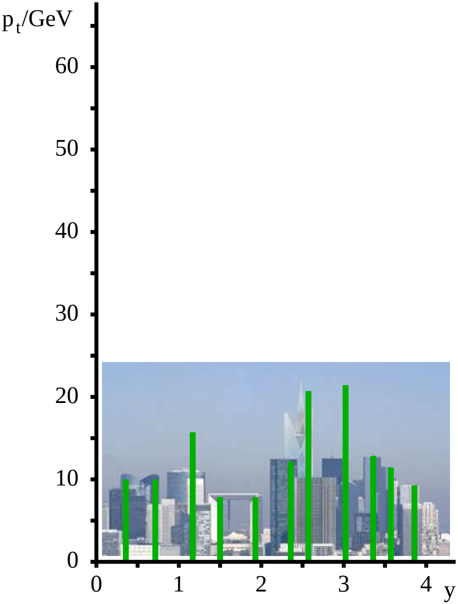

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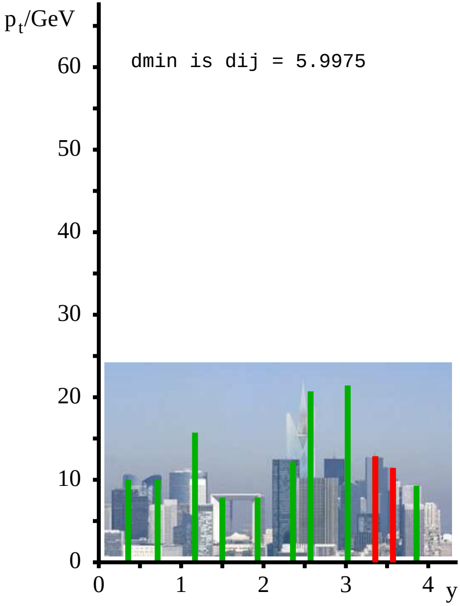

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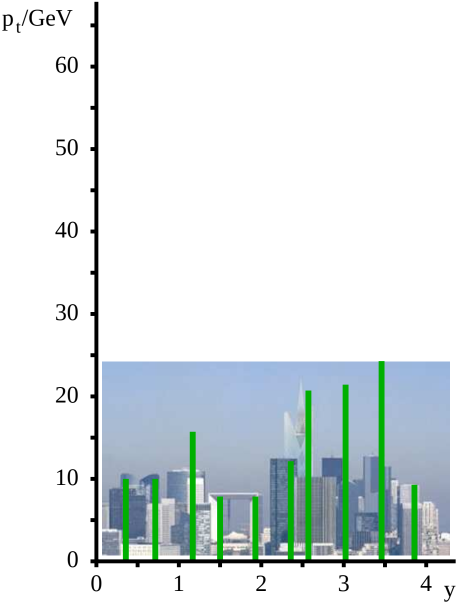

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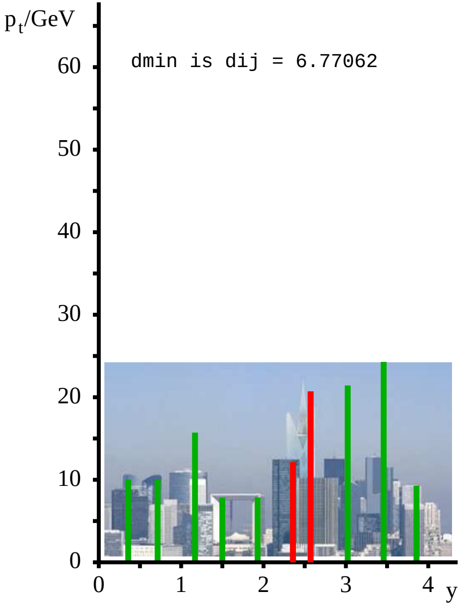

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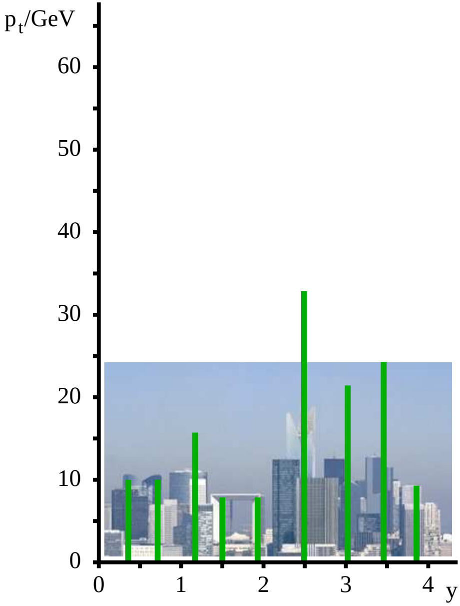

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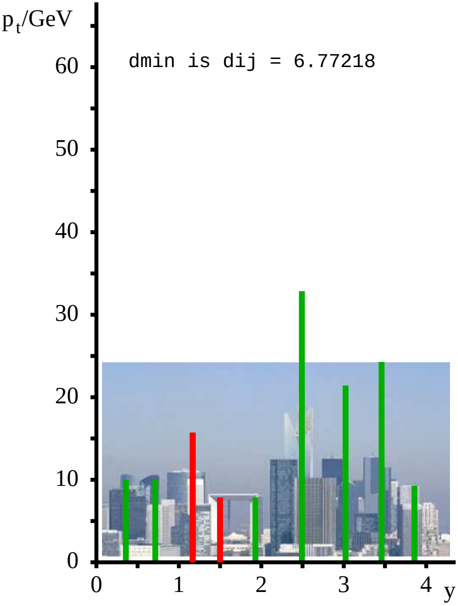

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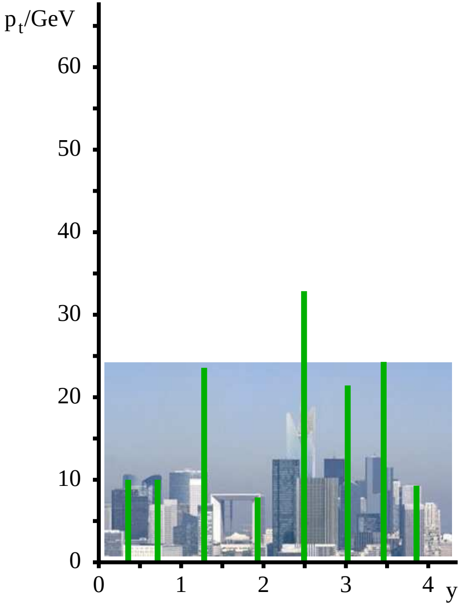

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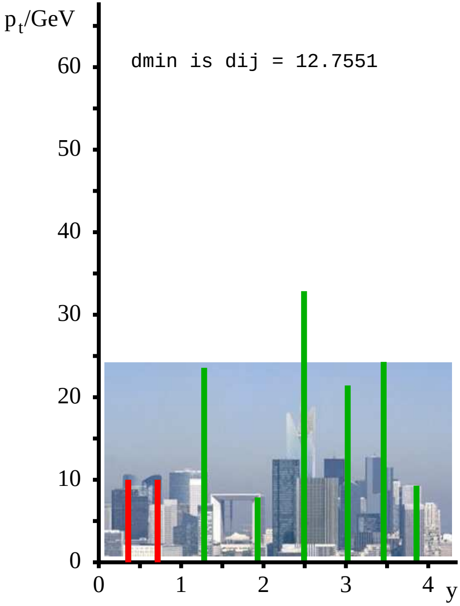

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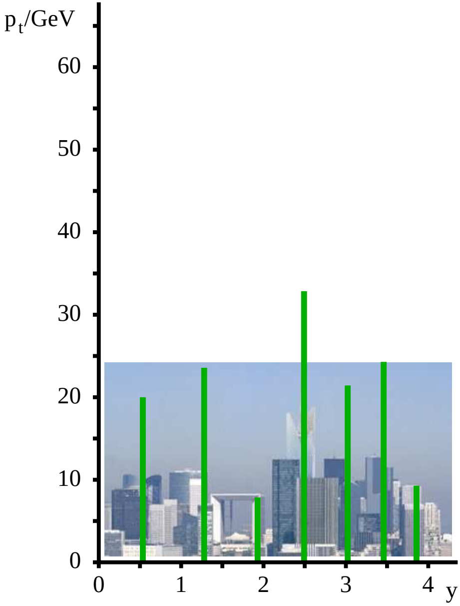

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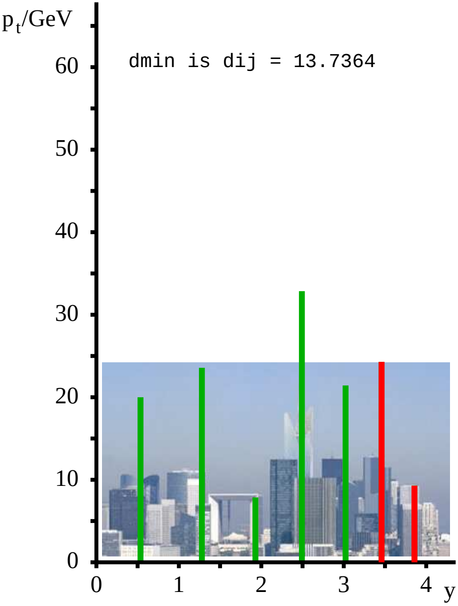

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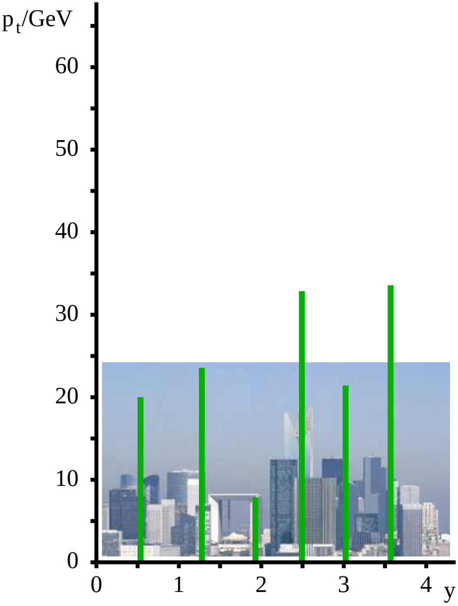

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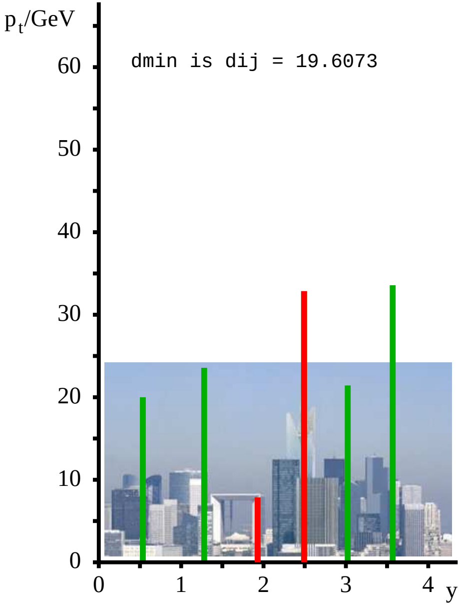

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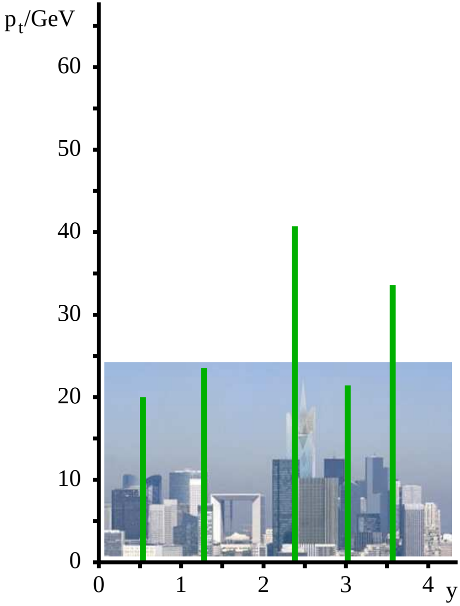

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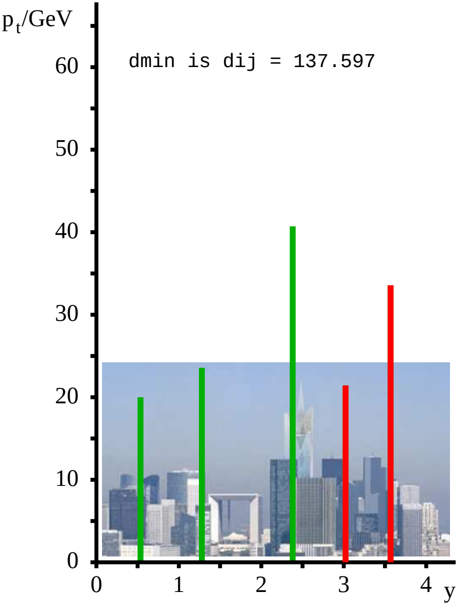

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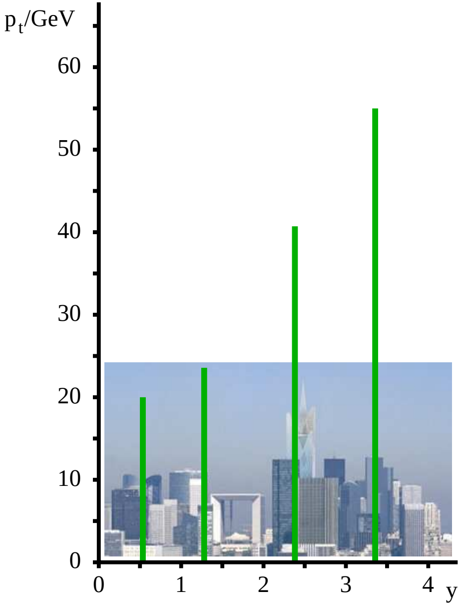

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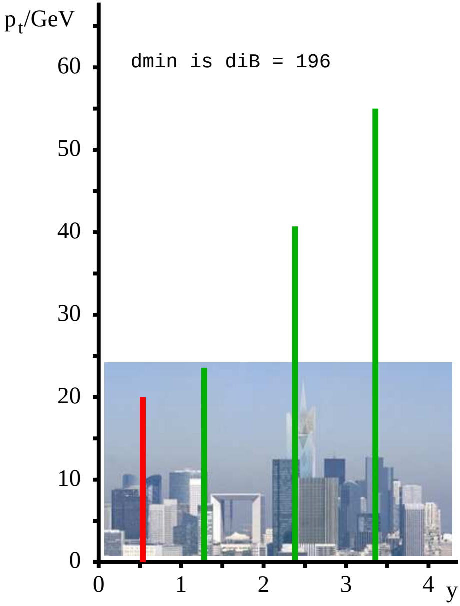

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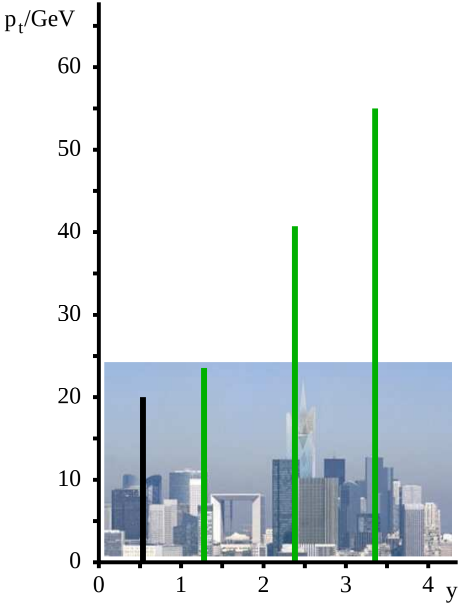

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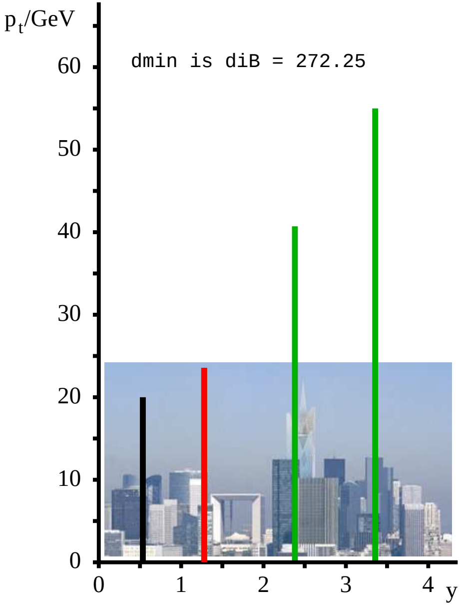
Example clustering with k_t algorithm, $R = 0.7$

ϕ assumed 0 for all towers

Sequential recombination



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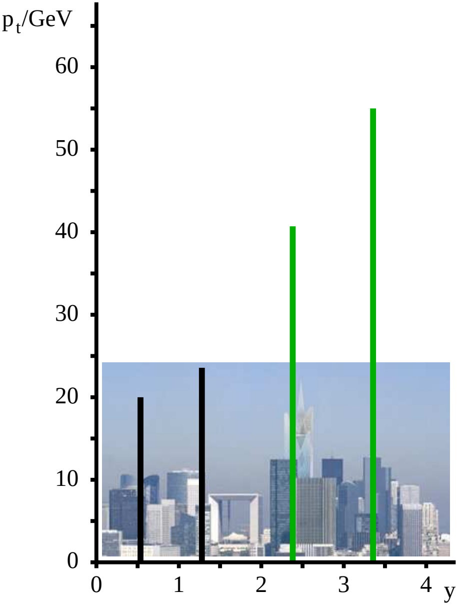

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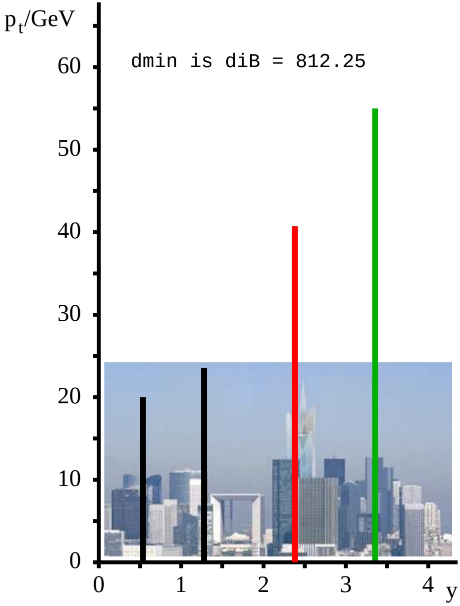

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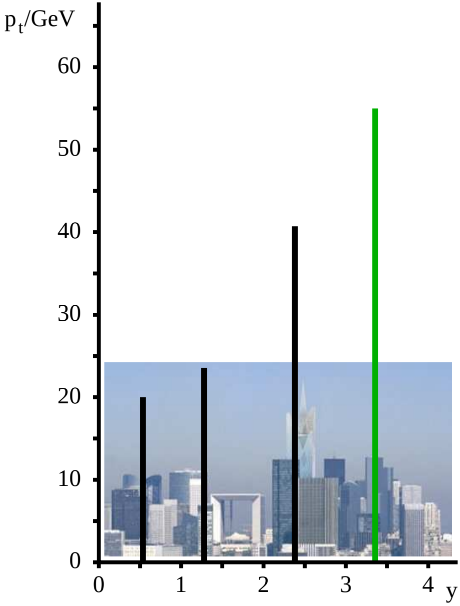

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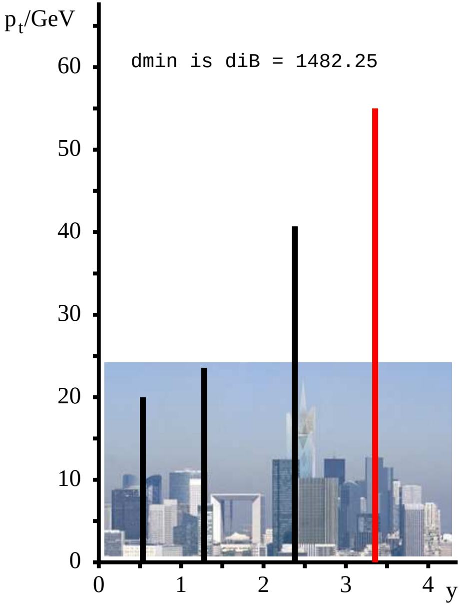

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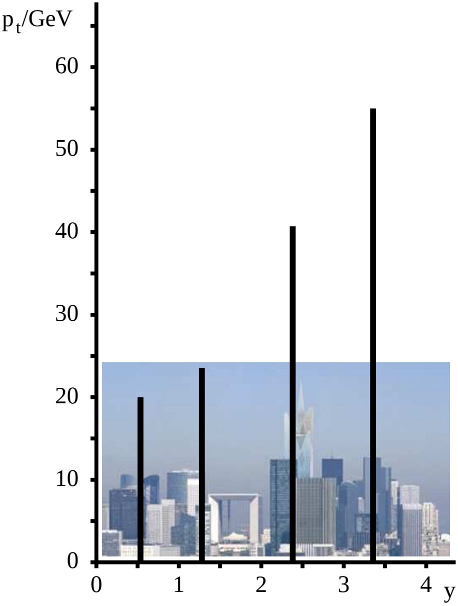

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Past methods

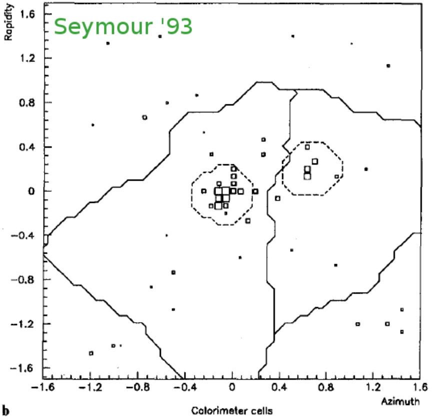
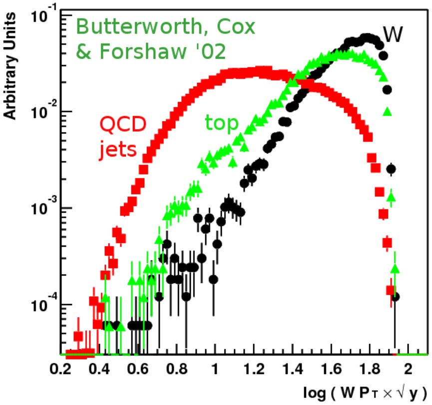


Fig. 2. A hadronic W decay, as seen at calorimeter level, **a** without, and **b** with, particles from the underlying event. Box sizes are logarithmic in the cell energy, lines show the borders of the sub-jets for infinitely soft emission according to the cluster (solid) and cone (dashed) algorithms

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

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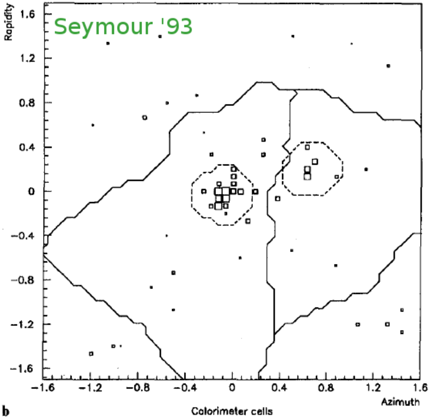

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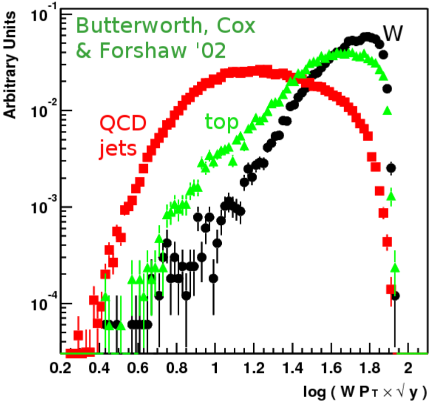

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#1: Our tool

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

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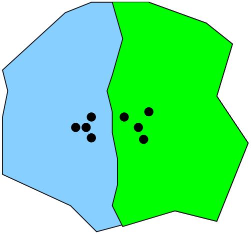
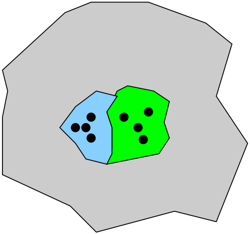
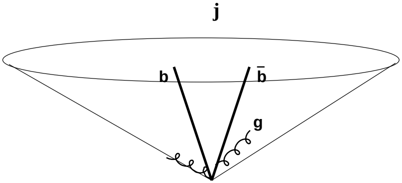


Cam/Aachen algorithm



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

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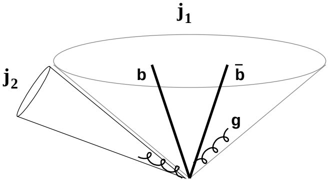

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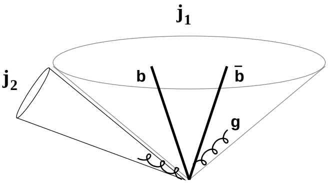

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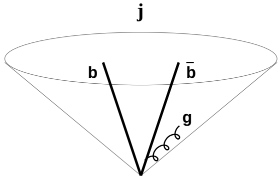

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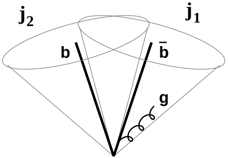

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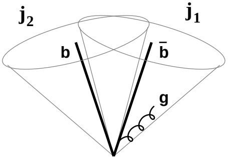

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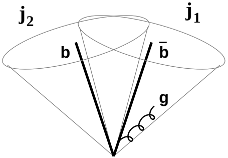

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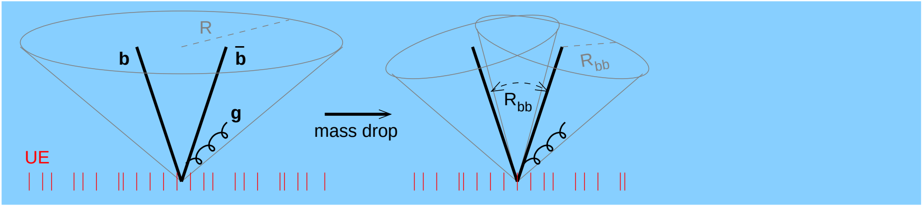

At moderate p_t, R_{bb} is quite large; *UE & pileup degrade mass resolution*

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

Filter the jet

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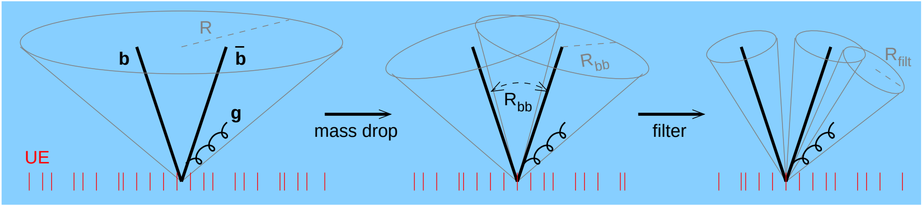

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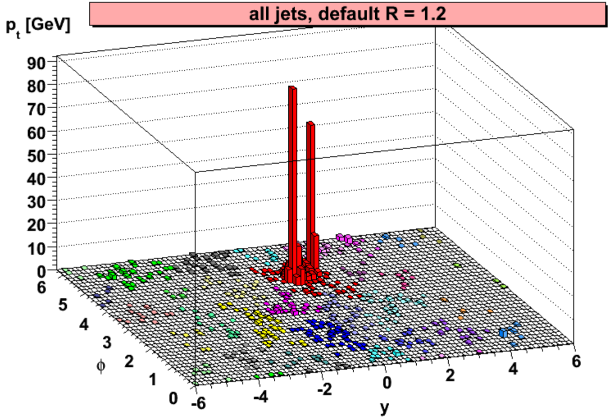
$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

Cluster event, C/A, R=1.2

arbitrary norm.

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

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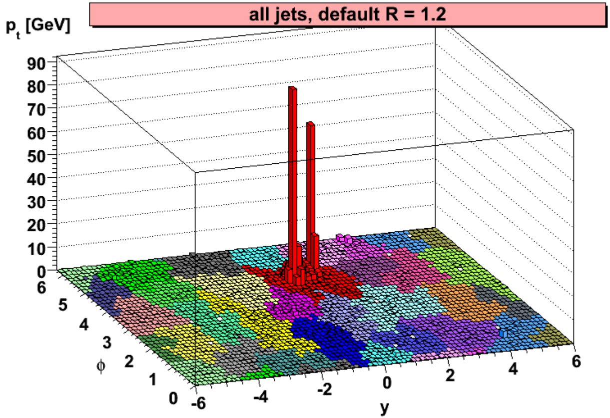

Zbb BACKGROUND

Fill it in, → show jets more clearly

arbitrary norm.

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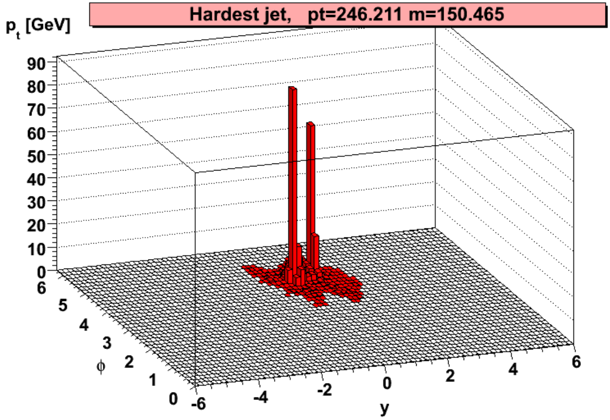
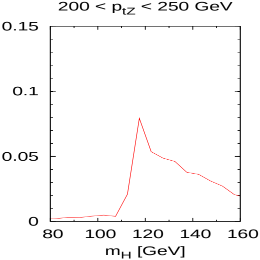


Consider hardest jet, $m = 150$ GeV

SIGNAL



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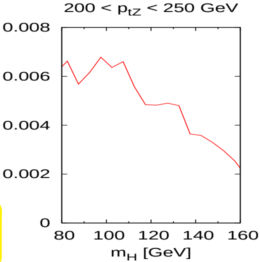

arbitrary norm.

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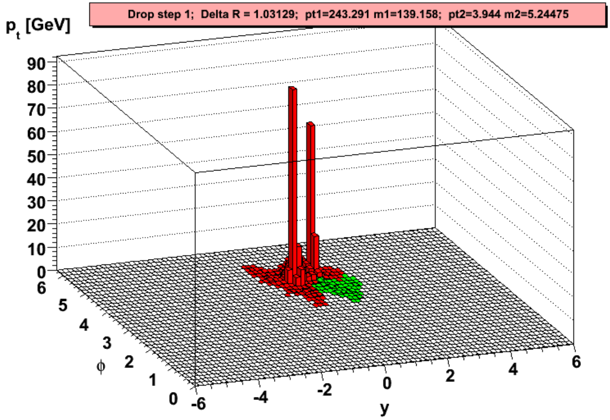
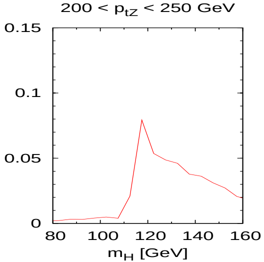
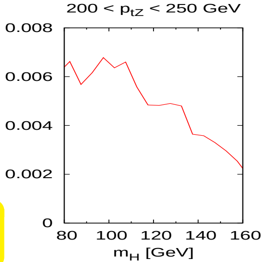


split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \longrightarrow$ repeat

SIGNAL



Zbb BACKGROUND



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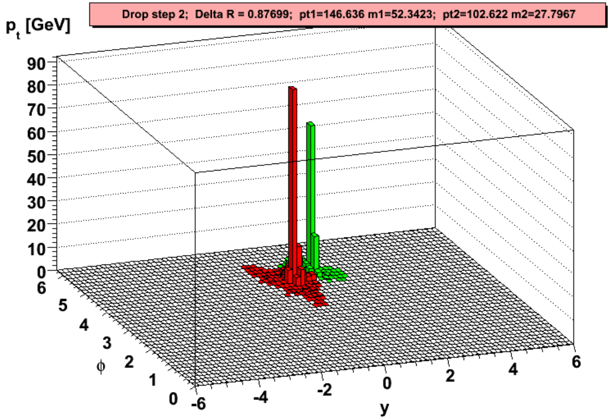

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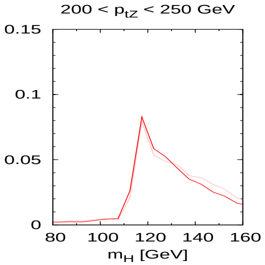

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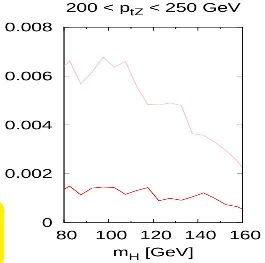

split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

arbitrary norm.

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

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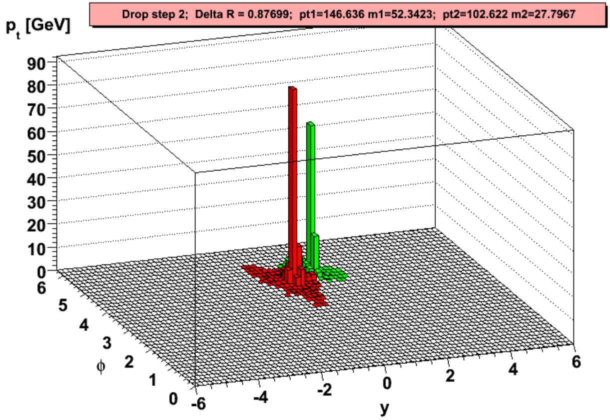

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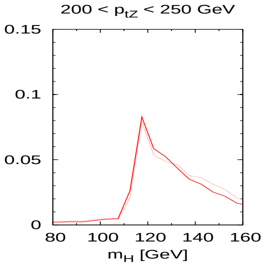

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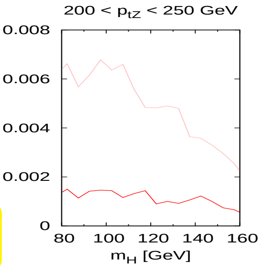

check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

arbitrary norm.

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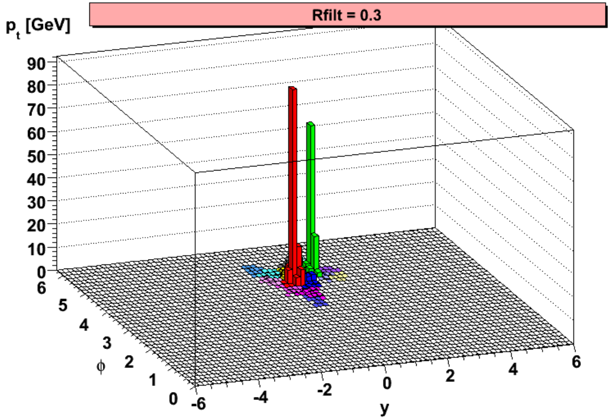

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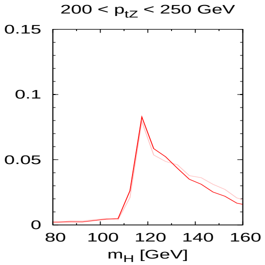

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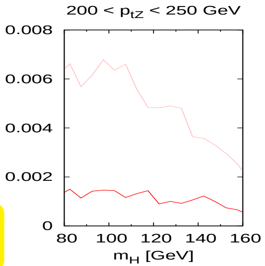

$R_{filt} = 0.3$

arbitrary norm.

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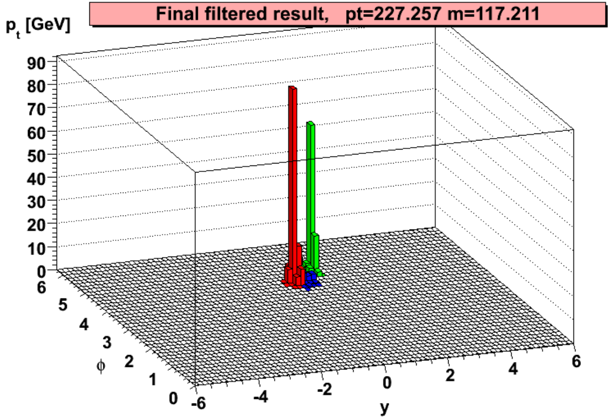
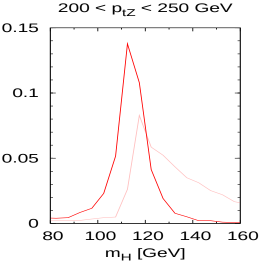


$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

SIGNAL



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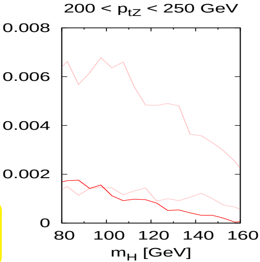
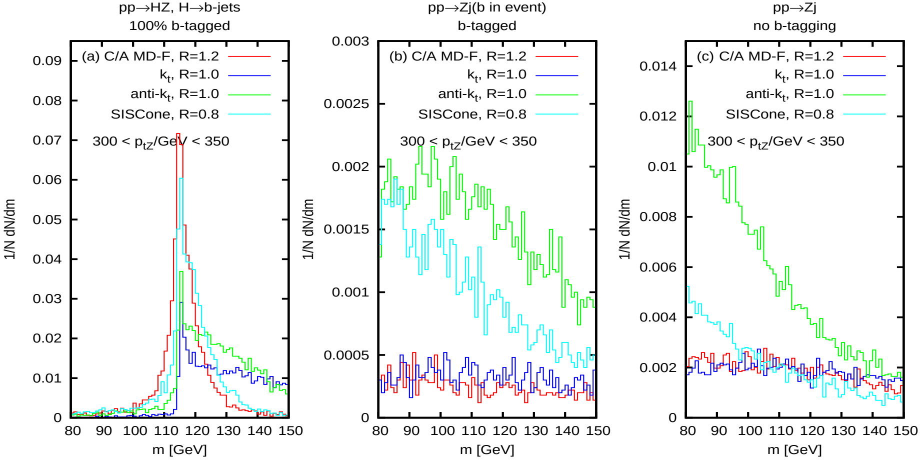


arbitrary norm.

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

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)

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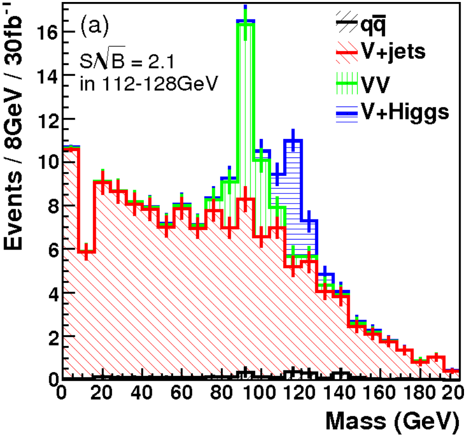
combine HZ and HW, $p_t > 200$ GeV

Leptonic channel



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- $S/\sqrt{B}$ from 16 GeV window

Leptonic channel

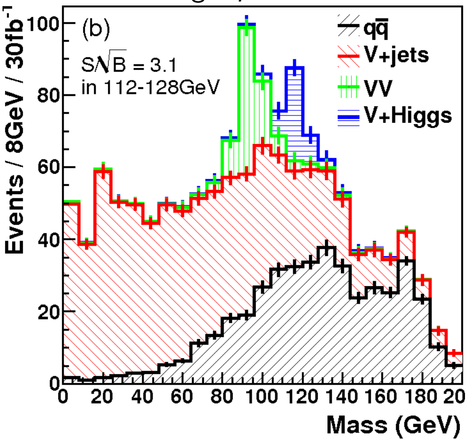
$Z \to \mu^+\mu^-, e^+e^-$

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

Missing E_T channel



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Missing-E_t channel

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

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

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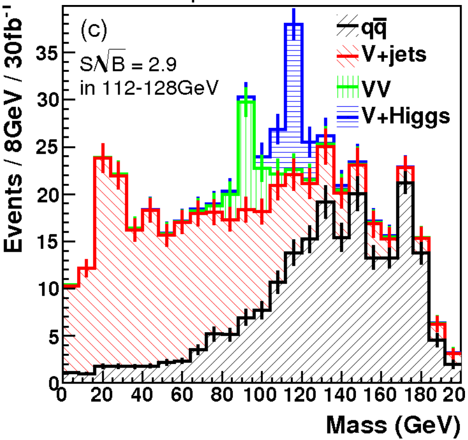
combine HZ and HW, $p_t > 200$ GeV



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- $S/\sqrt{B}$ from 16 GeV window

Semi-leptonic channel

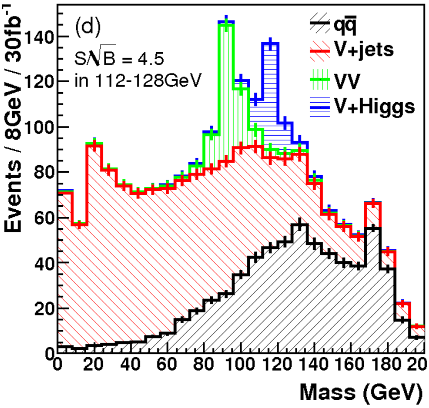
$W \to \nu\ell$

- $\not{E}_T > 30$ 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



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- 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

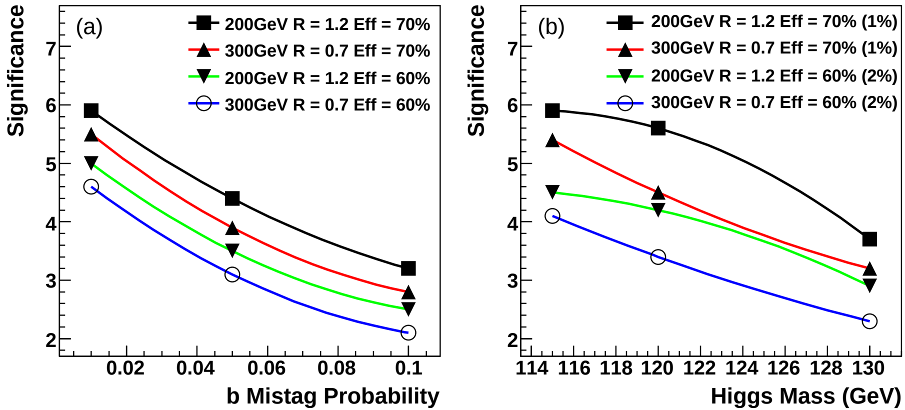
How can we be doing so well despite losing factor 20 in X-sct?

	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

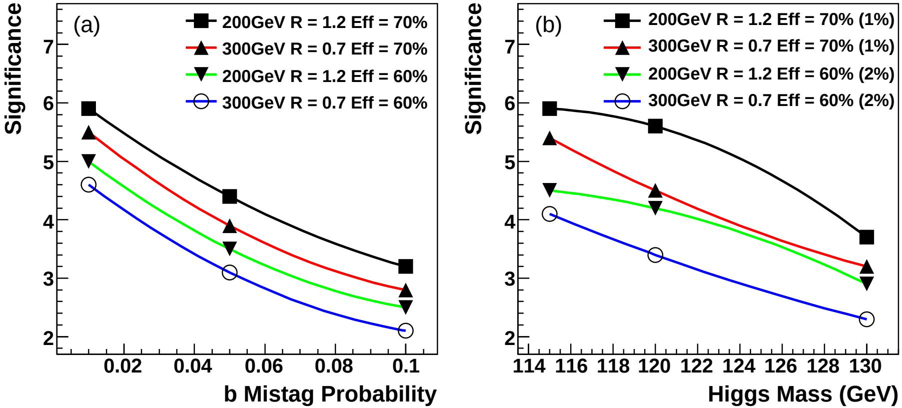


Most scenarios above 3σ

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

In nearly all cases, looks feasible for extracting *WH*, *ZH* couplings

Impact of *b*-tagging, Higgs mass



Most scenarios above 3σ

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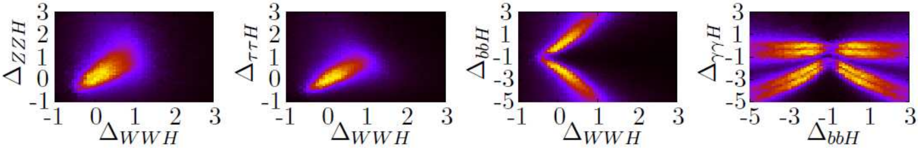
In nearly all cases, looks feasible for extracting *WH*, *ZH* couplings

Higgs coupling measurements

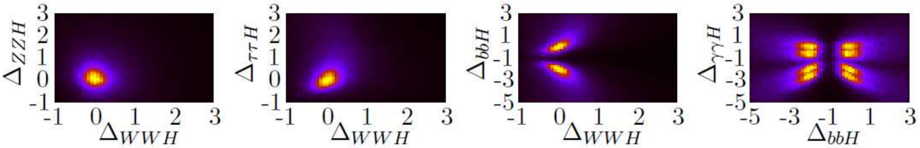
You only know it's the SM Higgs if couplings agree with SM expectations.

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

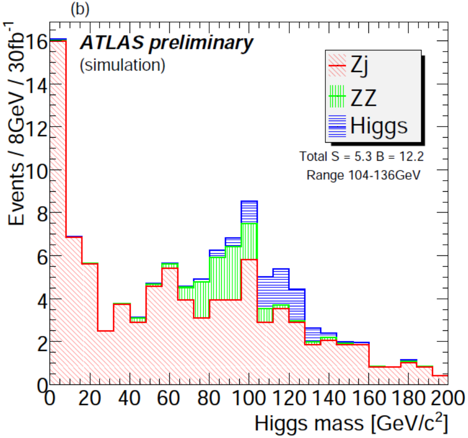
As of August 2009: ATLAS have preliminary public analysis of this channel
ATL-PHYS-PUB-2009-088

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*
- *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



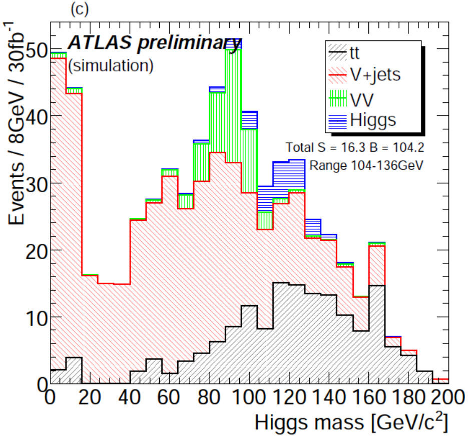
What changes compared to particle-level analysis?

$\sim 1.5\sigma$ as compared to 2.1σ

Expected given larger mass window

ATLAS results

Missing E_T channel



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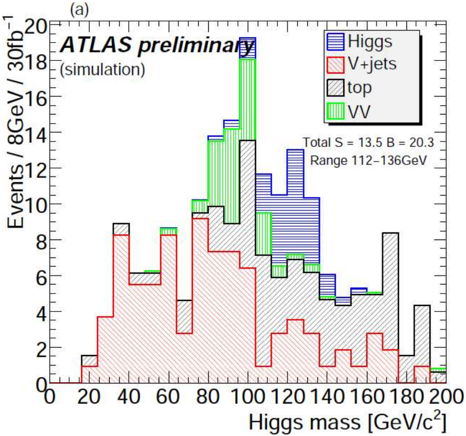
$\sim 1.5\sigma$ as compared to 3σ

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

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

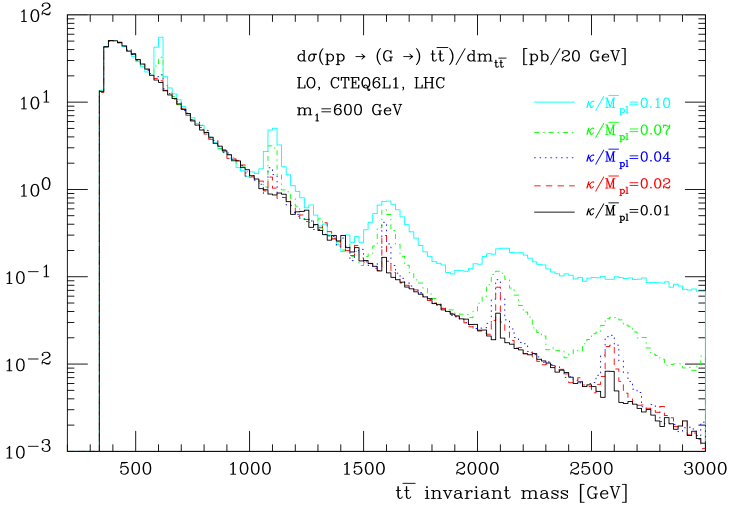
Combination of different kinematic regions

- 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 → $t\bar{t}$, from Frederix & Maltoni, 0712.2355

NB: QCD dijet spectrum is ∼ 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.

6 papers on top tagging in '08-'09 (at least). All use the jet mass + something extra.

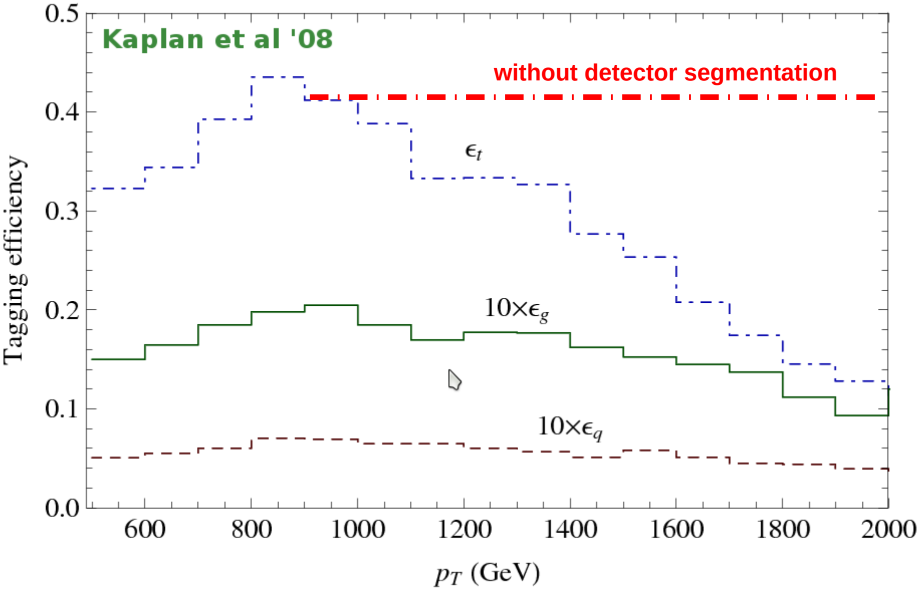
Questions

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

Rough results for top quark with $\mathbf{p_t \sim 1}$ 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	–	–
ATLAS '09	3,4 k_t subjets, d_{cut} MC likelihood	90%	15%

Efficiency v. p_t (ideal detector)



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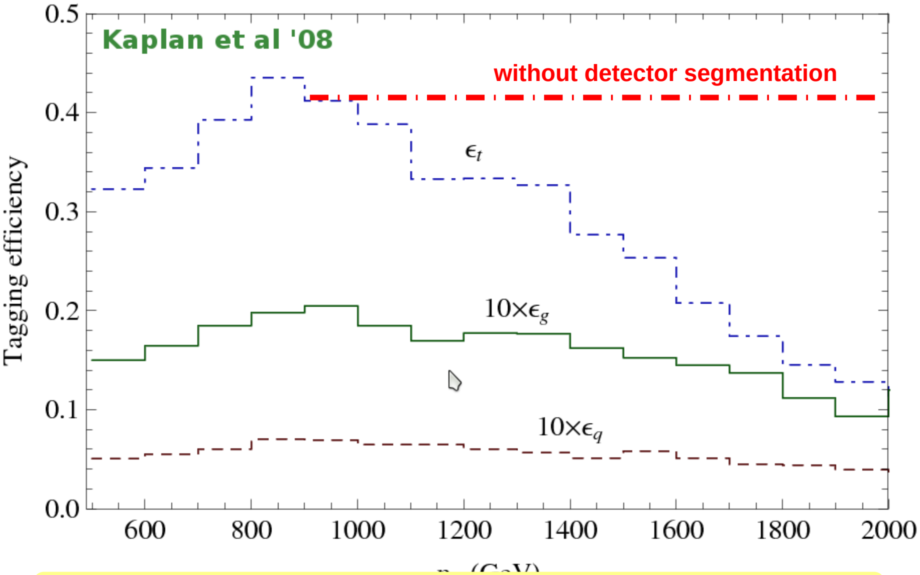
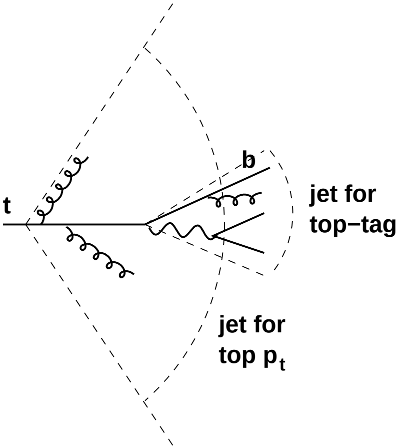


1-TeV Top tagging looks almost as good as 50 GeV *b*-tagging!

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

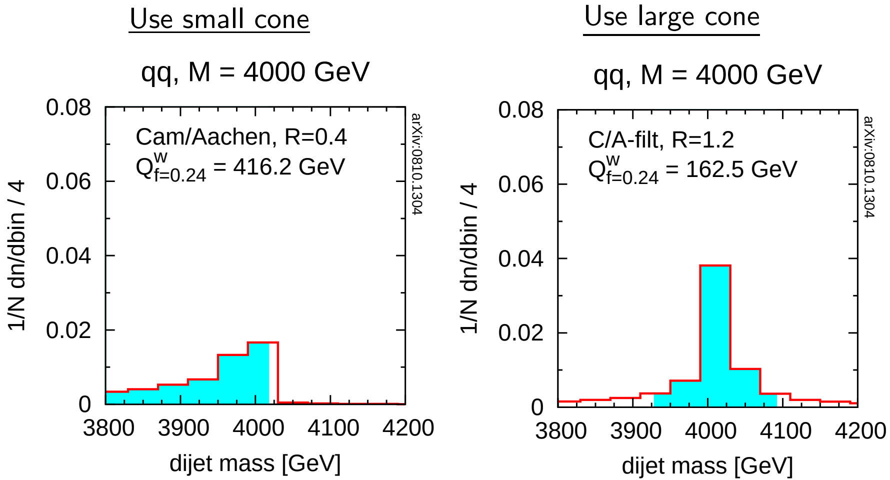


Figure actually from 0810.1304 (Cacciari, Rojo, GPS & Soyez)
for light $q\bar{q}$ resonance — but $t\bar{t}$ will be similar

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

R-parity violating SUSY

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

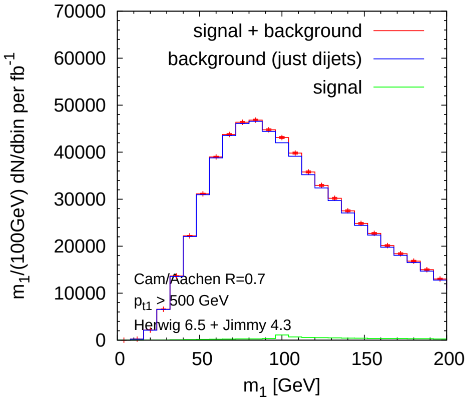
Normal SPS1A type SUSY scenario, *except* that neutralino is not LSP, but instead decays, $\tilde{\chi}_1^0 \to qqq$.

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 $\to$ jet with substructure

Butterworth, Ellis, Raklev & GPS '09

RPV SUSY, SPS1a, 1 fb^{-1}, single-jet mass



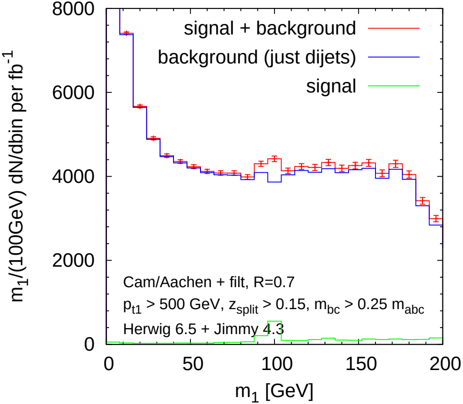
- Plot $\frac{m}{100\text{ GeV}}\frac{dN}{dm}$ for hardest jet ($p_t > 500$ GeV)
- Require 3-pronged substructure
- And third jet
- And fourth central jet

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

- And 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}, single-jet mass



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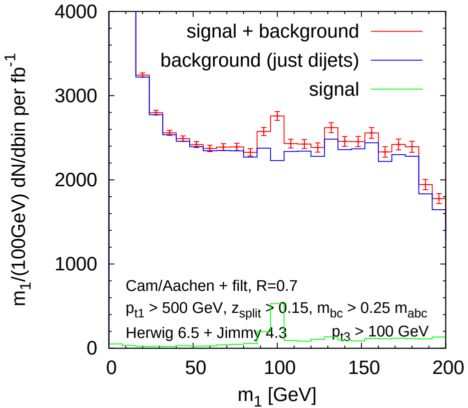

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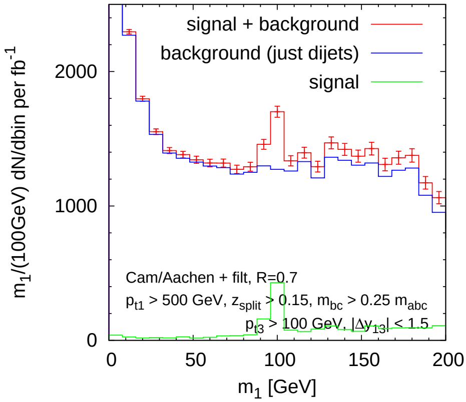

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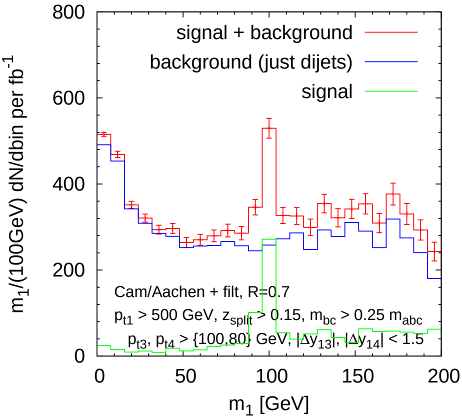

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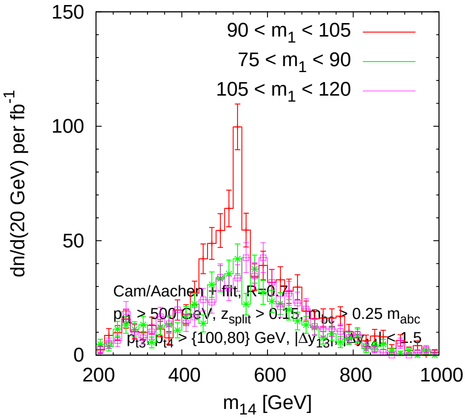

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Conclusions

Higgs discovery

- high-p_t limit recovers WH and ZH channel at LHC
- Separately see *WH*, *ZH* couplings
- First in-depth experimental study from ATLAS has promising results

Work continues in ATLAS. Also being looked at in CMS

New Physics searches

- Can be used for ID of high-p_t top from decaying multi-TeV resonances

  40%/1% efficiency / fake rate is similar to 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

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	$S/\sqrt{B \cdot \mathrm{fb}}$
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

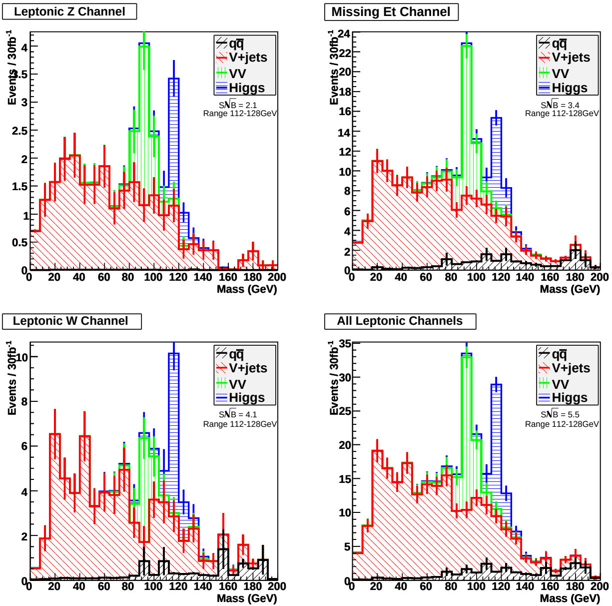
Analysis shown without K factors. What impact do they have?

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