Theory review: hadronic jets with substructure

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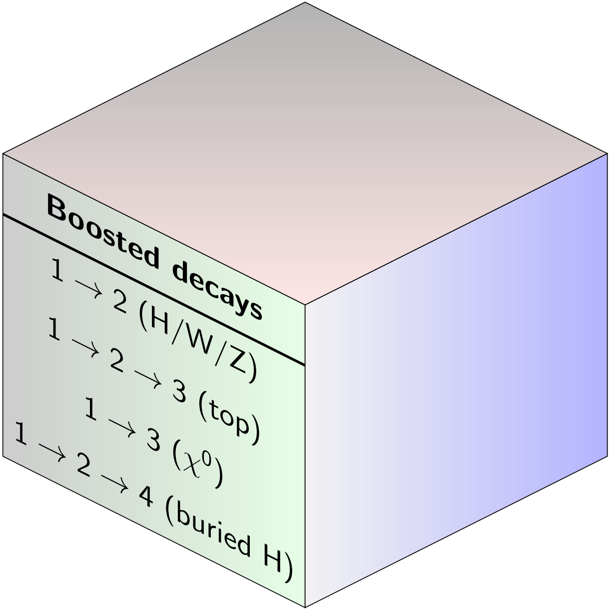
2 motivations for boosted studies:

Something heavy (e.g. Z') decays to something light ($t/W/Z/H/\ldots$), which is then naturally boosted

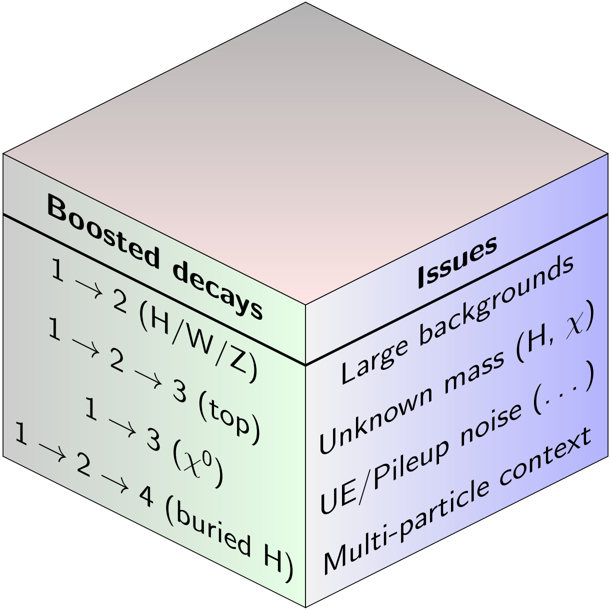
A new light particle ($H/\chi^0/\ldots$) emerges more clearly above backgrounds in the small fraction of events where it's produced boosted

$\sqrt{s_{LHC}} \gg m_{EW}$ makes both of these relevant

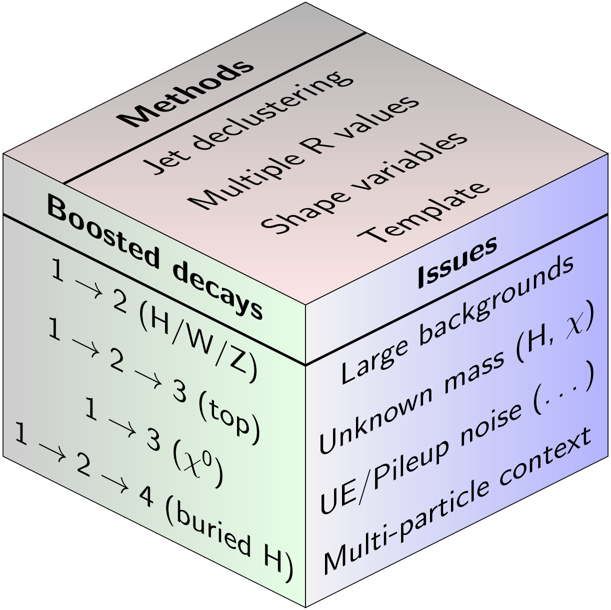
Different facets



Different facets



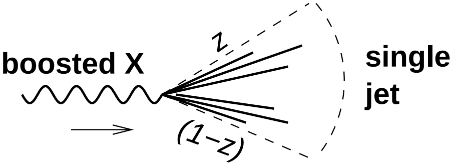
Different facets



Basics

Boosted massive particles, e.g.: EW bosons

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



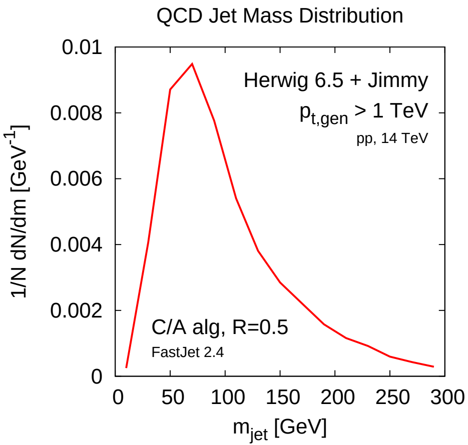
$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

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

Jet mass



For boosted heavy object, obvious thing to tag on is the jet mass.

But QCD jets also have masses → large backgrounds, sometimes peaked in same mass region as signal.

So how can do we do better?

3 principles can help us

- Heavy-object decays share energy symmetrically, QCD background events with same mass share energy asymmetrically

  Measuring energy-sharing inside jet gives clue as to origin

- QCD radiation from a colour-neutral heavy-object decay is limited by angular ordering

  Tells us where to "look for the right mass"

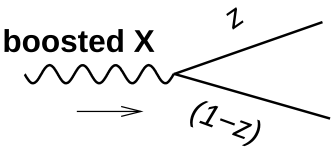
  Radiation outside that region may hint that jet is background

- QCD radiation from Higgs decay products is point-like, noise (UE, pileup) is diffuse

  Helps us get the right mass

QCD principle: soft divergence

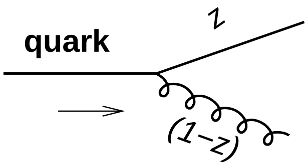
Signal



Splitting probability for Higgs:

$$P(z) \propto 1$$

Background



Splitting probability for quark:

$$P(z) \propto \frac{1+z^2}{1-z}$$

$1/(1-z)$ divergence enhances background

Remove divergence in bkdg with cut on z
Can choose cut analytically so as to maximise $S/\sqrt{B}$

Originally: cut on (related) k_t-distance
Butterworth, Cox & Forshaw '02

Higgs searches

$H \to b\bar{b}$ boosted search channel at LHC

- Hint of $H \to b\bar{b}$ in SUSY searches — Butterworth, Ellis & Raklev '07
- Proposal that boosted regime recovers WH & ZH channels at LHC
  Butterworth, Davison, Rubin & GPS '08
- Confirmation that this works with realistic detector simulation
  ATLAS '09
- Proposal that boosted H recovers ttH channel
  Plehn, GPS & Spannowsky '09
- Possibility of $H \to b\bar{b}$ discovery in SUSY events
  Kribs, Martin, Roy & Spannowsky '09–'10
- Optimising $H \to b\bar{b}$ significance over bkdg by combining filtering / pruning / trimming — Soper & Spannowsky '10

Early declustering methods

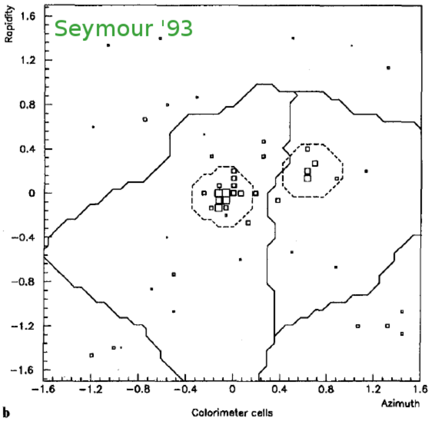
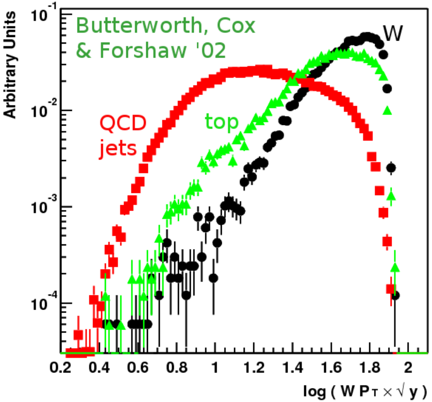


Fig. 2. A hadronic W decay, as seen at calorimeter level, **a** without, and **b** with, particles from the underlying event. Box sizes are logarithmic in the cell energy, lines show the borders of the sub-jets for infinitely soft emission according to the cluster (solid) and cone (dashed) algorithms

Use k_t jet-algorithm's hierarchy to split the jets



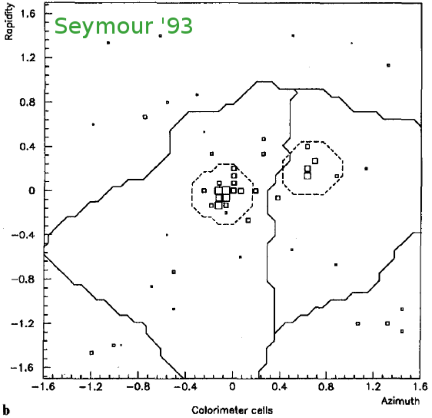
Use k_t alg.'s distance measure (rel. trans. mom.) to cut out QCD bkgd:

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

Y-splitter

only partially correlated with mass

Early declustering methods



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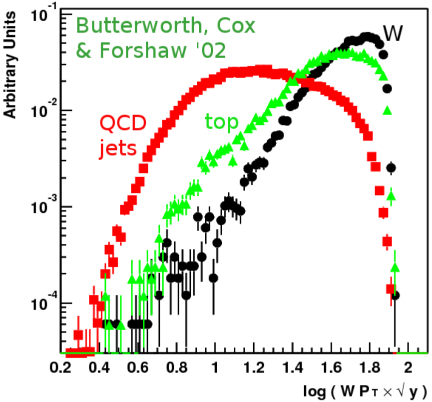

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The Cambridge/Aachen algorithm

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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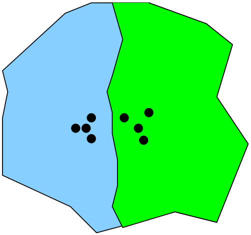
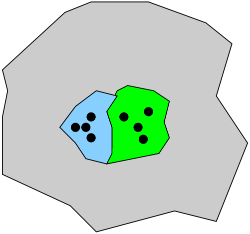
k_t algorithm



Cam/Aachen algorithm

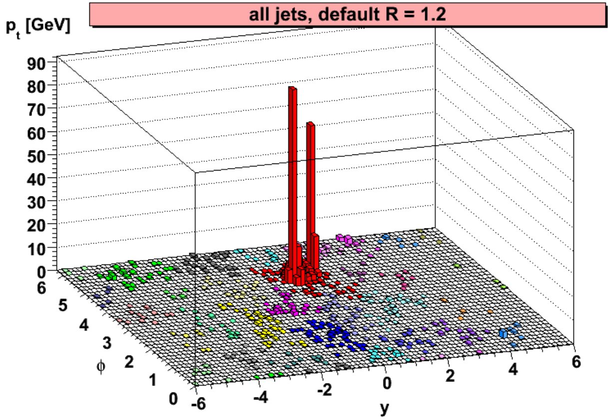


Allows you to "dial" the correct R to keep perturbative radiation, but throw out UE

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

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

Cluster event, C/A, R=1.2

arbitrary norm.

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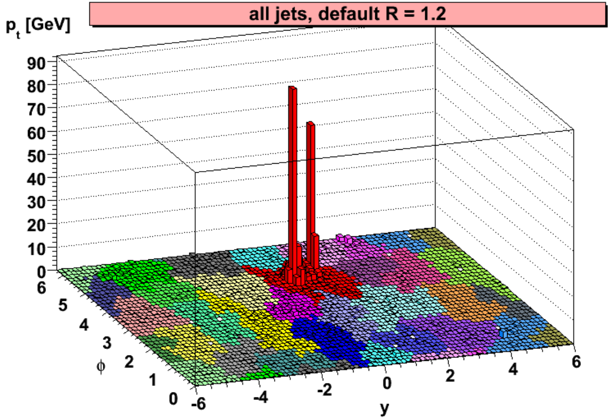

Zbb BACKGROUND

Fill it in, $\to$ show jets more clearly

arbitrary norm.

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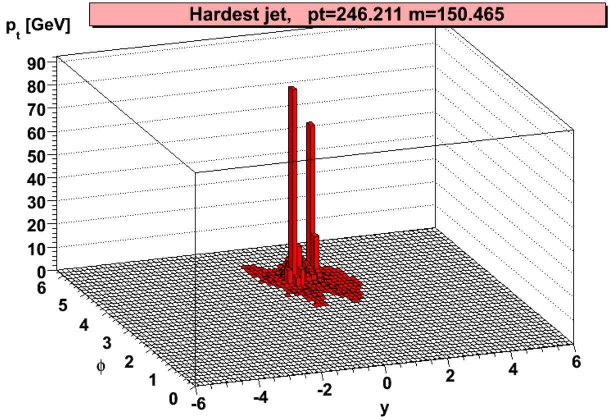
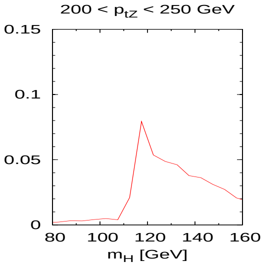
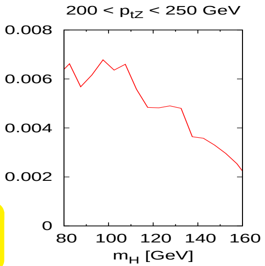


Consider hardest jet, $m = 150$ GeV

SIGNAL



Zbb BACKGROUND



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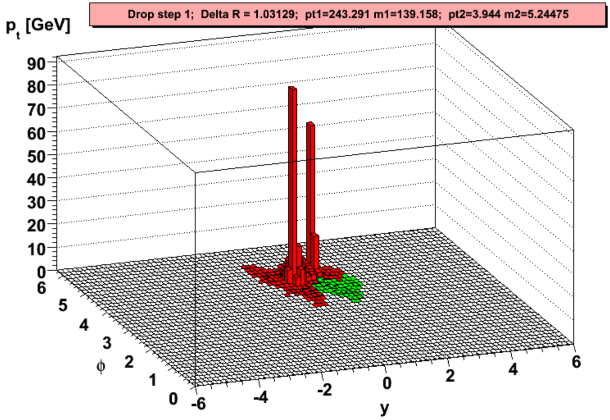
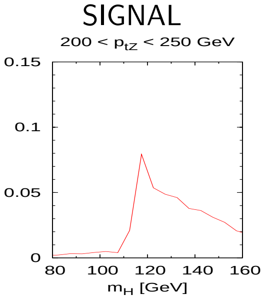
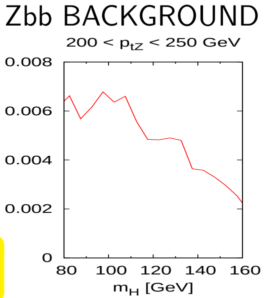


split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat





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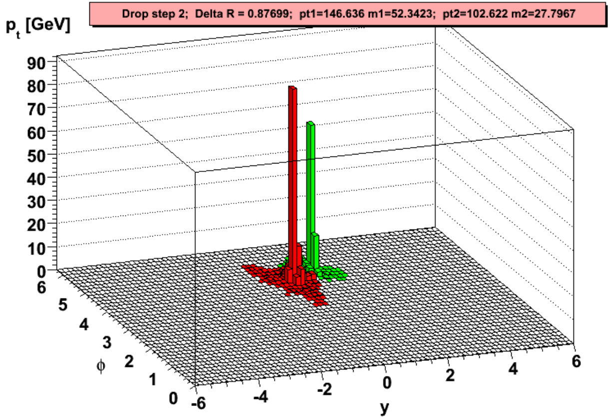
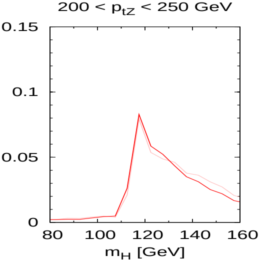
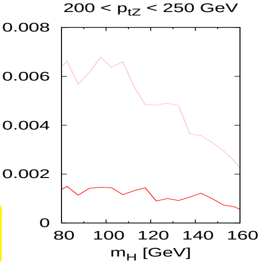


split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

SIGNAL



Zbb BACKGROUND



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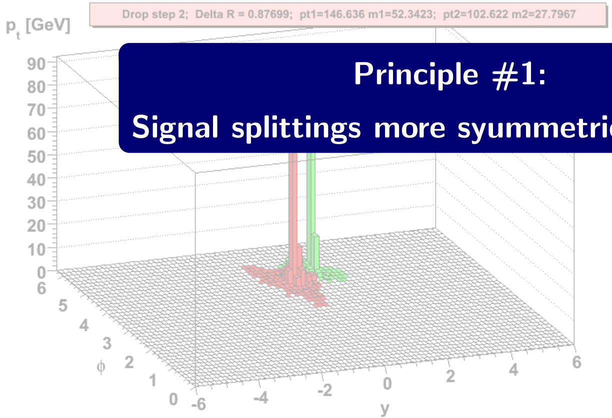
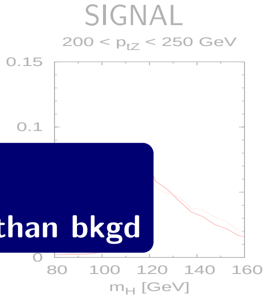
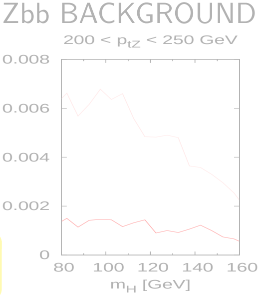


Principle #1:

Signal splittings more syummetric than bkgd





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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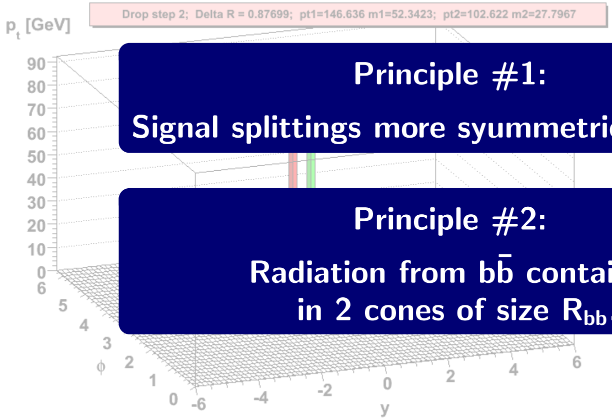
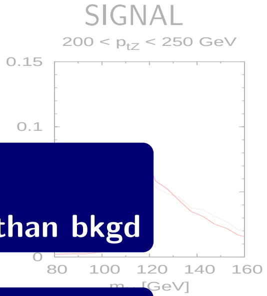


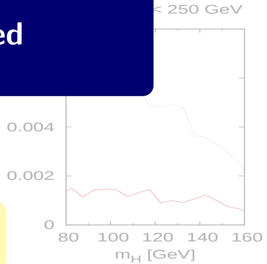


Principle #1:

Signal splittings more syummetric than bkgd

Principle #2:

Radiation from $b\bar{b}$ contained in 2 cones of size R_{bb}.



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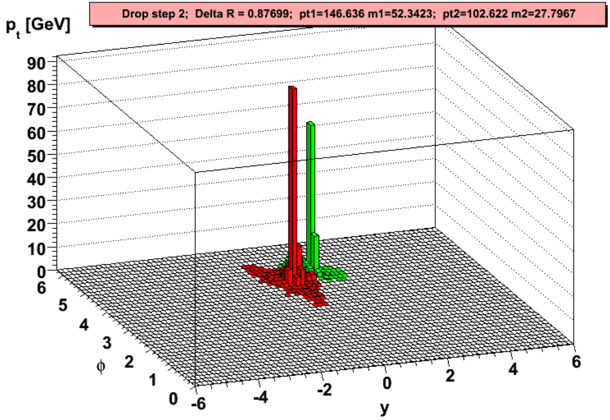

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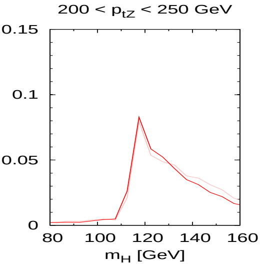
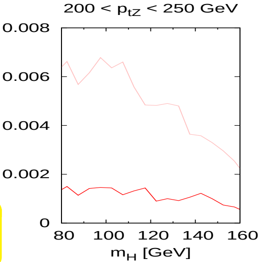
SIGNAL



Zbb BACKGROUND



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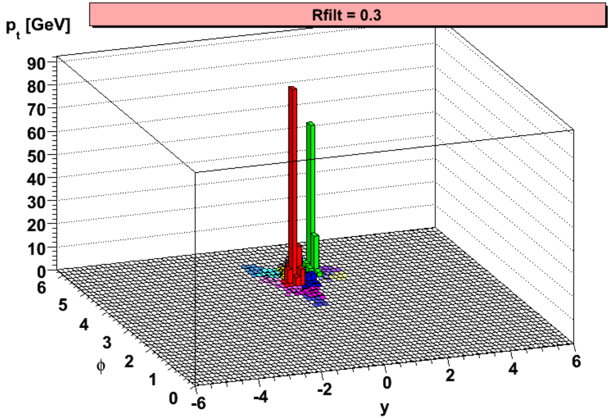
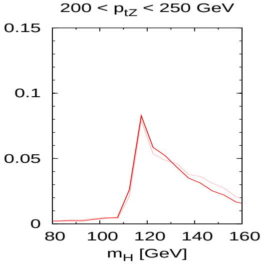


$R_{filt} = 0.3$

SIGNAL



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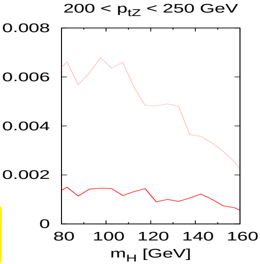

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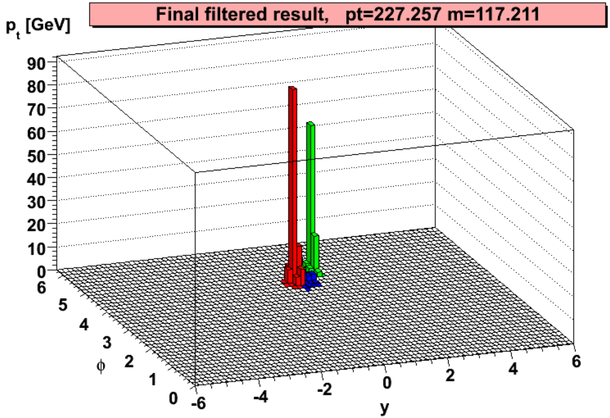
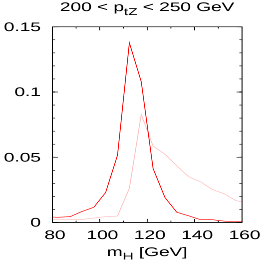


$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

SIGNAL



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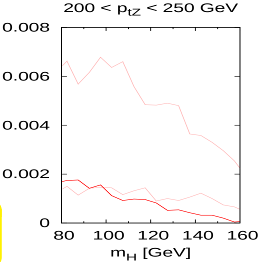

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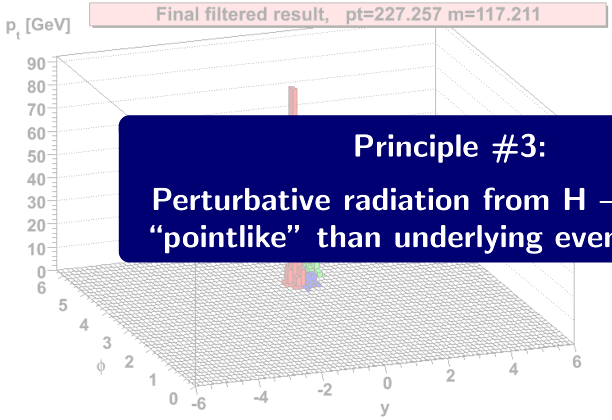

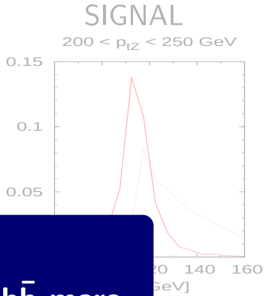

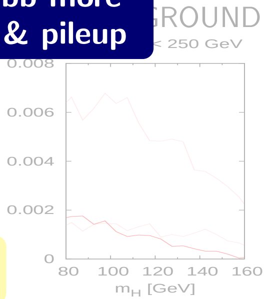

Principle #3:

Perturbative radiation from $H \to b\bar{b}$ more "pointlike" than underlying event & pileup

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

arbitrary norm.

Noise removal

UE adds $\Lambda \simeq 10 - 15$ GeV of noise per unit rapidity. For a jet of size R, effect on jet mass goes as

$$\langle \delta m^2 \rangle \simeq \Lambda p_t \frac{R^4}{4} \sim 4\Lambda \frac{m^4}{p_t^3}$$

Dasgupta, Magnea & GPS '07

Filtering, Pruning & Trimming are all intended to reduce this noise.
Viewing the jet on some smaller scale R_{sub}, throw out softest subjets:

- **Filtering**: break jet into subjets on angular scale R_{filt}, take n_{filt} hardest subjets — Butterworth, Davison, Rubin & GPS '08
- **Trimming**: break jet into subjets on angular scale R_{trim}, take all subjets with $p_{t,sub} > \epsilon_{trim} p_{t,jet}$ — Krohn, Thaler & Wang '09
- **Pruning**: as you build up the jet, if the two subjets about to be recombined have $\Delta R > R_{prune}$ and $\min(p_{t1}, p_{t2}) < \epsilon_{prune}(p_{t1} + p_{t2})$, discard the softer one. — Ellis, Vermilion & Walsh '09

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Dasgupta, Magnea & GPS '07

Filtering, Pruning & Trimming are all intended to reduce this noise. Viewing the jet on some smaller scale R_{sub}, throw out softest subjets:

These techniques matter most for moderate $\mathbf{p_t}$ objects

(And also for high-mass resonances $\rightarrow$ jets)

- … 08
- … s with $p_{t,sub} > \epsilon_{trim} p_{t,jet}$ Krohn, Thaler & Wang '09
- **Pruning**: as you build up the jet, if the two subjets about to be recombined have $\Delta R > R_{prune}$ and $\min(p_{t1}, p_{t2}) < \epsilon_{prune}(p_{t1} + p_{t2})$, discard the softer one. Ellis, Vermilion & Walsh '09

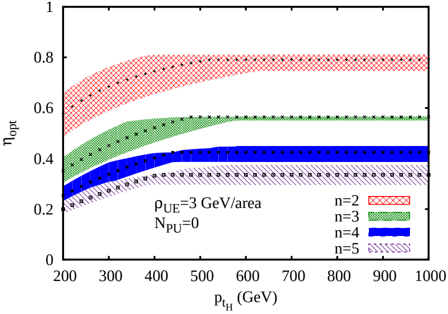
Optimising "jet cleaning"

Analytically optimize filtering as a function of p_t, amount of pileup, etc.

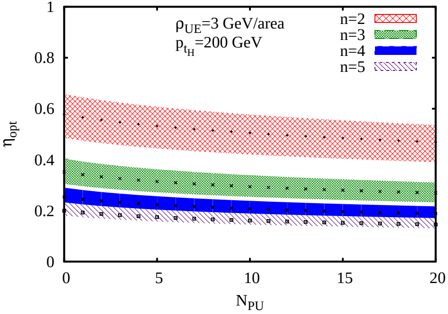
Put together QCD resummations, modelling of UE/PU, understanding of jet areas, etc. Rubin '10

Also Soyez '10 for choice of jet radius

Best R_{filt}/R_{bb} vs. p_{tH}



Best R_{filt}/R_{bb} vs. pileup

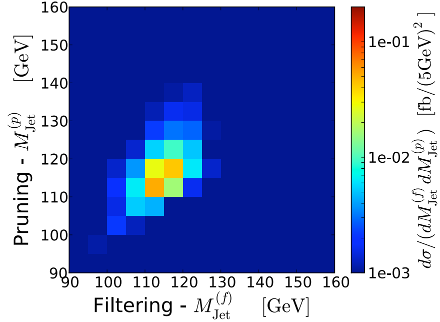


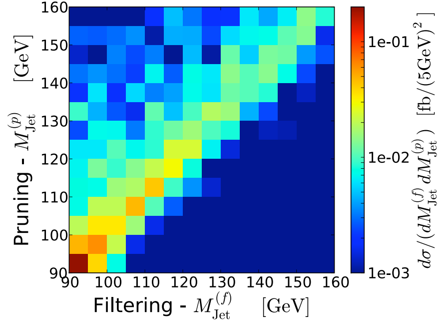
Combining tools on ZH events

Filtering, Pruning, Trimming: do they all do the same thing?

Soper & Spannowsky '10

Signal masses more strongly correlated between different methods than are background masses. Helps reject background more effectively / increase significance.





But not clear what physics is driving this?

"Buried Higgs": $H \to 2\eta \to 4g$

$m_\eta \lesssim 10$ GeV $< 2m_b$ implies $\eta \to 2g$

Bellazzini, Csáki, Falkowski & Weiler '09

Very difficult to observe at LHC (or Tevatron?) with usual methods.

Two groups have tackled this with "boosted" methods:

Chen, Nojiri & Sreethawong '10

Falkowski et al '10

- Even for Higgs at rest, η is produced boosted
- η is colour-neutral; using a *veto* on radiation in its neighbourhood helps kill backgrounds (and it's rare for a jet to be so light)

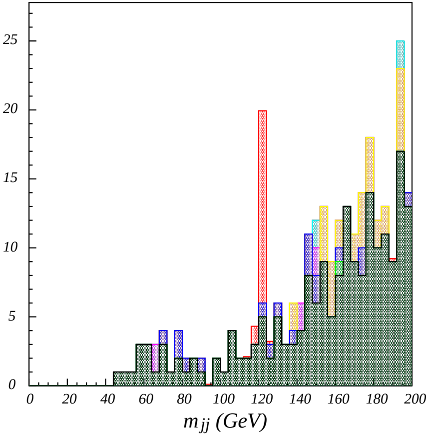
Related "superstructure" ideas used in other contexts by

Gallicchio & Schwartz '09; Almeida et al '10

$H \to 2\eta \to 4g$ results

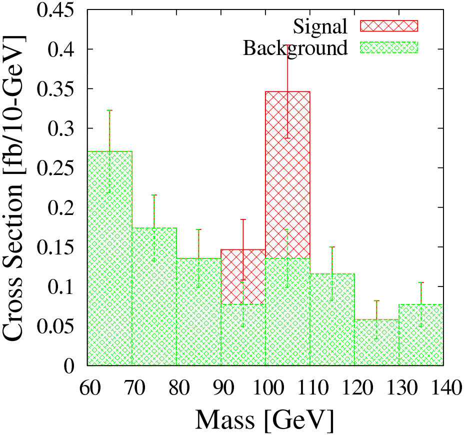
WH

Chen, Nojiri & Sreethawong '10



ttH

Falkowski et al '10



$m_\eta = 8$ GeV in both cases

Top

Many new-physics models involve signals of high-p_t tops

(KK resonance$\to t\bar{t}$, $\tilde{t}\bar{\tilde{t}} \to t\bar{t}$+MET, etc.)

Compared to W/H/Z, two extra handles to tag on:

3-body decay structure

Presence of W mass among subjets

Tagging boosted top-quarks

Many papers on top tagging in '08-'10: jet mass + something extra.

Questions

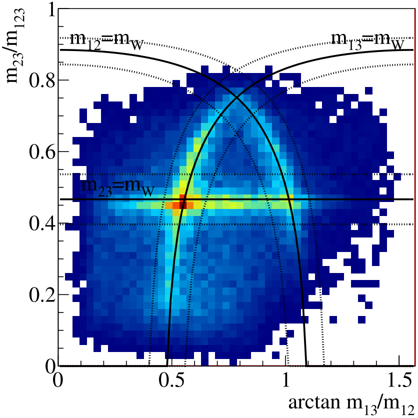
- What efficiency for tagging top?
- What rate of fake tags for normal jets?

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%
Ellis et al. '09	C/A pruning	10%	0.05%
ATLAS '09	3,4 k_t subjets, d_{cut} MC likelihood	90%	15%
Chekanov & P. '10	Jet shapes	60%	10%
Almeida et al. '08–'10	Template + shapes	13%	0.02%
Plehn et al. '09–'10	C/A MD, θ_h/Dalitz [busy evs, $p_t \sim 300$]	35%	2%

New top developments 2010

New ways of pulling out the W
Together with filtering for low-p_t top



Plehn et al '10

Template methods

Almeida et al. '10

Build catalog of all possible partonic top-decay configurations.

Look to see if there's a template that gives a good match to the current event. That tells you if you've tagged a top.

Underlying similarlity to cut-based methods? Angular limits placed on the "acceptable" templates.

Measuring efficiencies

Efficiencies / fake-rates depend a lot on how you measure them.

Numbers quoted before taken/deduced straight from papers

Take example of Johns Hopkins (JH) top tagger

Kaplan, Rehermann, Schwartz & Tweedie '08

Generate Herwig 6.5 & Pythia 6.4 samples with $p_{t,top} > 1$ TeV. Use JH tagger with fixed $R = 0.5$. Look at hardest jet.

	Efficiencies		**Fake Rates**	
mass cuts	HW 6.5	PY 6.4	HW 6.5	PY 6.4
$145 < m_t < 205$, $65 < m_W < 95$	40%	40%	1.2%	0.6%
$160 < m_t < 190$, $73 < m_W < 89$	30%	30%	0.4%	0.2%

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Take exam…

…weedie '08

What's a reasonable mass range?

Which MC is closer to the truth?

Generate H… …se JH tagger with fixed $R = 0.5$. Look at hardest jet.

mass cuts	Efficiencies HW 6.5	Efficiencies PY 6.4	Fake Rates HW 6.5	Fake Rates PY 6.4
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NB: could use recent NLO W+3jet results to get non-MC numbers

Fake rate beyond MC

Two non-MC ways to determine true fake rates:

- **Experimentally:** to know what will happen for 1 TeV jets at LHC14, examine LHC7 data for 500 GeV jets ($\sigma \sim 50$ pb^{-1}) with all dimensionful cuts in the top-taggers scaled by factor $\frac{1}{2}$.
  Scale down cuts even further to increase cross-section
- **From QCD:** run top-tagger on hadronic side of high-p_t NLO W+3jet events
  Could use BlackHat and/or Rocket programs

Outlook

Conclusions/Outlook

The subject has seen a high level of activity in the past two years.

Boosted objects will undoubtedly be part of the scene for LHC searches.

Anytime you do a search you should keep an eye on substructure

Open questions?

- Mostly, so far, developments have been based on a mixture of inspiration and trial+error. Can we give our methods a more quantitative foundation? Will this be of concrete benefit?

  E.g. flat backgrounds of χ^0 search in Butterworth et al. '09

- There's still wok to be done in comparing tools (quoted numbers not always comparable) Public code for all tools would help

- Coming year offers much promise for first studies with early data. Studies need to be formulated so that data tells us both about efficiencies and fake rates.

Extras

R-parity violating SUSY

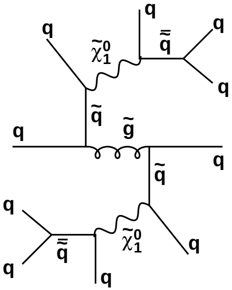
As an example, a search for neutralinos in R-parity violating supersymmetry.

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



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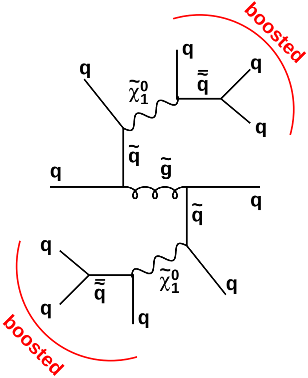


Analytics (back-of-the-enveolope)

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 ($z > z_{min}$):

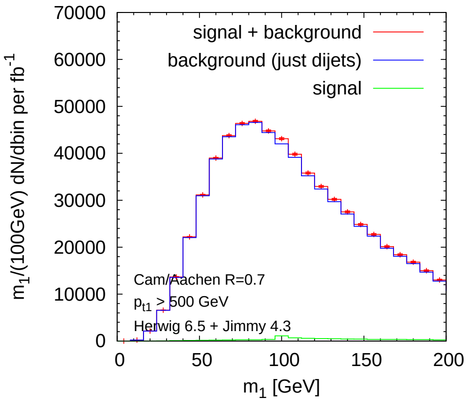
$$\frac{1}{N}\frac{dN}{dm} \sim \frac{C'\alpha_s(m)}{m} e^{-C'\alpha_s \ln Rp_t/m + \cdots}$$

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

Procedure gives nearly flat distribution in $m dN/dm$

Neutralino procedure involves 2 hard substructures, but ideas are similar

RPV SUSY, SPS1a, 1 fb^{-1} [14 TeV]



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!

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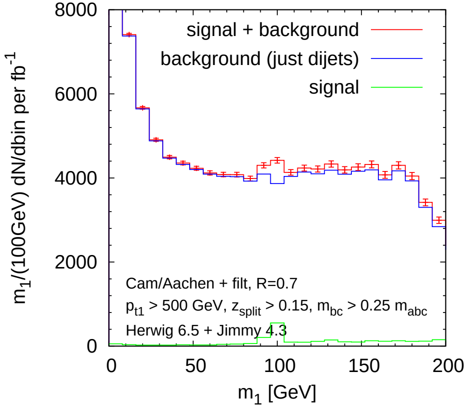

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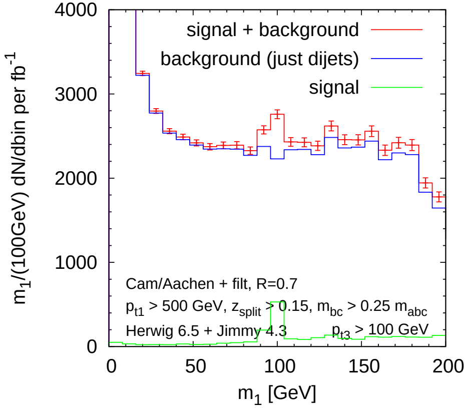

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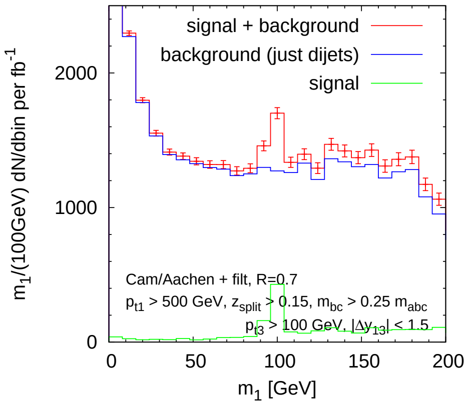

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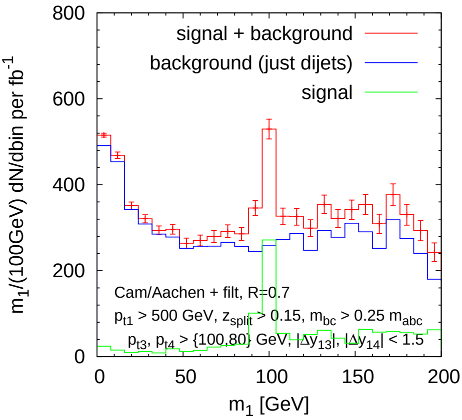

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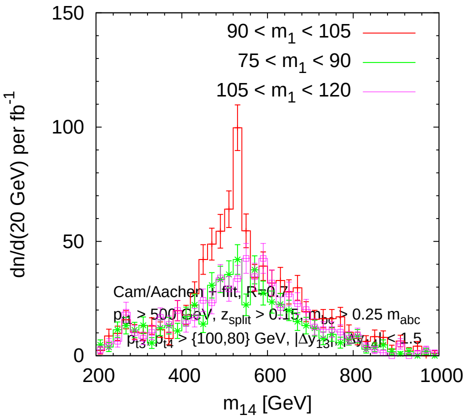

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