Higgs and Jets at the LHC

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7 + 8 TeV data:

Recently observed clear excesses in 3 independent channels:

- 2 Photons
- 4 Leptons (electrons/muons)
- 2 Leptons (electrons/muons) + MET
Combined results for each experiment

- **ATLAS** has a local significance of 5.9 sigma
- **CMS** has a local significance of 5.8 sigma

→ **Discovery**

- Particle consistent with Higgs boson, predicted 50 years ago
- Huge international and intergenerational success!
Higgs mechanism a brief review

Purpose: explain existence of massive particles consistent with gauge invariance

Symmetry of the Lagrangian

\[ SU(2)_L \times U(1)_Y \]

Higgs doublet

\[ \Phi = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \]

\[ V(\Phi) = \lambda \left[ \Phi^\dagger \Phi - \frac{v^2}{2} \right]^2 \]

Symmetry of the vacuum

\[ U(1)_{em} \]

Vacuum expectation value

\[ \langle \Phi \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \]

\[ v = 246 \text{ GeV} \]

couplings to

- gauge bosons
  \[ g_{VVH} = \frac{2m_V^2}{v} \]
  \[ \lambda_{HHH} = -3 \frac{m_H^2}{v} \]

- fermions
  \[ g_{f\bar{f}H} = \frac{m_f}{v} \]
  \[ \lambda_{HHHH} = -3 \frac{m_H^2}{v^2} \]

Higgs mass:

\[ m_H = \sqrt{2\lambda v} \]

Higgs selfcouplings
What's next?

- Is what we observe "THE HIGGS BOSON"?
- Is minimal SSB mechanism realized in nature?
After discovery the Higgs couplings have to be measured:

Present status:

- CMS and ATLAS did fit for couplings already
- For the overall CS CMS has
  \[ \frac{\sigma}{\sigma_{SM}} = 0.87 \pm 0.23 \]
- Green band indicates ±1\(\sigma\) uncertainty including stat. and sys. uncertainties
- Decay to photons a bit high to taus a bit low, but so far all in all good agreement with SM
- Channels are mutually related!
Production cross section at hadron colliders

\( \sigma(pp \rightarrow H + X) \quad [\text{pb}] \)

\( \sqrt{s} = 14 \text{ TeV} \)

MRST/NLO

\( m_t = 178 \text{ GeV} \)
Predicted decay channels

**Figure 2.25:** The SM Higgs boson decay branching ratios as a function of $M_H$.

**Figure 2.26:** The SM Higgs boson total decay width as a function of $M_H$.

$m_H=125$ GeV is smooth spot. Important couplings accessible.
• If the Higgs is SM-like it has to show up in several channels

Need cross correlation between many channels:

<table>
<thead>
<tr>
<th>production</th>
<th>decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow H$</td>
<td>$ZZ$</td>
</tr>
<tr>
<td>$qqH$</td>
<td>$ZZ$</td>
</tr>
<tr>
<td>$gg \rightarrow H$</td>
<td>$WW$</td>
</tr>
<tr>
<td>$qqH$</td>
<td>$WW$</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>$WW(3\ell)$</td>
</tr>
<tr>
<td>$\bar{t}tH$</td>
<td>$WW(2\ell)$</td>
</tr>
<tr>
<td>inclusive</td>
<td>$\gamma\gamma$</td>
</tr>
<tr>
<td>$qqH$</td>
<td>$\gamma\gamma$</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>$\gamma\gamma$</td>
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<tr>
<td>$WH$</td>
<td>$\gamma\gamma$</td>
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<tr>
<td>$ZH$</td>
<td>$\gamma\gamma$</td>
</tr>
<tr>
<td>$qqH$</td>
<td>$\tau\tau(2\ell)$</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>$\tau\tau(1\ell)$</td>
</tr>
<tr>
<td>$WH/ZH$</td>
<td>$bb$ (subjet)</td>
</tr>
</tbody>
</table>

\[ \text{Production} \quad \sigma \cdot BR \propto g_p^2 \frac{g_d^2}{\Gamma_H} \]

- Decay into spec. channel
- Sum of all possible decays

assumed: \( \Gamma_H = \sum_{SM} \Gamma_i \) \quad \( \Gamma_i \sim g_d^2 \)

Uncertainty of all coupling measurements driven by total width, i.e. channel with largest BR: H\(\rightarrow bb\)

Hbb difficult but can use new techniques, i.e. Jet substructure!
Higgs at the LHC

production

decay

\( gg \rightarrow H ZZ \)

\( qqH ZZ \)

\( gg \rightarrow H WW \)

\( qqH WW \)

\( t \bar{t}H \)

\( t \bar{t}H \) (3ℓ)

\( t \bar{t}H \) (2ℓ)

inclusive

\( \gamma\gamma \)

\( \gamma\gamma \)

\( \gamma\gamma \)

\( \gamma\gamma \)

\( \gamma\gamma \)

\( \tau\tau \) (2ℓ)

\( \tau\tau \) (1ℓ)

\( t \bar{t}H \)

\( b \bar{b} \)

\( b \bar{b} \) (subjet)

Total width

degeneracy

\( \sigma \cdot BR \propto g^2_g \cdot p_g^2 \cdot d \Gamma_H \)

Here:

\( \Gamma_H = \sum_{SM} \Gamma_i \) [GeV]

\( m_H \)

110 120 130 140 150 160 170 180 190

• Huge improvement from boosted Higgs analysis

• also for non-\( b \) decay modes due to better knowledge of total width

To reduce uncertainty for all coupling, need to measure \( b \) and \( t \) coupling
Higgs at the LHC

production

decay

\[ g g \rightarrow H ZZ \]

\[ q q H \rightarrow W W \]

\[ t \bar{t} H \rightarrow \ell \ell \]

\[ \tau \tau H \]

\[ \gamma \gamma H \]

Total width

degeneracy

\[ \sigma \cdot \text{BR} \propto g^2 \]

Here:

\[ \Gamma_H = \sum_{S M} \Gamma_i \ [\text{GeV}] \]

\[ m_{H, 110, 120, 130, 140, 150, 160, 170, 180, 190} \]

• Huge improvement from boosted Higgs analysis

• also for non-b decay modes due to better knowledge of total width

To reduce uncertainty for all coupling, need to measure b and t coupling
New techniques face difficult environment:

$O(1000)$ particles

Tedious for theorists and experimentalists
New techniques face difficult environment:

Tedious for theorists and experimentalists
Using jet substructure at LHC requires understanding of all radiation in event

At the LHC many sources of radiation:

- Pileup $\rightarrow$ Can add up to 100 GeV of soft radiation per unit rapidity
  
  [Cacciari, Salam, Sapeta JHEP 1004]

- Underlying Event $\rightarrow$ $\langle \delta m_j^2 \rangle \simeq \Lambda_{\text{UE}} p_{T,j} \left( \frac{R_4^4}{4} + \frac{R_8^8}{4608} + O(R^{12}) \right)$ with $\Lambda_{\text{UE}} \sim \mathcal{O}(10)$ GeV
  
  [Dasgupta, Magnea, Salam JHEP 0802]

- Initial state radiation (ISR)

- Hard radiation from many resonances in event

$\rightarrow$ Need methods to separate final state radiation (FSR) from rest of event
Mass not a good discriminator → look into jet substructure

order of recombination defined by some metric, e.g. kT distance

\[ d_{j_1,j_2} = \frac{\Delta R_{j_1j_2}^2}{D^2} \min(p_{T,j_1}^2, p_{T,j_2}^2) \]
Intrinsic scales and energy sharing of jet substructure different

→ Can be used to discriminate QCD jet from resonance jet

Higgs-boson jet

QCD jet
I. Measuring the Higgs-bottom coupling using jet substructure

Collect FSR

Reject ISR and UE

e.g. $pp \rightarrow ZH$

$H \rightarrow b, b\bar{b}$

$Z \rightarrow l^+l^-$

$R=1.2$

[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]
I. Measuring the Higgs-bottom coupling using jet substructure

Collect FSR
Reject ISR and UE

e.g. \( pp \rightarrow ZH \)

\[ \begin{align*}
\text{bbar} & \quad \text{b} \\
H & \rightarrow b, \overline{b} \text{bar} \\
Z & \rightarrow l^+ l^-
\end{align*} \]


[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]
mass drop:

1) check for mass drop
   \[ m_{j1} < 0.66 \, m_j \]

2) check “asymmetry”
   \[ y = \frac{\min(p_{t,j1}^2, p_{t,j2}^2)}{m_j^2} \Delta R_{j1,j2}^2 > y_{\text{cut}} \]
**HV – Higgs discovery channel**

[B Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

Apply filtering and take 3 hardest subjets

Use b-tagging on 2 hardest subjets

\[ \text{Apply filtering and take 3 hardest subjets} \]

\[ \text{Use b-tagging on 2 hardest subjets} \]

\[ H \rightarrow b, b\bar{b} \]

\[ Z \rightarrow l^+ l^- \]
The leading order (LO) estimates of the cross-section were checked by comparing to next-to-leading order and is a good approximation in the signal region of the processes. For this analysis, signal processes were generated, as well as WIG 6.510 with CTQ6L PDFs. The main other backgrounds are from dijets and the underlying event model was chosen in line with the event selection. The signal reconstruction was also done with HERWIG, C/A MD-F with BDRS. In both cases, estimates ought not to be too strongly affected by higher logarithms.

Let us now turn to the details of the event selection. Increasing the minimal transverse momentum \( p_T \) at the generation level, has a K-factor of about 2 (found for various values of \( \hat{\chi} \) and \( \bar{\chi} \)). The selection of the vector boson, to recover signal may also be possible, by using similar techniques to reconstruct the leptonic vector boson, and no jet mass reconstruction to all jets, the mass resolution in [30].

The missing transverse momentum \( \Delta R \) indicates an optimum value 0.5. In both cases, \( \Delta R \) indicates an optimum value 0.5. For channel (c), where the jet have a high mass, the Higgs is seen with a significance for channel (c), where the jet have a high mass, the Higgs is seen with a significance 2.1 in 112-128 GeV. The vector bosons selections were cross-checked with PYTHIA with “ATLAS tune”.

Confirms in ATLAS full detector simulation.
Jet substructure methods can still be improved a lot!

Our approach:

Shower deconstruction

- Maximal information approach to discriminate signal from backgrounds
  \[\rightarrow\] UE, ISR, FSR, hard process

- We want one discriminating analytic function

- Have to respect experimental limitations

[Soper, MS PRD 84 (2011)]

Playground: Boosted HZ final state
Fat jet: $R=1.2$, anti-$kT$

microjets $R=0.15$, $kT$

Build all possible shower histories
signal vs background hypothesis based on:
- Emission probabilities
- Color connection
- Kinematic requirements
- $b$-tag information
Fat jet: $R=1.2$, anti-$kT$

Build all possible shower histories

signal vs background hypothesis based on:

- Emission probabilities
- Color connection
- Kinematic requirements
- $b$-tag information
Higgs has to decay:

\[ H e^{-S} = 16\pi^2 \frac{\Theta(|m_{b\bar{b}} - m_H| < \Delta m_H)}{4m_H \Delta m_H} \]

\[ \frac{1}{4(2\pi)^3} \int dm_{b\bar{b}}^2 \int dz \int d\varphi \ H e^{-S} = 1 \]

Mass window

\[ \Delta m_H = 10 \text{ GeV} \]
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Signal hypothesis

\[ \int d\mathcal{P} = \int d\mu_j^2 \int d\Delta \phi \int d\Delta y \sum_s J H e^{-S} \]

\[
S \approx \int d\mu_j^2 \Theta(\mu_j^2 < \tilde{\mu}_j^2) \int d\Delta \bar{y} \int d\Delta \tilde{\phi} \sum_{\bar{s}} J(\bar{p}_A, \bar{p}_B) H(\bar{p}_A, \bar{p}_B) \Theta(\{\bar{p}_A, \bar{p}_B\} \in \text{fat jet})
\]

\[
H_{qqg} = H_{\bar{q}\bar{g}q} = 8\pi C_F \frac{\alpha_s(\mu_j^2)}{\mu_j^2} \frac{k_J}{k_g} \left[ 1 + \left( \frac{k_q}{k_J} \right)^2 \right] \frac{\theta_{gk}^2}{\theta_{qg}^2 + \theta_{gk}^2} \Theta \left( 2 \frac{\mu_J^2}{k_J} < \frac{\mu_K^2}{k_K} \right)
\]
Background hypothesis

\[ H_{IS} \quad H_H \]

**b**-quarks radiate gluons

\[
\int d\mathcal{P} = \int d\mu_j^2 \int d\Delta \phi \int d\Delta y \sum_s J \, H e^{-S}
\]

\[
S \approx \int d\mu_j^2 \Theta(\mu_j^2 < \bar{\mu}_j^2) \int d\Delta \bar{y} \int d\Delta \bar{\phi} \sum_{\bar{s}} J(\bar{p}_A, \bar{p}_B) \, H(\bar{p}_A, \bar{p}_B) \, \Theta(\{\bar{p}_A, \bar{p}_B\} \in \text{fat jet})
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\]
We use $k$ of parton $o$ formed from parton $A$ and parton $k_3 = B$, and we suppose that the daughter partons are labelled $k_s$ for $a$ $k$ specifies which color connected partner to choose.

FIG. 14: Sudakov factor between final state emission of a gluon from a signal.

Wrapping up all factors gives weight for shower history

$$
\chi = \frac{\sum_{ISR/Hard} \left( \sum_i ISR_i \times \sum_j Signal_j \right)}{\sum_{ISR/Hard} \left( \sum_i ISR_i \times \sum_j Backg_j \right)}
$$

Here $\text{Signal}_1 = H_H H_{\text{split}} e^{-S_{\text{split}}} H_{bbg} e^{-S_b} e^{-S_b'} e^{-S_g} H'_{bbg} e^{-S_b} e^{-S_b'} e^{-S_g'}$

Seminar RHUL 26 Michael Spannowsky 07.11.2012
Results of shower deconstruction (SD)

\[ \chi(p, t)_N = \frac{P(p, t)_N | S)}{P(p, t)_N | B)} \]

![Graph showing the results of shower deconstruction](image)

imperfect b-tagging (60%, 2%) no b-tag required
**First studies of method using data:** (see ATLAS 1203.4606)

- Jet mass in good agreement with MC
- $\gamma$-splitter observable in good agreement with MC
- Massdrop + Filtering as predicted by MC
- Pileup under control so far:

\[
\text{ATLAS} \int L = 35 \text{ pb}^{-1}
\]

\[
\text{anti-}k_t \text{ jets, } p_T > 300 \text{ GeV, } |y| < 2
\]

\[
R=1.0: \frac{d \langle m \rangle}{d N_{\text{PV}}} = 3.0 \pm 0.1
\]

\[
R=0.6: \frac{d \langle m \rangle}{d N_{\text{PV}}} = 0.7 \pm 0.1
\]

\[
R=0.4: \frac{d \langle m \rangle}{d N_{\text{PV}}} = 0.2 \pm 0.1
\]

\[
\text{ATLAS} \int L = 35 \text{ pb}^{-1}
\]

\[
\text{Before Splitting/Filtering}
\]

\[
\text{After Splitting/Filtering}
\]

\[
\text{After Splitting Only}
\]

Cambridge-Aachen $R=1.2$ jets

Split/Filtered with $R_{\text{tag}} > 0.3$

$p_T > 300 \text{ GeV, } |y| < 2$

\[
\frac{d\langle m \rangle}{dN_{\text{PV}}} = 2.9 \pm 0.3 \text{ GeV}
\]

\[
\frac{d\langle m \rangle}{dN_{\text{PV}}} = 0.1 \pm 0.2 \text{ GeV}
\]

\[
\frac{d\langle m \rangle}{dN_{\text{PV}}} = 4.2 \pm 0.1 \text{ GeV}
\]

**All measurements indicate large potential for jet substructure techniques and good agreement with MC**
II. Measuring the Higgs–top coupling using boosted techniques

Motivation:
- sizable cross-section
- Higgs discovery contribution in low mass range
- access to t- and b-Yukawa couplings

High expectations:

Cammin and Schumacher (ATLAS)

\[
S/B \approx 1/9
\]

\[
S/\sqrt{B} \approx 2.2
\]

Expected Performance of the ATLAS Experiment,
CERN-OPEN-2008-020

ATLAS

\[ L = 10 \text{ fb}^{-1} \]

[ATLAS TDR 1999]
$tth$ (Signal)  
Beenakker et al.,
PRL 87 2001;  
Reina et al.,
PRD 65 2002  
\[ \rightarrow K=1.57 \]

$ttbb$  
Bredenstein et al.,
PRL 103 2009;  
Belivacqua et al.,
JHEP 0909 2009  
\[ \rightarrow K=2.3 \]

$tt+jets$  
Dittmaier et al.,
PRL 98 2007  
Bevilacqua et al.,
PRL 104 2010  
\[ \rightarrow K=1.0 \]

$ttz$  
Lazopoulos et al.,
PLB 666 2008  
\[ \rightarrow k=1.53 \]

$w+jets$  
negligible after b-tags and taggers
Signal and backgrounds

An additional background is -jet production with a QCD jet, to fake a Higgs candidate. This topology is the most dangerous and can be essentially removed by the two

Asking for two very hard jets, mimicking the boosted production we do not apply a higher-order correction because the background rejection cuts drives it into kinematical reliability of bottom tags in QCD background rejection we also simulate the

Finally, the bottom from the hadronic top can also leak into the Higgs jet and combine with a QCD jet, to fake a Higgs candidate. This topology is the most dangerous and can be essentially removed by the two

The maximum Higgs jet rapidity is the most dangerous and can be essentially removed by the two

We have verified that we obtain consistent results for signal and background using Alpgen and Herwig 6.5. To test the generator, we use MadEvent and CMS triggers. The main backgrounds are top decay. The latter allows the events to pass the Atlas detector simulation. The outline of our analysis is summarized in Tab. I:

(3) to compute the statistical significance we require that it be possible to tag its

If two jets pass we choose the one whose top candidate is closer to the top mass.
Problems in event reconstruction:
- (b-)jet multiplicity
- reconstruction efficiency

Boost should help but need tagger for this environment

Cambridge/Aachen Jet-Alg

R=1.5
How does the HEPTopTagger work?

I. Find fat jets (C/A, R=1.5, pT>200 GeV)

II. Find hard substructure using mass drop criterion

Undo clustering, \( m_{\text{daughter}_1} < 0.8 \, m_{\text{mother}} \) to keep both daughters
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III. Apply jet grooming to get top decay candidates

IV. Choose pairing based on kinematic correlation, e.g. top mass, W mass and invariant subjet masses
IV. check mass ratios

Cluster top candidate into 3 subjets $\hat{j}_1, \hat{j}_2, \hat{j}_3$

No fix pairing for W mass reconstruction

Only invariants for reconstruction
IV. check mass ratios

Cluster top candidate into 3 subjets $j_1, j_2, j_3$

No fix pairing for W mass reconstruction

Only invariants for reconstruction
Top quark momentum reconstruction

- Great reconstruction of top quark momentum
- 35% tagging efficiency
- 2% W+jets fake rate
- Tagger used in resonance searches in ATLAS: 1207.2409

- pT > 200 GeV
- pT > 300 GeV

Efficiencies

- R=1.5
- inside fat jet
- tagged
- tagged (unmatched)

- Number of tops
- Number of tops
Results for $t\bar{t}h$

- 5 sigma sign. with 100 $1/\text{fb}$
- Development of Higgs and top tagger for busy final state
- Improvement of S/B from $1/9$ to $1/2$

$t\bar{t}h$ might be a window to Higgs-top coupling
III. Measuring the CP of the Higgs boson

- For light Higgs with 125 GeV CP can be measured using angular correlations of tagging jets in Gluon Fusion with 2 additional jets
  
  \[ \text{Interaction:} \]
  
  \[ \mathcal{L} = \frac{\alpha_s}{12\pi v} H G^\alpha_{\mu\nu} G^\alpha_{\mu\nu} + \frac{\alpha_s}{16\pi v} A G^\alpha_{\mu\nu} \tilde{G}^\alpha_{\mu\nu} \]

  For tagging jets with \( |p_z^J| \gg |p_{x,y}^J| \)

  \[ \mathcal{M}_{\text{even}} \sim J_1^\mu J_2^\nu \left[ g_{\mu\nu} (q_1 \cdot q_2) - q_1^\nu q_2^\mu \right] \]

  \[ \sim \left[ J_1^0 J_2^0 - J_1^3 J_2^3 \right] p_T^J_1 \cdot p_T^J_2 \sim 0 \text{ for } \Delta \phi_{jj} = \pi/2 \]

  \( \mathcal{M}_{\text{odd}} \) contains Levi-Civita tensor which is 0 if two of momenta linearly dependent, i.e. if \( \Delta \phi_{jj} = 0 \) or \( \Delta \phi_{jj} = \pi \)
Event shapes

- Event shapes well studied experimentally and theoretically
  
  [Banfi et al., JHEP 0408]  [Gehrmann-De Ridder et al., JHEP 0712]

- Event shape measurements established in experimental collaborations already now
  [CMS, PLB 699 (2011)]

  e.g.

  transverse thrust
  \[ T_{\perp,g} = \max_{n_T} \frac{\sum_i |\mathbf{p}_{\perp,i} \cdot \mathbf{n}_T|}{\sum_i |\mathbf{p}_{\perp,i}|} \]

  transverse thrust minor
  \[ T_{m,g} = \frac{\sum_i |\mathbf{p}_{\perp,i} \times \mathbf{n}_T|}{\sum_i |\mathbf{p}_{\perp,i}|} \]
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  - [Kluth. et al, EPJC 21 (2011)]
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  transverse thrust minor
  \[ T_{m,g} = \frac{\sum_i |p_{\perp,i} \times n_T|}{\sum_i |p_{\perp,i}|} \]
Tagging jets approach:

azimuthal angle between all jets with larger or smaller rapidity wrt Higgs

\[ p^\mu_< = \sum_{j \in \{ \text{jets: } y_j < y_H \}} p^\mu_j \]
\[ p^\mu_> = \sum_{j \in \{ \text{jets: } y_j > y_H \}} p^\mu_j \]
\[ \Delta \Phi_{jj} = \phi(p_>) - \phi(p_<) \]
Tagging jets approach:

azimuthal angle between all jets with larger or smaller rapidity wrt Higgs

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\[ p^\mu_> = \sum_{j \in \{\text{jets: } y_j > y_H\}} p^\mu_j \]

\[ \Delta \Phi_{jj} = \phi(p_>) - \phi(p_<) \]

Jet 1  
Jet 2  
Higgs  

\[ \frac{1}{\sigma} \frac{d\sigma}{d\Delta \Phi_{jj}} [1/0.503] \]

\[ \Delta \Phi_{jj} \]

Jet 1  
Jet 2  
Higgs  

\[ p_T \text{ plane} \]

\[ p_T \text{ plane} \]
Obvious correlation between thrust and $\Delta \Phi_{jj}$

(a) $CP$ even Higgs

(b) $CP$ odd Higgs
Event selection cuts

two tagging jets: \( p_{T,j} \geq 40 \text{ GeV}, \) and \( |y_j| \leq 4.5 \)

\[
m_{jj} = \sqrt{(p_{j,1} + p_{j,2})^2} \geq 600 \text{ GeV}
\]

two taus, hard and central: \( p_{T,\tau} \geq 20 \text{ GeV}, \) and \( |y_\tau| \leq 2.5 \)

\[
|m_{\tau\tau} - m_H| < 20 \text{ GeV}
\]

For event shapes use either constituents with

\[
p_{T,i} \geq 1 \text{ GeV} \quad |\eta_i| \leq 4.5
\]

or, to reduce pileup sensitivity \( p_{T,j} \geq 40 \text{ GeV}, \) if \( 2.5 \leq |y_j| \leq 4.5, \) and

\[
p_{T,j} \geq 10 \text{ GeV}, \text{ if } |y_j| \leq 2.5.
\]
FIG. 8: Normalized distributions of ∆Φjj and of the event shape observables of Sec. II for separate weak boson fusion and gluon fusion contributions in case of the CP-even SM Higgs. The cuts of Sec. III B have been applied. There is no meaning in performing a hypothesis test, so we limit ourselves to a discussion of the normalized distributions in the following. Forming ratios of different cut-scenarios in an ABCD-type approach, e.g., comparing 0.1 ≤ B_W ≤ 0.15 with the complementary region in a background-subtracted sample allows to extract the WBF and GF contributions (we stress again that interference is negligible for the chosen cuts). An assessment of the uncertainty of such an extraction, however, requires a realistic simulation, taking into account experimental systematics, and is beyond the scope of our work.

D. Impact of pile-up

A potential drawback, which has not been discussed in depth so far, arises from the unexpectedly high pile-up activity reported by both Cms and Atlas for the 2011 run. Because soft tracks enter the evaluation of the event shape observables, which contain information about CP or WBF vs. GF, (cf. Fig. 9), we expect pile-up to have an impact on the event shape phenomenology. Especially in the forward region of the detector pile-up subtraction is not available. A way to weaken the phenomenological impact of pile-up is to use jet constituents as input for the event shape observables. This can distort many of the theoretical properties of event shapes (in particular resummation becomes more involved due to introduction of new scales to the problem). Hence, the potential theoretical improvements are bound to the experimental capabilities to subtract or reduce pile-up by the time the resonance is established.
In the central region infer the number of primary vertices of the event and here Eqs. (6b)-(7), but modify our jet pre-selection. Again we try to keep as much soft central sensitivity in the signal cross sections due to the modified selection criteria. Decreases to 1 if all particles, we analyze the event shapes again for a direct global thrust and central wide broadening. For even CP quantum numbers, have reported an excess. Sensitivity in telling apart weak boson fusion production, hypotheses once a resonance is established. While there are scarce and we rely exclusively on the hardness of the constituents as outlined in Sec. IV D. To understanding how much our sensitivity decreases for odd CP quantum numbers. If 2 ≤ \(|y_{j}|\) ≤ 5 pile-up subtraction strategies, then we have reported an excess. Sensitivity in physics at a new energy frontier. Addressing these questions is needed, we find excellent discrimination power for event shape observables to discriminate between different CP eigenstates.

\[\frac{1}{\sigma} \frac{d\sigma}{d T_{m,g}} \text{[fb/0.04]}\]
\[\frac{1}{\sigma} \frac{d\sigma}{d T_{\perp,g}} \text{[fb/0.02]}\]
\[\frac{1}{\sigma} \frac{d\sigma}{d B_{W}} \text{[fb/0.04]}\]
\[\frac{d\sigma}{d B_{T}} \text{[fb/0.04]}\]

Distributions CP-odd vs CP-even

Seminar RHUL 47 Michael Spannowsky 07.11.2012
We see from Fig. 6 that event shapes indeed provide a clearly assuming Gaussian-like probability density functions.

Also, from a phenomenological point of view (and this is one of our assumptions in Sec. III B), the resonance was one of our assumptions in Sec. III B), the resonance has been discovered before we address its spin and CP-parity of shapes will be used to extract information on spin and CP-parity. Hence, it is reasonable to study the discriminative power of the event shapes in comparison to CP-violating coupling is not expected from a theoretical perspective. Actually, the strategy outlined in Secs. III B, IV A and IV B does not sufficient to be successful.

In fact, the relative contribution of WBF and GF to the cross section heavily influences the quantities Eqs. (2)–(4), and therefore drives the observed sensitivity in the previous section of the observables to help separating WBF from GF contributions in Fig. 8 and we see a similar behavior as encountered in Fig. 1.

Keeping that in mind, we can use the correlations (5), and therefore drives the observed sensitivity in the previous section of the observables to help separating WBF from GF contributions in Fig. 8 and we see a similar behavior as encountered in Fig. 1.

We plot the confidence levels obtained from the hypothesis tests. The dotted line corresponds to a 5σ limit, and the solid lines indicate the dependence on luminosity. When the confidence level (which should be reflected by the binning in Figs. 4 and 5) is decreased to 0.1, the sensitivity that arises only through the overall normalization after cuts of pseudoscalar and thrust minor 

\[ \Delta \Phi_{jj} \]

thrust

\[ \Delta \Phi_{bf} \]

central wide broadening

\[ \Delta \Phi_{ff} \]

central broadening

\[ \sigma_{GF} \]

total central broadening

\[ \sigma_{WBF} \]

sensitivity that arises only through the overall normalization after cuts of pseudoscalar and thrust minor

\[ \sigma_{CP} \]

sensitivity that arises only through the overall normalization after cuts of pseudoscalar and thrust minor

\[ \sigma_{CP} \]

sensitivity that arises only through the overall normalization after cuts of pseudoscalar and thrust minor

\[ \sigma_{CP} \]

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\[ \sigma_{CP} \]

sensitivity that arises only through the overall normalization after cuts of pseudoscalar and thrust minor
IV. Measuring the Higgs self-coupling at the LHC

\[ V(H^\dagger H) = \mu^2 H^\dagger H + \eta (H^\dagger H)^2 \]
\[ \supset \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\eta}{2}} m_h h^3 + \frac{\eta}{4} h^4 \]
\[ H = (0, v + h)^T / \sqrt{2} \quad \lambda_{SM} = \sqrt{\frac{\eta}{2}} m_h \]

- For EWSB Higgs potential needed \(\rightarrow\) measure self-coupling
- Measuring Higgs potential ‘holy grail’ of Higgs physics
  - \(\lambda_{HHHH}\) absolutely hopeless at LHC (and any of the others...)
  - \(\lambda_{HHH}\) very difficult to measure at the LHC
Rate of di-Higgs production small!

[Dawson, Dittmaier, Spira PRD 58 (1998)]
[Binoth, Karg, Kauer, Ruckl PRD 74 (2006)]
However, kinematic even more problematic

- Destructive interference in signal
- 1/s suppression for $\lambda_{HHH}$ diagram
- But signal is naturally boosted

Need large BR due to small signal but need to discriminate from backgrounds
Novel idea: include a hard jet to make Higgs softer

- ameliorates the 1/s suppression
- rescues sensitivity on selfcoupling for boosted Higgs
- However, comes at the price of even smaller rate
Several reconstruction approaches tried in

[Baur, Plehn, Rainwater PRD 69 (2004)]  [Dolan, Englert, MS 1206.5001]

[Papaefstathiou, Yang, Zurita 1209.1489]

Most promising final states probably $\bar{b}b\gamma\gamma$, $\bar{b}b\tau^+\tau^-$, $4\tau(?)$

HH:

<table>
<thead>
<tr>
<th>$\xi$</th>
<th>cross section before cuts</th>
<th>$\bar{b}b\tau\tau$</th>
<th>$\bar{b}b\tau\tau$ [ELW]</th>
<th>$\bar{b}bW^+W^-$</th>
<th>ratio to $\xi = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi = 0$</td>
<td>59.48</td>
<td>28.34</td>
<td>13.36</td>
<td>67.48</td>
<td>8.73</td>
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<tr>
<td>$\xi = 1$</td>
<td>2.05</td>
<td>1.94</td>
<td>0.91</td>
<td>2.51</td>
<td>1.10</td>
</tr>
<tr>
<td>$\xi = 2$</td>
<td>2.27</td>
<td>1.09</td>
<td>0.65</td>
<td>1.29</td>
<td>0.84</td>
</tr>
<tr>
<td>reconstructed Higgs from $\tau$s</td>
<td>4.05</td>
<td>1.94</td>
<td>0.91</td>
<td>2.51</td>
<td>1.10</td>
</tr>
<tr>
<td>fatjet cuts</td>
<td>2.27</td>
<td>1.09</td>
<td>0.65</td>
<td>1.29</td>
<td>0.84</td>
</tr>
<tr>
<td>kinematic Higgs reconstruction ($m_{bb}$)</td>
<td>0.41</td>
<td>0.26</td>
<td>0.15</td>
<td>0.104</td>
<td>0.047</td>
</tr>
<tr>
<td>Higgs with double $b$-tag</td>
<td>0.148</td>
<td>0.095</td>
<td>0.053</td>
<td>0.028</td>
<td>0.020</td>
</tr>
</tbody>
</table>

HHj:

<table>
<thead>
<tr>
<th>$\xi$</th>
<th>cross section before cuts</th>
<th>$\bar{b}b\tau^+\tau^- j$</th>
<th>$\bar{b}b\tau^+\tau^- j$ [ELW]</th>
<th>$tt\bar{t}$</th>
<th>ratio to $\xi = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi = 0$</td>
<td>6.45</td>
<td>3.24</td>
<td>1.81</td>
<td>66.0</td>
<td>1.67</td>
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<tr>
<td>$\xi = 1$</td>
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<td>0.22</td>
<td>0.12</td>
<td>37.0</td>
<td>0.94</td>
</tr>
<tr>
<td>$\xi = 2$</td>
<td>0.29</td>
<td>0.16</td>
<td>0.10</td>
<td>2.00</td>
<td>0.150</td>
</tr>
<tr>
<td>2 $\tau$s</td>
<td>0.07</td>
<td>0.04</td>
<td>0.02</td>
<td>0.042</td>
<td>0.018</td>
</tr>
<tr>
<td>Higgs rec. from taus + fatjet cuts</td>
<td>0.07</td>
<td>0.04</td>
<td>0.02</td>
<td>0.042</td>
<td>0.018</td>
</tr>
<tr>
<td>kinematic Higgs rec.</td>
<td>0.07</td>
<td>0.04</td>
<td>0.02</td>
<td>0.042</td>
<td>0.018</td>
</tr>
<tr>
<td>$2b + hh$ invariant mass + $p_{T,j}$ cut</td>
<td>0.010</td>
<td>0.006</td>
<td>0.004</td>
<td>&lt;0.0001</td>
<td>0.0022</td>
</tr>
</tbody>
</table>

Channels are being studied: [ATLAS-PHYS-PUB-2012-001]
Di-Higgs production can discriminate between different BSM scenarios

For example resonant di-Higgs production in the MSSM:

\[
\begin{align*}
\lambda_{hhh} &= 3 \cos 2\alpha \sin(\beta + \alpha) \\
\lambda_{Hhh} &= 2 \sin 2\alpha \sin(\beta + \alpha) - \cos 2\alpha \cos(\beta + \alpha) \\
\lambda_{HHh} &= -2 \sin 2\alpha \cos(\beta + \alpha) - \cos 2\alpha \sin(\beta + \alpha).
\end{align*}
\]

Assuming decoupling limit such that \( MH > 2 \ Mh \) and \( \text{BR}(H\rightarrow hh) = 45\% \)

[Dolan, Englert, MS 1210.8166]

\( \lambda_{Hhh} \) dominates resonant production

\( \frac{d\sigma}{dm_{hh}} \) in [fb/GeV]

Off-shell, continuums production

Allows measurement of alpha and beta angles
Conclusions

- A new resonance has been found at the LHC, consistent with long predicted Higgs boson

- To confirm it is Higgs boson couplings and quantum numbers have to be measured

- Measuring hadronic decays (i.e. H→bb) and Higgs production in association with Jets is paramount for this program

- Jet substructure can help to perform this task

- Jet physics will be active field for long time to come