Jet structures in New Physics and Higgs searches

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LPTHE, UPMC Paris 6 & CNRS

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

LHC will (should...) span two orders of magnitude in p_t:

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

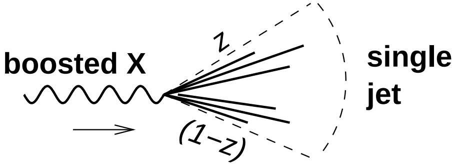
That's why it's being built

In much of that range, EW-scale particles are **light**
[a little like *b*-quarks at the Tevatron]

This talk:
about reconstructing high-p_t EW-scale particles

Boosted massive particles, e.g.: EW bosons

Hadronically decaying EW boson at high $\mathbf{p_t} \neq$ two jets



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

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 ($\frac{1}{8} < z < \frac{7}{8}$) — $R \gtrsim 0.6$

Relevant in (at least) two ways

New heavy particles can decay to W, Z, top → hadrons

- Need "taggers" for boosted hadronic SM particles
- To help extract new-physics signals; help identify their decays

Continue here: top-quark ID

New EW-scale particles may be *easier* to discover at high-p_t

- Some relevant fraction produced at high-p_t ($\sqrt{s} \gg m$)
- Jet combinatorics are easier at high p_t — cleaner events
- Easier to organise cuts so as not to sculpt backgrounds

Start here: light Higgs-boson search

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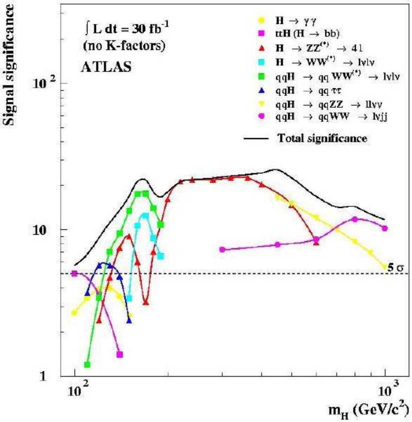


Low-mass Higgs search @ LHC: complex because dominant decay channel, $H \to bb$, often swamped by backgrounds.

Various production processes

- $gg \to H \; (\to \gamma\gamma)$ feasible
- $WW \to H \to \dots$ feasible
- $gg \to t\bar{t}H$ v. hard
- $q\bar{q} \to WH, ZH$

small; but gives access to *WH* and *ZH* couplings

Currently considered impossible

WH/ZH search channel @ LHC

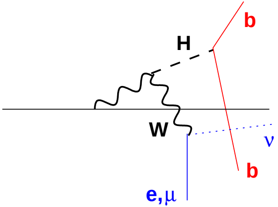
- Signal is $W \to \ell\nu$, $H \to b\bar{b}$.

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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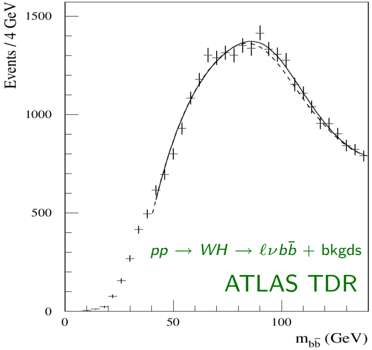

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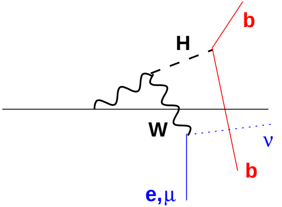

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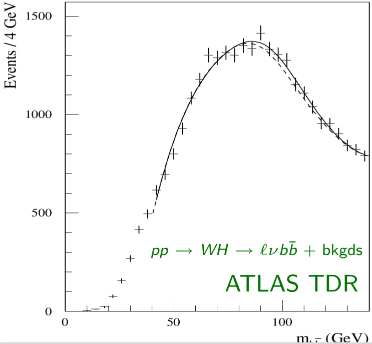

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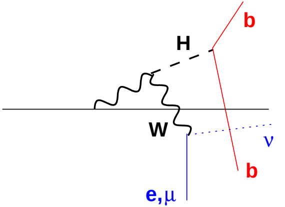
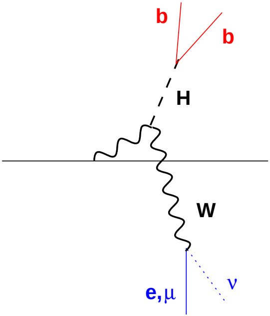
Conclusion (ATLAS TDR):

"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 [...]"



Study subset of WH/ZH with high p_t



At 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?

Finding a boosted Higgs?

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

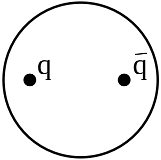
Special case of general (unanswered) question: how do we best do jet-finding?

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

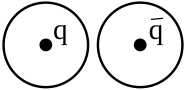
ETC.

Boosted ID strategies



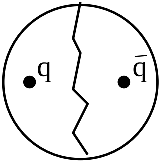
Select on the jet mass with one large (cone) jet

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

Past methods

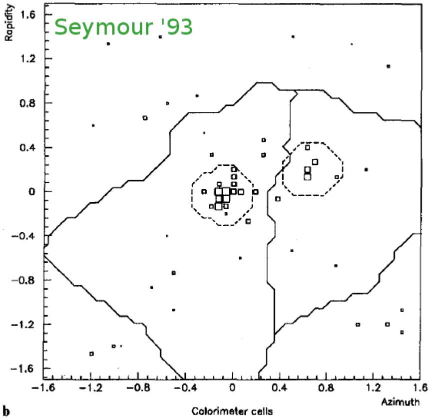
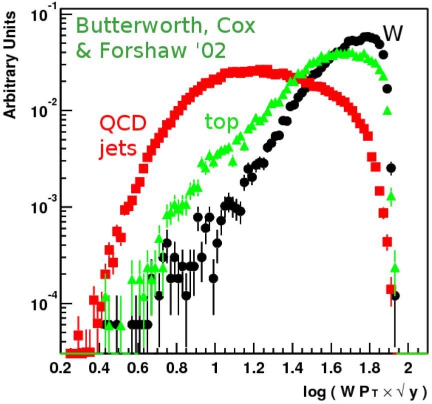


Fig. 2. A hadronic W decay, as seen at calorimeter level, **a** without, and **b** with, particles from the underlying event. Box sizes are logarithmic in the cell energy, lines show the borders of the sub-jets for infinitely soft emission according to the cluster (solid) and cone (dashed) algorithms

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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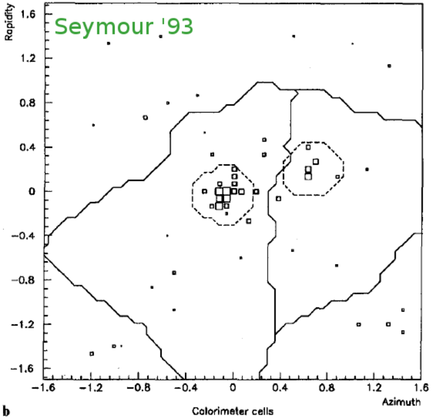

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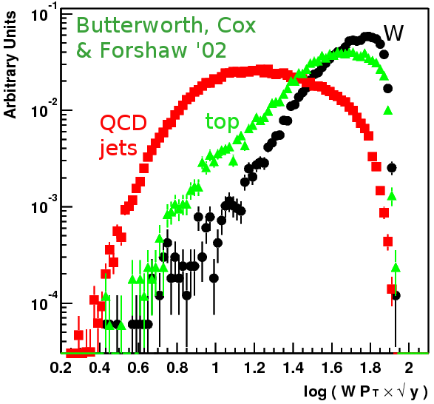

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#1: Our tool

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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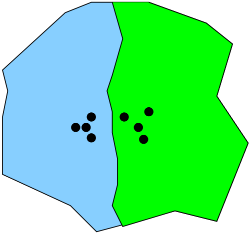
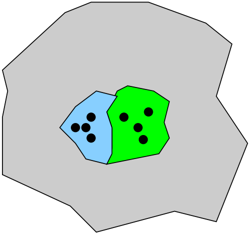
k_t algorithm

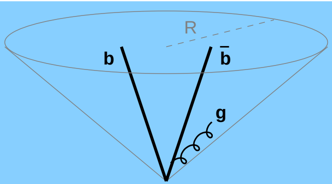


Cam/Aachen algorithm



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.
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

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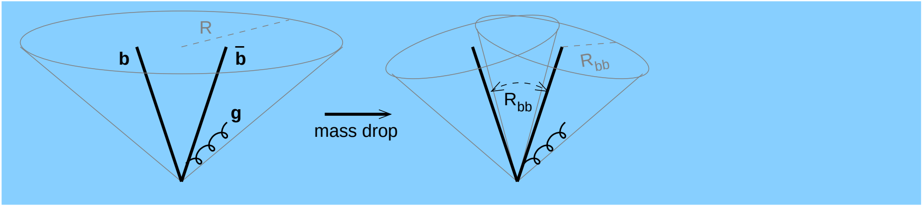

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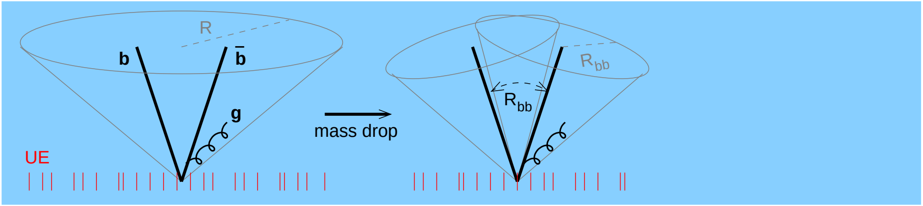
#3: jet filtering



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

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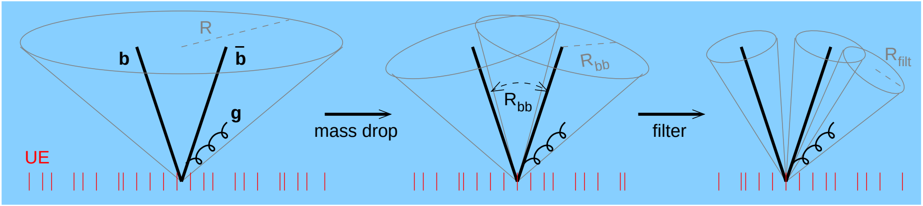

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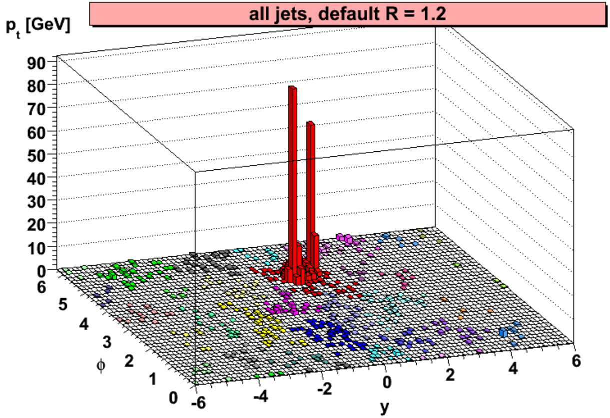
$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

Cluster event, C/A, R=1.2

arbitrary norm.

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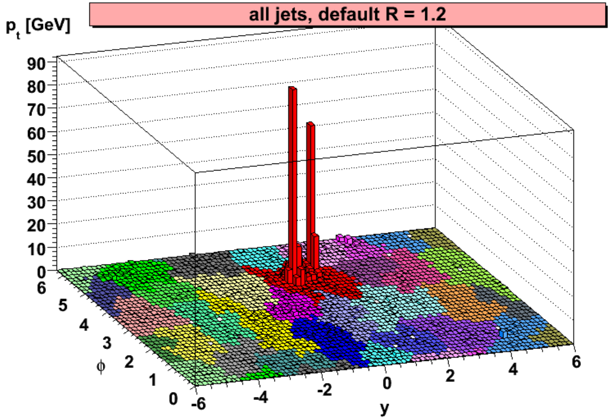

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Fill it in, → show jets more clearly

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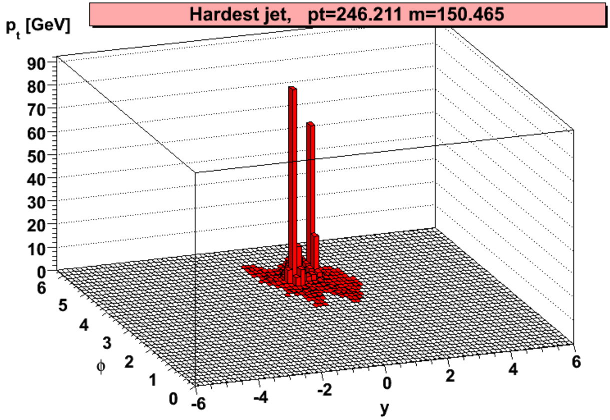
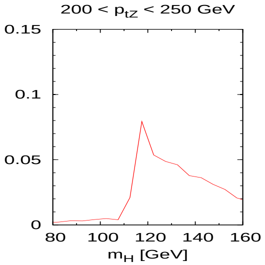


Consider hardest jet, $m = 150$ GeV

SIGNAL



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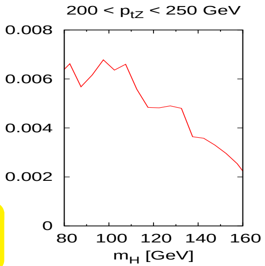

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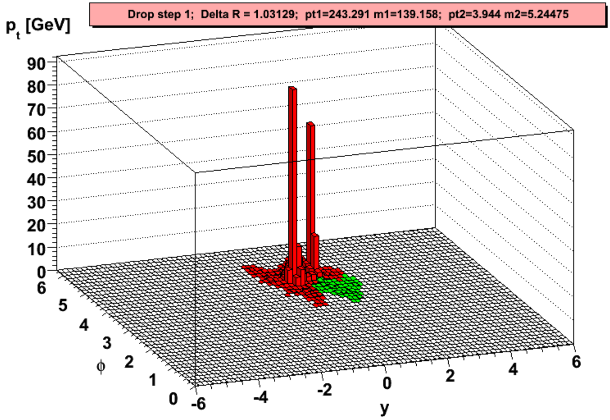

split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

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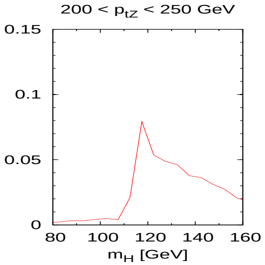

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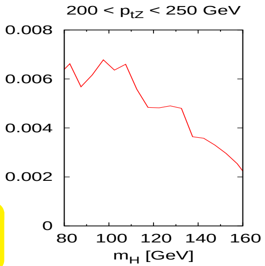

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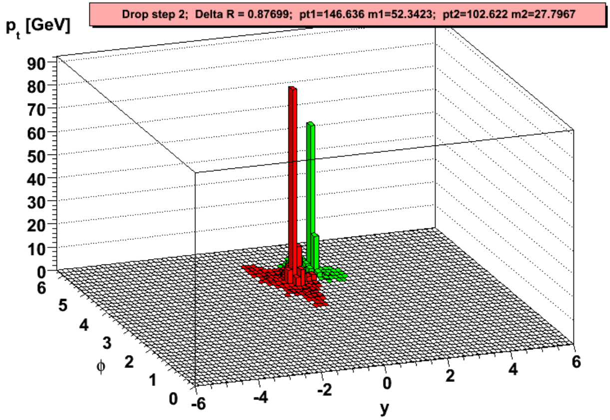
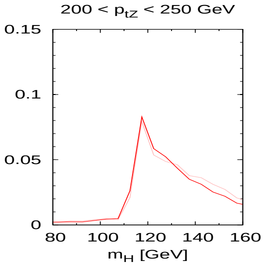


split: $m = 139$ GeV, $\frac{\max(m_1,m2)}{m} = 0.37 \to$ mass drop

SIGNAL



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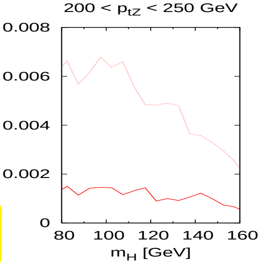

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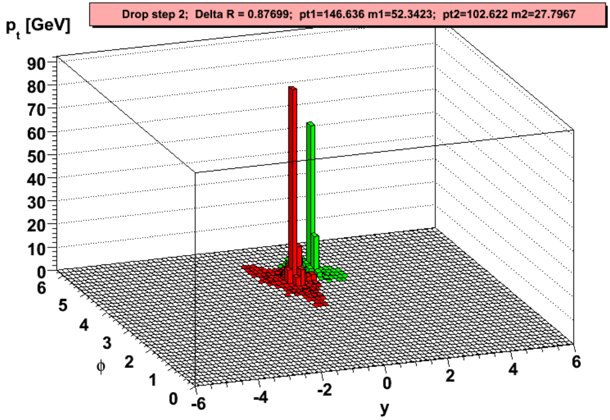

check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

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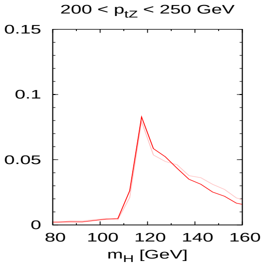

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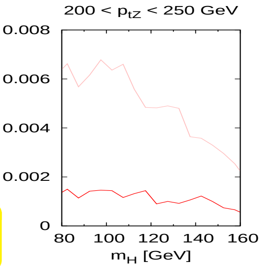

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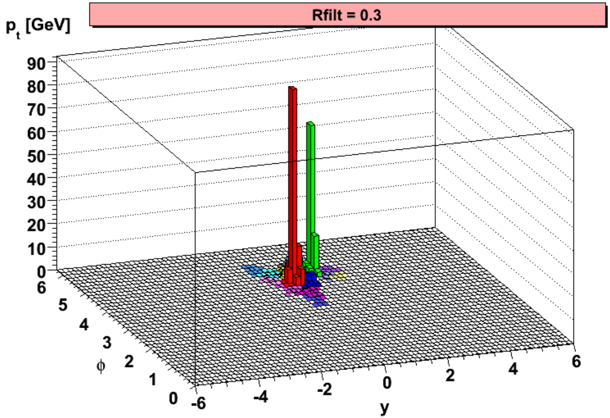

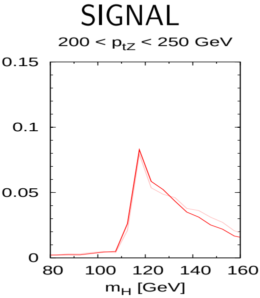

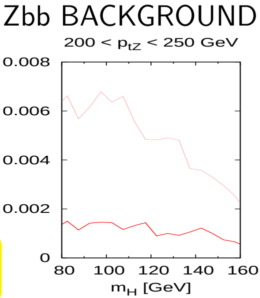

$R_{filt} = 0.3$

arbitrary norm.

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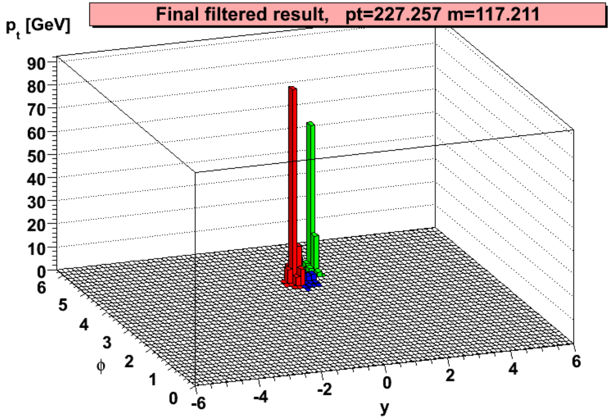
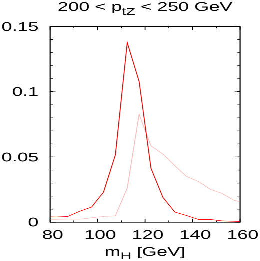
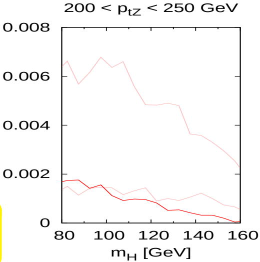


$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

SIGNAL



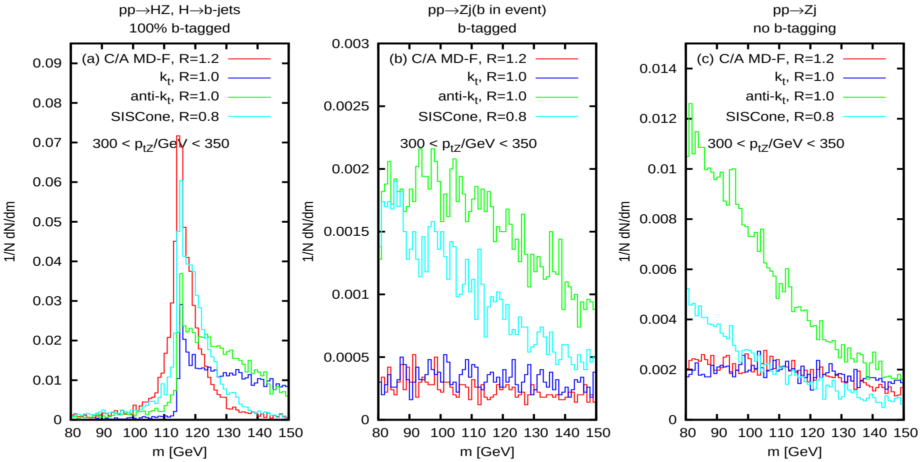
Zbb BACKGROUND



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

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 slide

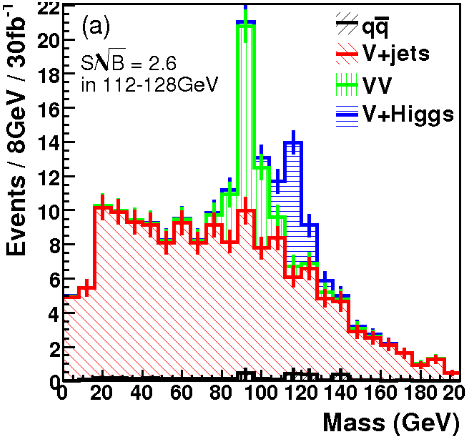
Assumptions

- Real/fake b-tag rates: 0.7/0.01 — optimistic, but not inconceivable
- $S/\sqrt{B}$ 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: 0.7/0.01
- $S/\sqrt{B}$ from 16 GeV window

Leptonic channel

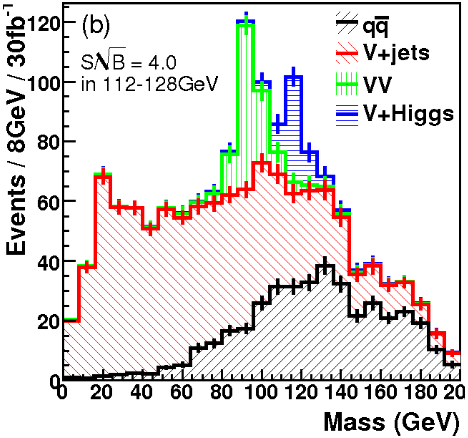
$Z \to \mu^+\mu^-, e^+e^-$

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

At 5.9σ 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



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: 0.7/0.01
- $S/\sqrt{B}$ from 16 GeV window

Missing-E_t channel

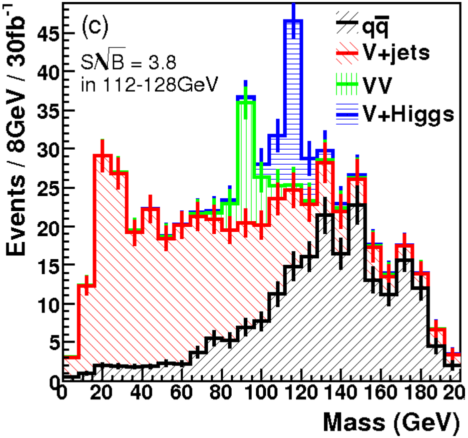
$Z \to \nu\bar{\nu}$, $W \to \nu[\ell]$

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

At 5.9σ 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: 0.7/0.01
- $S/\sqrt{B}$ from 16 GeV window

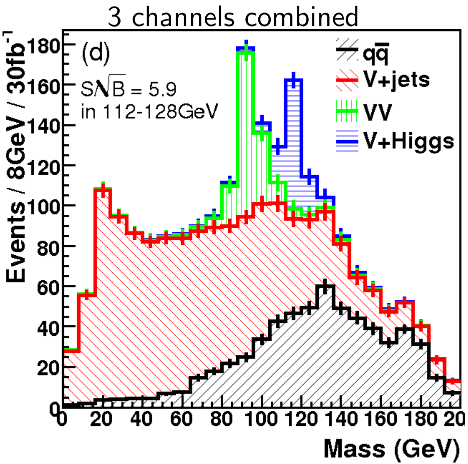
Semi-leptonic channel

$W \to \nu\ell$

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

At 5.9σ 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
- $|\eta_H| < 2.5$
- $[p_{t,\ell} > 30 \text{ GeV}, |\eta_\ell| < 2.5]$
- No extra ℓ, b's with $|\eta| < 2.5$
- Real/fake b-tag rates: 0.7/0.01
- $S/\sqrt{B}$ 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 5.9σ 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

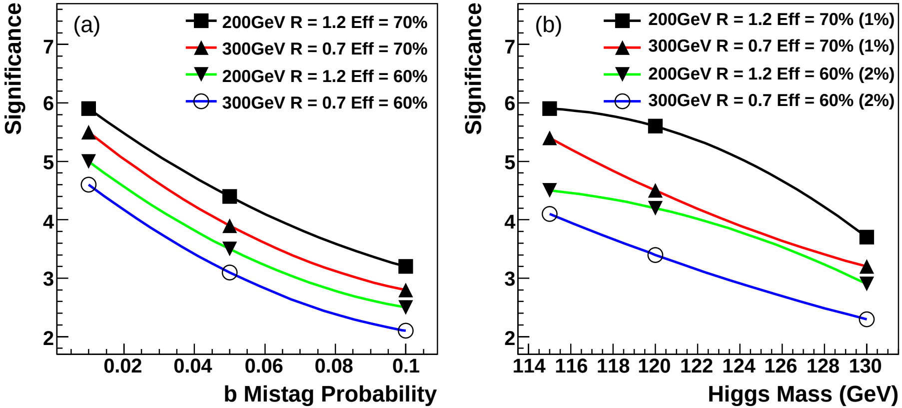
How can we be doing so well despite losing factor 20 in X-sct?

	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

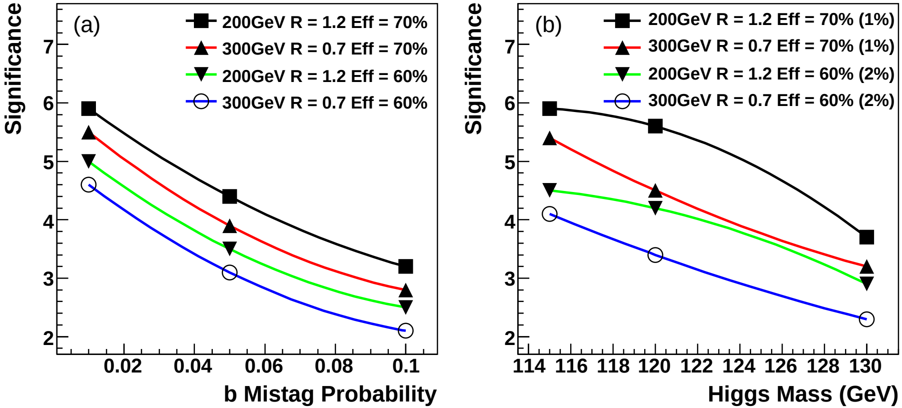


Most scenarios above 3σ

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



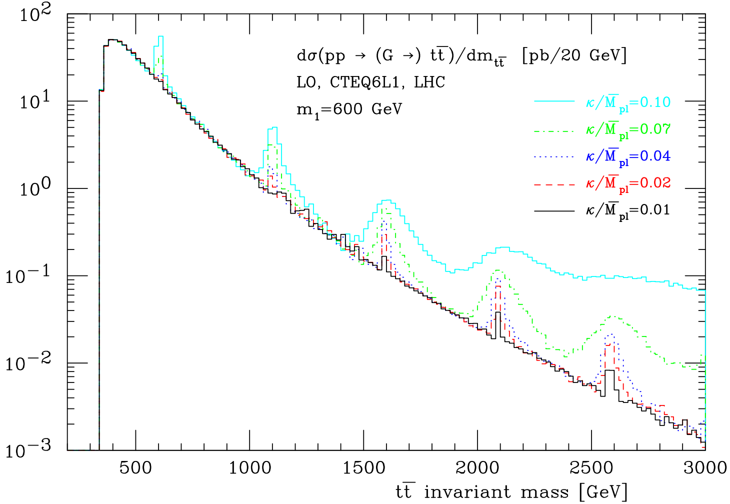
Most scenarios above 3σ

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

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.

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

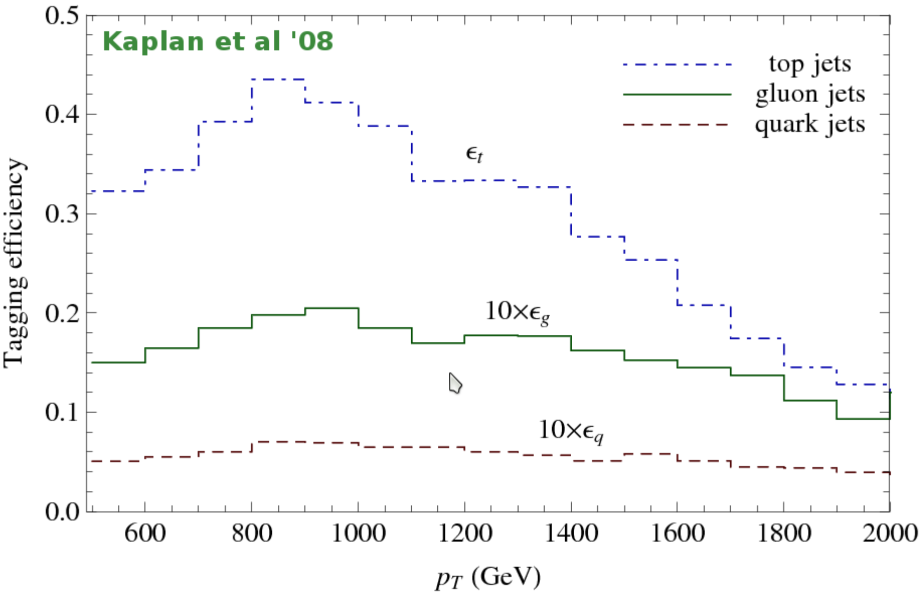
Questions

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

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

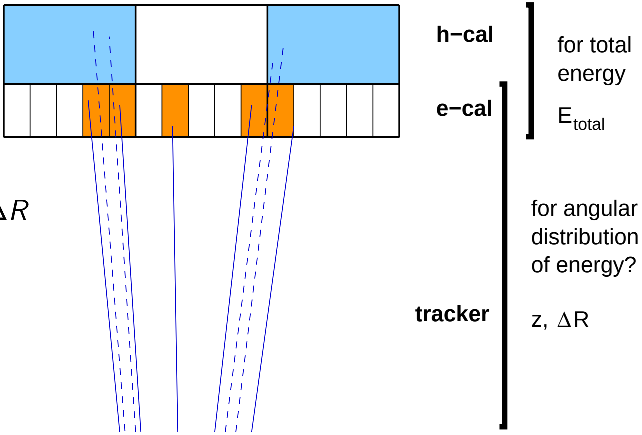
	"Extra"	eff.	fake
[from T&W]	just jet mass	50%	10%
Brooijmans	3,4 k_t subjets, d_{cut}	45%	5%
Thaler & Wang	2,3 k_t subjets, z_{cut} + various	40%	5%
Kaplan et al.	3,4 C/A subjets, $z_{cut} + \theta_h$	40%	1%
Almeida et al.	predict mass dist^n, use jet-shape	–	–

Efficiency v. p_t with calo (0.1x0.1)



Fair assumptions for detector?

Theory $t\bar{t}$ studies use $\eta - \phi$ segmentation of 0.1. *Limiting when $\Delta R \sim 0.1$*
But charged tracks and EM-calo provide much better angular resolution.



two-body mass

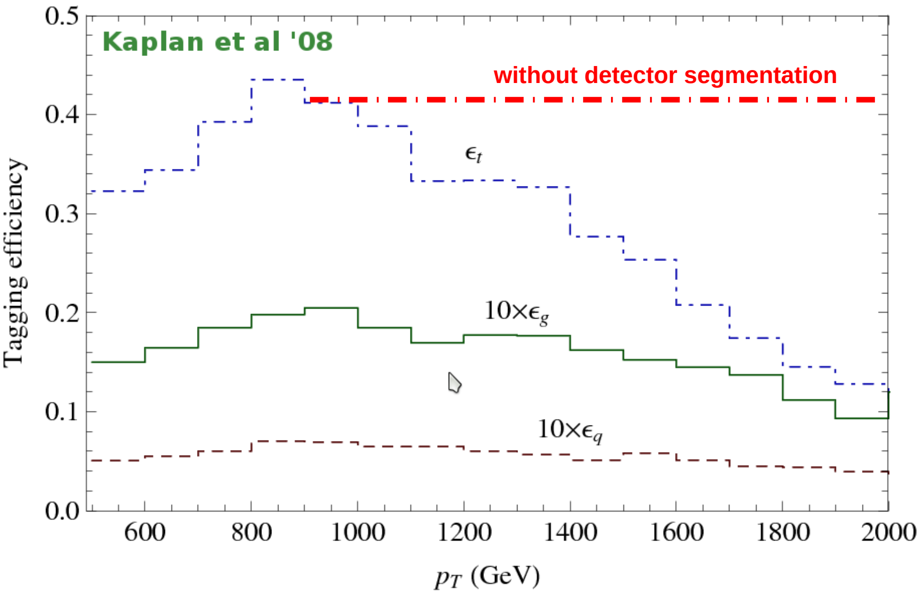
$$m \simeq E_{total}\sqrt{z(1-z)}\Delta R$$

For $z \geq 0.2$:

25% error on z ⇔
$\lesssim$ 10% error on mass

Even rough info from tracks & e-cal very valuable

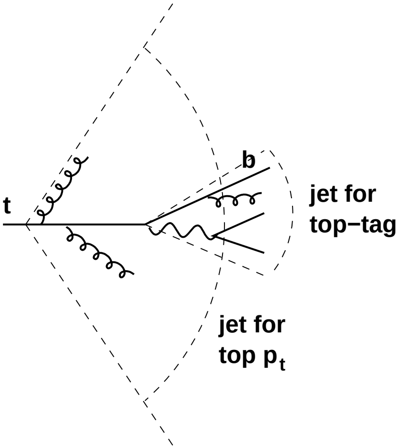
Efficiency v. p_t (ideal detector)



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

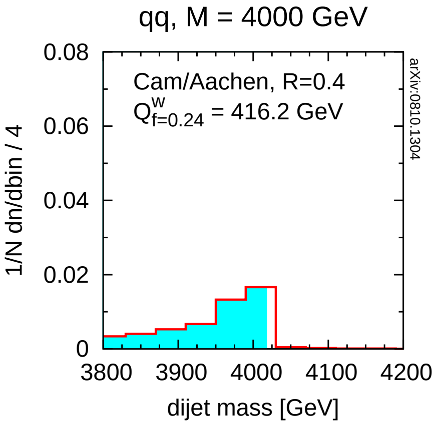
Outside dead cone, you have radiation from top quark

essential for top p_t

Cacciari, Rojo, GPS & Soyez '09

Impact of using small cone angle

Use small cone



Use large cone

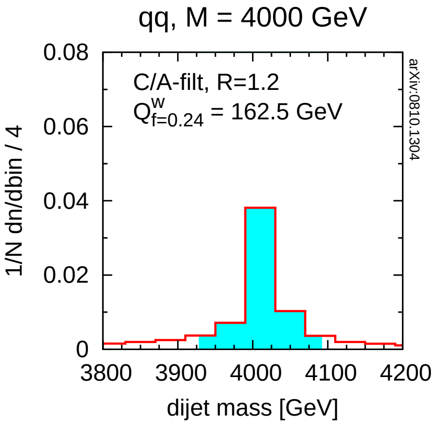


Figure actually from 0810.1304 (Cacciari, Rojo, GPS & Soyez)
for light $q\bar{q}$ resonance — but $t\bar{t}$ will be similar

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

Conclusions

General

- Boosted EW-scale particles can be found in jets
- Cambridge/Aachen alg. is very powerful (flexible, etc.) tool for this
- General two-body eff/fake is 60% v. $3-7\%$

Higgs discovery

- high-p_t limit recovers WH and ZH channel at LHC
- Separately see WH, ZH couplings
- Deserves & needs in-depth experimental study

ongoing/starting within ATLAS/CMS

Top

- Efficiencies/fake rates: up to 40/1(2)%
- Only get this if detector can resolve fine structure
- Top-quark at decay (the one you tag) and top-quark at production are different objects

need different R for them

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

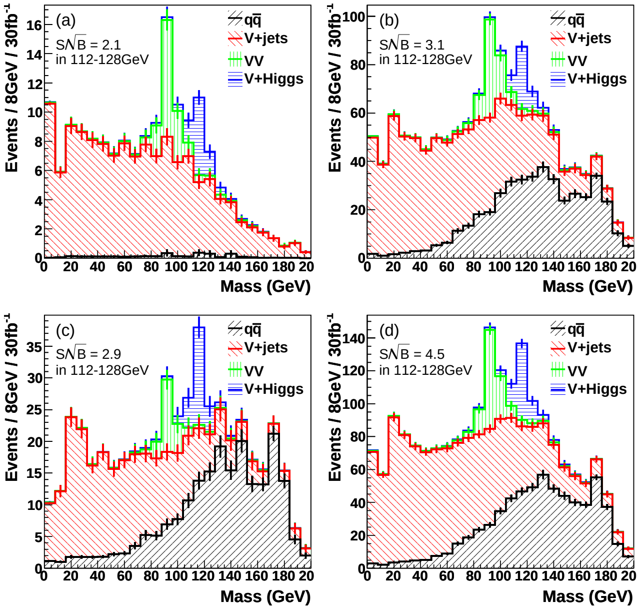
Analysis shown without K factors. What impact do they have?

Determined with MCFM, MC@NLO

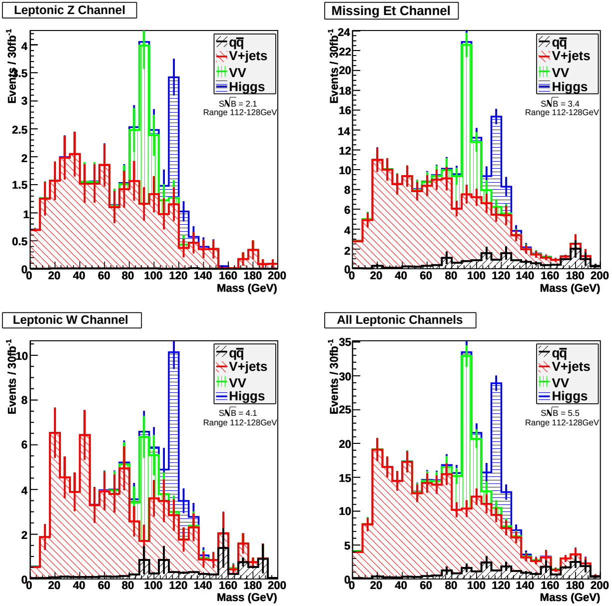
- Signal: $K \sim 1.6$
- Vbb backgrounds: $K \sim 2 - 2.5$
- $t\bar{t}$ backgrounds: $K \sim 2$ — for total; not checked for high-p_t part

Conclusion: $S/\sqrt{B}$ should not be severely affected by NLO contributions

Worsen *b*-tagging: 60%/2%



Raise p_t cut to 300 GeV



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