Boosted Higgs → bb in association with a vector boson, at 14 TeV

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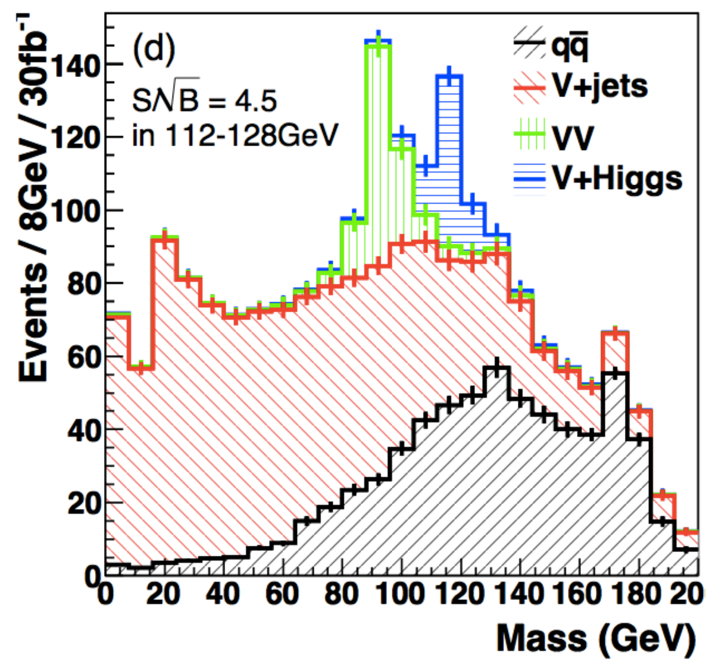
arXiv:1506.04973, in EPJC

Some History

- BDRS "**Jet substructure as a new Higgs search channel at the LHC**" arXiv:0802.2470
  - "Rescued" VH, H→bb for light Higgs boson
    - main search channel at Tevatron, not deemed feasible in e.g. ATLAS physics TDR
  - Yet substructure not used in Run I searches in this channel
  - What happened? Why?
  - How will it change in Run 2?

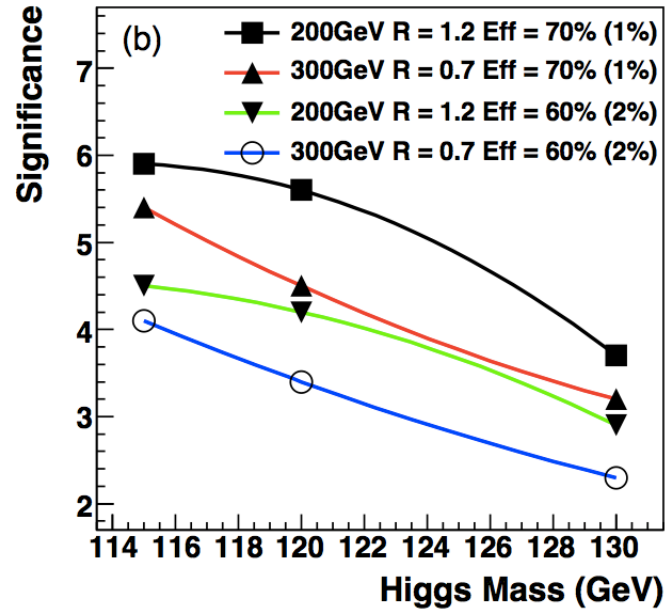


What was promised

- Several factors led to the improvement:
  - **BOOST!**
    - Reduced combinatorial backgrounds
    - Include $Z \rightarrow \nu\nu$ channel
    - Beat down top background for $W \rightarrow \nu\mu$, $Z \rightarrow \nu\nu$ channel (b-jets on opposite sides)
  - **Jet substructure**
    - Recover merged jets, IR safe (remember, were still using legacy cone algorithms in 2007)

What happened

- Higgs was 'medium'…
- Anti-k_T was born, and is *very good*
- The LHC ran at lower energy
  - Lower cross section, especially at high p_T
  - Lower fractional tt background
- Boost still worked!



Further categorisation is performed according to the transverse momentum of the vector boson, p_T^V, to take advantage of the better signal-to-background ratio at high p_T^V. The

(e.g from ATLAS paper, arXiv:1409.6212)

- Substructure was tried but wasn't needed

Substructure shadow analysis

- 'Shadow analysis' performed by Inês Ochoa
  - while working on published ATLAS Run 1 result
  - See CERN-THESIS-2015-029 22/01/2015 (UCL)

Table 6.2.: Values of S/B and $S/\sqrt{B}$ for the best performing substructure methods. A mass window of 110-140 GeV is considered.

Method	$S/\sqrt{B}$	S/B (%)
Resolved (two anti-k_t $R = 0.4$ jets)	0.56	10.57
Cambridge/Aachen splitting and filtering, $R = 1.2$	0.48	12.54
anti-k_t $R = 1.0$ pruned ($z_{cut} = 0.15$, $R_{cut} = 0.4$)	0.43	13.27
anti-k_t $R = 1.0$ trimmed ($f_{cut} = 0.05$, $R_{sub} = 0.3$)	0.46	14.80
anti-k_t $R = 1.0$ trimmed ($f_{cut} = 0.05$, $R_{sub} = 0.2$)	0.42	15.22
anti-k_t $R = 1.5$ trimmed ($f_{cut} = 0.03$, $R_{sub} = 0.3$), $\tau_{21} < 0.4$	0.52	12.11

What about Run 2?

- Higher beam energies, but…
  - Higgs is still 125 GeV
  - Anti-k_T is still good
  - Top background gets worse
  - Let's see.
- Study WH as the (most challenging) example, at $p_T(V)>200$ GeV
- Compare two example techniques:
  - 'Standard' ATLAS resolved approach, Anti-k_T R=0.4
  - 'Standard' BDRS approach C/A R=1.2
  - Yes, there are other, probably better, options available, but a major goal was to benchmark against pre-data situation and Run 1 results

Event generation

- 14 TeV
- Background processes considered:
  - W+bb, top-pair production,WZ, single-top Wt
  - for Wt, Diagram Removal scheme is used to handle interference with ttbar (thanks to Rikkert Frederix)
- aMC@NLO used to generate both signal and background matrix elements
  - NLO corrections in QCD
  - matched with Herwig++
  - MadSpin to simulate the decays of the top, W and H (except for Wt)
  - considering only muon-channel for the W leptonic decays
- No pile-up
- UE and hadronisation handled by Herwig++
- Particle-level study

Event generation

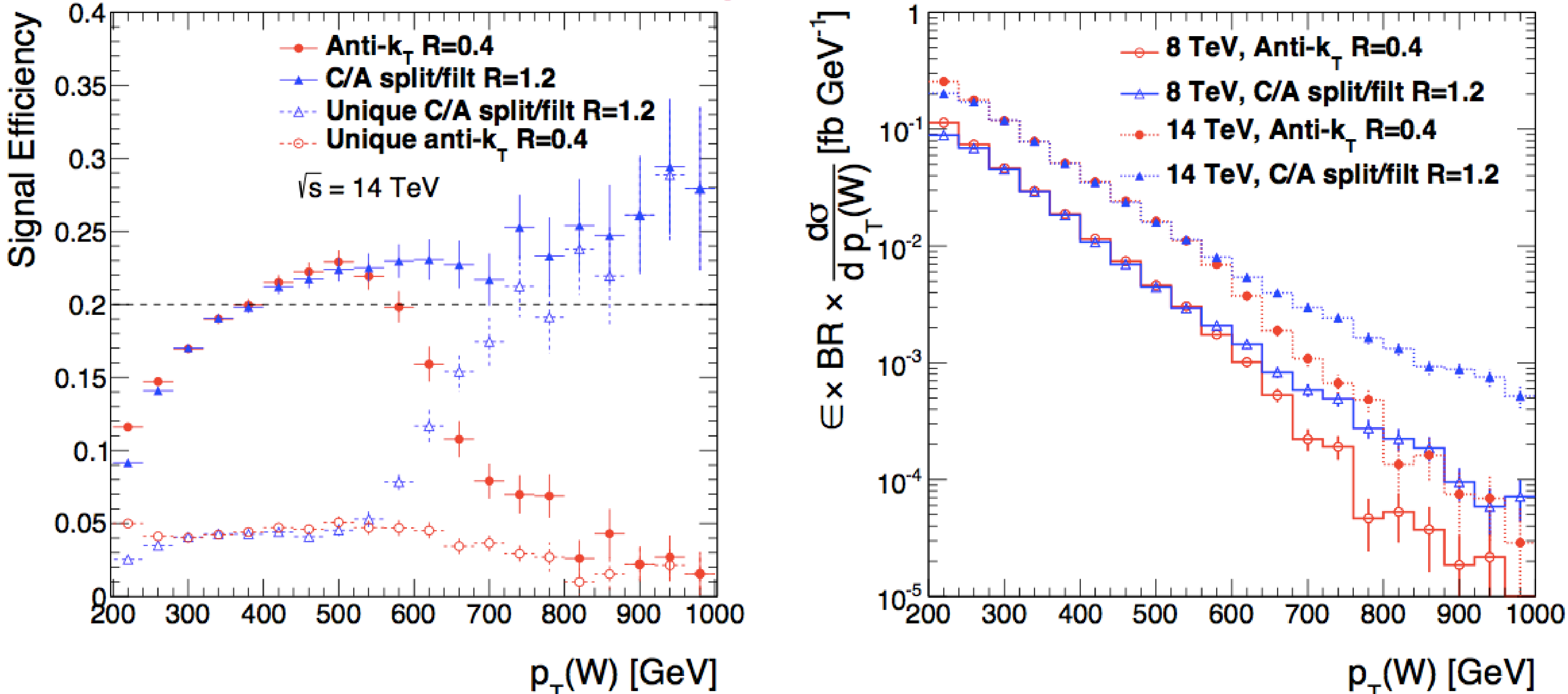
- Flavour labelling
  - geometrical matching of jets/subjets to B-hadrons with pT > 5 GeV
  - if a jet/subjet is not matched, an additional check is performed for C-hadrons
  - if both fail, jet/subjet is labelled as light
- All yields corrected by b-tagging efficiencies:
  - working points: 75%/15%/1% for B/C/light jets
- Other normalisation corrections:
  - top-pair: scaled by 1.25 to include NNLO corrections in QCD
  - W+bb: scaled by 1.2 to take into account W+cc contribution (estimated from EPS'13 ATLAS results)

Event Selection

- W candidate
  - muon with p_T > 20 GeV and |η|<3.0,
  - Neutrino with p_T > 20 GeV, $p_T(W)$ > 200 GeV
- "Resolved"approach:
  - at least two anti-k_T R=0.4 jets with pT > 20 GeV and |η|<3.0
  - ΔR<1.4 between two leading jets, both matched to a B-hadron
- "Substructure"approach:
  - at least one C/A R=1.2 split/filtered jet, pT > 180 GeV and|η|<3.0
  - two leading subjets matched to a B-hadron
- Mass window:
  - dijet/filtered jet invariant mass within 110 and 130 GeV
- No jet veto is applied (yet)

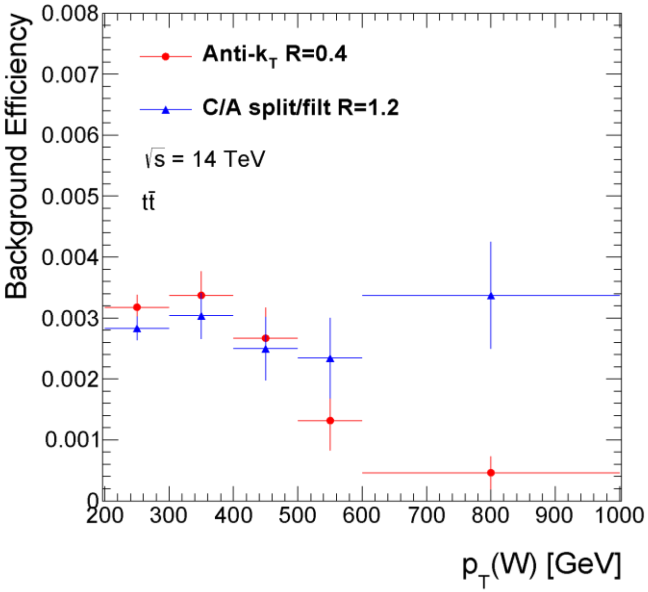
Signal Efficiency

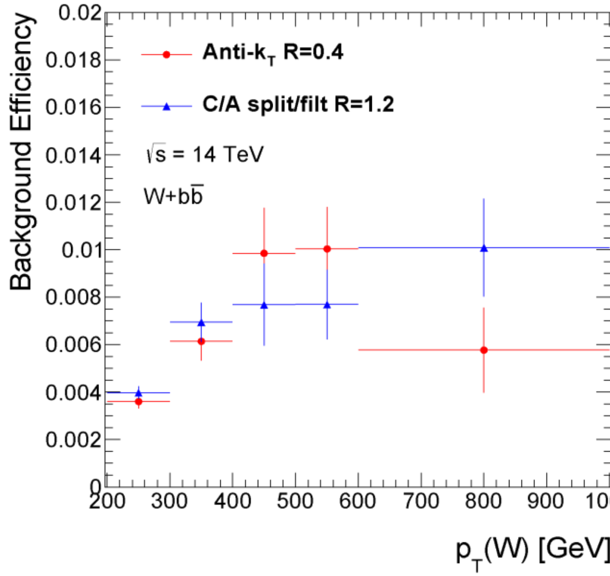
including mass window cut

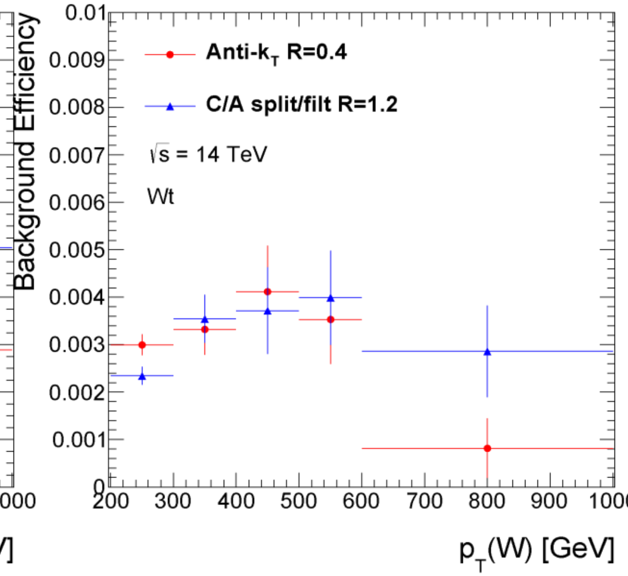


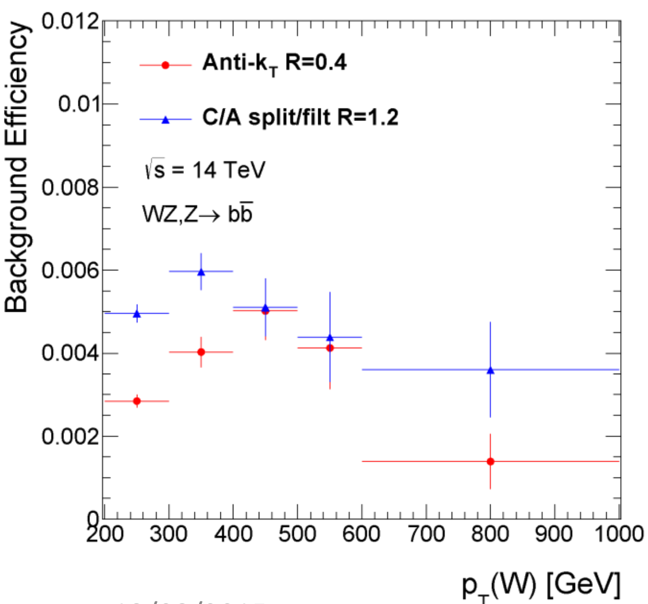
- Contribution from unique substructure events (μ channel, lumi=150 fb^{-1})
  - ~30 events in $p_T(W)$ > 200 GeV (with ~120 in resolved case) → ~20%
  - ~3 events in $p_T(W)$ > 600 GeV (with ~1 in resolved case) → ~70%
- Searches & measurements in regions w $p_T(W)$ > ~500 GeV require substructure methods (or smaller-R jets)

Background ‘efficiency’







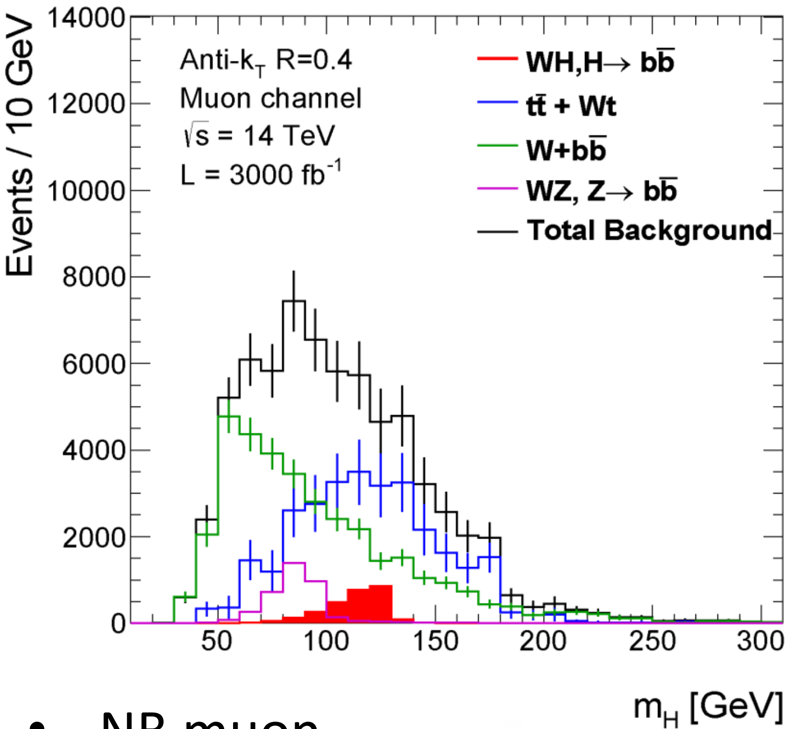


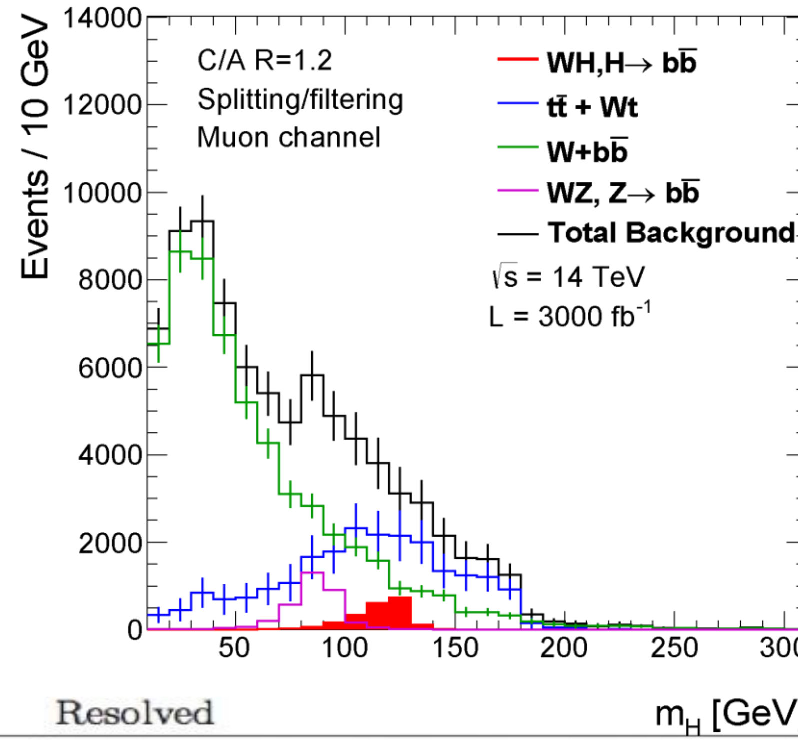
- Generally similar features to signal
  - Resolved approach kills both signal and background at high p_T
- Exceptions
  - Wbb, continual feed-in from wide-angle bb pairs (not a real boosted object!)
  - W/Z Z→ bb Substructure lets more in at lower p_T (Z mass is lower, more boost)

Jet Veto

- Jet veto is applied in order to suppress backgrounds (mainly tt)
  - Not the main point of this analysis, clearly would be optimised differently in a real analysis
  - Challenging cut: pile-up effects, theoretical uncertainties
  - same veto definition for both approaches, for comparison (*)
- Definition:
  - Events with more than 3 anti-k_T jets with p_T > 20 GeV and $|\eta|<5.0$ are rejected
  - The third jet, if present, is either low p_T (<10% $p_T(W)$) or forward ($|\eta|>3.0$)
- Rejects 30-40% of signal events in Higgs mass window in resolved & substructure selections, respectively
- Rejects over 90% of ttbar events in both cases
- Rejects 30% of W+bb events in resolved case, 50% in substructure case

Invariant-mass distributions





- NB muon channel only. Integrated lumi 3000 fb^{-1}.
- Table also has mass window applied (110-130 GeV)

Resolved

$p_T(W)$ [GeV]	Signal	$W + b\bar{b}$	$t\bar{t}$	Wt	WZ	Total Background
200 – 400	1405	2987	5024	1165	77	9253
400 – 600	208	541	361	112	15	1029
> 600	19	89	10	0	1	100
> 200	1632	3617	5395	1277	93	10382

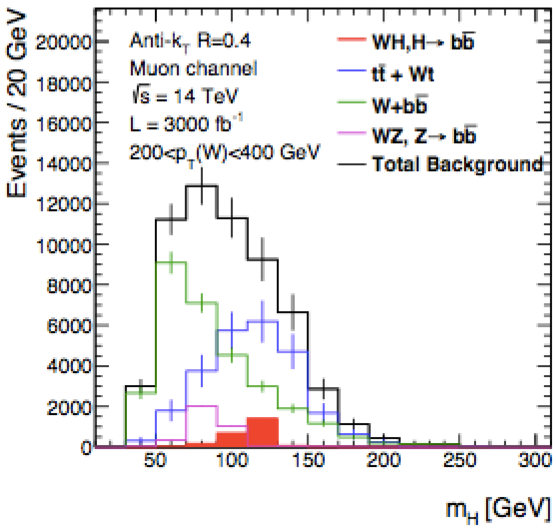
Substructure

$p_T(W)$ [GeV]	Signal	$W + b\bar{b}$	$t\bar{t}$	Wt	WZ	Total Background
200 – 400	1115	2069	2718	865	68	5720
400 – 600	184	278	505	67	9	859
> 600	54	184	148	13	3	348
> 200	1353	2531	3371	945	80	6927

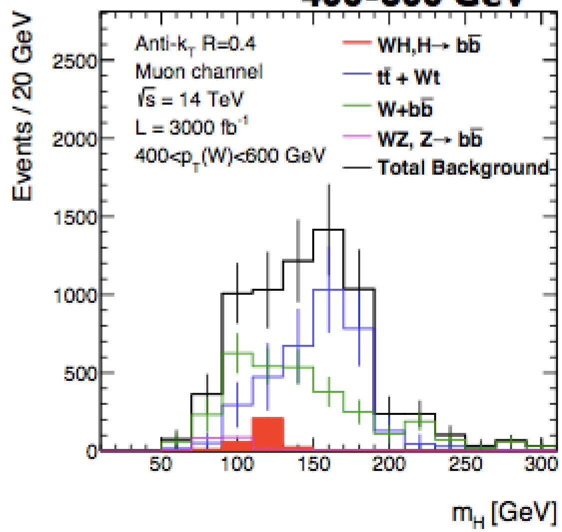
....in bins of W p_T

Resolved:

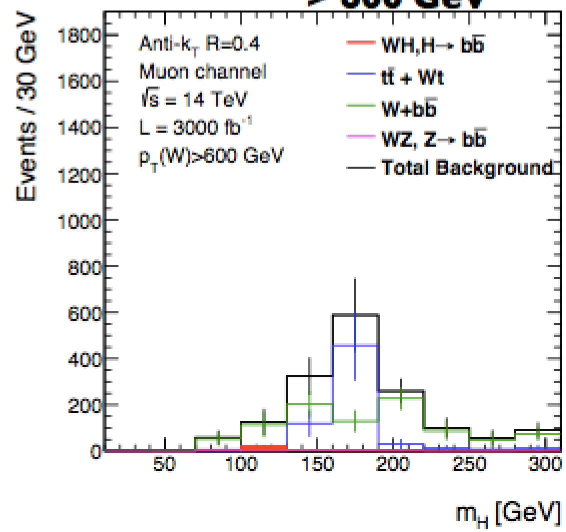
200-400 GeV



400-600 GeV

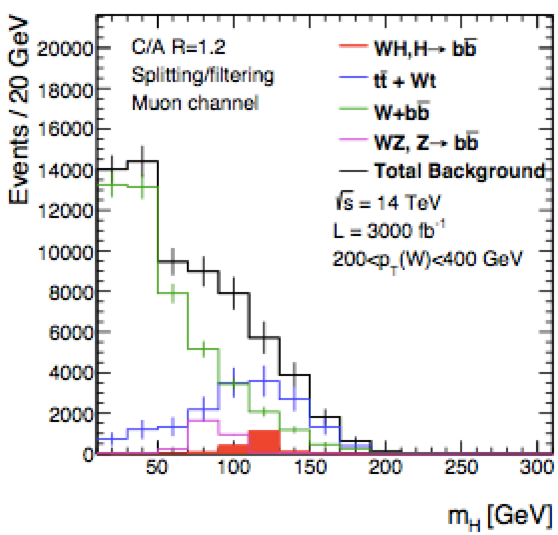


> 600 GeV

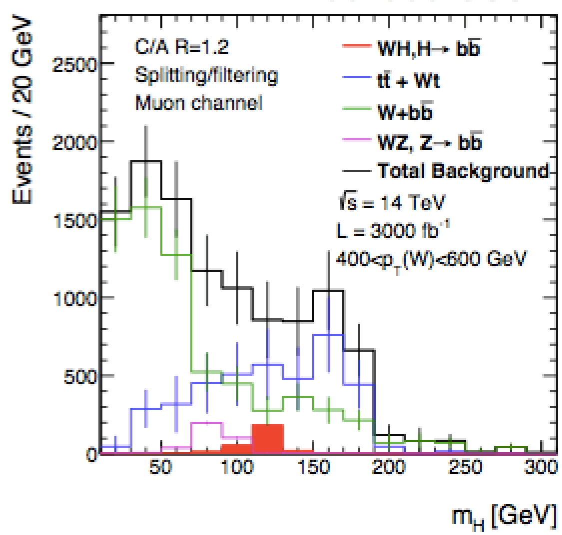


Substructure:

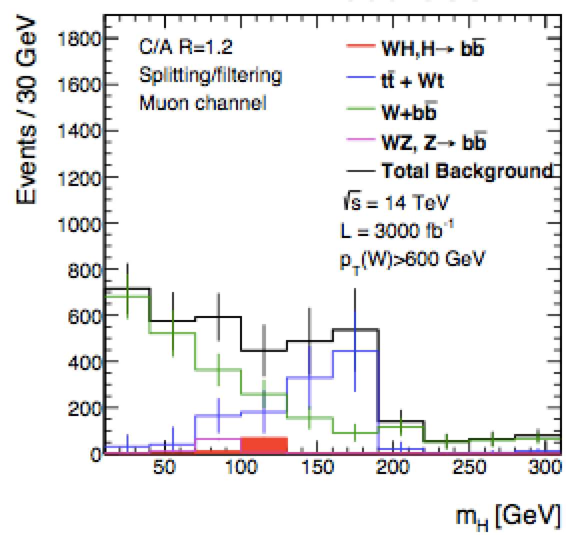
200-400 GeV



400-600 GeV



> 600 GeV



Background Composition

Resolved					
Flavour (%)	Signal	$W + b\bar{b}$	$t\bar{t}$	Wt	WZ
bb	99.9	93.1	32.8	7.2	94.5
bc	0.1	4.0	55.8	78.2	3.4
bl	0.0	2.9	11.5	14.6	2.1

Substructure					
Flavour (%)	Signal	$W + b\bar{b}$	$t\bar{t}$	Wt	WZ
bb	99.8	94.2	20.1	6.1	95.2
bc	0.2	3.2	63.7	78.9	2.9
bl	0.1	2.6	16.2	15.0	1.9

- Top is mostly *bc*, as expected: contribution increases with $p_T(W)$
  - improved charm rejection is essential to suppress largest background
- *bb* is the subleading contribution in top events:
  - However, at high boosts, tt+HF events are responsible for ~70% of the *bb* events that are selected by the substructure approach, which could be problematic, given the large theoretical uncertainties

Sig/Backgd & significance

Have now doubled cross section to account for electron channel (assuming similar efficiencies)

$S/B(\%)$

$p_T(W)$ [GeV]	Resolved	Substructure	Unique Substructure
200 – 400	15.2	19.5	8.7
400 – 600	20.3	21.5	6.0
> 600	19.2	15.6	13.9
> 200	16.0	19.9	9.1

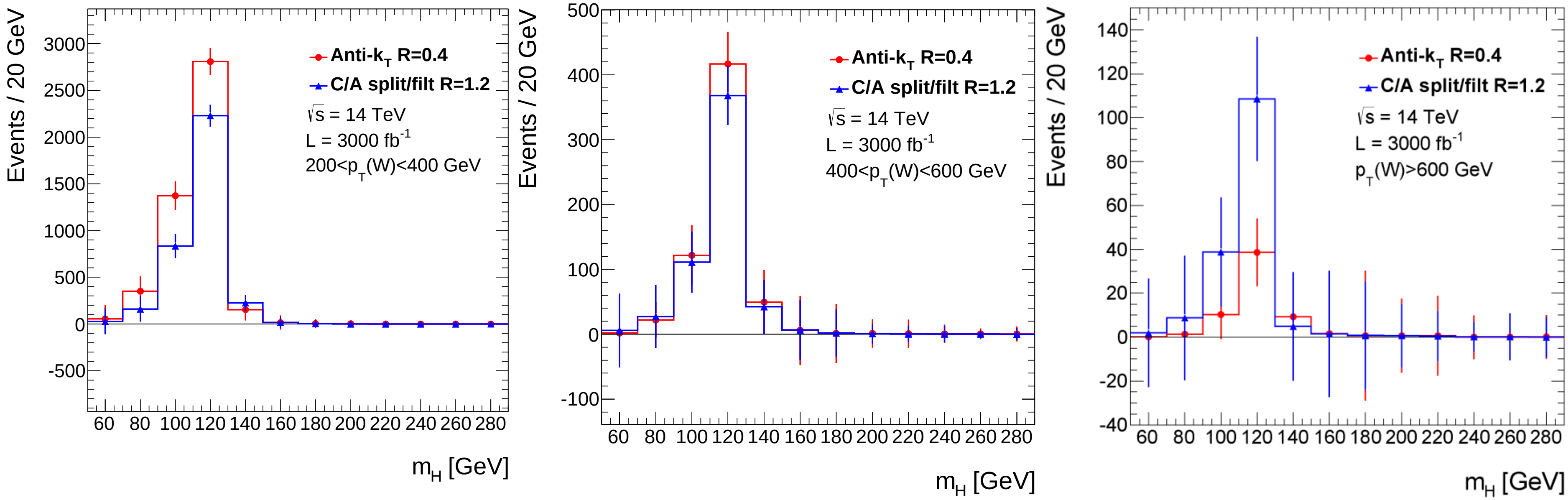
← contribution from events that are uniquely reconstructed by the substructure approach

$S/\sqrt{B}$, $L = 3000(150)$ fb^{-1}

$p_T(W)$ [GeV]	Resolved	Substructure	Unique Substructure
200 – 400	20.6 (4.6)	20.8 (4.7)	4.7 (1.1)
400 – 600	9.2 (2.1)	8.9 (2.0)	1.6 (0.4)
> 600	2.7 (0.6)	4.1 (0.9) +50%	3.4 (0.8) +60% if combined with resolved
> 200	22.7 (5.1)	23.0 (5.1)	5.9 (1.3)

- Signal significance peaks in $p_T(W)$ region of 200-400GeV, where both approaches work well
- Such boosts are enough to reduce combinatorial and top backgrounds
  - the significance then drops for higher $p_T(W)$
- Substructure case: higher S/B plus control region for W+bb could be promising

Expectations for HL-LHC?



- Notes:
  - Addition of ZH channels, as well as further optimization of event selection, should improve statistical sensitivity, assuming good control of systematic uncertainties can also be achieved.
- Systematic uncertainties not included

Conclusions

- Update of boosted WH,H→bb study at 14TeV, using ‘vanilla’ BDRS & resolved methods
- Most sensitive region remains $p_T(W)$=200 - 400GeV, even after increased beam energy
  - Main benefit of ‘boost’ already seen by this p_T. Higher boosts simply reduce cross sections.
- Both methods perform well in this region
  - Substructure improvement less dramatic given slightly heavier Higgs (BDRS was best for a 115 GeV boson)
- Combination of methods worth exploring, (some complementary information), or the equivalent in more recently developed approaches for Run 2 (see previous talks)
- Searches or measurements focusing on $p_T(W)$ > 500 GeV region require substructure techniques
- Top background mainly from mis-tagged charm jets
  - b-tagging techniques remains a central issue
- But don’t forget W+bb...