# Prospects for Observing Higgs Pair Production in the $b\bar{b}b\bar{b}$ Final State

**Katharina Behr**

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2012: Observation of a new scalar resonance with mass $\approx$ 126 GeV

$\Rightarrow$ Is it the Higgs boson predicted in the Standard Model (SM)?

- Subsequent measurements (rates, branching ratios, ...) in agreement with SM

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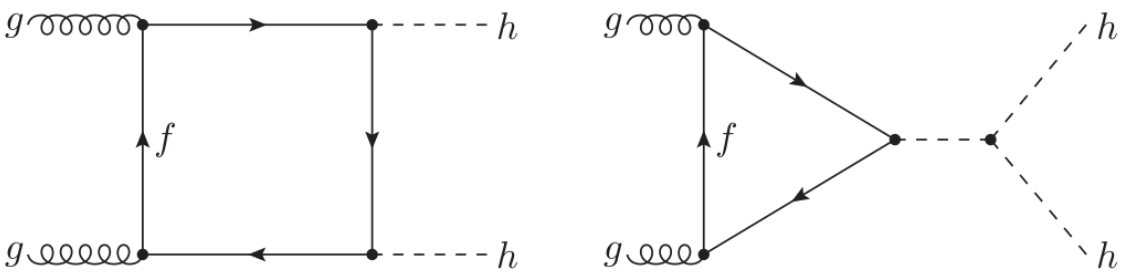
$\longrightarrow$ **Trilinear coupling** ($\lambda$) accessible via Higgs pair production



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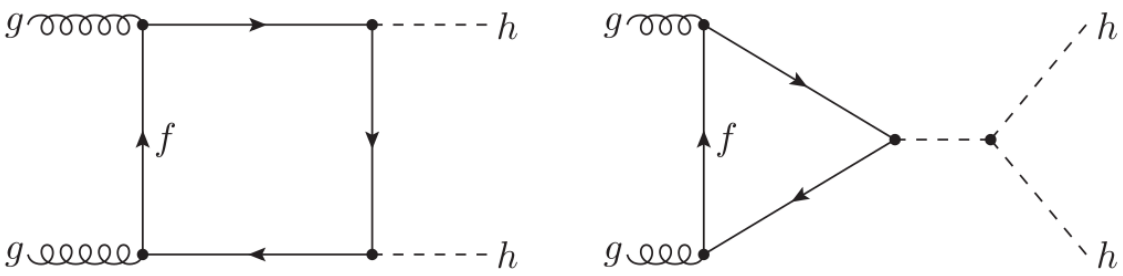


- **Important test of EWSB mechanism**
- **Sensitive to BSM physics**

$\Rightarrow$ **Measurement one of the central physics goals at the LHC!**

# The Challenge

**CAVEAT:** SM cross-section is small: $\sigma_{hh}^{SM,LO} \approx 3.4 \cdot 10^{-2}$ pb

For comparison: $t\bar{t}$ cross-section $\sigma_{t\bar{t}}^{SM} \approx 8.3 \cdot 10^{2}$ pb

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$\Rightarrow$ **More data!**

- LHC Run 2+3: $\mathcal{L} = 300$ fb$^{-1}$
- HL-LHC: $\mathcal{L} = 3000$ fb$^{-1}$

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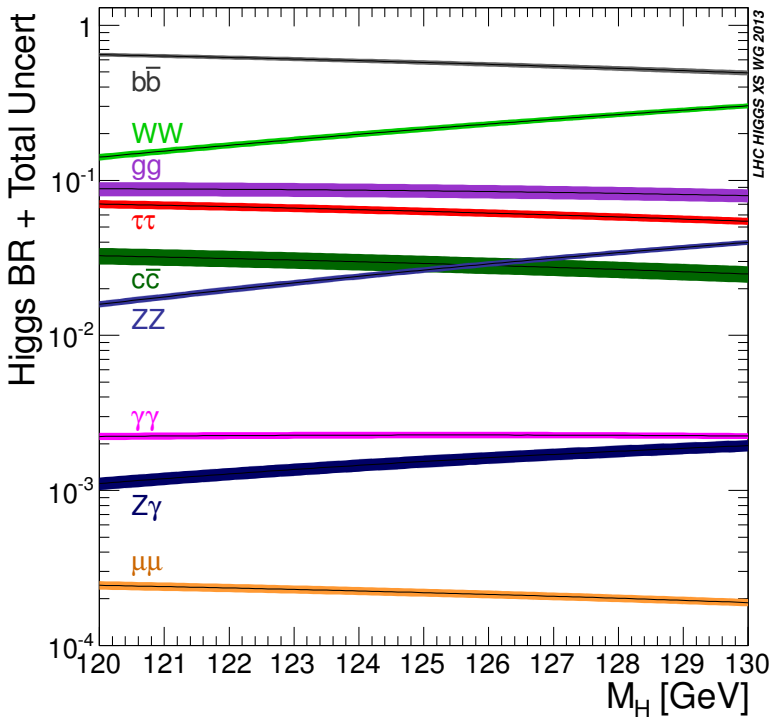
- LHC Run 2+3: $\mathcal{L} = 300$ fb$^{-1}$
- HL-LHC: $\mathcal{L} = 3000$ fb$^{-1}$

$\Rightarrow$ Identify and develop strategies for the most promising final states!

# Why the $b\bar{b}b\bar{b}$ final state?

**PRO:** Final state with **largest branching ratio**: $\mathrm{BR}(h \to b\bar{b}) \simeq 0.57$
$\Rightarrow$ Significantly increases reach in $m_{hh}$




**CON:** Overwhelming QCD multi-jets background

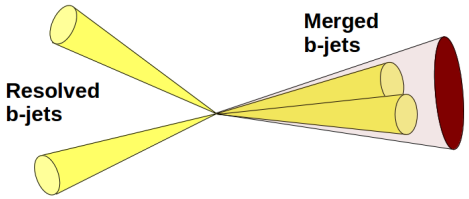
$\Rightarrow$ Previous studies: $S/\sqrt{B} \simeq 2$ @ HL-LHC (no PU, missing relevant backgrounds)

# Our strategy

KB, D. Bortoletto, J. Frost, N. Hartland, C. Issever. J. Rojo (2015) [arxiv:1512.08928] (Submitted to EPJC)

**Key ingredients:**

- Use multivariate analysis techniques on top of (loose) cut-based analysis
- Consider all possible di-Higgs decay topologies



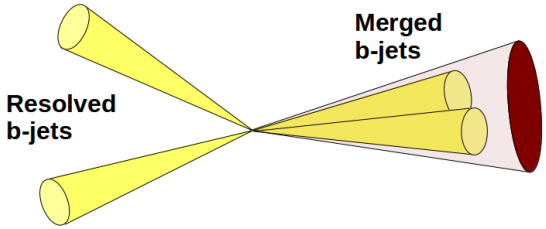

**In addition:**

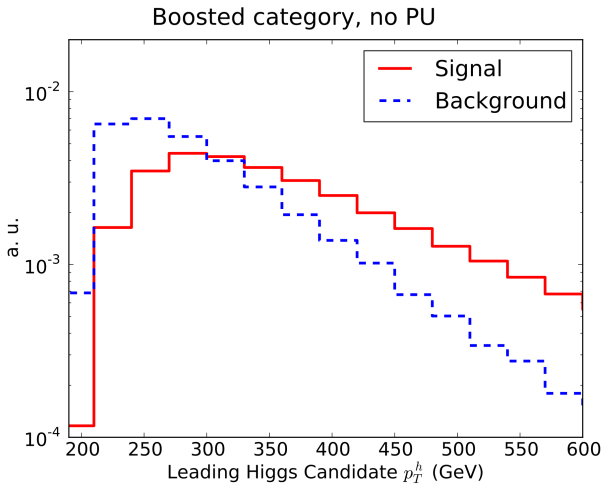
- Include all relevant background components (esp. $2b2j$)
- **Model pile-up effects** by superimposing $n_{\mathrm{PU}} = 80$ Minimum Bias events on each signal/background event

# Higgs Decay Toplogies

Separation between $b$-jets from $h \to b\bar{b}$ decays shrinks like: $\Delta R(b, \bar{b}) \sim \frac{2m^h}{p_T^h}$

$\Rightarrow$ Single large-$R$ jet for $p_T^h \sim 250$ GeV




## Resolved Higgs

- 2 AKT4 jets
- $p_T > 40$ GeV, $|\eta| < 2.5$

## $b$-tagging efficiencies

- $b$-jet: $f_b = 0.8$
- $c$-jet: $f_c = 0.1$
- light jet: $f_l = 0.01$

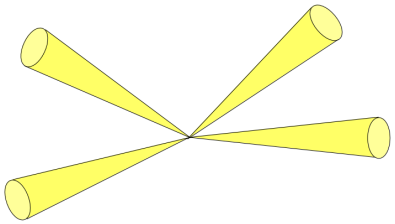
## Merged Higgs

- 1 AKT10 jet
- $p_T > 200$ GeV, $|\eta| < 2.5$
- **Higgs tagging**:
  BDRS mass-drop tagger
  [arxiv:0802:2470]

Large-$R$ jet $b$-tagged if two associated $b$-tagged small-$R$ jets

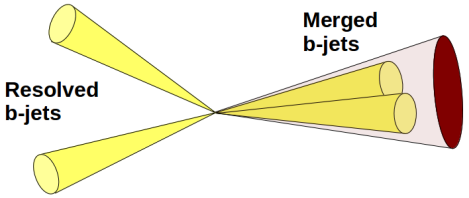
# Analysis Strategy

## Resolved



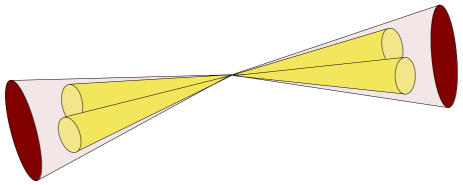
- $\geq 4$ $b$-tagged small-$R$ jets
- Higgs reconstruction from leading 4 jets
- Choice that minimises mass difference between dijet systems

## Intermediate




- $= 1$ large-$R$ jet (Higgs-tagged + $b$-tagged) (leading Higgs)
- $\geq 2$ $b$-tagged small-$R$ jets
- $\Delta R > 1.2$ w.r.t. large-$R$ jet
- Higgs reconstruction from leading 2 small-$R$ jets
- Choice that minimises mass difference of dijet system and large-$R$ jet

## Boosted



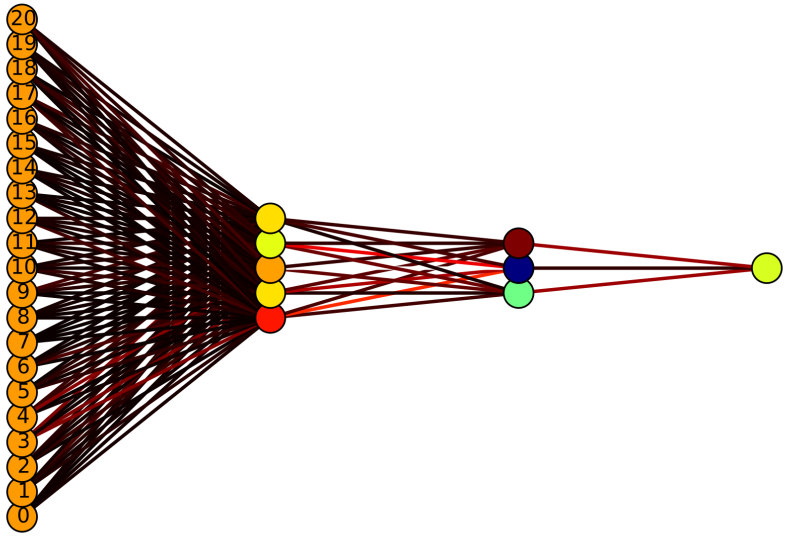
- $\geq 2$ large-$R$ jets (Higgs-tagged + $b$-tagged)
- Leading two jets taken as Higgs candidates

\+ **Loose Higgs mass window cut**: $|m_{h,j} - 125\ \mathrm{GeV}| < 40\ \mathrm{GeV}$ , $j = 1, 2$

\+ **Rank categories** by $S/\sqrt{B}$ to make them **exclusive**: boosted $>$ intermediate $>$ resolved

# Multivariate Analysis

Multi-layer feed-forward artifical neural net (ANN) - *perceptron*
Architecture: $N_{\mathrm{var}} \times 5 \times 3 \times 1$




- Trained on signal and background distributions of 21 input variables
- Separately for the 3 categories
- Input: Higgs candidates' transverse momenta, masses, angular separation, ... substructure variables, ...

# Signal and Background Processes

| Process | Generator | $N_{\mathrm{evt}}$ | $\sigma_{\mathrm{LO}}$ (pb) | $K$-factor |
|---|---|---|---|---|
| $pp \to hh \to 4b$ | MadGraph5_aMC@NLO | 1M | $6.2 \cdot 10^{-3}$ | 2.4 (NNLO+NNLL) |
| $pp \to b\bar{b}b\bar{b}$ | SHERPA | 3M | $1.1 \cdot 10^{3}$ | 1.6 (NLO) |
| $pp \to b\bar{b}jj$ | SHERPA | 3M | $2.7 \cdot 10^{5}$ | 1.3 (NLO) |
| $pp \to jjjj$ | SHERPA | 3M | $9.7 \cdot 10^{6}$ | 0.6 (NLO) |
| $pp \to t\bar{t} \to b\bar{b}jjjj$ | SHERPA | 3M | $2.5 \cdot 10^{3}$ | 1.4 (NNLO+NNLL) |

$\Rightarrow$ $b$-tagging crucial to reduce QCD multi-jet background(s)

# Role of Light- (and Charm-)Jet Misidentification

- Previous studies neglected reducible backgrounds such as $2b2j$
- Naive assessment: $2b2j$ suppressed w.r.t. $4b$

$$\frac{\mathrm{EFF}_{\mathrm{b-tag}}[2b2j]}{\mathrm{EFF}_{\mathrm{b-tag}}[4b]} \simeq \frac{f_b^2 f_l^2}{f_b^4} = \left(\frac{f_l}{f_b}\right)^2 \simeq 1.5 \cdot 10^{-4} \,. \tag{1}$$

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**This is wrong!**

- $b$-quark radiation in parton shower
  $\Rightarrow$ non-negligible fraction of $2b2j$ events with $\geq 2$ $b$-jets
- Additional light jets from parton shower
  $\Rightarrow$ Not all of the 4 leading jets in $4b$ events are $b$-jets

$$\frac{\mathrm{EFF}_{\mathrm{b-tag}}[2b2j]}{\mathrm{EFF}_{\mathrm{b-tag}}[4b]} \simeq 5 \cdot 10^{-3} \,. \tag{2}$$

# Results

- Signal significance **post-MVA**
- Luminosity: $\mathcal{L} = 3$ ab$^{-1}$
- Without PU $\leftrightarrow$ with PU
- Only $4b$ $\leftrightarrow$ all relevant backgrounds

| Category | | $S/\sqrt{B_{\mathrm{tot}}}$ | $S/\sqrt{B_{\mathrm{4b}}}$ |
|---|---|---|---|
| Boosted | no PU | 2.7 | 3.2 |
| | PU80+SK+Trim | **1.5** | 2.7 |
| Intermediate | no PU | 2.3 | 3.3 |
| | PU80+SK+Trim | **1.9** | 2.9 |
| Resolved | no PU | 1.9 | 2.7 |
| | PU80+SK | **2.0** | 2.6 |
| **Combined** | no PU | 4.0 | 5.3 |
| | PU80+SK+Trim | **3.1** | 4.7 |

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# Conclusion

Study focusing on challenging $b\bar{b}b\bar{b}$ final state:

- Combination of (loose) cut-based analysis and multivariate techniques
- All relevant backgrounds taken into account
- First study to combine three decay topologies for optimal sensitivity
- First study to consider PU

**Main Result:**

$$\left(\frac{S}{\sqrt{B}}\right)_{\text{tot}} \simeq \mathbf{3.1}\ (1.0)\,, \quad \mathcal{L} = 3000\ (300)\,\text{fb}^{-1}\,, \tag{3}$$

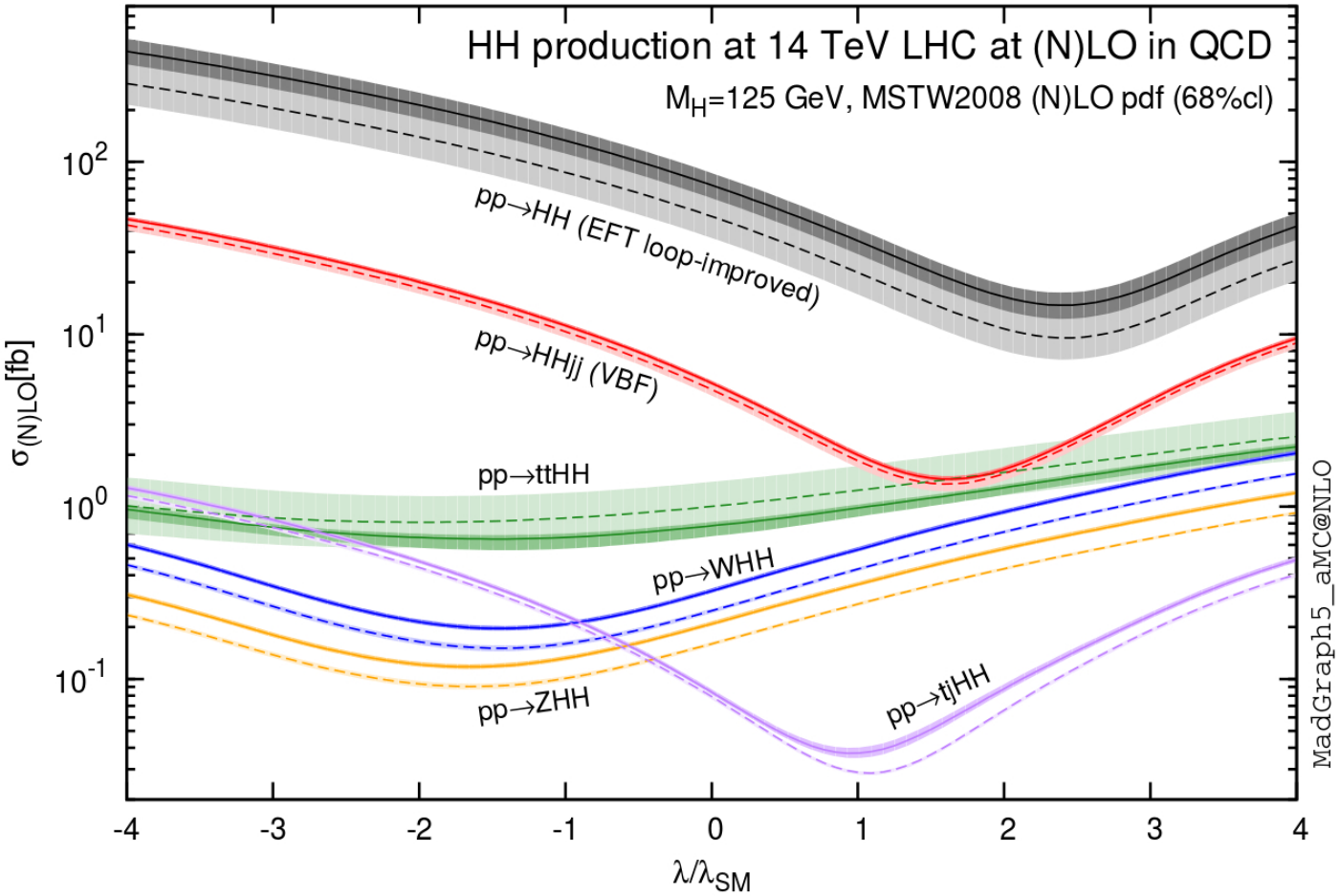
$\Rightarrow$ $b\bar{b}b\bar{b}$ **final state alone sufficient to claim evidence for Higgs pair production**

**Keys to further improvements:**

- Reduction of light- and charm-mistag rates
- Optimisation of PU mitigation techniques
- Improvement of jet mass resolution

# Outlook

Determine precision with which $\lambda$ can be measured in the $b\bar{b}b\bar{b}$ final state




$$\lambda_{\mathrm{SM}} = \frac{3m_h^2}{v} \tag{4}$$

Thank you!

# BACKUP

# Results

- Signal significance pre- and post- MVA
- Luminosity: $\mathcal{L} = 3$ ab$^{-1}$
- Including all relevant backgrounds + PU effects

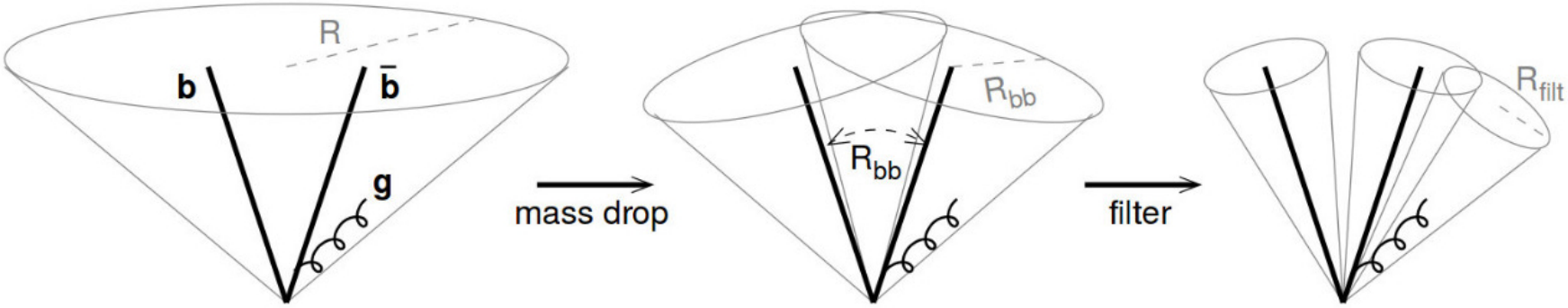
| HL-LHC, PU80+SK+Trim | | | | |
|---|---|---|---|---|
| Category | | $N_{\rm ev}$ signal | $N_{\rm ev}$ back | $S/\sqrt{B}$ |
| **Boosted** | $y_{\rm cut} = 0$ | 410 | $4.5 \cdot 10^5$ | 0.6 |
| | $y_{\rm cut} = 0.8$ | 290 | $3.7 \cdot 10^4$ | 1.5 |
| **Intermediate** | $y_{\rm cut} = 0$ | 260 | $7.7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

# Results: Signal Significance (no PU)

| HL-LHC, no PU | | | | |
|---|---|---|---|---|
| Category | | $N_{\mathrm{ev}}$ signal | $N_{\mathrm{ev}}$ back | $S/\sqrt{B}$ |
| **Boosted** | $y_{\mathrm{cut}} = 0$ | 440 | $7.6 \cdot 10^5$ | 0.5 |
| | $y_{\mathrm{cut}} = 0.90$ | 290 | $1.2 \cdot 10^4$ | 2.7 |
| **Intermediate** | $y_{\mathrm{cut}} = 0$ | 280 | $5.3 \cdot 10^5$ | 0.4 |
| | $y_{\mathrm{cut}} = 0.85$ | 130 | $3.1 \cdot 10^3$ | 2.3 |
| **Resolved** | $y_{\mathrm{cut}} = 0$ | 1500 | $1.5 \cdot 10^7$ | 0.4 |
| | $y_{\mathrm{cut}} = 0.60$ | 630 | $1.1 \cdot 10^5$ | 1.9 |

# BDRS Mass-drop Tagger

arXiv:0802.2470



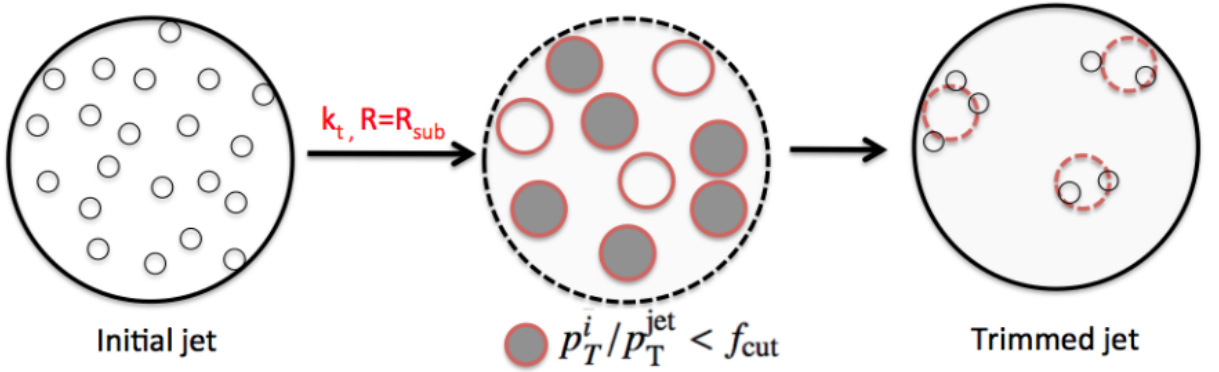
# Pile-up simulation and mitigation

- Up to 150 interactions per bunch-crossing @ HL-LHC
- Impact on signal significance:
  - Additional (hard) jets in reconstruction
  - Affects mass and substructure of large-$R$ jets
- **Not taken into account in previous studies**

**Strategy:**

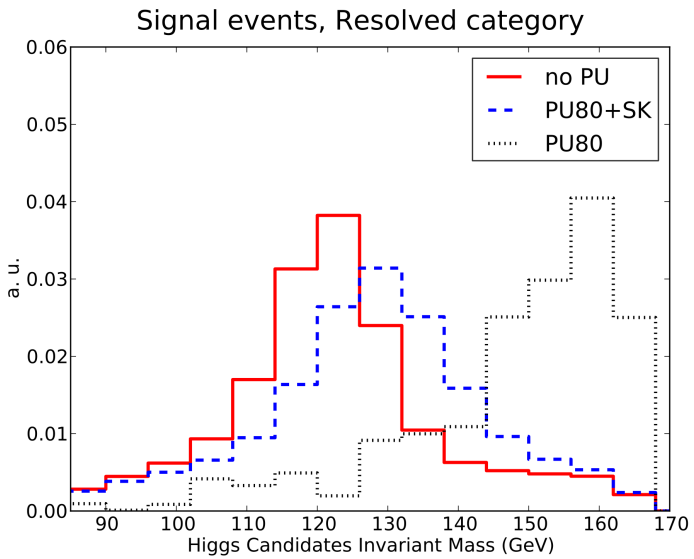
- Superimpose $n_{\mathrm{PU}} = 80$ Minimum Bias events on each signal/background event
- Pile-up mitigation
  - Event level: Remove soft particles using SoftKiller [arXiv:1407.0408]
  - Jet level: Apply trimming [arXiv:0912.1342] (large-$R$ jets only)

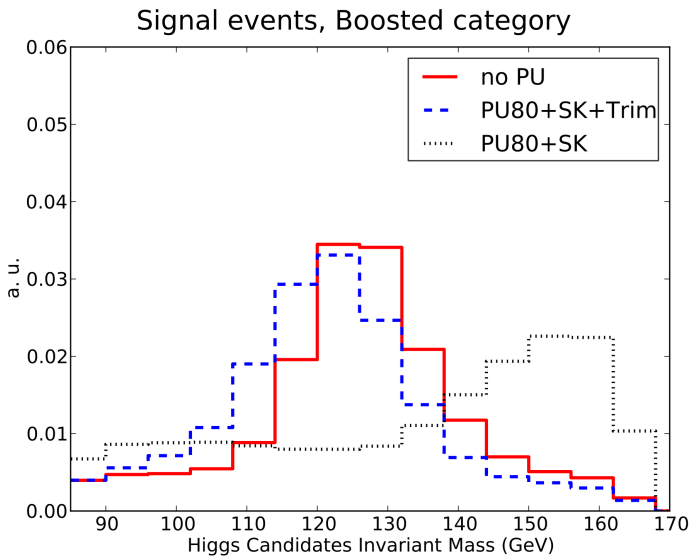
JHEP09 (2013) 076



# Pile-up Mitigation - Higgs Mass

Higgs mass distributions



# Jet Grooming (1)

- Large-R jets more susceptible to contaminations from Underlying Event and pile-up
- Soft radiation dilutes jet substructure
- **Grooming to remove soft, wide-angle contaminations!**
- Various algorithms available:
  - Trimming: Krohn, Thaler, Wang [arXiv:0912.1342]
    Widely used in ATLAS
  - Pruning: Ellis, Vermillion, Walsh [arXiv:0903.5081]
    Widely used in CMS
  - Filtering: Butterworth, Davison, Rubin, Salam [arXiv:0802.2470]

    HEPTopTagger uses filtering-like approach

**Example**: Trimming (ATLAS: $R_{sub} = 0.3, f_{cut} = 0.05$)

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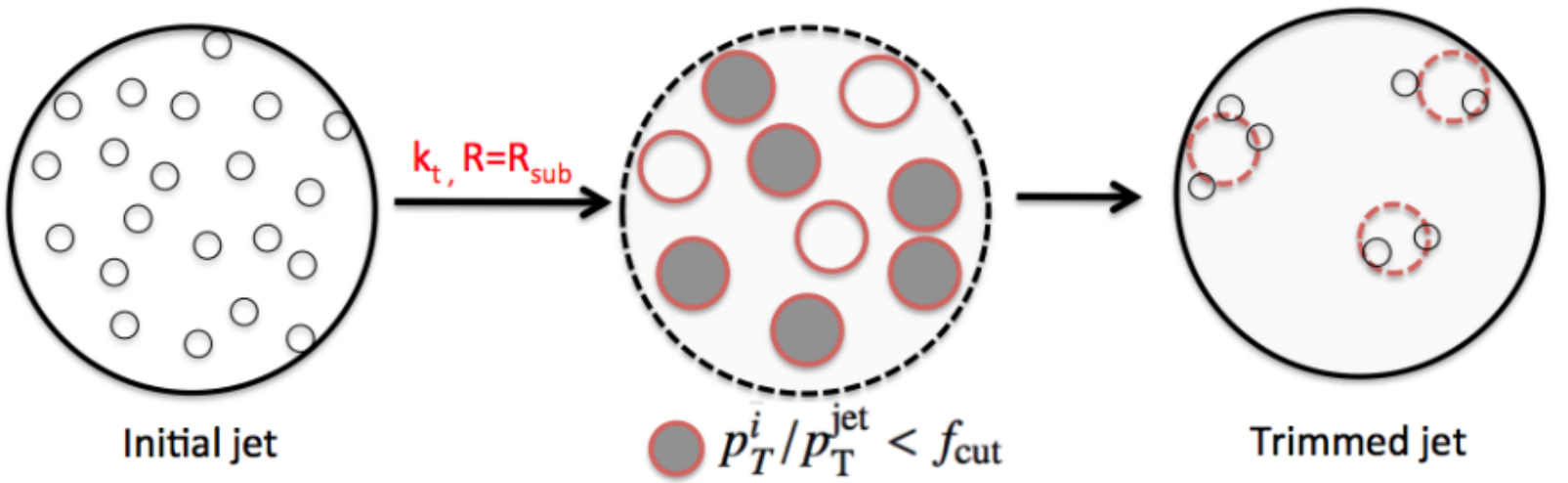
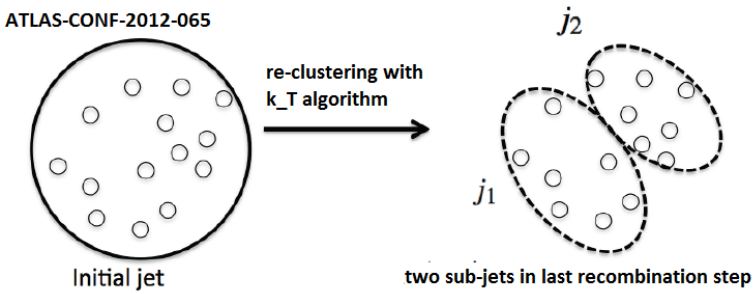


# Jet Grooming (2)

**Example**: **Jet mass** and **first $k_T$-splitting scale $\sqrt{d_{12}}$** in $Z' \to t\bar{t}$ events

- $\sqrt{d_{12}} = \min(p_{T1}, p_{T2})\Delta R_{12}$
- Calculated from the two proto-jets of last $k_T$ recombination step
- Expect $\sqrt{d_{12}} \approx m_t/2$ for $t \to Wb$

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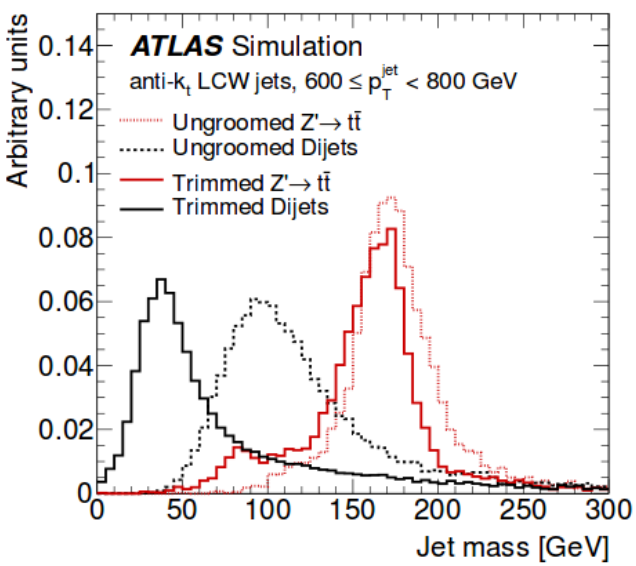


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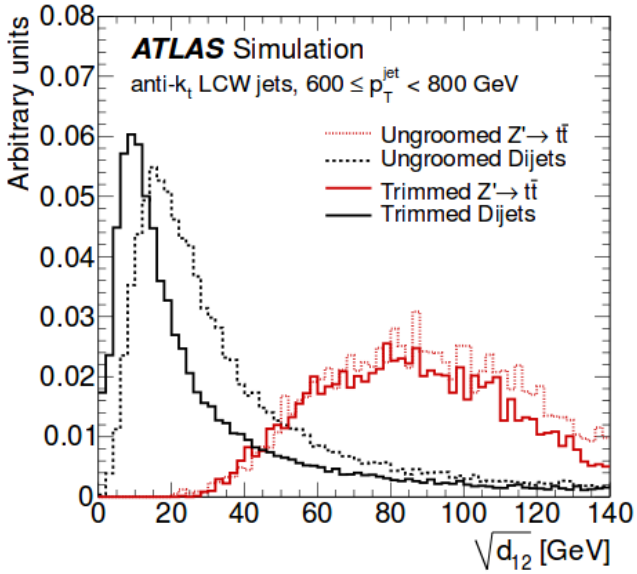


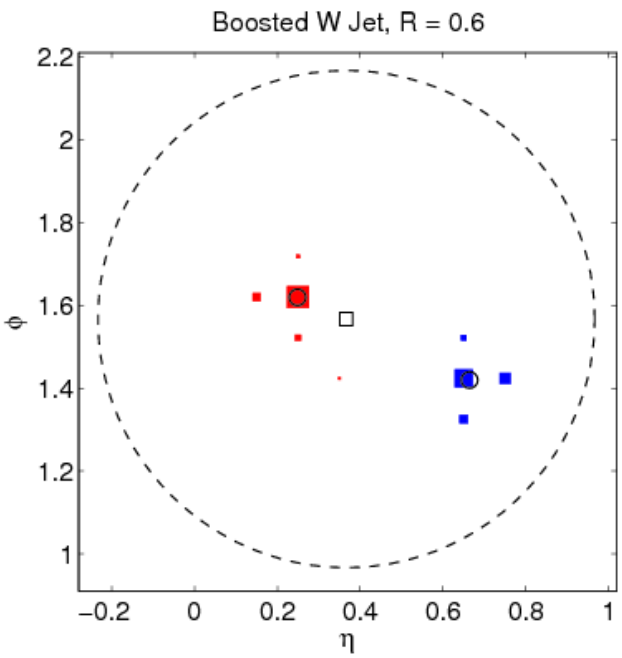

**Significantly improves mass resolution and hence discrimination against QCD jets!**

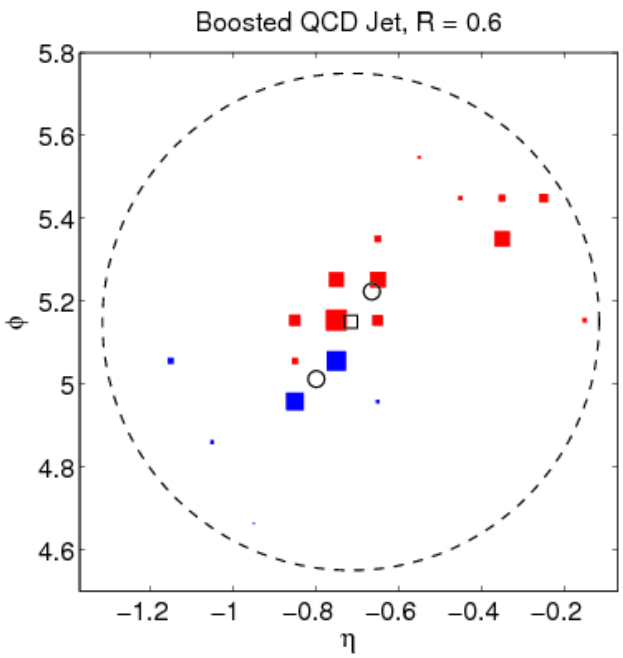
# Nsubjettiness

Thaler, Van Tilburg [JHEP 1103 (2011) 015]

- Re-cluster large jet of radius $R_0$ with $k_T$ algorithm until N subjets
- $\tau_N = 1/d_0 \cdot \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, ..., \Delta R_{N,k})$
- Where $d_0 = \sum_k p_{T,k} \cdot R_0$ and $k$ runs over all constituents

**Measure how compatible jet substructure is with "N subjets" hypothesis**




Ratios $\tau_{21} = \tau_2/\tau_1$, $\tau_{32} = \tau_3/\tau_2$ powerful discriminants against multijet bkgr

# MVA Input Variables (all categories)

- The transverse momenta of the leading and subleading Higgs ($p_{T,h_1}$, $p_{T,h_2}$).
- The transverse momentum of the reconstructed Higgs pair ($p_{T,hh}$).
- The invariant masses of the leading and sub-leading Higgs candidates ($m_{h,1}$, $m_{h,2}$).
- The invariant mass of the reconstructed Higgs pair ($m_{hh}$).
- The separation in the $\phi$–$\eta$ plane between the two Higgs candidates ($\Delta R_{hh}$)
- The separation in $\eta$ between the two Higgs candidates ($\Delta\eta_{hh}$).
- The separation in $\phi$ between the two Higgs candidates ($\Delta\phi_{hh}$).

In addition:

- **Boosted**: transverse momenta of the leading ($p_{T,h_{1,1}}$, $p_{T,h_{1,2}}$) and sub-leading ($p_{T,h_{2,1}}$, $p_{T,h_{2,2}}$) Higgs candidate AKT03 subjets
- **Intermediate:** transverse momenta of the subjets from the large-$R$ jet ($p_{T,h_{1,1}}$, $p_{T,h_{1,2}}$) and the transverse momenta $p_{T,i}$ of the two leading $b$-tagged small-$R$ jets
- **Resolved:** transverse momenta $p_{T,i}$ of the four leading $b$-tagged small-$R$ jets

# MVA Input Variables (boosted, intermediate)

- $k_t$ splitting scale ($\sqrt{d_{12}}$)
- ratio of 2-to-1 subjettiness ($\tau_{12}$)
- ratios of energy correlation functions $C_2^{(\beta)}$ and $D_2^{(\beta)}$.