BOOSTING $HH \to (b\bar{b})(b\bar{b})$ WITH MULTIVARIATE TECHNIQUES

BEHR, BORTOLETTO, FROST, ISSEVER, NH, ROJO [1512.08928]

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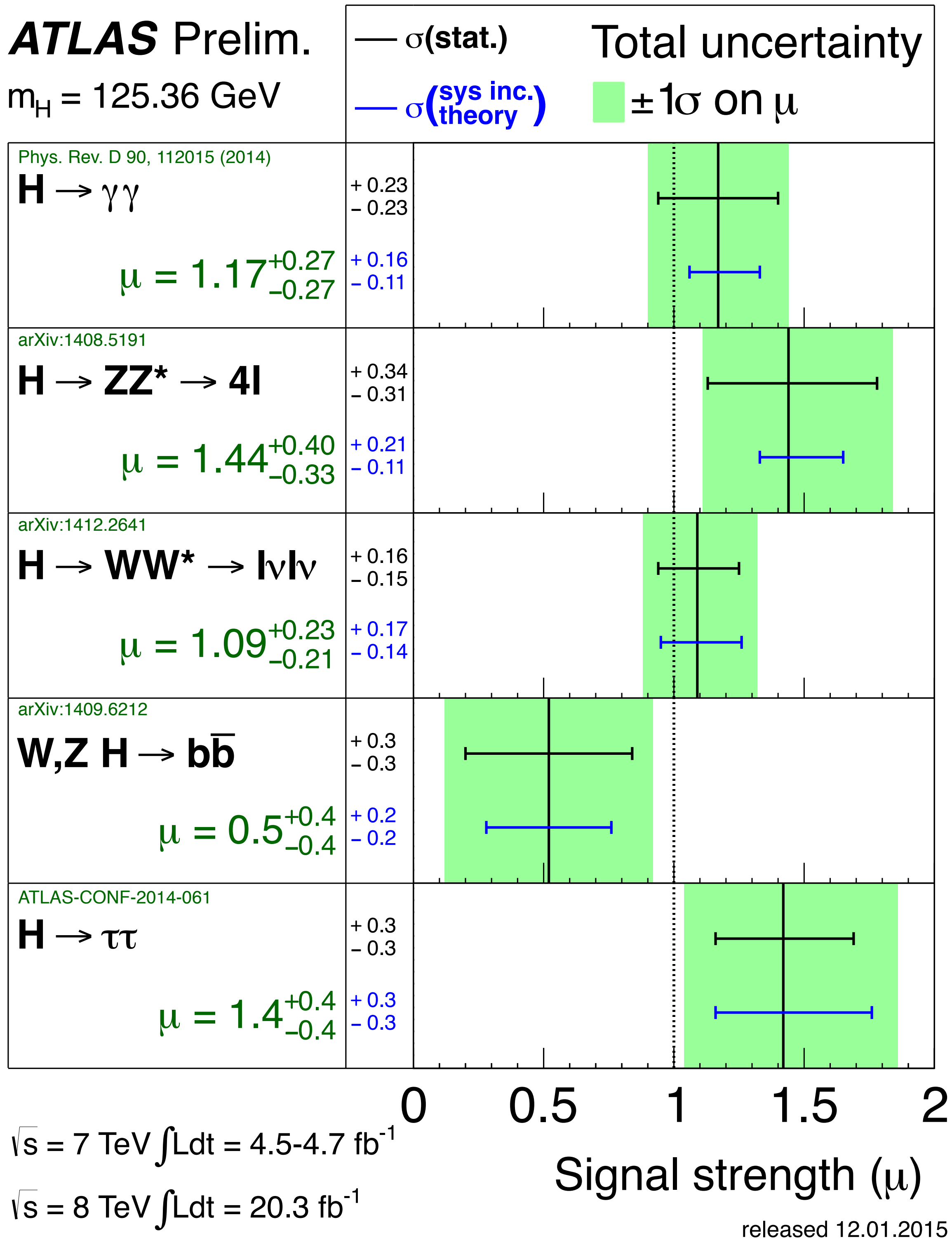
Torino, 26/05/16

HIGGS PHYSICS AT THE LHC



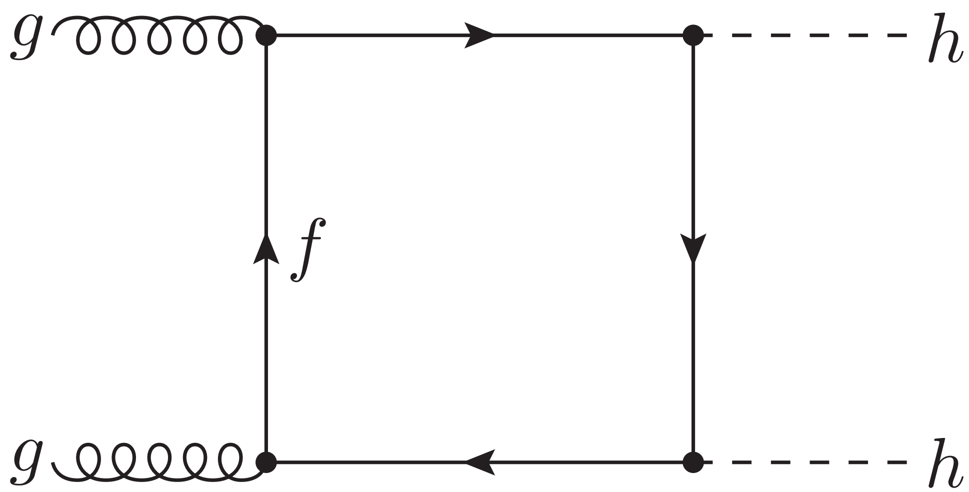
Resonance at ~126 GeV is pretty consistent with expectations for SM Higgs.

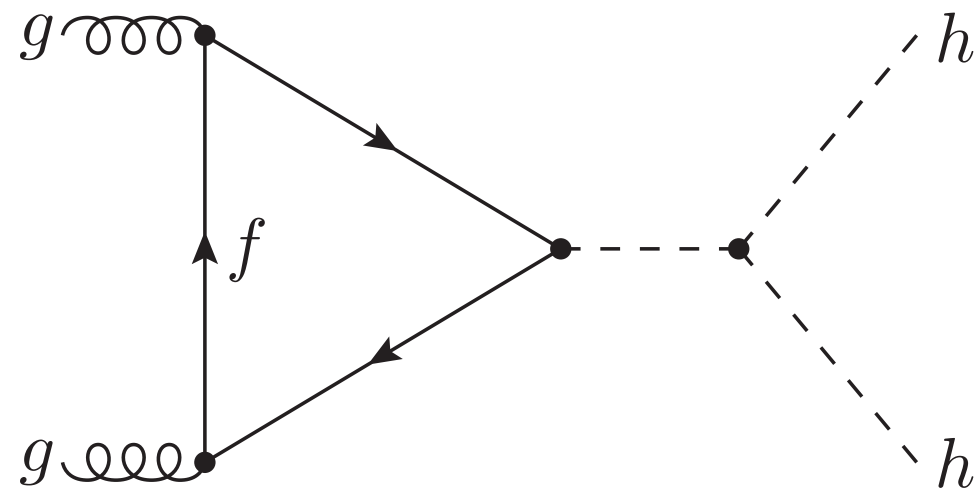
So far, we have only explored the **minimum** of the EWSB potential

$$V = \frac{1}{2} m_H^2 H^2 + v\lambda_3 H^3 + \frac{1}{4}\lambda_4 H^4$$

To understand the full potential, we need to measure (*at least*) double-Higgs production

DIHIGGS AT THE LHC





Clear difficulty: HH production cross-section at LHC is *tiny*

14TeV NNLO gluon fusion $\sigma_{HH} \simeq 40$ fb *factor of ~10³ smaller than single H*

Compounded by usual H reconstruction problems

Final State	BF
bbbb	33%
bbWW	13%
bb\tau\tau	3.5%
WWWW	5.3%

Pr. Mode	Cross-sec
ggF	40 fb
VBF	2.0 fb
hhtt	1.0 fb
W/Z hh	0.5 fb

DIHIGGS AT THE LHC

Several LHC feasibility studies in ggF

$$b\bar{b}\tau^+\tau^-$$

Dolan, Englert, Spannowsky [1206.5001]

Papaefstathiou, Yang, Zurita [1209.1489]

$$b\bar{b}W^+W^-$$

Baur, Plehn, Rainwater [hep-ph/0304015]

Barr, Dolan, Englert, Spannowsky [1309.6318]

Dolan, Englert, Spannowsky [1206.5001]

$$b\bar{b}\gamma\gamma$$

Baur, Plehn, Rainwater [hep-ph/0310056]

Barger, Everett, Jackson [1311.2931]

Lu, Chang, Cheung, Lee, [1505.00957]

$$b\bar{b}b\bar{b}$$

Baur, Plehn, Rainwater [hep-ph/0304015]

Dolan, Englert, Spannowsky [1206.5001]

Wardrope, Jansen, et al [1410.2794]

Ferreira de Lima et al [1404.7139]

General picture:

Data is king: 3000 fb^{-1} HL-LHC)

Significances ~ 1-3σ / channel

Discovery of HH will require the **combination** of channels

$HH \to (b\bar{b})(b\bar{b})$ BACKGROUNDS

Fully hadronic (gg)Higgs channel: experimentally challenging on a lot of fronts

Primary challenge: Overwhelming QCD background

Signal	Cross-section
HH	$4.0 \cdot 10^{-2}$ pb

Background	Cross-section
ZH	$7.7 \cdot 10^{-1}$ pb
ttH	$4.6 \cdot 10^{-1}$ pb
bbH	$6.1 \cdot 10^{-1}$ pb

Background	Cross-section
bbbb	$1.8 \cdot 10^{3}$ pb
bbjj	$3.5 \cdot 10^{5}$ pb
jjjj	$5.8 \cdot 10^{6}$ pb
tt(bbjjjj)	$3.5 \cdot 10^{3}$ pb

Previous studies: significances of order ~ **2σ**

(without PU and missing some backgrounds)

$HH \to (b\bar{b})(b\bar{b})$ BACKGROUNDS

Background	Cross-section
bbbb	$1.8 \cdot 10^3$ pb
bbjj	$3.5 \cdot 10^5$ pb

Contributions from light jets usually discounted by b-tagging arguments. Assume (optimistically):

$$\epsilon_{\rm tag} = 0.8 \qquad \epsilon_{\rm mistag} = 0.01$$

Then tagged 4b cross section ~ $\epsilon_{\rm tag}^4 \cdot \sigma_{bbbb} = 7.3 \cdot 10^2$ pb

and tagged 2b2j cross section ~ $\epsilon_{\rm tag}^2 \epsilon_{\rm mistag}^2 \cdot \sigma_{bbjj} = 22$ pb

Consider instead the fraction of events containing n b-jets

$(R = 0.4\ {\rm ak}_T \quad p_T > 20{\rm GeV})$

	0 b-jet	1 b-jet	2 b-jet	3 b-jet	4 b-jet	$\epsilon_{\rm sel}$
bbbb	1%	8%	27%	44%	20%	**8.4%**
bbjj	9%	42%	49%	1%	0.1%	**0.04%**

$$\epsilon_{{\rm sel},bbbb} \cdot \sigma_{bbbb} \simeq 150{\rm pb}$$

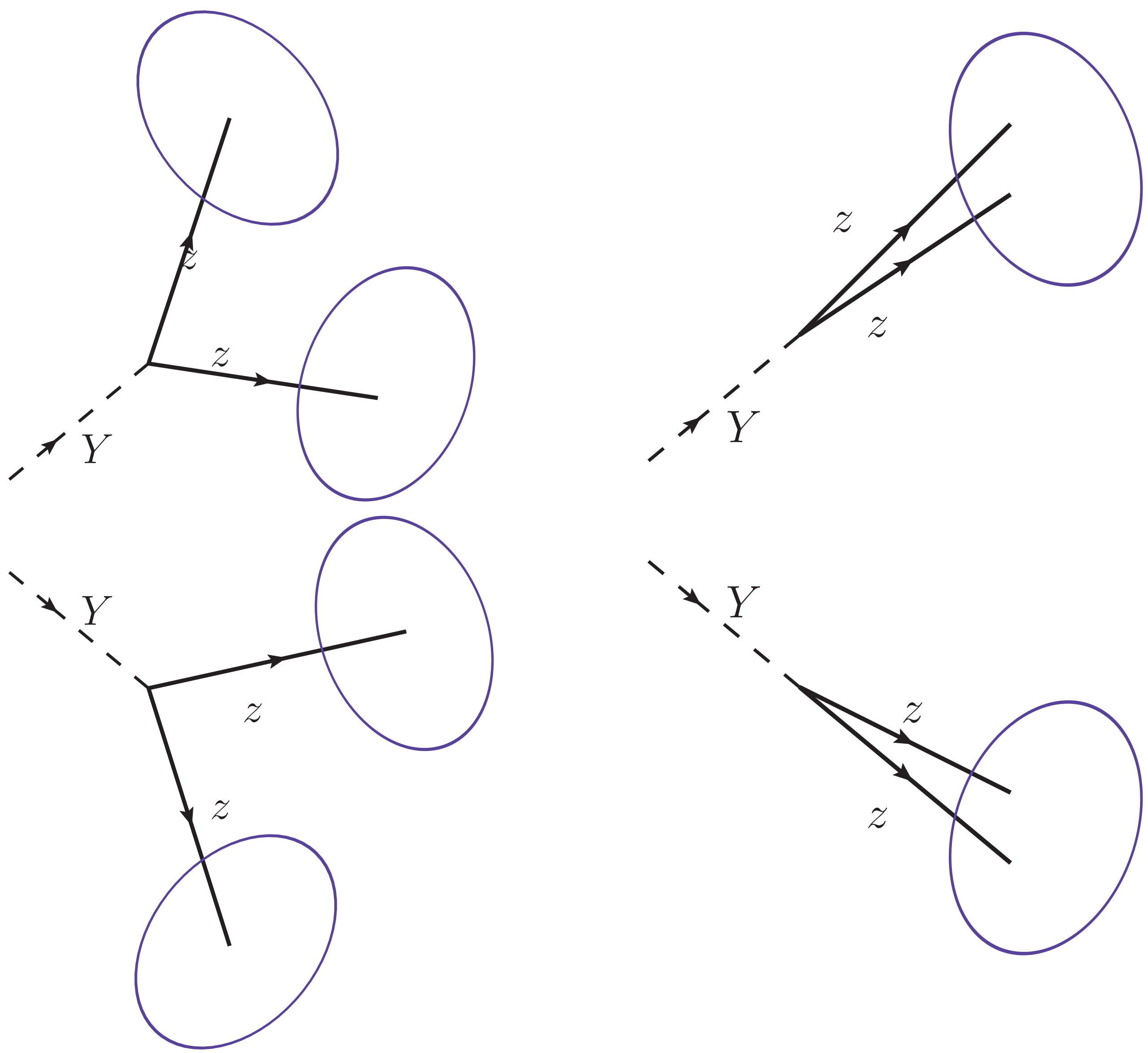
$$\epsilon_{{\rm sel},bbjj} \cdot \sigma_{bbjj} \simeq 140{\rm pb}$$

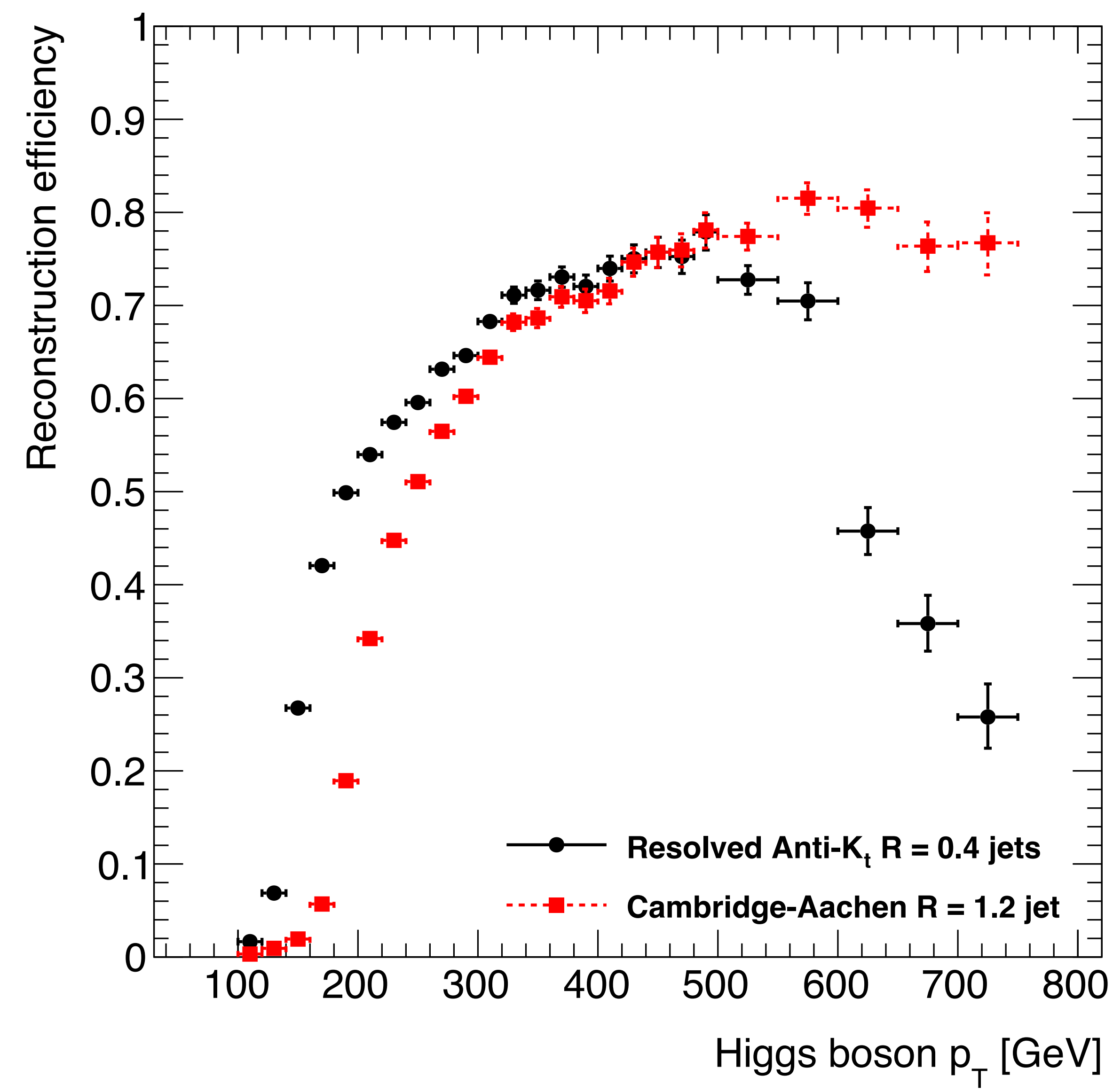
Contributions e.g bbjj are not negligible w.r.t 'irreducible' 4b background

HH RECONSTRUCTION

$HH \to (b\bar{b})(b\bar{b})$ ANALYSIS TOPOLOGIES

- **Resolved:** Reconstruct H decay products in four separate (small-R) jets
- **Boosted:** Reconstruct H decay products in two (large-R) jets

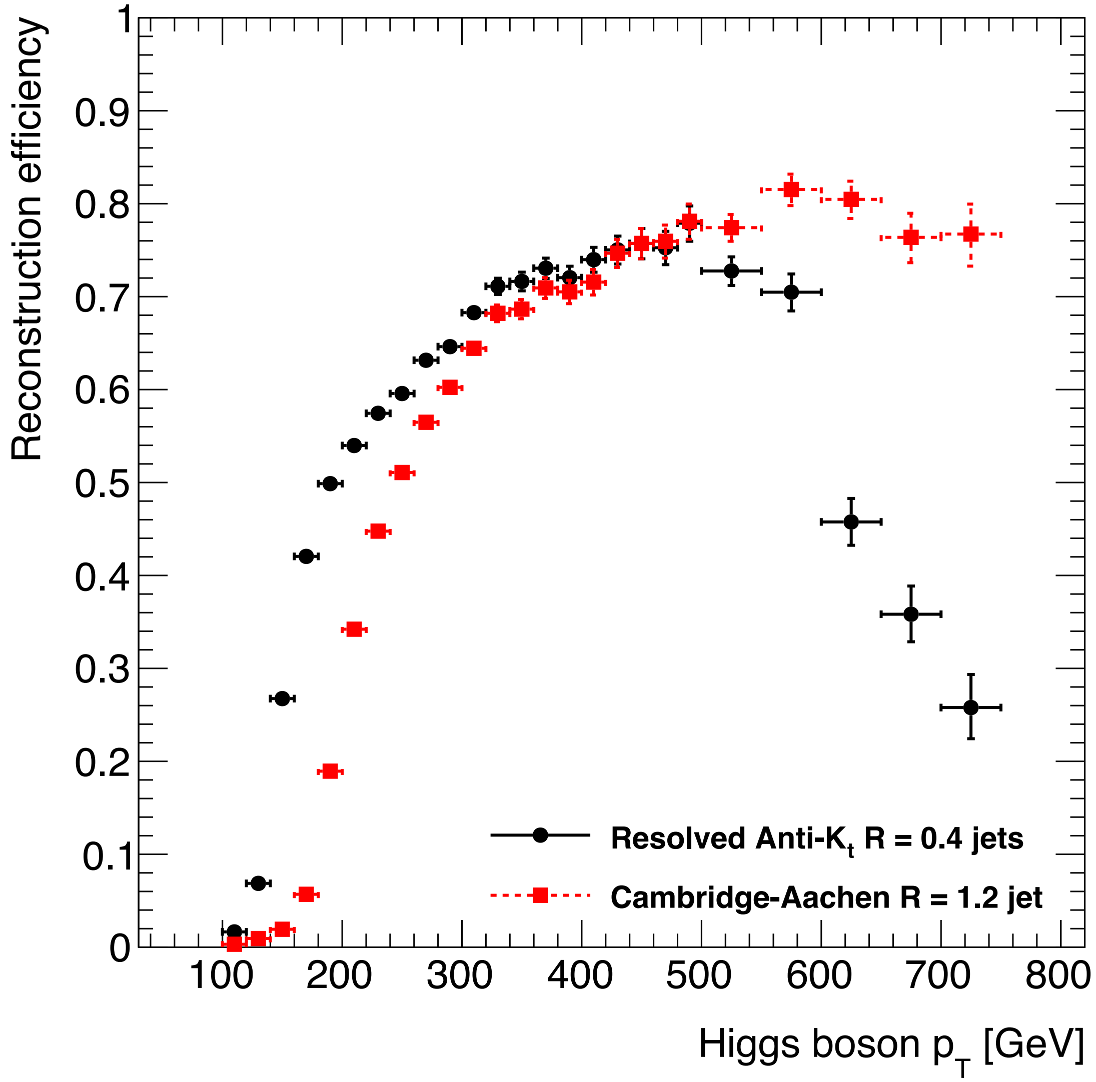


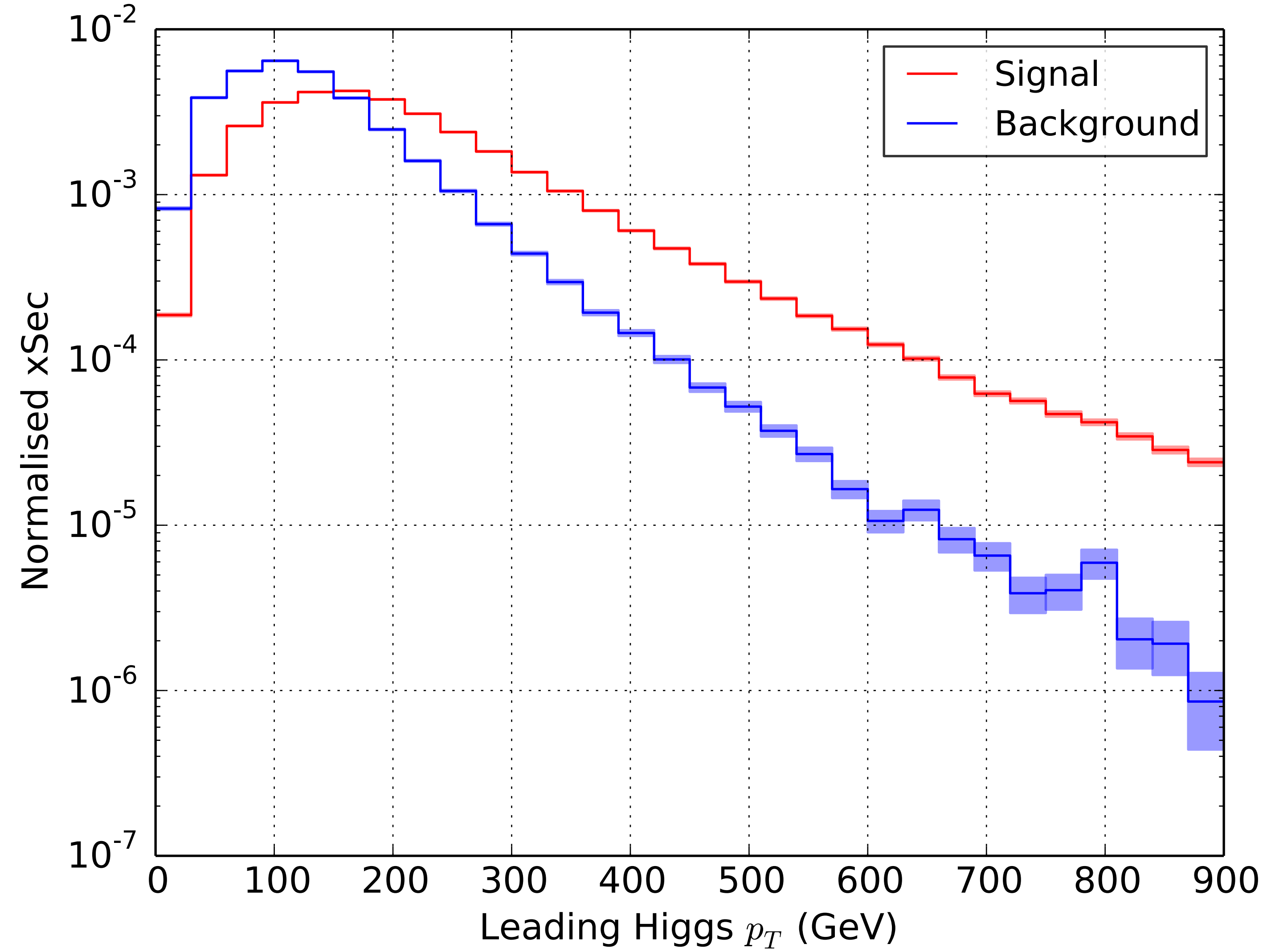


(Figs: Gouzevitch et al 1303.6636)

(Wardrope et al 1410.2794)

$HH \to (b\bar{b})(b\bar{b})$ ANALYSIS TOPOLOGIES





Resolved

- Captures bulk of HH cross-section
- Lower efficiency at high pT
- Challenging for triggers

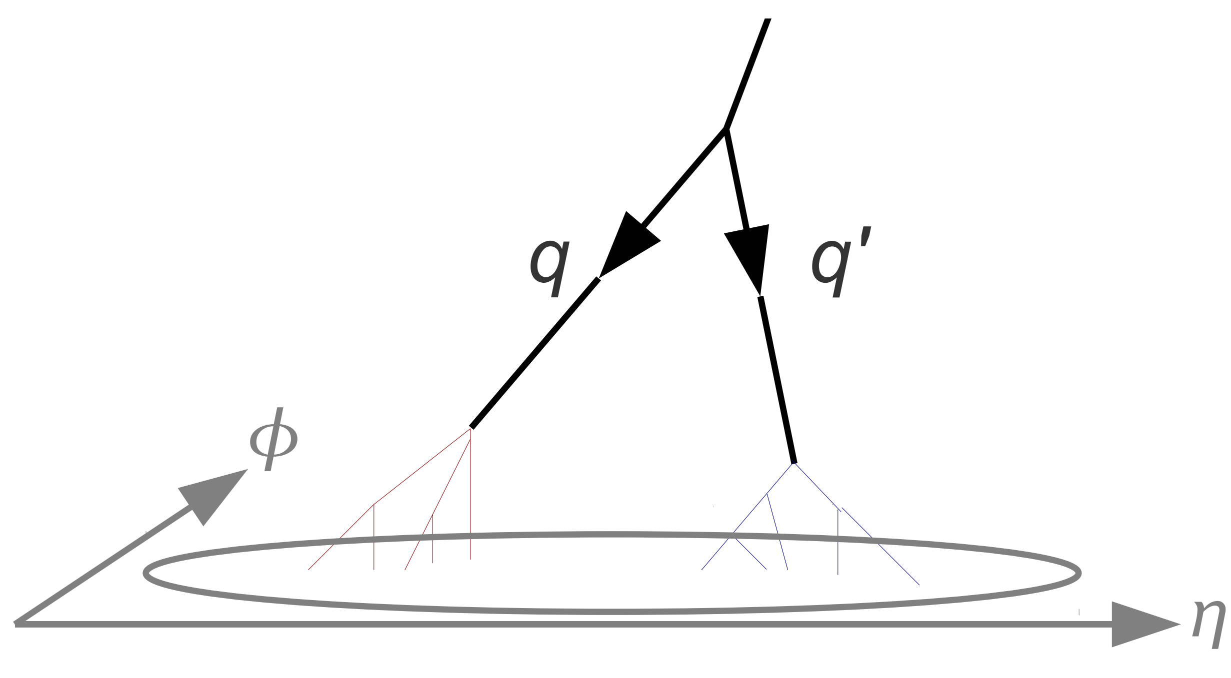
(e.g UCL Study [1410.2794])

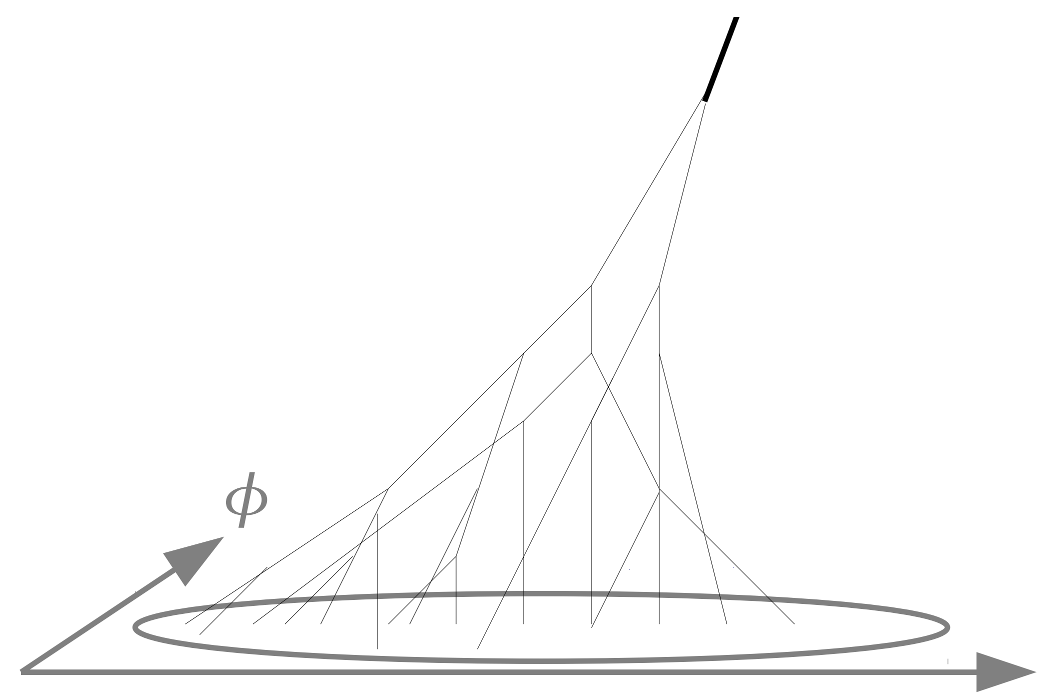
Boosted

- Better S/B but lower cross-sections
- Substructure tools available
- Greater sensitivity to pileup

(e.g Durham Study [1404.7139])

SUBSTRUCTURE FOR H->BB





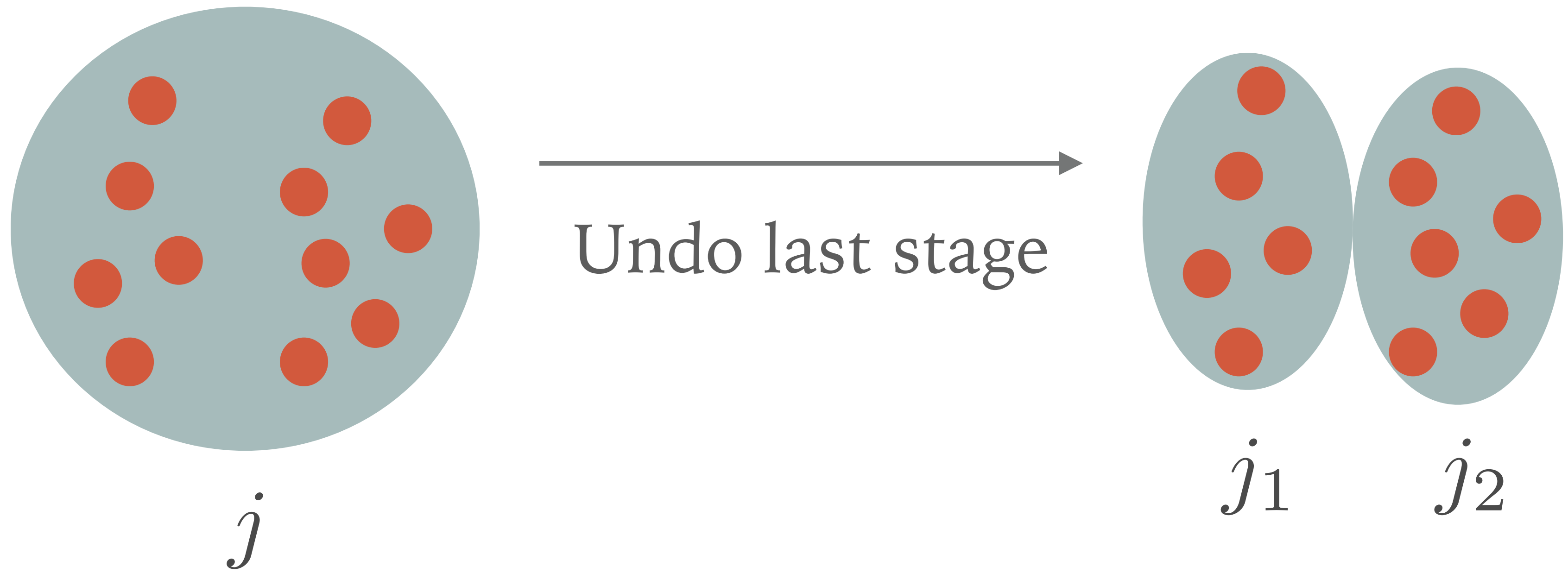
Figures - Thaler, Tilburg [1011.2268]

SUBSTRUCTURE - SPLITTING SCALES

[0802.2470], [hep-ph/0201098]

The kT algorithm clusters the two hardest subjets **last**

Cluster with large-R kT algorithm



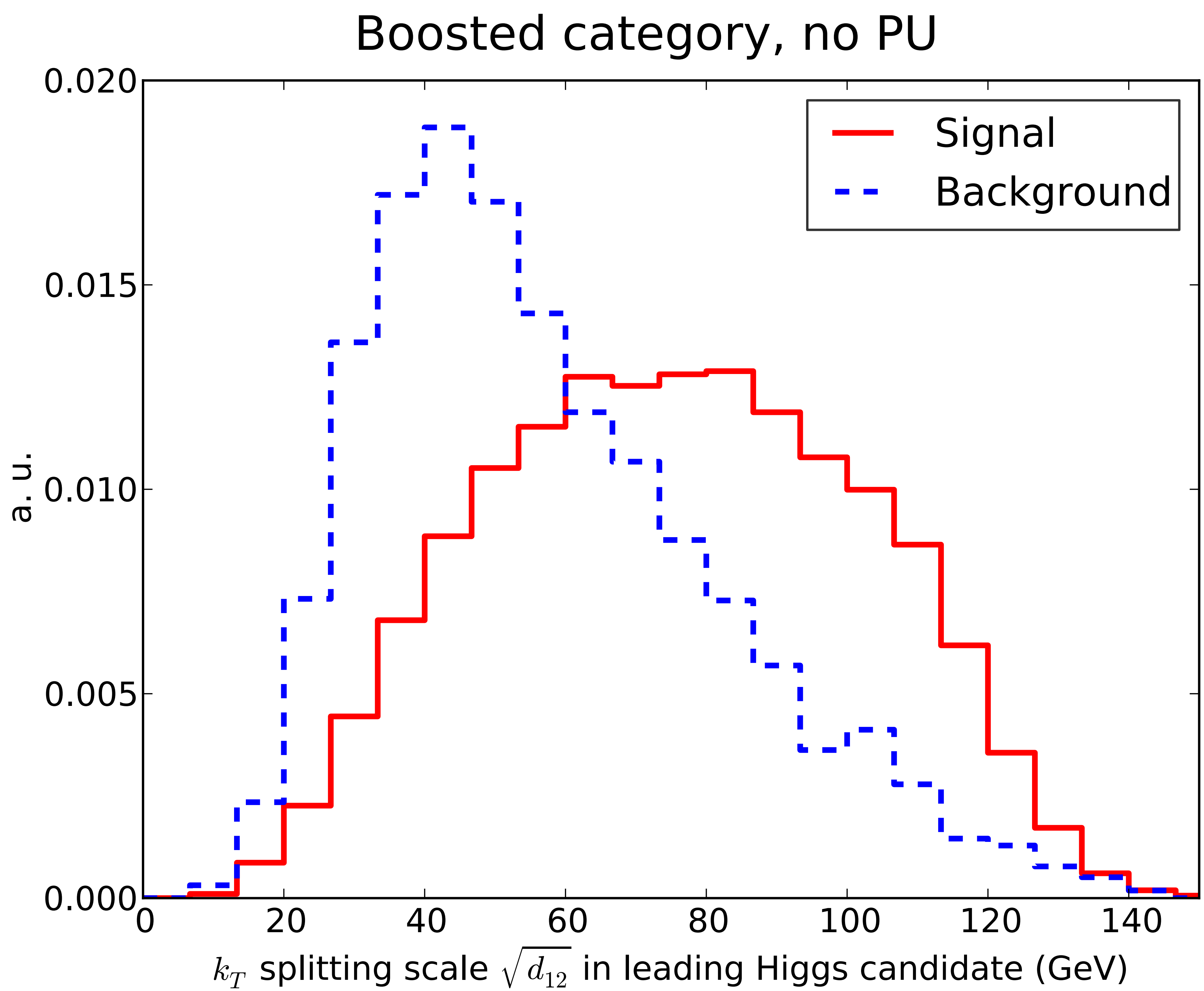
The kT splitting scale $\sqrt(d_{12}) = \min\left(p_{T,1}, p_{T,2}\right) \Delta R_{12}$

Is the jet measure separating the two subjets at the final point of the combination

When separating H decay from QCD multi-jet background

H decay products are typically **better separated** than QCD

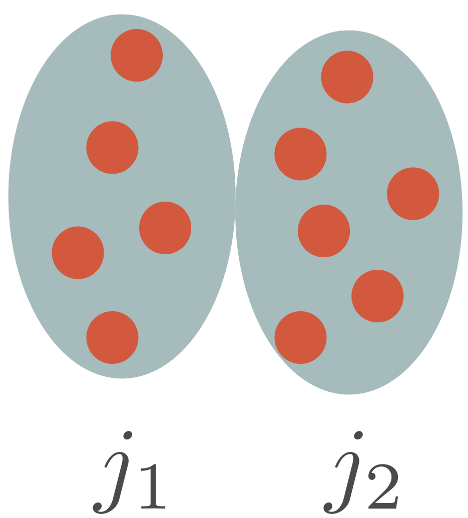
SUBSTRUCTURE - SPLITTING SCALES



SUBSTRUCTURE - N(SUB)-JETTINESS

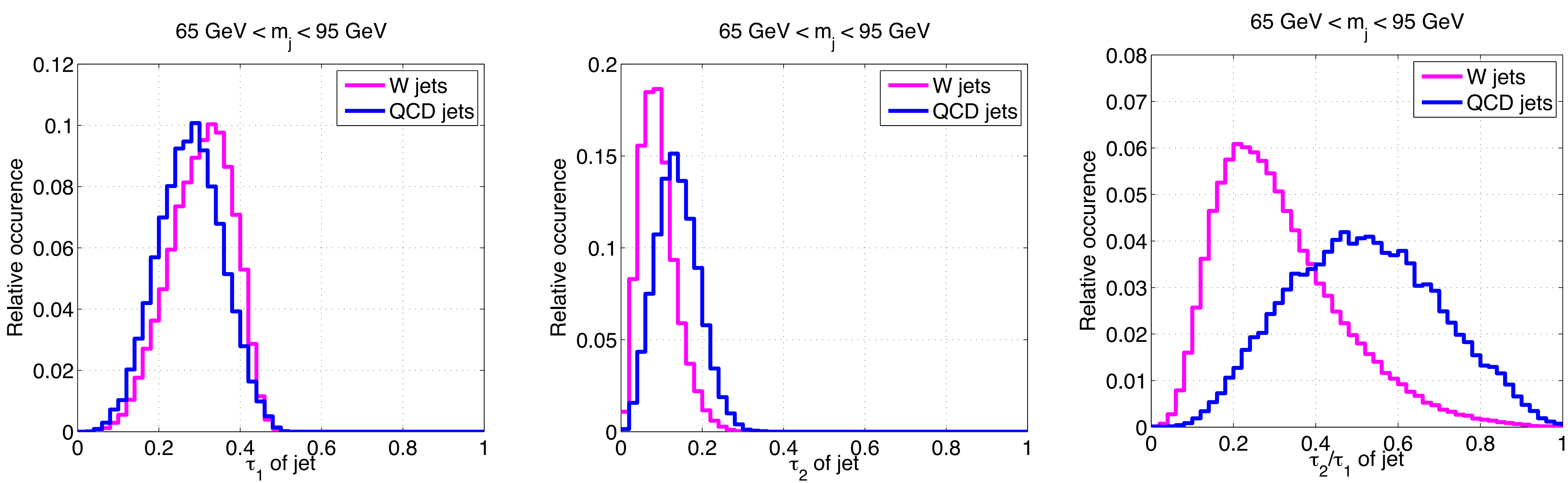
Thaler, Tilburg [1011.2268], [1108.2701]

Determine alignment of radiation along N subjet axes.



Recluster jet with exclusive kT algorithm to obtain N subjets, then compute how correlated jet radiation is along these axes

$$\tau_N \propto \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k} \ldots \Delta R_{N,k})$$



(Figures [1011.2268])

SUBSTRUCTURE - ENERGY CORRELATIONS

Old idea, generalised by Larkoski, Salam, Thaler, [1305.0007]

Compute N-point Energy Correlation Function $\mathrm{ECF}(N,\beta)$

e.g 2-point correlation $$\mathrm{ECF}(2,\beta) = \sum_{i<j\in J} p_{T\,i}\, p_{T\,j} (R_{ij})^{\beta},$$

Applied to a single jet

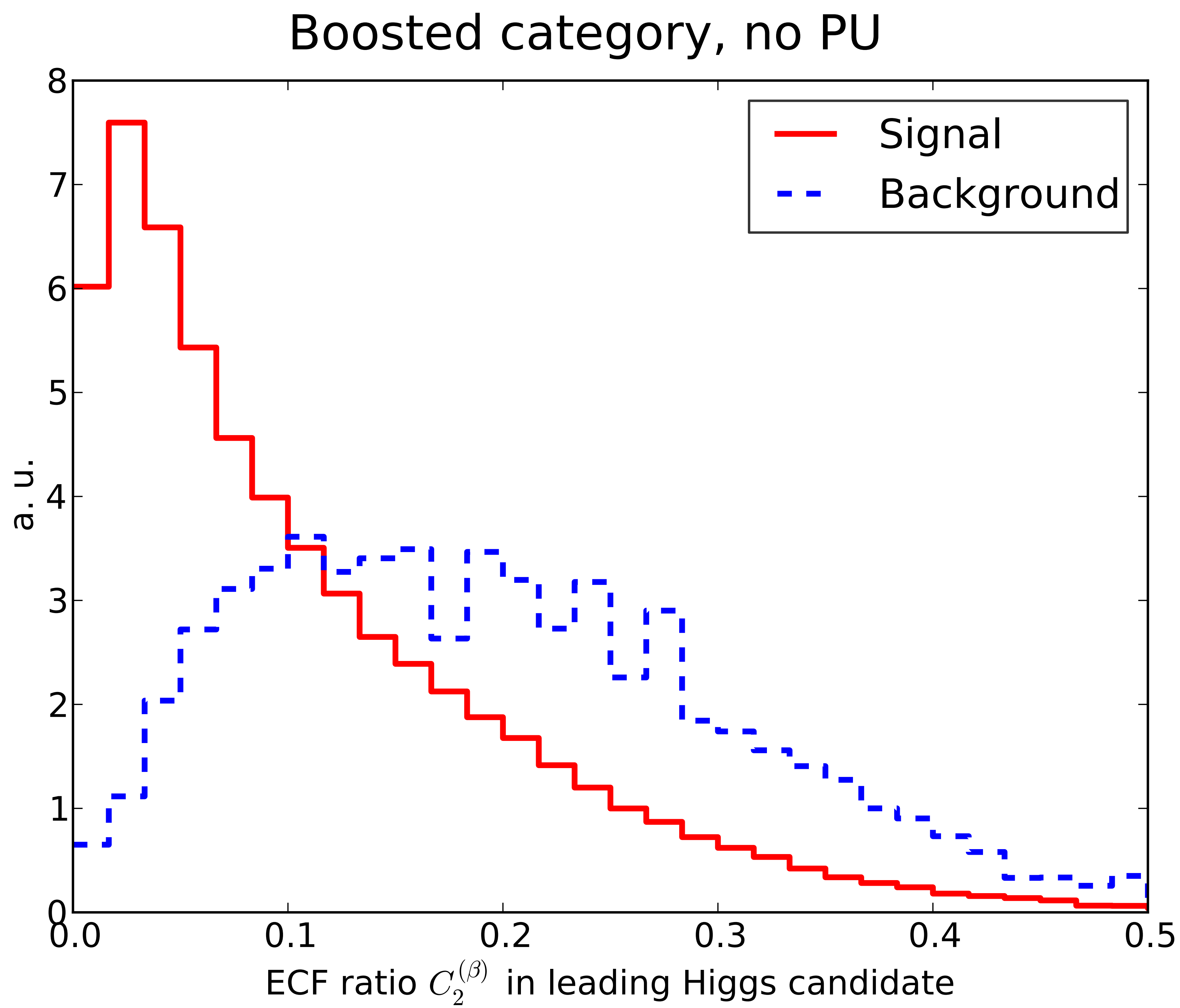
- *For soft and collinear radiation:* $\mathrm{ECF}(2,\beta>0) \to 0$

In order to get $\mathrm{ECF}(2,\beta) \gg 0$ *radiation must be* ***well-separated*** *and* ***hard***

Generally, N-point correlations are sensitive to (N-1) substructure

$$r_N^{(\beta)} \equiv \frac{\mathrm{ECF}(N+1,\beta)}{\mathrm{ECF}(N,\beta)}$$ *behaves similarly to N-subjettiness*

SUBSTRUCTURE - ENERGY CORRELATIONS



***Double-Ratios** of ECFs (e.g C_2, D_2) probe substructure like Nsubjettiness ratios*

- but no need to define subjet axes!

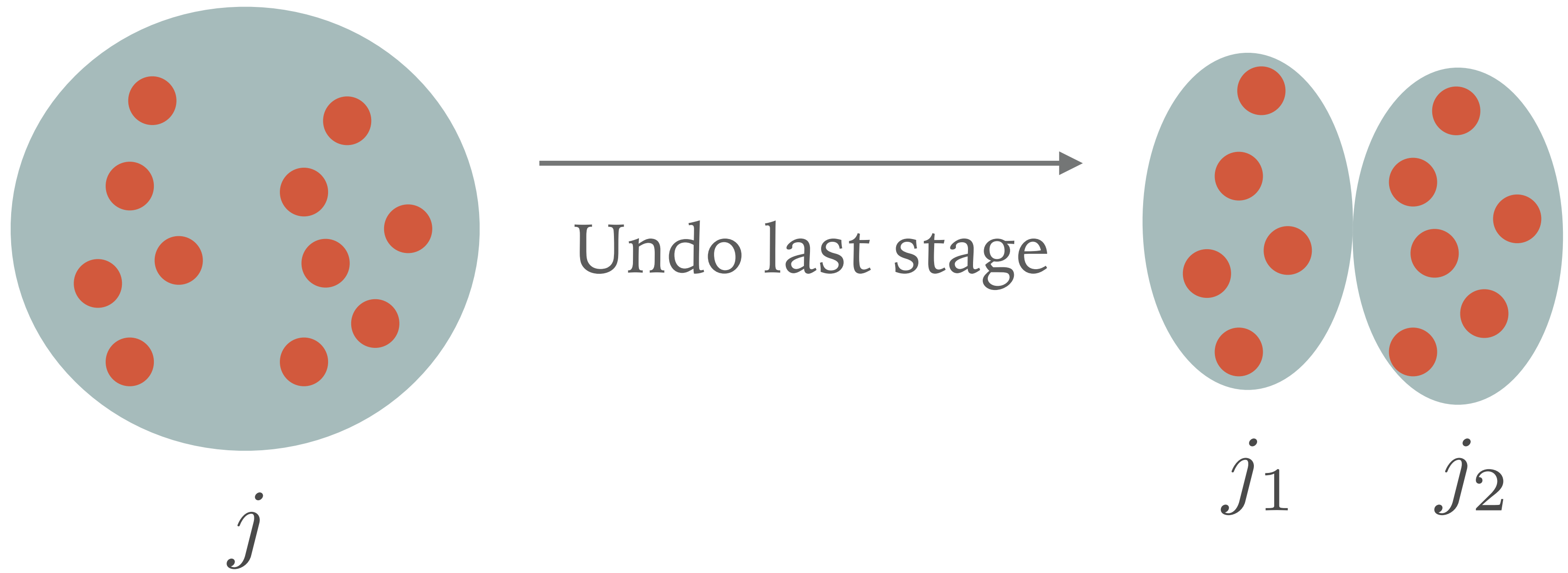
SUBSTRUCTURE - MASS DROP TAGS

Proposal of BDRS [0802.2470] for H->bb

Identify fairly symmetric subjets with a significant drop in mass

Cluster with large-R

Cambridge-Aachen



Require $\max(m_{j1}, m_{j2}) < \mu m_j$

From symmetric subjets:

$$y = \min\left(p_T^{(j1)}, p_T^{(j2)}\right) \frac{\Delta R^2_{j1,j2}}{m_j^2} > y_{\mathrm{cut}} \qquad y \sim \frac{\min(z_{j1}, z_{j2})}{\max(z_{j1}, z_{j2})}$$

Provides good separation between heavy resonance decays and QCD

BOOSTING $HH \to (b\bar{b})(b\bar{b})$

OUR APPROACH

- **Consider closely QCD multi-jet background (not just 4b)**

  Assuming relatively optimistic b-tagging parameters

  $$\epsilon_b = 0.8, \quad \epsilon_c = 0.1, \quad \epsilon_j = 0.01$$

- **Handle boosted and resolved analysis topologies**

  Ensure good coverage of final state phase space

- **Use plenty of information on jet substructure**

  MD tags, Splitting scales, N-subjettiness, Energy correlations

- **Investigate how multivariate analysis can boost significances**

  Keep cut-based analysis loose, try to to make as much use as possible of MVA

- **Assess robustness of results under the addition of pile-up (PU)**

  How feasible are these methods in a more realistic environment?

ANALYSIS DETAILS

Monte Carlo

Process	Generator	N_{evt}	σ_{LO} (pb)	K-factor
$pp \to hh \to 4b$	`MadGraph5_aMC@NLO`	1M	$6.2 \cdot 10^{-3}$	2.4 (NNLO+NNLL [18, 19])
$pp \to b\bar{b}b\bar{b}$	`SHERPA`	3M	$1.1 \cdot 10^{3}$	1.6 (NLO [63])
$pp \to b\bar{b}jj$	`SHERPA`	3M	$2.7 \cdot 10^{5}$	1.3 (NLO [63])
$pp \to jjjj$	`SHERPA`	3M	$9.7 \cdot 10^{6}$	0.6 (NLO [77])
$pp \to t\bar{t} \to b\bar{b}jjjj$	`SHERPA`	3M	$2.5 \cdot 10^{3}$	1.4 (NNLO+NNLL [78])

Basic detector modelling

p_T *Gaussian smear* $p_T^{(i)} \to p_T^{(i)\prime} = (1 + r_i \cdot \sigma_E)\, p_T^{(i)}$

Calorimeter resolution $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

‘Small-R jet’

b-tagged aKT R=0.4 jet

$p_T > 40\,\text{GeV},\ |\eta| < 2.5$

‘Large-R jet’

double b-tagged aKT R=1.0 jet

$p_T > 200\,\text{GeV},\ |\eta| < 2.5$

Require BDRS mass-drop tag

Higgs candidate (di-)jets required to have $|m - 125| \leq 40$ GeV

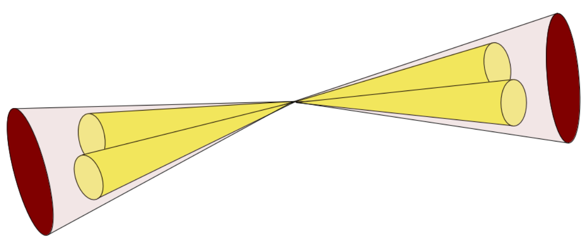
ANALYSIS DETAILS - SCALE INVARIANT RECONSTRUCTION

Need to make use of as much HH cross-section as possible

Combine all final state topologies Gouzevitch et al [1303.6636]

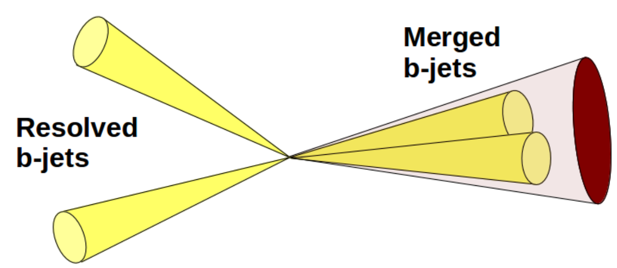
Boosted

Two Large-R jets



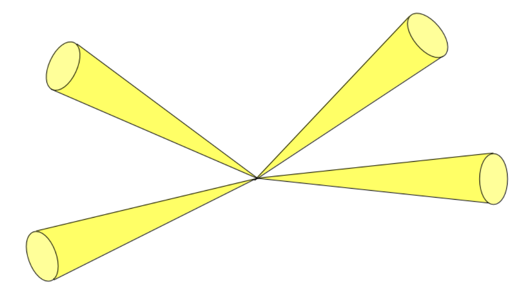
Intermediate

One Large-R jet, two Small-R jets



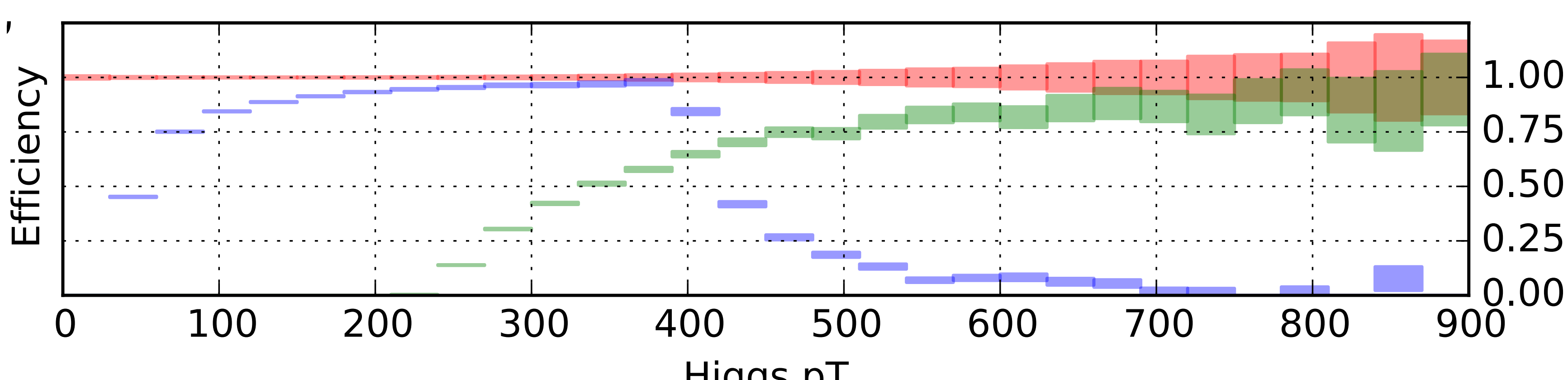
Resolved

Four Small-R jets



Prioritise selection Boosted-Intermediate-Resolved

Combined analysis covers wide range of Higgs pT



Blue: Resolved efficiency

Green: Boosted efficiency

PILEUP SIMULATION

PU may damage a measurement by (primarily)

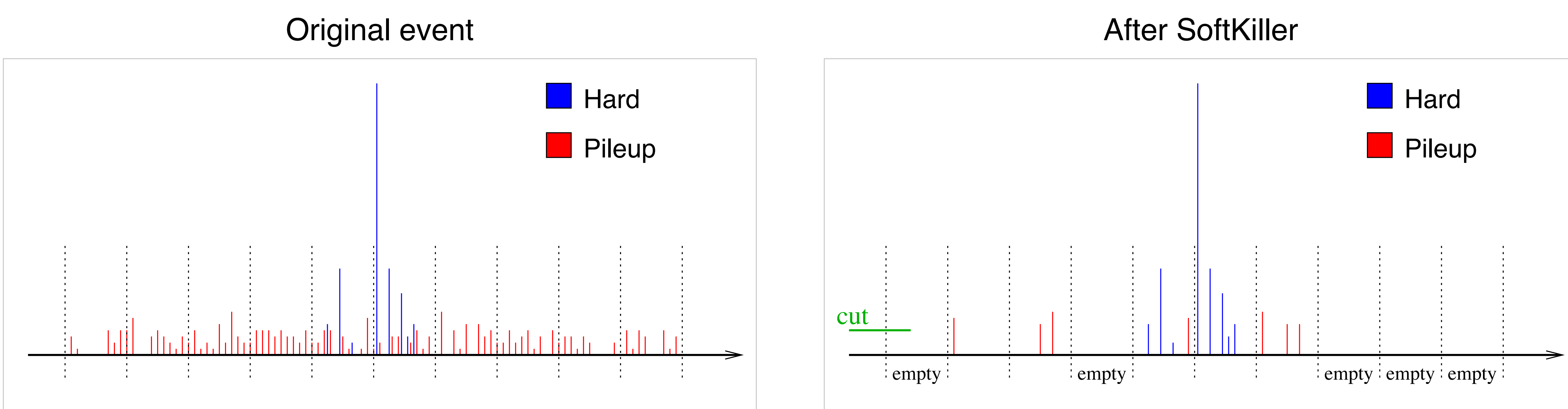
- ➤ The introduction of new jets in reconstruction
- ➤ Distortion of jet masses and substructure

*PU management will be a **significant** issue - particuarly in boosted analyses.*

-Introduce an additional 80 PU vertices per hard event.

PU is managed by a combination of

- **SoftKiller** subtraction at the event level **[Cacciari et al 1407.0408]**



- ➤ *Divide event into patches of* $\Delta\eta \times \Delta\phi = a$
- ➤ *Remove softest radiation until half of these patches are empty*

PILEUP SIMULATION

PU may damage a measurement by (primarily)

- ➤ The introduction of new jets in reconstruction
- ➤ Distortion of jet masses and substructure

*PU management will be a **significant** issue - particularly in boosted analyses.*

-Introduce an additional 80 PU vertices per hard event.

PU is managed by a combination of

- **SoftKiller** subtraction at the event level [Cacciari et al 1407.0408]
- Large-R jets **trimmed** [Krohn et al 0912.1342]

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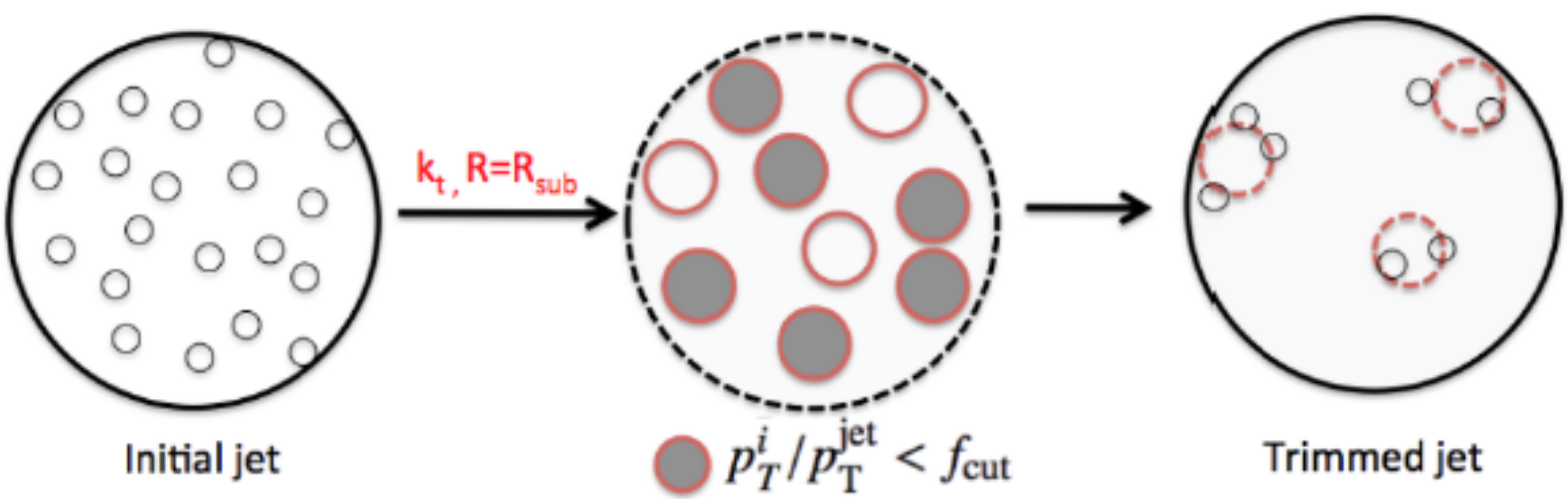


ANALYSIS RESULTS

ANALYSIS RESULTS

Results after **cut-based analysis + PU80**

	S/sqrt(B)	S/B
Boosted	0.6	9.0E-04
Intermediate	0.3	3.4E-04
Resolved	0.4	6.5E-05

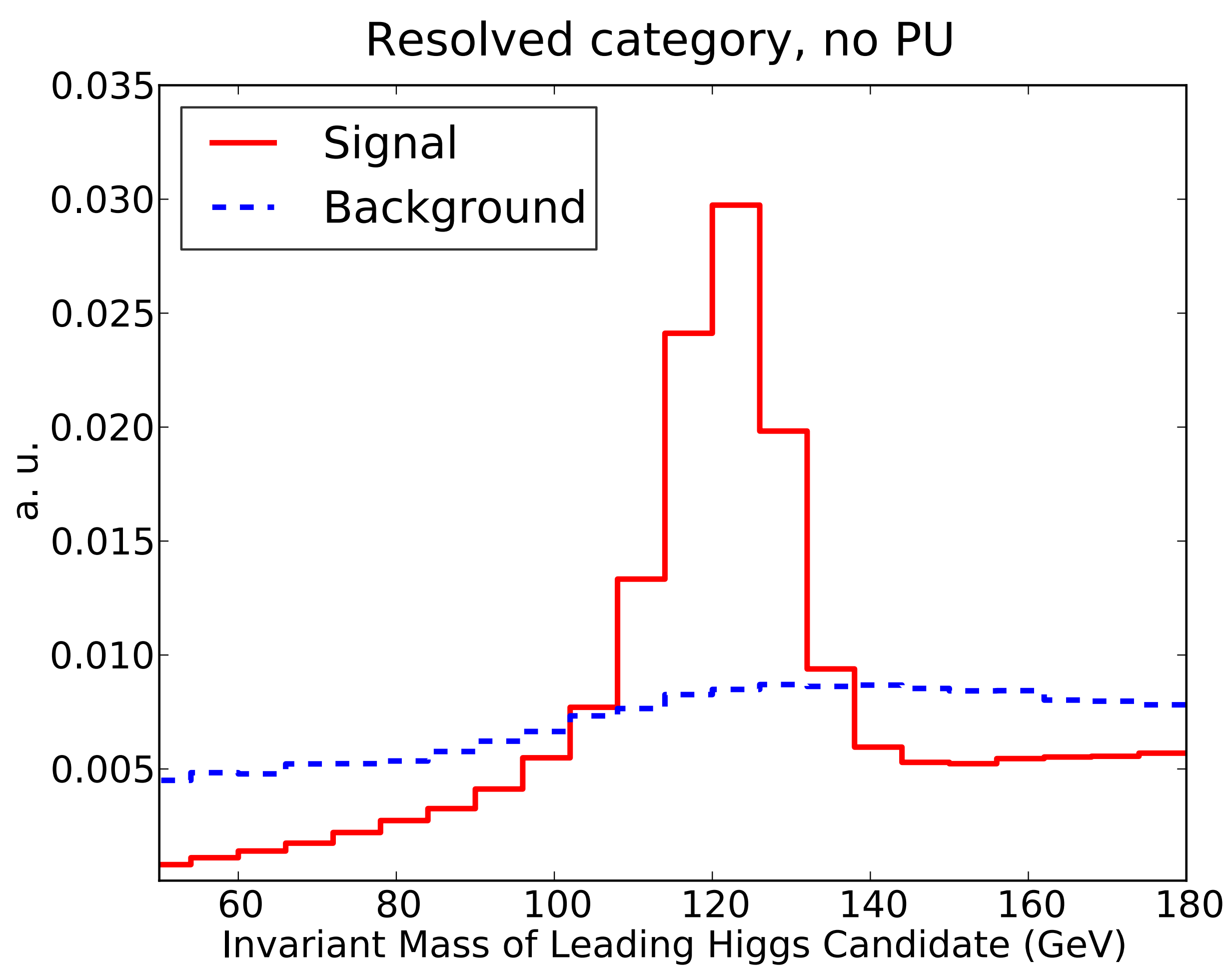
HL-LHC	NSIG	NBKG
Boosted	410	4.5E+05
Intermediate	260	7.7E+05
Resolved	1800	2.7E+07

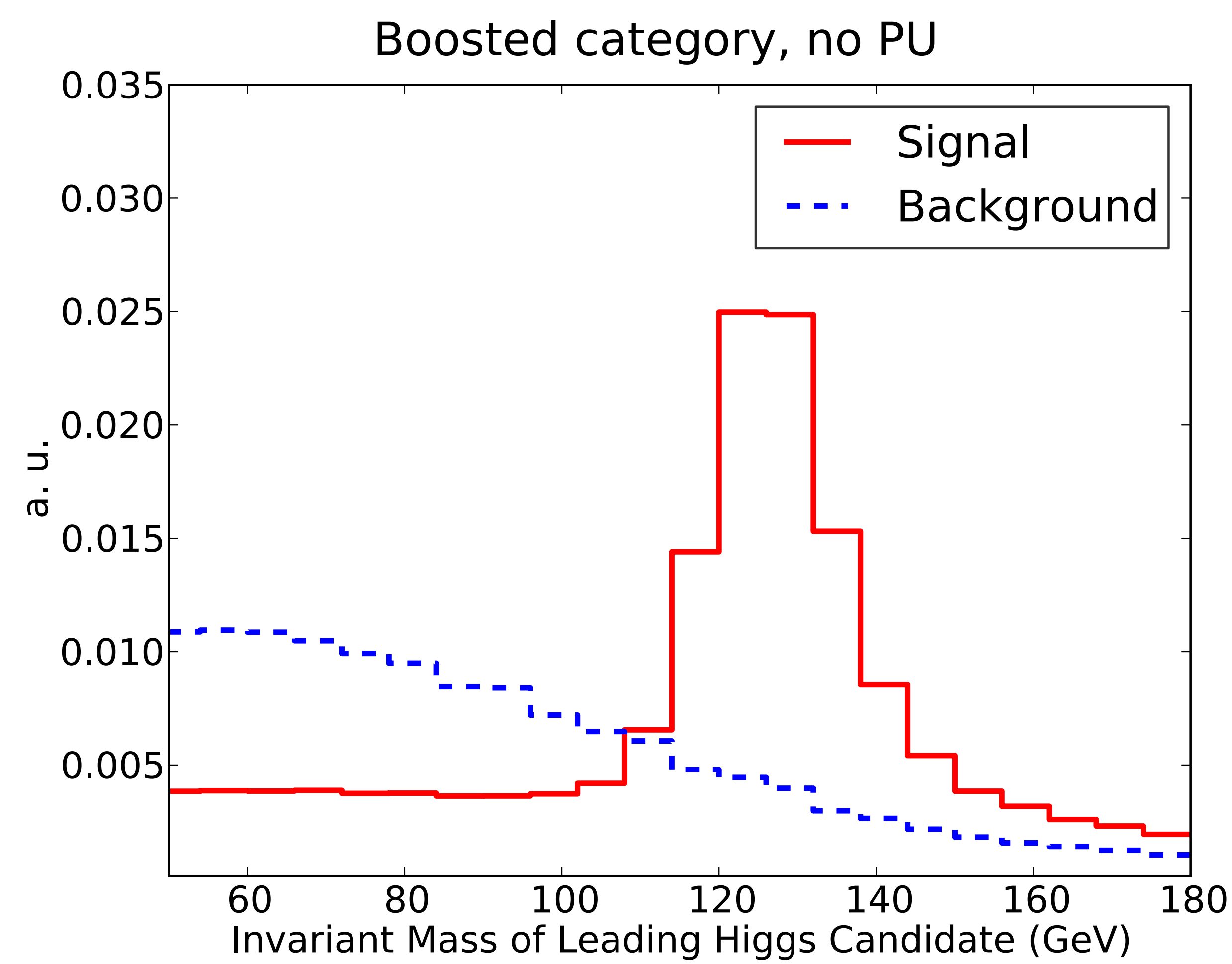
Combined statistical significance before MVA $\sim$ ***0.8σ***

Resolved	HH	QCD 4b	QCD 2b2j	QCD 4j	QCD ttbar
Reco (fb)	11	1.5E+05	3.0E+07	4.1E+08	2.6E+05
Final (fb)	0.6	3.5E+03	5.1E+03	3.1E+02	50

Boosted	HH	QCD 4b	QCD 2b2j	QCD 4j	QCD ttbar
Reco (fb)	3.5	1.0E+04	2.7E+06	3.8E+07	2.0E+04
Final (fb)	0.14	40	86	22	1.8

ANALYSIS RESULTS - PU AND JET MASSES

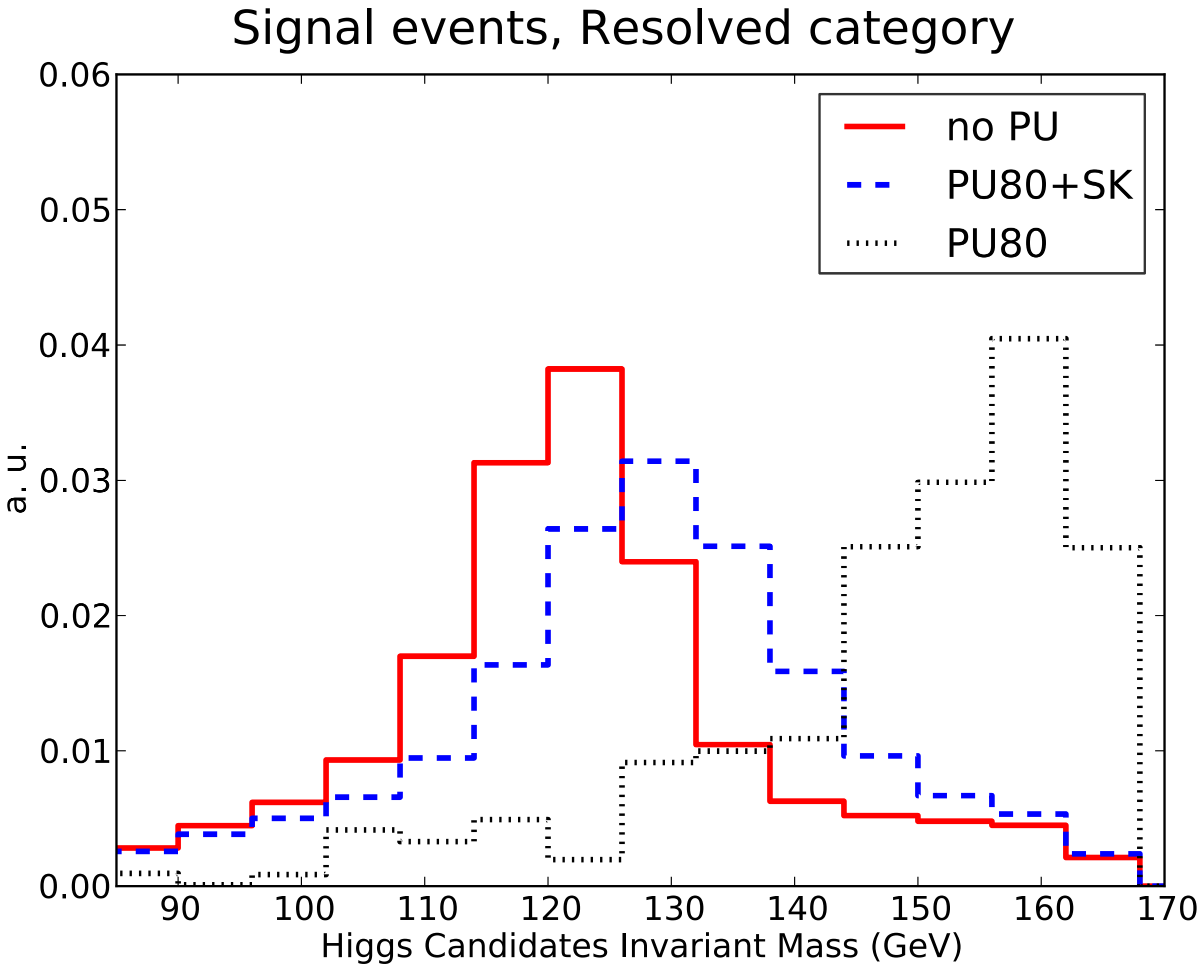


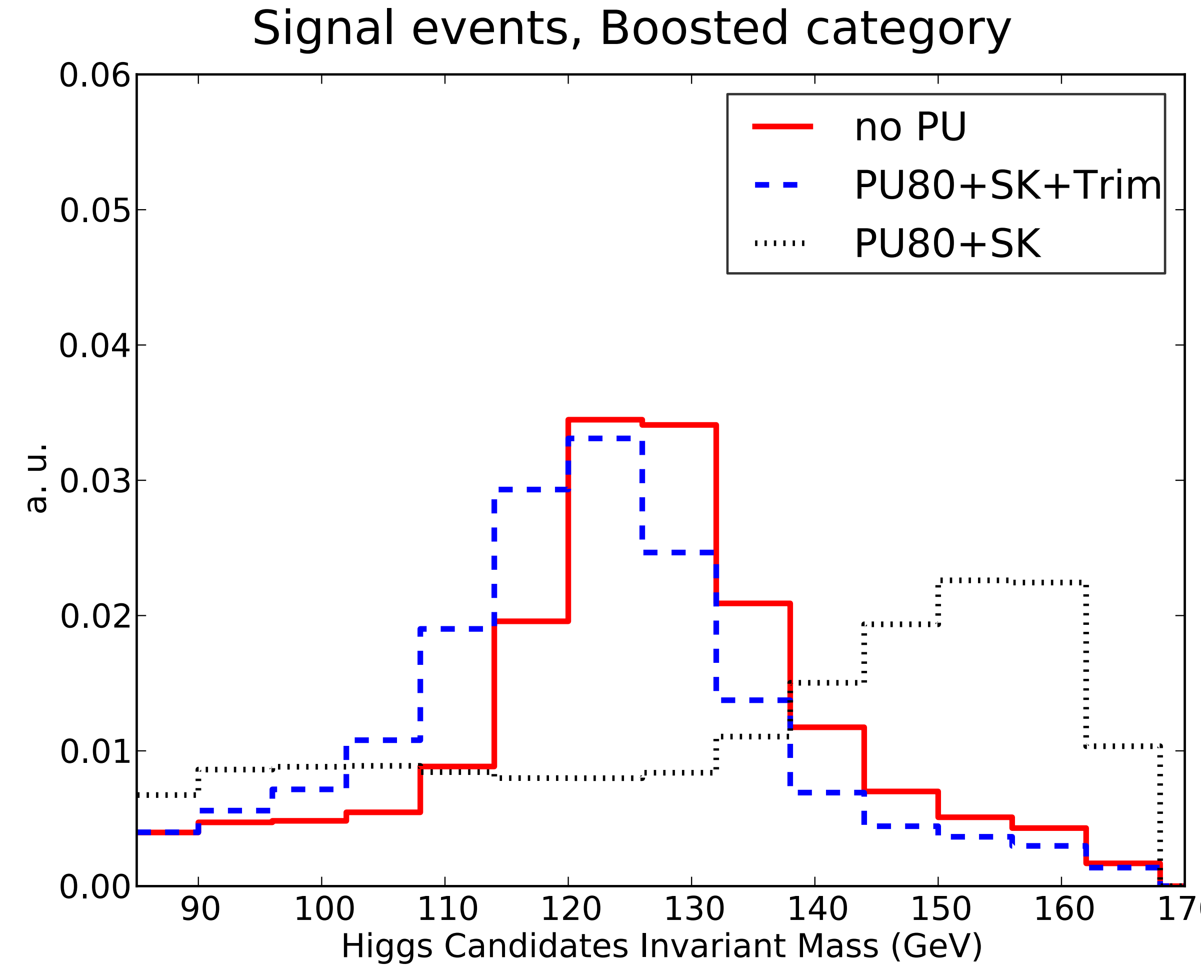


- *(di)-jet masses are naturally a vital component in any H measurement*

  - Can the effects of pile-up be successfully mitigated?

ANALYSIS RESULTS - PU AND JET MASSES

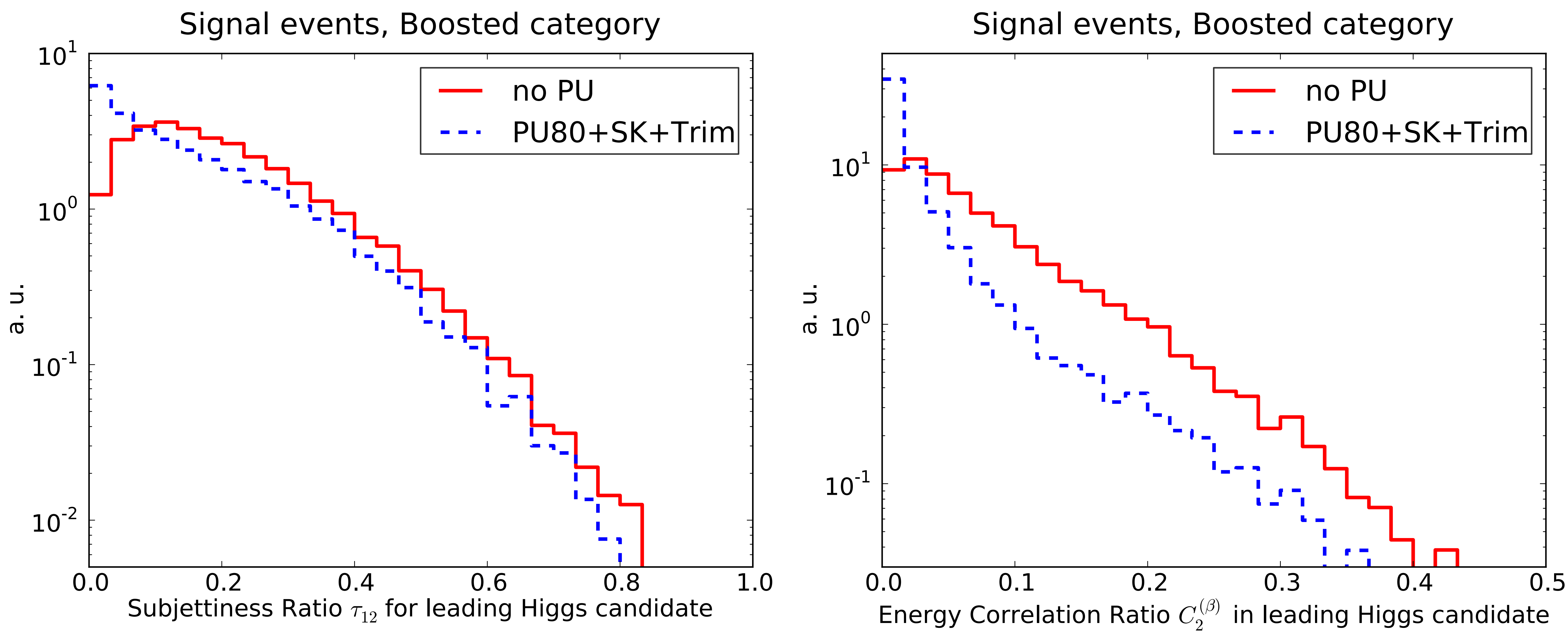




- *Resolved di-jet masses: **SoftKiller** appears to function well*
- *Boosted jet masses: SoftKiller itself isn't sufficient, some **Grooming** required*

ANALYSIS RESULTS – SUBSTRUCTURE AND PILEUP

- *Substructure observables are often naturally sensitive to pile-up*



With SK + Trimming for pile-up subtraction:

Principle features of substructure variables appear to be fairly robust

MULTIVARIATE $HH \rightarrow (b\bar{b})(b\bar{b})$

MULTIVARIATE ANALYSIS - NEURAL NET CLASSIFIERS

Cuts so far are rather loose - how can we best make use of our information?

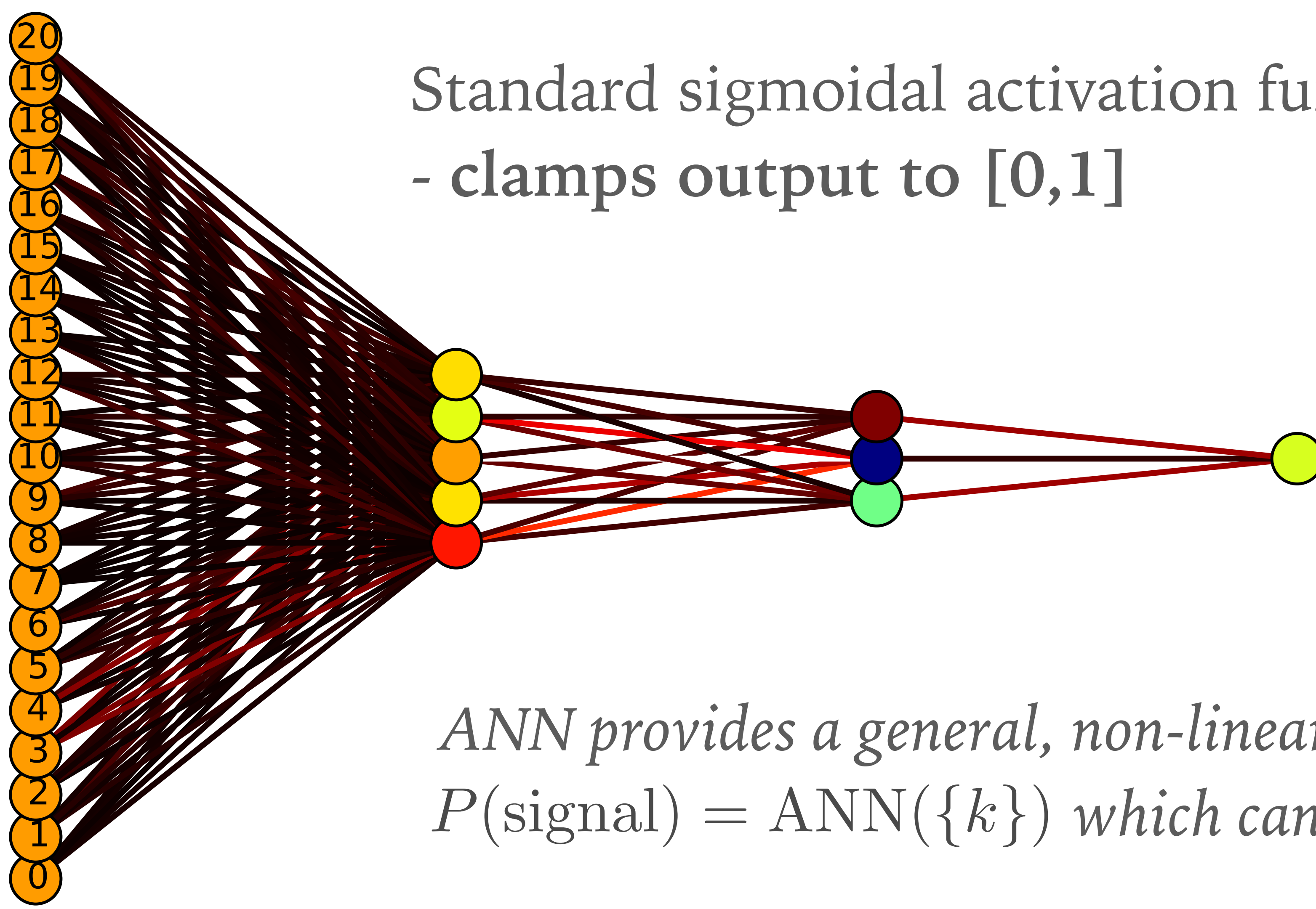
Classify events as signal/background with ANN

$N \times 5 \times 3 \times 1$ *(Similar architecture to NNPDF)*

Standard sigmoidal activation function

- clamps output to [0,1]

Event kinematics



P(signal)

ANN provides a general, non-linear mapping

$P(\text{signal}) = \text{ANN}(\{k\})$ *which can be optimised*

MULTIVARIATE ANALYSIS - KINEMATIC INPUTS

Event kinematics used as input to the neural network

For each event

- $p_{T,H_1},\ p_{T,H_2},\ p_{T,HH}$
- $m_{H_1},\ m_{H_2},\ m_{HH}$
- $\Delta R_{HH},\ \Delta\eta_{HH},\ \Delta\phi_{HH}$
- $p_{T,b-\mathrm{jet}}$ *for each b-(sub)jet*

For each large-R jet

- k_T *splitting scales* $\sqrt{(d_{12})}$
- *2/1 - subjettiness* τ_2/τ_1
- *ECF double ratio* $C_2^{(\beta)}$
- *ECF double ratio* $D_2^{(\beta)}$

Channel	#inputs
Boost	21
Inter.	17
Resol.	13

ANN untroubled by $\mathcal{O}(10)$ inputs:
Let the MVA decide which variables are the most discriminating

MULTIVARIATE ANALYSIS - TRAINING

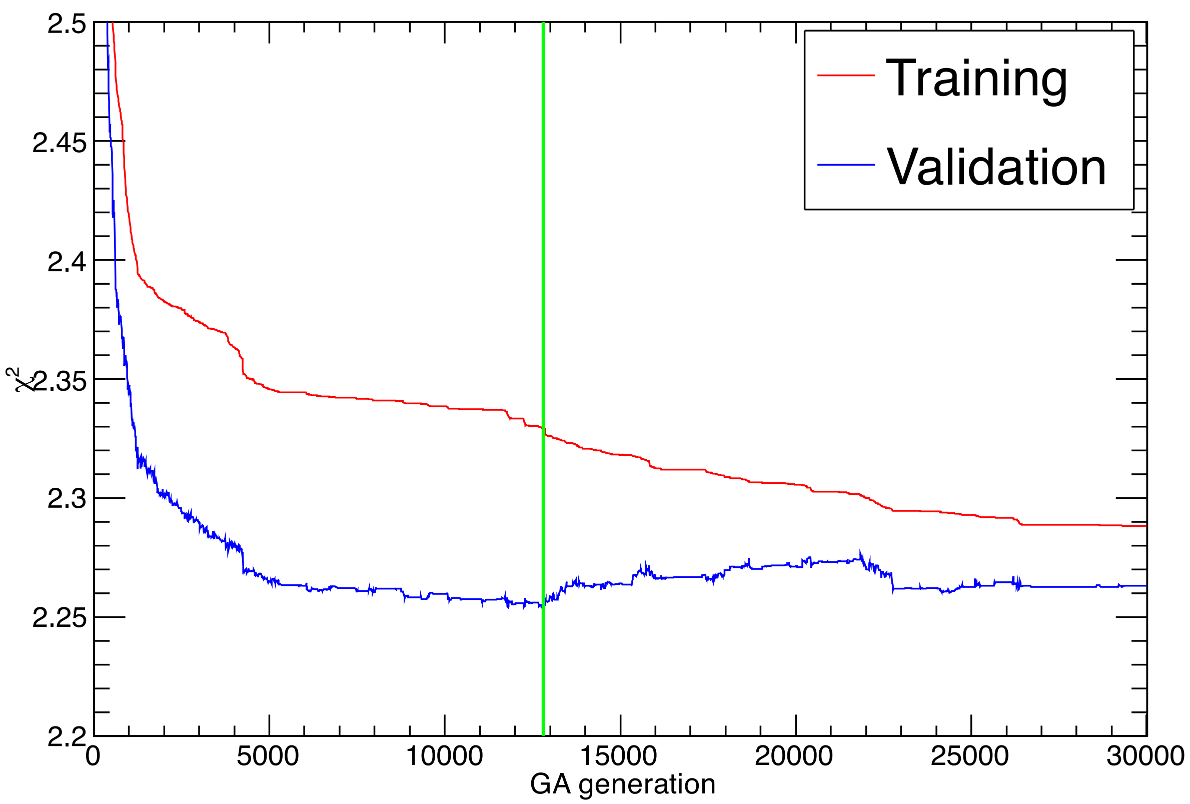
*The neural network is **trained** upon Monte Carlo events*

*The optimisation consists of minimising the **Cross-Entropy***

$$E(\{\omega\}) \equiv -\log\left(\prod_i^{N_{\mathrm{ev}}} P(y_i'|\{k\}_i,\{\omega\})\right)$$

$$= \sum_i^{N_{\mathrm{ev}}} \left[y_i' \log y_i + (1-y_i')\log(1-y_i)\right]$$

- The minimisation progresses through a basic **genetic algorithm**
- Over-fitting is prevented by 'look-back' **cross-validation**

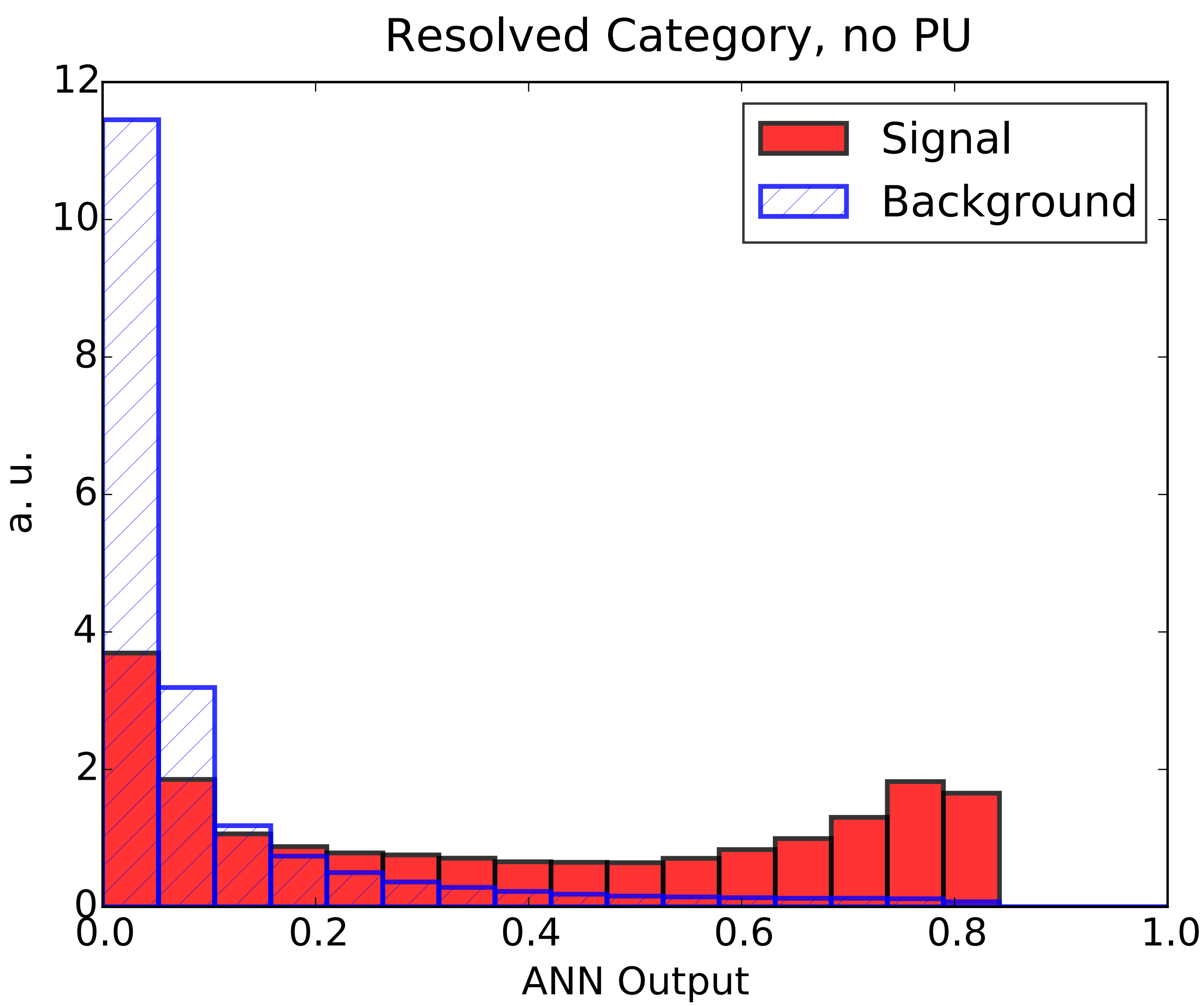


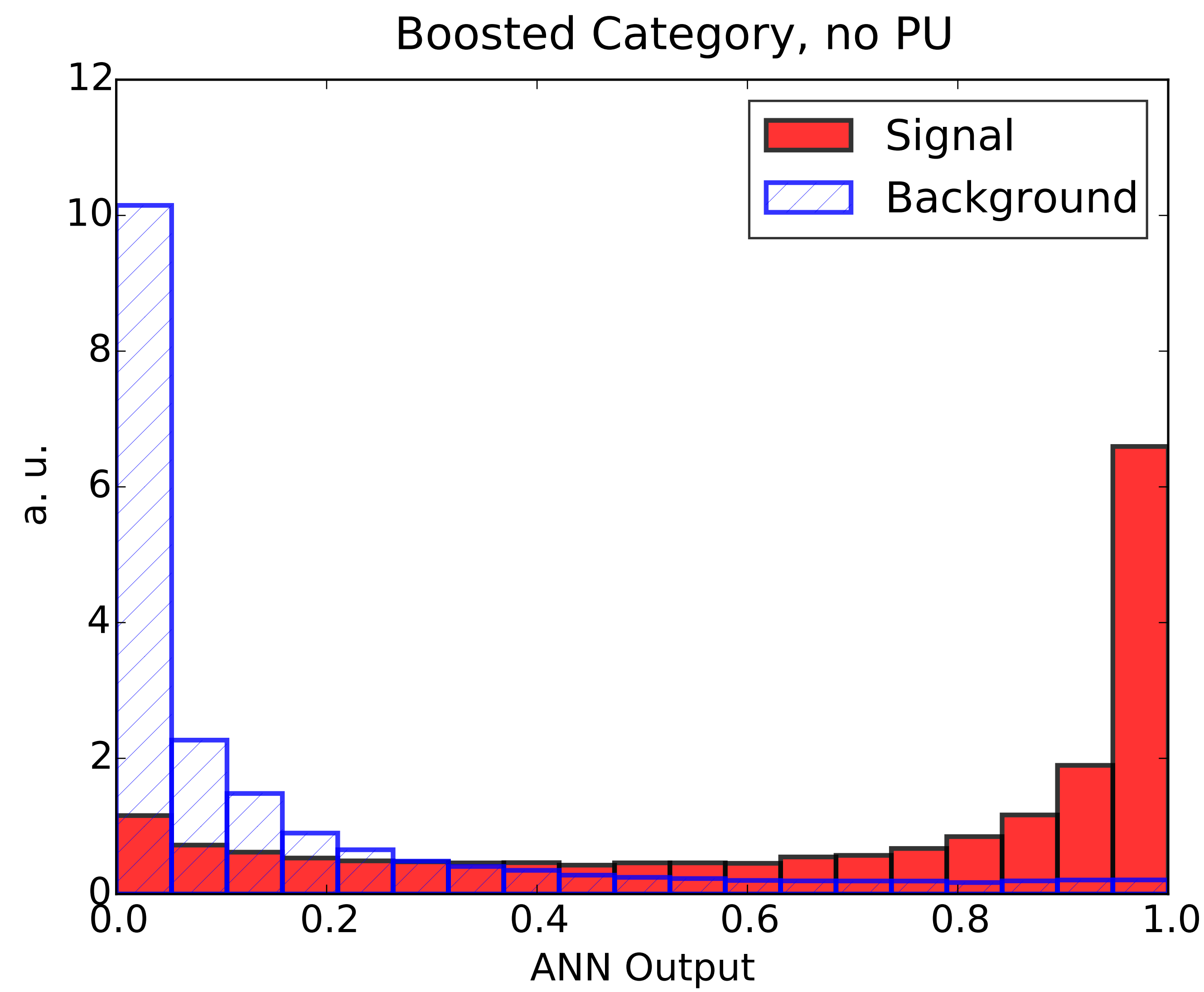
- Split data into training and validation

- Minimise to training data

- Select GA iteration providing the best fit to the validation data

MULTIVARIATE ANALYSIS - RESULTS

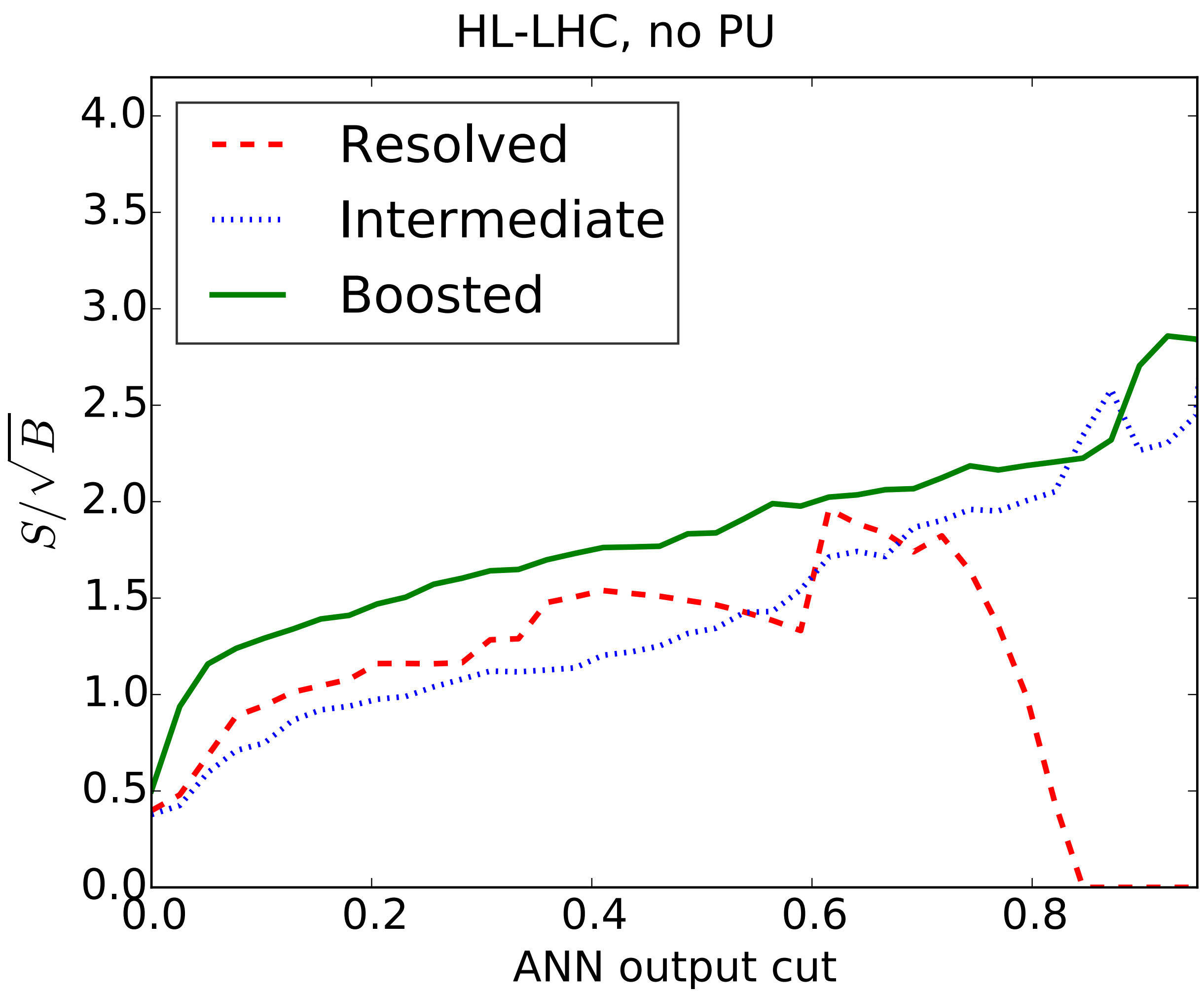


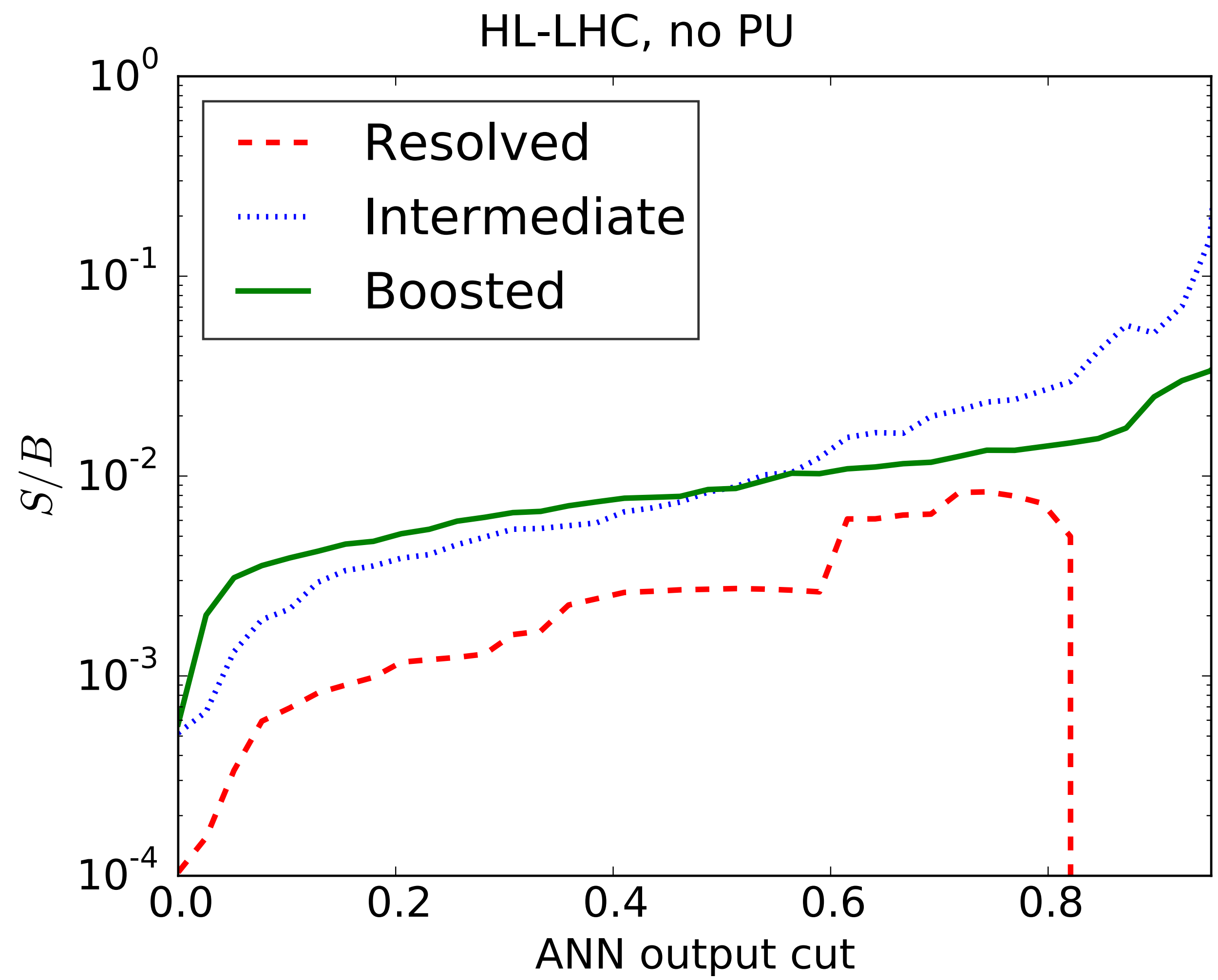


Simple ANN training yields reasonable signal-background separation

MULTIVARIATE ANALYSIS - RESULTS

- *Vary the cut in ANN output (no pileup case)*



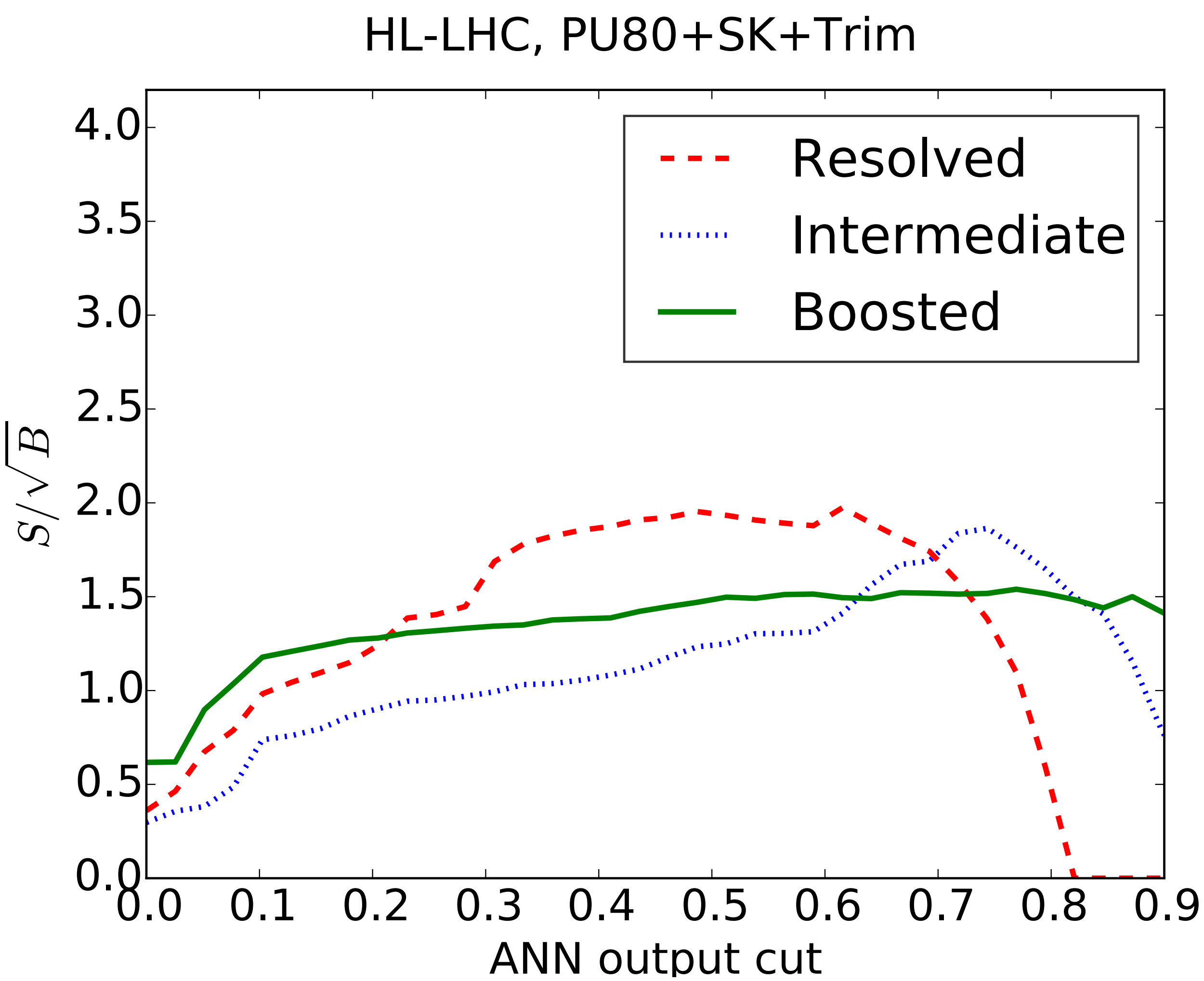


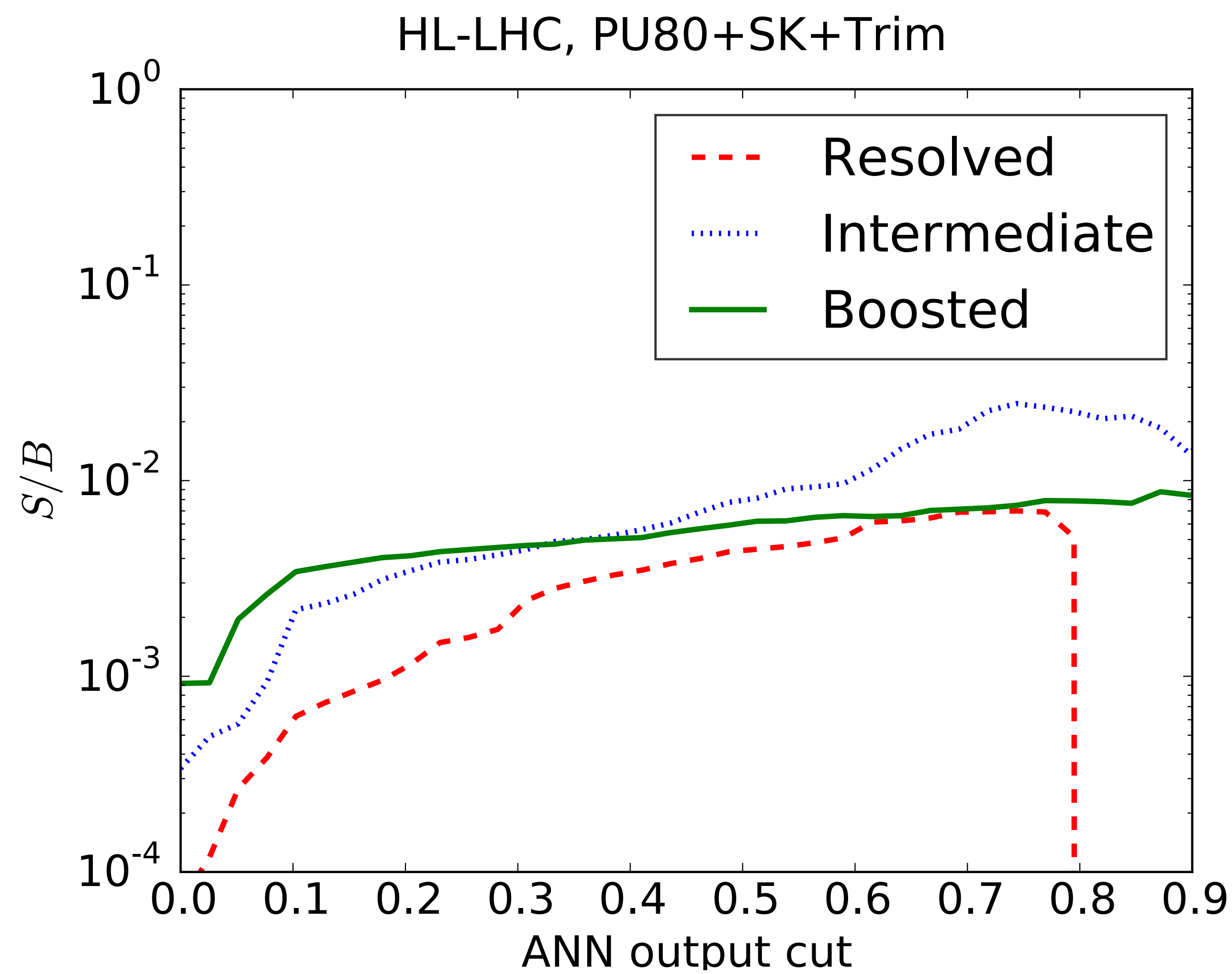
Boosted topologies most effective without pileup

Generally good balance between topologies

MULTIVARIATE ANALYSIS – RESULTS

➤ *Vary the cut in ANN output, under the addition of pileup*





Significances reshuffle - boosted topologies damaged

Boosted topologies remain less sensitive to systematics

MULTIVARIATE ANALYSIS – RESULTS

HL-LHC, PU80+SK+Trim					
Category		$N_{\rm ev}$ signal	$N_{\rm ev}$ back	$S/\sqrt{B}$	S/B
Boosted	$y_{\rm cut} = 0$	410	$4.5 \cdot 10^5$	0.6	10^{-3}
	$y_{\rm cut} = 0.8$	290	$3.7 \cdot 10^4$	1.5	0.01
Intermediate	$y_{\rm cut} = 0$	260	$7.7 \cdot 10^5$	0.3	$3 \cdot 10^{-4}$
	$y_{\rm cut} = 0.75$	140	$5.6 \cdot 10^3$	1.9	0.03
Resolved	$y_{\rm cut} = 0$	1800	$2.7 \cdot 10^7$	0.4	$7 \cdot 10^{-5}$
	$y_{\rm cut} = 0.60$	640	$1.0 \cdot 10^5$	2.0	0.01

- *Combined signal significance ~* ***3.1σ*** *after MVA (0.8σ before)*

$S/\sqrt{B}$	no PU	PU80 + sub
pre-MVA	0.8	0.8
post-MVA	4.0	3.1

Significances for the HL-LHC
$(\mathcal{L} = 3000 \text{fb}^{-1})$

CONCLUSIONS

$HH \to (b\bar{b})(b\bar{b})$ *is a **tough** process to measure, however*

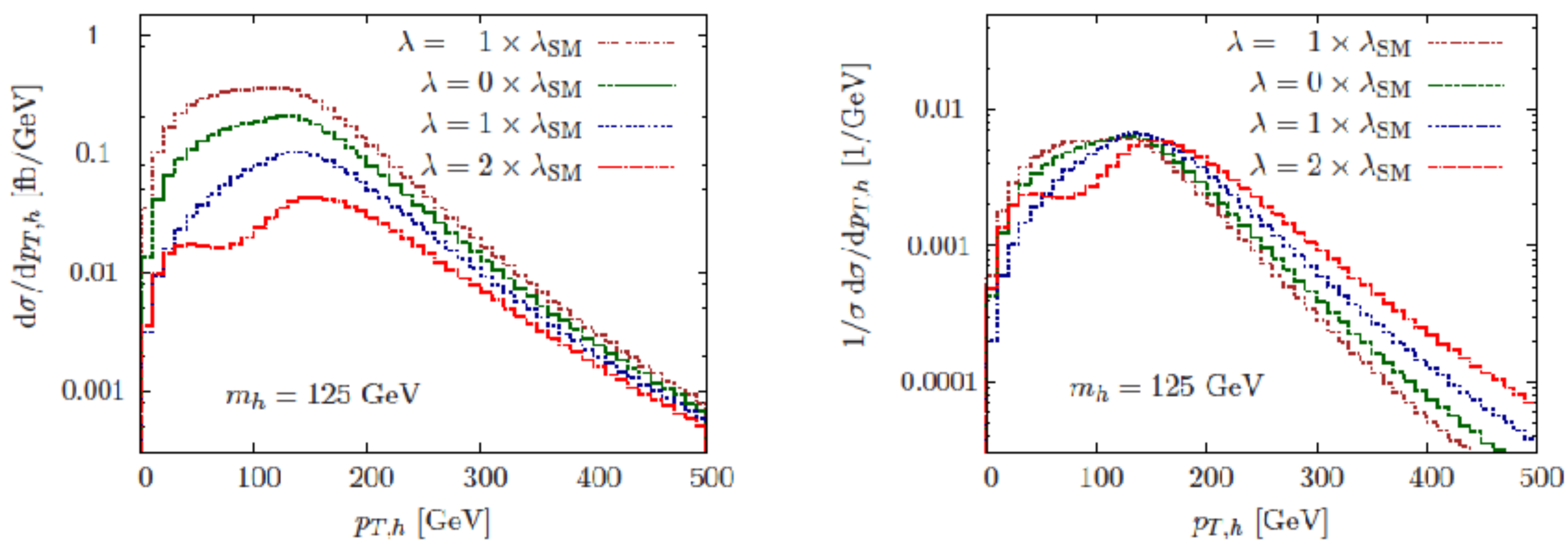
With a combined arms strategy:

- ***Multiple topologies***
- ***Substructure***
- ***Multivariate-analysis***

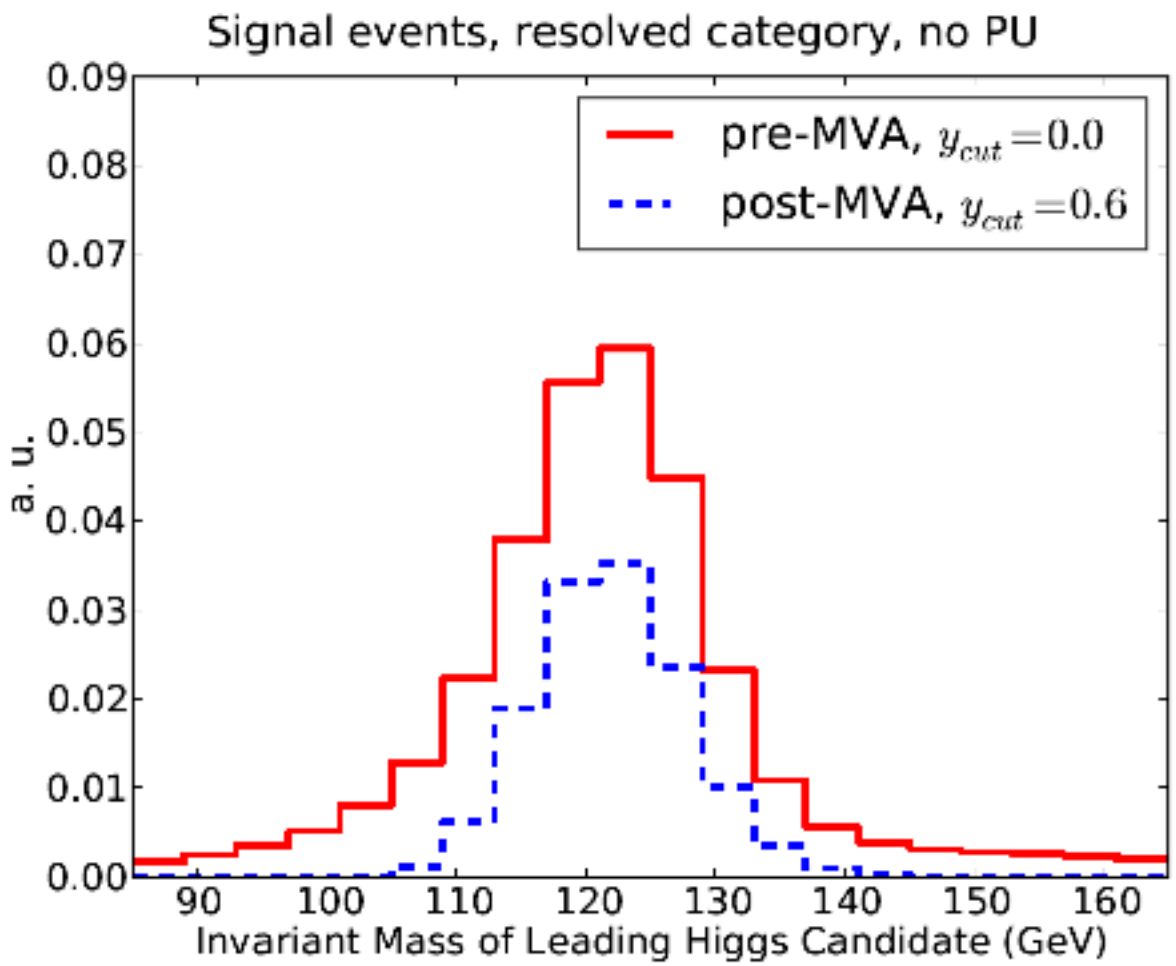
An observation of HH production in the bbbb channel is feasible at the HL-LHC

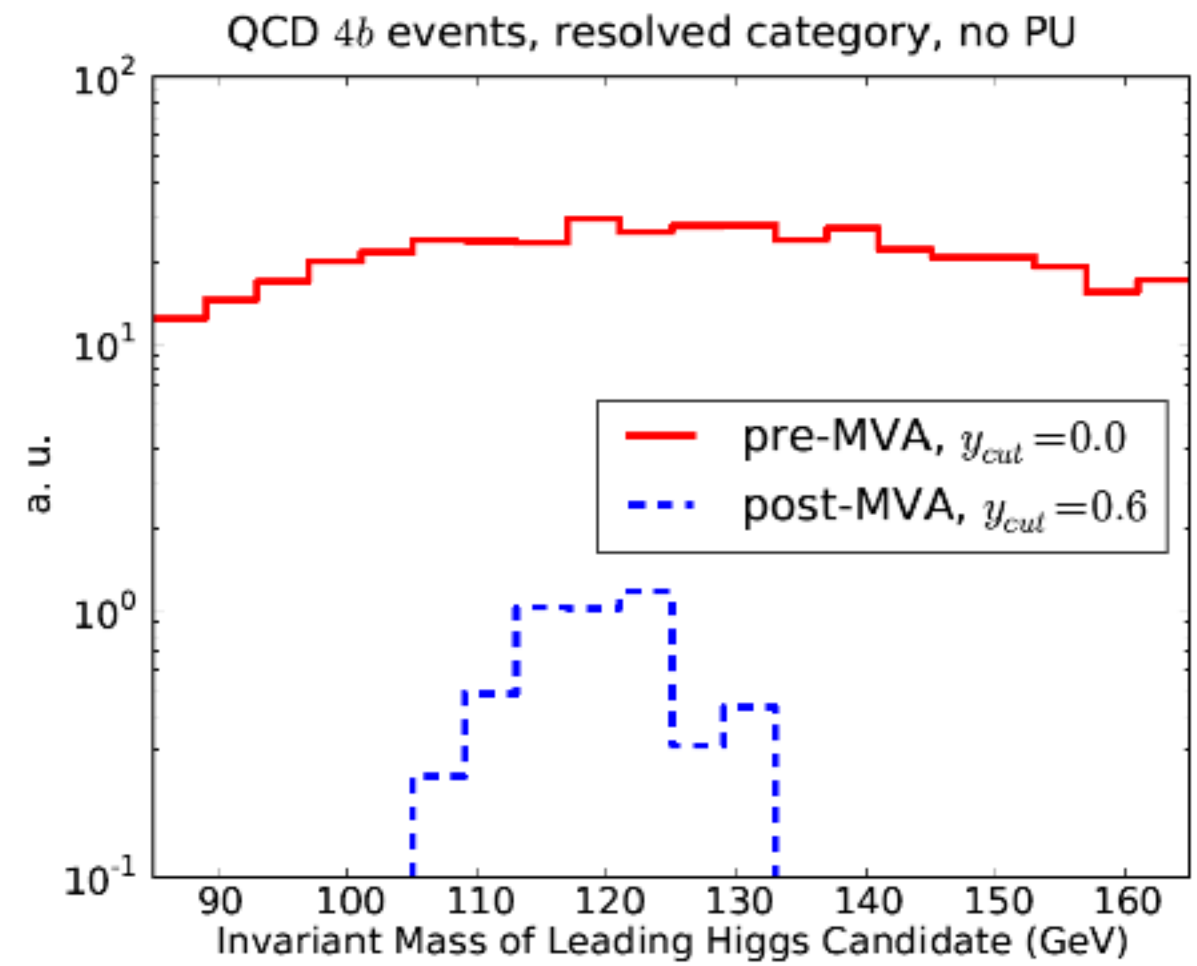
Combined $S/\sqrt{B} \sim 3.1$ *after MVA*

Next steps - *what bounds can we obtain upon* λ?



MVA AT WORK


Signal events, resolved category, no PU
pre-MVA, $y_{cut}=0.0$
post-MVA, $y_{cut}=0.6$
a. u.
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
90
100
110
120
130
140
150
160
Invariant Mass of Leading Higgs Candidate (GeV)


QCD $4b$ events, resolved category, no PU
pre-MVA, $y_{cut}=0.0$
post-MVA, $y_{cut}=0.6$
a. u.
10^2
10^1
10^0
10^{-1}
90
100
110
120
130
140
150
160
Invariant Mass of Leading Higgs Candidate (GeV)

MULTIVARIATE ANALYSIS - TRAINING

*The neural network is **trained** upon Monte Carlo events*

An event **i** originates from either the **signal** $y'_i = 1$
or **background** $y'_i = 0$ processes

It carries a set of kinematic variables $\{k\}_i$
and is processed by an NN with parameters $\{\omega\}$

For each event we have the NN output: $y_i = P(y'_i = 1 | \{k\}_i, \{\omega\})$

and therefore per-event likelihood: $P(y'_i | \{k\}_i, \{\omega\}) = y_i^{y'_i} (1 - y_i)^{1 - y'_i}$,

So the optimisation consists of

*minimising the **Cross-Entropy***

$$E(\{\omega\}) \equiv -\log\left(\prod_i^{N_{\mathrm{ev}}} P(y'_i | \{k\}_i, \{\omega\})\right)$$

$$= \sum_i^{N_{\mathrm{ev}}} \left[y'_i \log y_i + (1 - y'_i) \log (1 - y_i) \right]$$

ANALYSIS BREAKDOWN – NO PILEUP

HL-LHC, Resolved category, no PU										
	Cross-section [fb]						S/B		$S/\sqrt{B}$	
	$hh4b$	total bkg	$4b$	$2b2j$	$4j$	$t\bar{t}$	tot	$4b$	tot	$4b$
C1a	9	$2.2 \cdot 10^8$	$6.9 \cdot 10^4$	$1.5 \cdot 10^7$	$2.0 \cdot 10^8$	$2.1 \cdot 10^5$	$4.0 \cdot 10^{-8}$	$1.3 \cdot 10^{-4}$	0.03	1.9
C1b	9	$2.2 \cdot 10^8$	$6.9 \cdot 10^4$	$1.5 \cdot 10^7$	$2.0 \cdot 10^8$	$2.1 \cdot 10^5$	$4.0 \cdot 10^{-8}$	$1.3 \cdot 10^{-4}$	0.03	1.9
C1c	2.6	$4.4 \cdot 10^7$	$1.6 \cdot 10^4$	$3.2 \cdot 10^6$	$4.1 \cdot 10^7$	$8.8 \cdot 10^4$	$6.1 \cdot 10^{-8}$	$1.6 \cdot 10^{-4}$	0.02	1.1
C2	0.5	$4.9 \cdot 10^3$	$1.7 \cdot 10^3$	$2.9 \cdot 10^3$	$2.1 \cdot 10^2$	47	$1.1 \cdot 10^{-4}$	$2.9 \cdot 10^{-4}$	0.4	0.6

HL-LHC, Intermediate category, no PU										
	Cross-section [fb]						S/B		$S/\sqrt{B}$	
	$hh4b$	total bkg	$4b$	$2b2j$	$4j$	$t\bar{t}$	tot	$4b$	tot	$4b$
C1a	2.8	$8.4 \cdot 10^7$	$2.1 \cdot 10^4$	$5.3 \cdot 10^6$	$7.9 \cdot 10^7$	$3.3 \cdot 10^4$	$3.4 \cdot 10^{-8}$	$1.3 \cdot 10^{-4}$	0.02	1.1
C1b	2.6	$5.8 \cdot 10^7$	$1.4 \cdot 10^4$	$3.6 \cdot 10^6$	$5.5 \cdot 10^7$	$3.0 \cdot 10^4$	$4.5 \cdot 10^{-8}$	$1.9 \cdot 10^{-4}$	0.02	1.2
C1c	0.5	$3.5 \cdot 10^6$	$8.7 \cdot 10^2$	$2.1 \cdot 10^5$	$4.3 \cdot 10^7$	$8.8 \cdot 10^3$	$1.6 \cdot 10^{-7}$	$6.1 \cdot 10^{-4}$	0.02	1.0
C2	0.09	$1.8 \cdot 10^2$	56	96	22	3.1	$5.3 \cdot 10^{-4}$	$1.6 \cdot 10^{-3}$	0.4	0.6

HL-LHC, Boosted category, no PU										
	Cross-section [fb]						S/B		$S/\sqrt{B}$	
	$hh4b$	total bkg	$4b$	$2b2j$	$4j$	$t\bar{t}$	tot	$4b$	tot	$4b$
C1a	3.9	$4.6 \cdot 10^7$	$1.1 \cdot 10^4$	$2.9 \cdot 10^6$	$4.3 \cdot 10^7$	$2.4 \cdot 10^4$	$8.2 \cdot 10^{-8}$	$3.4 \cdot 10^{-4}$	0.03	2.0
C1b	2.7	$3.7 \cdot 10^7$	$7.5 \cdot 10^3$	$2.1 \cdot 10^6$	$3.5 \cdot 10^7$	$2.2 \cdot 10^4$	$7.4 \cdot 10^{-8}$	$3.7 \cdot 10^{-4}$	0.03	1.7
C1c	1.0	$3.9 \cdot 10^6$	$8.0 \cdot 10^2$	$2.3 \cdot 10^5$	$3.7 \cdot 10^6$	$7.1 \cdot 10^3$	$2.6 \cdot 10^{-7}$	$1.3 \cdot 10^{-3}$	0.03	2.0
C2	0.16	$2.5 \cdot 10^2$	53	$1.9 \cdot 10^2$	13	1.6	$5.7 \cdot 10^{-4}$	$2.7 \cdot 10^{-3}$	0.5	1.1

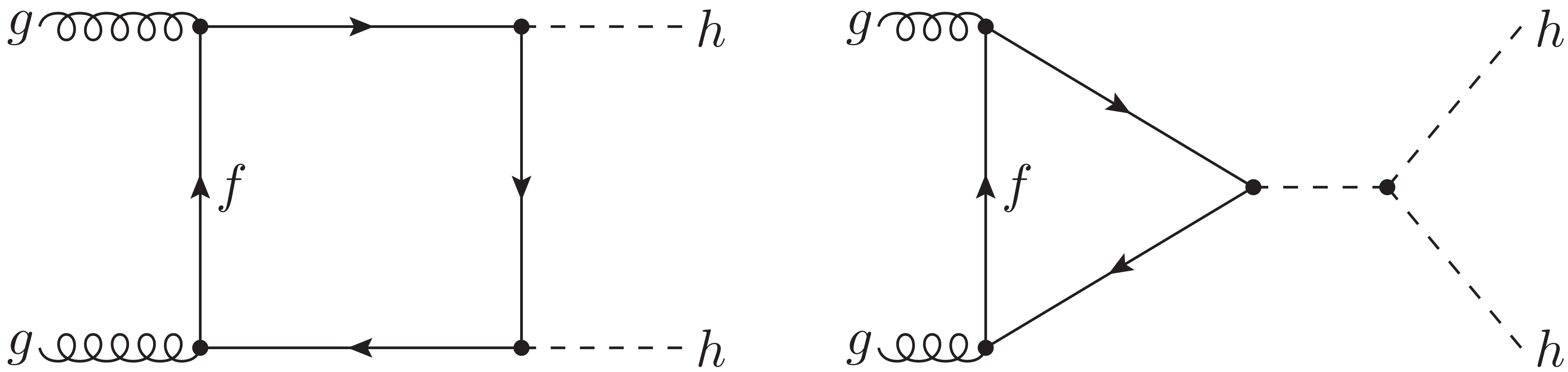
ANALYSIS BREAKDOWN – INCLUDING PILEUP

HL-LHC, Resolved category, PU+SK with $n_{\rm PU}=80$										
	Cross-section [fb]						S/B		$S/\sqrt{B}$	
	$hh4b$	total bkg	$4b$	$2b2j$	$4j$	$t\bar{t}$	tot	$4b$	tot	$4b$
C1a	11	$4.4\cdot10^{8}$	$1.5\cdot10^{5}$	$3.0\cdot10^{7}$	$4.1\cdot10^{8}$	$2.6\cdot10^{5}$	$2.4\cdot10^{-8}$	$7.2\cdot10^{-5}$	0.03	1.5
C1b	11	$4.4\cdot10^{8}$	$1.5\cdot10^{5}$	$3.0\cdot10^{7}$	$4.1\cdot10^{8}$	$2.6\cdot10^{5}$	$2.4\cdot10^{-8}$	$7.2\cdot10^{-5}$	0.03	1.5
C1c	3	$1.1\cdot10^{8}$	$4.2\cdot10^{4}$	$7.7\cdot10^{6}$	$9.9\cdot10^{7}$	$1.1\cdot10^{5}$	$2.8\cdot10^{-8}$	$7.4\cdot10^{-5}$	0.02	0.8
C2	0.6	$9.0\cdot10^{3}$	$3.5\cdot10^{3}$	$5.1\cdot10^{3}$	$3.1\cdot10^{2}$	50	$6.5\cdot10^{-5}$	$1.7\cdot10^{-4}$	0.4	0.5

HL-LHC, Intermediate category, PU+SK+Trim with $n_{\rm PU}=80$										
	Cross-section [fb]						S/B		$S/\sqrt{B}$	
	$hh4b$	total bkg	$4b$	$2b2j$	$4j$	$t\bar{t}$	tot	$4b$	tot	$4b$
C1b	2.7	$8.1\cdot10^{7}$	$2.1\cdot10^{4}$	$5.2\cdot10^{6}$	$7.6\cdot10^{7}$	$3.0\cdot10^{4}$	$3.4\cdot10^{-8}$	$1.3\cdot10^{-4}$	0.02	1.0
C1c	2.6	$6.2\cdot10^{7}$	$1.5\cdot10^{4}$	$3.9\cdot10^{6}$	$5.8\cdot10^{7}$	$2.8\cdot10^{4}$	$4.1\cdot10^{-8}$	$1.7\cdot10^{-4}$	0.02	1.1
C1d	0.5	$2.8\cdot10^{6}$	$7.9\cdot10^{2}$	$1.9\cdot10^{5}$	$2.7\cdot10^{6}$	$6.5\cdot10^{3}$	$1.8\cdot10^{-7}$	$6.2\cdot10^{-4}$	0.02	1.0
C2	0.09	$2.6\cdot10^{2}$	47	$1.8\cdot10^{2}$	30	2.2	$3.4\cdot10^{-4}$	$1.8\cdot10^{-3}$	0.3	0.7

HL-LHC, Boosted category, PU+SK+Trim with $n_{\rm PU}=80$										
	Cross-section [fb]						S/B		$S/\sqrt{B}$	
	$hh4b$	total bkg	$4b$	$2b2j$	$4j$	$t\bar{t}$	tot	$4b$	tot	$4b$
C1a	3.5	$4.1\cdot10^{7}$	$1.0\cdot10^{4}$	$2.7\cdot10^{6}$	$3.8\cdot10^{7}$	$2.0\cdot10^{4}$	$8.6\cdot10^{-8}$	$3.4\cdot10^{-4}$	0.03	1.9
C1b	2.5	$3.2\cdot10^{7}$	$6.8\cdot10^{3}$	$1.9\cdot10^{6}$	$3.0\cdot10^{7}$	$1.9\cdot10^{4}$	$7.8\cdot10^{-8}$	$3.6\cdot10^{-4}$	0.02	1.6
C1c	0.8	$2.2\cdot10^{6}$	$5.4\cdot10^{2}$	$1.4\cdot10^{5}$	$2.0\cdot10^{6}$	$4.8\cdot10^{3}$	$3.8\cdot10^{-7}$	$1.6\cdot10^{-3}$	0.03	2.0
C2	0.14	$1.5\cdot10^{2}$	40	86	22	1.8	$9.0\cdot10^{-4}$	$3.5\cdot10^{-3}$	0.6	1.2

DIHIGGS AT THE LHC



Clear difficulty: HH production cross-section at LHC is *tiny*

14TeV NNLO gluon fusion $\sigma_{HH} \simeq 40$ fb *factor of ~10^3 smaller than single H*

Compounded by usual H reconstruction problems

Final State	BF
bbbb	33%
bbWW	13%
bb\tau\tau	3.5%
WWWW	5.3%

Lots of cross-section decaying to ***challenging*** *fully hadronic final state*

Recent ATLAS bound:

$$\sigma(pp \to hh \to b\bar{b}b\bar{b}) < 1.22 \text{ pb}$$

(ATLAS-CONF-2016-017)

(Data is king: 3000 fb^{-1} HL-LHC)