The Higgs boson
Decays to b-quarks and more...

Patricia Conde Muño
(IST & LIP)
# Higgs lectures so far...

**Course on Physics at the LHC**

**From Monday, 2 March 2020 (07:00) to Friday, 26 June 2020 (18:40)**

**LIP (Conference Room)**

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<thead>
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</tbody>
</table>
|    | Experimental program at the LHC  
*João Varela (LIP Laboratório de Instrumentação e Física Experimental de Partículas)* (Conference Room)  
Lecture1-Exp at LHC.pdf | Standard Model at the LHC  
*João Varela (LIP Laboratório de Instrumentação e Física Experimental de Partículas)* (Conference Room)  
Lecture2-SM at LHC.pdf | Detectors 1  
*Pedro Vieira De Castro Ferreira Da Silva (CERN)*  
*Michele Gallinaro (LIP Lisbon)* (Conference Room)  
detectors_March2019.pdf | Detectors 2  
*Pierro Vieira De Castro Ferreira Da Silva (CERN)* (Conference Room)  
detectors_March2019.pdf | Statistics 1  
*Pietro Vischia (Université Catholique de Louvain (UCL))* (Conference Room)  
[2023-03-18to18_Statistics_LHC-Course_vischia_part1.pdf](#) |
|    | 17:00               | 17:00               | 17:00               | 17:00               | 17:00               |
| PM | 17:00               | 17:00               | 17:00               | 17:00               | 17:00               |
|    | 17:00               | 17:00               | 17:00               | 17:00               | 17:00               |
|    | Top Physics 1  
*Michele Gallinaro (LIP Lisbon)* (Conference Room)  
[2020_course_Top_Lecture1.pdf](#) | Top Physics 2  
*Michele Gallinaro (LIP Lisbon)* (Conference Room)  
[2020_course_Top_Lecture2.pdf](#) | Top Physics 3  
*Antonio Onofre (Universidade de Coimbra (PT))* (Conference Room)  
TopTopCouplings_AO.pdf | Higgs Physics 1  
*Ricardo Jose Morais Silva Goncalo (LIP Laboratório de Instrumentação e Física Experimental de Partículas)* (Conference Room)  
HiggsLecture1.pdf | Higgs Physics 2  
*Pedro Vieira De Castro Ferreira Da Silva (CERN)* (Conference Room)  
higgsproperties_6Apr2020.pdf |
Higgs lectures so far...

**Wednesday, 1 April**

17:00 → 18:30  **Higgs Physics 1**

- Introduction
- Reminder of some shortcomings of the SM: masses, WW scattering.
- The Higgs mechanism.
- Production and decay of the Higgs boson at colliders: LEP, Tevatron and LHC.
- Previous searches at LEP and the Tevatron.

*Speaker: Ricardo Jose Morais Silva Goncalo* (IP Laboratorio de Instrumentacao e Fisica Experimental de Part)

[Link to HiggsLecture1.pdf](HiggsLecture1.pdf)

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**Monday, 6 April**

17:00 → 18:30  **Higgs Physics 2**

- Models, properties, and interpretation.
- Case-study of the coupling strengths.
- Case study of the hypothesis test for different spin-parity assignments.

*Speaker: Pedro Vieira De Castro Ferreira Da Silva* (CERN)

[Link to higgsproperties_6A.pdf](higgsproperties_6A.pdf)
In this lecture

✴ Reminder
  - The Higgs Lagrangian in the SM and how to probe it
✴ Challenges and difficulties of the Higgs boson study at the LHC
✴ Photon reconstruction and the searches in the $H \rightarrow \gamma\gamma$ channel
✴ The $H \rightarrow bb$ search
  - Event selection
  - Background measurement
  - Fits
  - Combinations
✴ Other channels to look at the Higgs couplings to quarks
  - Is it possible to improve/complement the measurements done?
Lots of different measurements…

- How to make sense of them?
SM Higgs Lagrangian after symmetry breaking

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2} (H^\dagger H)^2 - (y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.})$$

★ Very predictive theory:

★ Can calculate everything but the Higgs boson mass...

★ Once the Higgs boson is found... we can also probe everything!

★ $m_H = \sqrt{2\mu} = \sqrt{\lambda v}$ ($v = \text{vacuum expectation value}$)
The SM Higgs Lagrangian after symmetry breaking

\[ \mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2} (H^\dagger H)^2 - (y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}) \]

Couplings to EW gauge bosons

\[ [m_W^2 W^{\mu+} W_{\mu-} + \frac{1}{2} m_Z^2 Z^{\mu0} Z_{\mu}^0] \cdot (1 + \frac{\lambda}{v})^2 \]

\[ m_H = \sqrt{2} \mu = \sqrt{\lambda v} \quad (v = \text{vacuum expectation value}) \]

\[ 2i \frac{m_W^2}{2v} g_{\mu\nu} \]

\[ 2i M_W^2 v g_{\mu\nu} \]

\[ 2i M_Z^2 4v g_{\mu\nu} \]
Higgs decays to vector bosons

\[ \mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger. \]

Couplings to EW gauge bosons

\[ [m_W^2 W^\mu W^- \mu + \frac{1}{2} m_Z^2 Z^\mu Z^\mu] \cdot (1 + \frac{4}{3} \alpha) \]

\[ m_H = \sqrt{2\mu} = \sqrt{\lambda v} (v = \frac{1}{2}) \]

\[ \times H \rightarrow WW \]

\[ \times H \rightarrow ZZ \]

\[ \times \text{First observation} \]

\[ \times \text{Cross sections at 7, 8 and 13 TeV} \]

Differential distributions
Higgs couplings to fermions

- Couplings to fermions
- Experimental measurements:
  Decay rates to quarks & leptons

\[
\mathcal{L} = \lambda_h^4 - \sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right) - i \frac{m_f^2}{v^2} + h.c.
\]
Higgs couplings to fermions

- Couplings to fermions
- Experimental measurements:
  - Decay rates to quarks & leptons
  - Top quark coupling:
    - Indirect: gg fusion production mode
    - But model dependent —> need direct probes!
  - ttH associated production
  - Rare decays
Higgs couplings to fermions

- Couplings to fermions
- Experimental measurements:
  - Decay rates to quarks & leptons
  - Top quark coupling:
    - Indirect: gg fusion production mode
    - But model dependent —> need direct probes!
  - ttH associated production
- Rare decays

\[
(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.})
\]

\[
h^4 - \sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)
\]

\[
i \frac{m_{\mu}^2}{v^2} \rightarrow -i \frac{m_{\tau}}{v}
\]

References:
- Phys. Rev. Lett. 120 (2018) 211802
- ATLAS-CONF-2018-053
- arXiv:1811.08856
- ATLAS-CONF-2018-026
New particles? What about dark matter?

\[ \mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2} (H^\dagger H)^2 - (y_{ij} H \bar{\psi}_i \psi_j + h.c.) \]

- Couplings to new particles?
- Experimental measurements:
  - Search for invisible decays
  - Total decay width:
    - Constraint from visible decays
    - Interference effects in ZZ production
Higgs self interactions

\[ \mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2} (H^\dagger H)^2 - (y_{ij} H \bar{\psi}_i \psi_j + h.c.) \]

- **Higgs potential**
- **Experimental measurements:**
  - Higgs mass
  - HH production

ATLAS-CONF-2018-043
The search for H→bb decays

- Higgs boson observed & measured mainly in bosonic channels (γγ, WW, ZZ)
  - All results compatible with SM
- H→bb: largest BR in the SM (~58%)
  - Constrain total width and measure absolute couplings
  - Probe the Higgs couplings to up-type quarks
- Evidence of fermionic decays in Run 1:
  - H→γγ: 5.5σ (expected 5σ)
  - H→bb: 2.6σ (expected 3.7σ)
- Run 1 signal strength for H→bb: $\mu_{bb}^{CMS+ATLAS} = 0.70^{+0.29}_{-0.27}$
The ATLAS detector
Identification of particles in ATLAS
Jets

- Quarks/gluons hadronize producing a colimated spray of particles: jets
Jets reconstruction and calibration

- Complex underlying physics
  - spectator interactions
  - initial and final state gluons
  - energy from different pp interactions
  - different types of jets: light quarks, gluons, b/c/t
- Complex detector properties:
  - non-linear energy response
  - non-instrumented regions,
  - dead material
  - invisible energy
- Algorithm effects:
  - Out of cone radiation, infrared safeness
ATLAS and LHC operation

- Integrated luminosity
  - 158 fb$^{-1}$ delivered
  - 140 fb$^{-1}$ recorded
- Average pile-up at 13 TeV
  - 34.2 interactions/BX
Pile-up

- Event with a $Z \rightarrow \mu \mu$ decay plus 65 additional pp interactions
- Very difficult to reconstruct and distinguish different particles
Standard Model backgrounds

Production cross section of
- Jets $\sim 10^8$ larger than $\sigma_H$
- B-jets $\sim 10^7$ times larger than $\sigma_H$
- W-bosons: nearly 10000 times higher than $\sigma_H$

We need
- Clear experimental signatures in the detector

For $H \rightarrow bb$ search:
- Use sub-dominant production modes
- Associated production with vector bosons
- Vector boson fusion
Higgs production at the LHC

- Dominant gluon-gluon fusion
- Sub-dominant:
  - Vector boson fusion
  - WH and ZH associated production
  - ttH associated production

At the LHC... can only measure production and decay together
H→bb decay

Searches performed using sub-dominant production modes:

- WH and ZH associated production (VH)
  - Three different channels: 0, 1 and 2 charged leptons
- VBF analysis
  - Considered final states with/out additional γ
    - Final state photon helps reducing the background due to interference effects for the background
- ttH production
**VH(bb) searches: 3 channels**

- **0-lepton:**
  \[ E_{\text{miss}}^T > 150 \text{ GeV} \]

- **1-lepton:**
  \[ e/\mu, p_T > 25 \text{ GeV} \]
  \[ \text{Tight isolation} \]
  \[ \text{Missing } E^T_\tau > 30 \text{ GeV} \text{ (e chn)} \]
  \[ p_T^{V>150} \text{ GeV} \]

- **2-leptons:**
  \[ \text{Isolated ee, } \mu\mu \]
  \[ p_T^{1>25} \text{ GeV, } p_T^{2>7} \text{ GeV} \]
  \[ p_T^{V>75} \text{ GeV} \]
  \[ m_{ll} \text{ compatible with } m_Z \]

**Plus:**

- **Two jets**
  \[ \text{anti-kT with } R=0.4 \]
  \[ p_T^{j1>45} \text{ GeV} \]
  \[ p_T^{j2>20} \text{ GeV} \]

- **B-tagging**
  \[ \text{Eff: 70\%, light jet mistag rate: 0.3\%,} \]
  \[ \text{charm mistag rate: 8\%} \]

- **Analysis categories:**
  \[ 2/3 \text{ jets (0/1lepton)} \]
  \[ 2/\geq3 \text{jets (2lept.)} \]
  \[ p_T^{V>75} \text{ GeV} \text{ bins} \]
  \[ 75-150, >150 \text{ GeV (2lepton)} \]
  \[ >150 \text{ GeV (0/1lepton)} \]
Invariant mass resolution

- Mass resolution improvements
  - b-jets need dedicated calibration
  - Add muons in the vicinity (semi-lep. decays)
  - Simple average jet pT correction. Accounts for neutrinos, and interplay of resolution and pT spectrum effects.
- Improvement ~ 18%

- Kinematic fit for leptons:
  - Profit from the good lepton resolution
  - Constraint jet kinematics
  - Improvement ~40%
Main backgrounds

- $W$+jets, $Z$+jets production
- Di-boson production
  - $WW$, $WZ$, $ZZ$
- Top production:
  - $t$-$t\bar{t}$
  - Single top
VH(bb) Main backgrounds

- Dominant backgrounds dependent on channel
  - Z+bjets dominates in 0, 2 lepton channels
  - Top quark and W+jets in 1 lepton channel
  - Multi-jet important in 1 lepton channel
Multi-variate analysis

➢ Boosted decision tree (BDT)

Combine many different variables
Trained in 8 categories:
   3 lepton, 2/3 jets, low/high $p_T$ bin (2 lepton channel)

➢ Most discrimination from $m_{bb}$ and $\Delta R(b_1, b_2)$

➢ New in run 2: $m_{Top}$, $|\Delta Y(V,H)|$
   $\rightarrow$ +7% in sensitivity

<table>
<thead>
<tr>
<th>Variable</th>
<th>0-lepton</th>
<th>1-lepton</th>
<th>2-lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^V$</td>
<td>$\equiv E_T^{\text{miss}}$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
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<tr>
<td>$p_T^{b_1}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
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<tr>
<td>$p_T^{b_2}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$m_{bb}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$\Delta R(b_1, b_2)$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \eta(b_1, b_2)</td>
<td>$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$\Delta \phi(V, b\bar{b})$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
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<tr>
<td>$</td>
<td>\Delta \eta(V, b\bar{b})</td>
<td>$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$m_{\text{eff}}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$\min[\Delta \phi(\ell, b)]$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$m_W$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$m_{\ell\ell}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}/\sqrt{S_T}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$m_{\text{top}}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta Y(V, b\bar{b})</td>
<td>$</td>
<td>$\times$</td>
</tr>
</tbody>
</table>

Only in 3-jet events

$\not{p}_T^{\text{jet}_3}$ | $\times$ | $\times$ | $\times$ |

$m_{bbj}$ | $\times$ | $\times$ | $\times$ |
**VH(bb) Combined fit**

- Signal strength from profiled likelihood fit
  - Take into account all event categories
- Use BDT discriminant as input
- Control regions to constrain the backgrounds
Use state-of-the-art MC generators (except MJ which is modelled in 1-lepton using a data-driven method)

Constrain (shape and normalization) from data by using high purity control regions

Main background normalizations floating in the fit

<table>
<thead>
<tr>
<th>Process</th>
<th>Normalisation factor</th>
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<tbody>
<tr>
<td>$t\bar{t}$ 0- and 1-lepton</td>
<td>0.98 ± 0.08</td>
</tr>
<tr>
<td>$t\bar{t}$ 2-lepton 2-jet</td>
<td>1.06 ± 0.09</td>
</tr>
<tr>
<td>$t\bar{t}$ 2-lepton 3-jet</td>
<td>0.95 ± 0.06</td>
</tr>
<tr>
<td>$W + HF$ 2-jet</td>
<td>1.19 ± 0.12</td>
</tr>
<tr>
<td>$W + HF$ 3-jet</td>
<td>1.05 ± 0.12</td>
</tr>
<tr>
<td>$Z + HF$ 2-jet</td>
<td>1.37 ± 0.11</td>
</tr>
<tr>
<td>$Z + HF$ 3-jet</td>
<td>1.09 ± 0.09</td>
</tr>
</tbody>
</table>

Parametrize extrapolation uncertainties across regions as uncertainties on ratios of yields

Shape uncertainties on BDTs
Post-fit distributions

➢ Control regions are used to constrain the backgrounds

**$E_T^{miss}$**

0 lep, 2jets, 2tags

**W transverse mass**

1 lep., 3jets, 2 btags

**$p_T^W \geq 150$ GeV**

**BDT discriminant**

2 leptons, 2 tags, 2 jets
Diboson VZ ($Z \rightarrow bb$) "search"

- Search for the known signal $Z \rightarrow bb$ (diboson search)
  - Test the fit and the all the analysis procedures
### Systematic uncertainties

**Analysis dominated by systematic uncertainties**

Measured by impact on signal strength ($\mu$)

**Many important sources!**

- **$b$-tagging** both $b$ and $c$ jet tagging calibration
  - Resp. $\sim 3\%$ and $\sim 10\%$ per jet
- **Background modelling** $Z+hf, W+hf, tt\bar{t}$
  - Mainly shape and extrapolation uncertainties
- **Signal modelling** little impact on significance
  - Dominated by systematic uncertainties on the acceptance
- **MC stats** never-ending race between data stat and MC stat
  - Use of dedicated MC filters
  - Not easy in all cases, e.g. $tt\bar{t}$ phase space in 0/1-lepton

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\sigma_\mu$</th>
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<tbody>
<tr>
<td>Total</td>
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<tr>
<td>Statistical</td>
<td>0.161</td>
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<tr>
<td>Systematic</td>
<td>0.203</td>
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<tr>
<td><strong>Experimental uncertainties</strong></td>
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<tr>
<td>Jets</td>
<td>0.035</td>
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<tr>
<td>$E_{T}^{\text{miss}}$</td>
<td>0.014</td>
</tr>
<tr>
<td>Leptons</td>
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<tr>
<td><strong>$b$-tagging</strong></td>
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<tr>
<td>$b$-jets</td>
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</tr>
<tr>
<td>$c$-jets</td>
<td>0.042</td>
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<tr>
<td>light-flavour jets</td>
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<tr>
<td>extrapolation</td>
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<tr>
<td><strong>Pile-up</strong></td>
<td>0.007</td>
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<tr>
<td><strong>Luminosity</strong></td>
<td>0.023</td>
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<tr>
<td><strong>Theoretical and modelling uncertainties</strong></td>
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<tr>
<td>Signal</td>
<td>0.094</td>
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<tr>
<td>Floating normalisations</td>
<td>0.035</td>
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<tr>
<td>$Z + $jets</td>
<td>0.055</td>
</tr>
<tr>
<td>$W +$ jets</td>
<td>0.060</td>
</tr>
<tr>
<td>$tt\bar{t}$</td>
<td>0.050</td>
</tr>
<tr>
<td>Single top quark</td>
<td>0.028</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.054</td>
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<tr>
<td>Multi-jet</td>
<td>0.005</td>
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<tr>
<td><strong>MC statistical</strong></td>
<td>0.070</td>
</tr>
</tbody>
</table>
Di-jet mass analysis

- 3.6σ observed
- 3.5σ expected

\[
\mu_{VH}^{bb} = 1.06^{+0.36}_{-0.33} = 1.06 \pm 0.20(\text{stat.})^{+0.30}_{-0.26}(\text{syst.})
\]
WH and ZH with $H \rightarrow bb$ results

- 79 fb$^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV
  - 4.9$\sigma$ evidence observed (4.3$\sigma$ expected)
  - systematic uncertainties start to dominate!!

\[ \mu_{VH}^{bb} = 1.16^{+0.27}_{-0.25} = 1.16 \pm 0.16\text{(stat.)}^{+0.21}_{-0.19}\text{(syst.)} \]

Dominant systematics from b-tagging, background normalisation & modelling (W+jets, Z+jets, top)
H$\rightarrow$bb Run 1 + Run 2 combination

- Includes ttH and vector boson fusion (with H$\rightarrow$bb) channels
- 5.4$\sigma$ observation!! (5.5$\sigma$ expected)
Observation of VH production

- Combination of $H \rightarrow bb$ with two more channels
  - Four leptons ($ZZ^*$)
  - $\gamma\gamma$
- Direct observation of the Higgs produced in association with vector bosons!

<table>
<thead>
<tr>
<th>Channel</th>
<th>Significance</th>
<th>Exp.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>1.1</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>1.9</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>4.3</td>
<td>4.9</td>
<td></td>
</tr>
<tr>
<td>VH combined</td>
<td>4.8</td>
<td>5.3</td>
<td></td>
</tr>
</tbody>
</table>
CMS VH with $H\rightarrow bb$ observation

\[ 5.1 \text{ fb}^{-1}(7 \text{ TeV}) + 18.9 \text{ fb}^{-1}(8 \text{ TeV}) + 77.2 \text{ fb}^{-1}(13 \text{ TeV}) \]
CMS inclusive H → bb search

Simultaneous fit to search for Z → bb and H → bb signals
Boosted
H→bb
Decay (VH production)

More sensitive to
new physics
effects!
New physics in the hWW vertex?

- New physics can modify the hWW vertex structure
  - Will affect cross sections
    - Particularly at high $p_T$
  - CP-even and CP-odd operators
    - CP odd operators can introduce CP violation
    - Angular observables to disentangle these contributions in future!

$$i\Gamma^\mu\nu_{\text{HWW}}(k_1, k_2) = i(g_2 m_W) \left[ g^\mu\nu \left( 1 + a_W - \frac{b_{W1}}{m_W^2} (k_1 \cdot k_2) \right) + \frac{b_{W1}}{m_W^2} k_1^\mu k_2^\nu + \frac{c_W}{m_W^2} \epsilon^{\mu\nu\rho\sigma} k_1^\rho k_2^\sigma \right]$$
ATLAS VH boosted studies

Binned profile likelihood fit in $m_j$ in 14 regions

→ simultaneously extracting $VH \rightarrow bb$ and $VZ \rightarrow bb$ signal strengths

$$\mu_{VZ}^{bb} = 0.91^{+0.29}_{-0.23} = 0.91 \pm 0.15\text{(stat.)}^{+0.25}_{-0.17}\text{(syst.)}$$

Obs. (exp.) significance: 5.2 (5.7) $\sigma$

H. Arnold, Seminar @ CERN
Yesterday!

$$\mu_{VH}^{bb} = 0.72^{+0.30}_{-0.36} = 0.72^{+0.29}_{-0.23}\text{(stat.)}^{+0.26}_{-0.23}\text{(syst.)}$$

Obs. (exp.) significance: 2.1 (2.7) $\sigma$

- **Good compatibility**
  - between signal strengths in different channels / regions
  - With the SM prediction
  - Analysis statistically limited
- Leading systematic uncertainties: $m_j$ resolution, background modelling and MC stat. unc.
Cross section as a function of $p_T(V)$

- Resolved analysis
- Boosted analysis
Higgs couplings to fermions

- Couplings to fermions
- Experimental measurements:
  
  Decay rates to quarks & leptons
Second generation: $H \rightarrow \mu\mu$ and $H \rightarrow cc$

- $H \rightarrow \mu\mu$
  - Very low branching fraction but sensitivity reaching close to SM
- $H \rightarrow cc$:
  - Extremely challenging: huge backgrounds
  - Similar strategy as VH with $H \rightarrow bb$
  - Expected sensitivity $\sim 150 \times SM$

<table>
<thead>
<tr>
<th>Process</th>
<th>$\int \mathcal{L} dt$ ($fb^{-1}$)</th>
<th>$95%$ CL upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>78.9</td>
<td>$2 \times SM$</td>
</tr>
<tr>
<td>$H \rightarrow cc$</td>
<td>36.1</td>
<td>$150^{+80}_{-40} \times SM$</td>
</tr>
</tbody>
</table>
Higgs couplings to fermions

- Couplings to fermions
- Experimental measurements:
  - Decay rates to quarks & leptons
  - Top quark coupling:
    - Indirect: gg fusion production mode
    - But model dependent —> need direct probes!
  - \( t\bar{t}H \) associated production

Rare decays
Probing the Hbb coupling

- Questions
  - Is it really as the SM predicts?
  - What is the sign of the coupling?
  - Are there anomalous components?

- Probing the sign of the Hbb coupling:
  - Decay $H \rightarrow \gamma \gamma$
    - Interference between two difference diagrams results in very low BR
    - Can be enhanced if the sign of the coupling is the opposite!
    - Very difficult channel $\rightarrow$ will need HL-LHC

T. Modak et al.  
Hcc and Hbb vertices

- Rare decays sensitive to Hcc or Hbb vertex
  - Direct and indirect contributions
- Could be enhanced due to BSM physics
- No signal observed → imposed limits on BR

### ATLAS

<table>
<thead>
<tr>
<th>Branching fraction limit (95% CL)</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(H \to J/\psi \gamma)$</td>
<td>3.0$^{+1.4}_{-0.8}$</td>
<td>3.5</td>
</tr>
<tr>
<td>$\mathcal{B}(H \to \psi(2S) \gamma)$</td>
<td>15.6$^{+7.7}_{-4.4}$</td>
<td>19.8</td>
</tr>
<tr>
<td>$\mathcal{B}(Z \to J/\psi \gamma)$</td>
<td>1.1$^{+0.5}_{-0.3}$</td>
<td>2.3</td>
</tr>
<tr>
<td>$\mathcal{B}(Z \to \psi(2S) \gamma)$</td>
<td>6.0$^{+2.7}_{-1.7}$</td>
<td>4.5</td>
</tr>
<tr>
<td>$\mathcal{B}(H \to \Upsilon(1S) \gamma)$</td>
<td>5.0$^{+2.4}_{-1.4}$</td>
<td>4.9</td>
</tr>
<tr>
<td>$\mathcal{B}(H \to \Upsilon(2S) \gamma)$</td>
<td>6.2$^{+3.0}_{-1.7}$</td>
<td>5.9</td>
</tr>
<tr>
<td>$\mathcal{B}(H \to \Upsilon(3S) \gamma)$</td>
<td>5.0$^{+2.5}_{-1.4}$</td>
<td>5.7</td>
</tr>
</tbody>
</table>

### CMS

<table>
<thead>
<tr>
<th>Channel</th>
<th>Polarization</th>
<th>$B(Z \rightarrow J/\psi \gamma) \text{ at } 95% \text{ CL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow J/\psi \gamma$</td>
<td>Unpolarized</td>
<td>$1.4 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>$1.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>$H \rightarrow J/\psi \gamma$</td>
<td>Longitudinal</td>
<td>$1.2 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>$7.6 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
CMS search for $H \to J/\psi \ J/\psi, \ H \to \gamma \gamma$

- Expected BR~$10^{-9}, 10^{-8}$
- Search performed by CMS recently
  - Z channel used as reference
    - Important also to understand theoretical calculations/uncertainties

<table>
<thead>
<tr>
<th>Process</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(H \to J/\psi J/\psi)$</td>
<td>$1.8 \times 10^{-3}$</td>
<td>$(1.8^{+0.2}_{-0.1}) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\mathcal{B}(H \to YY)$</td>
<td>$1.4 \times 10^{-3}$</td>
<td>$(1.4 \pm 0.1) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\mathcal{B}(Z \to J/\psi J/\psi)$</td>
<td>$2.2 \times 10^{-6}$</td>
<td>$(2.8^{+1.2}_{-0.7}) \times 10^{-6}$</td>
</tr>
<tr>
<td>$\mathcal{B}(Z \to YY)$</td>
<td>$1.5 \times 10^{-6}$</td>
<td>$(1.5 \pm 0.1) \times 10^{-6}$</td>
</tr>
</tbody>
</table>
Higgs self interactions

\[ \mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2} (H^\dagger H)^2 - (y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}) \]

**Higgs potential**

**Experimental measurements:**
- Higgs mass
- HH production

- arXiv:1811.04671
- arXiv:1804.06174
- ATLAS-CONF-2018-043
Search for di-Higgs production

- Sensitive to Higgs self coupling and new physics
- Many different final states studied
  - $WW^*WW^*$, $bbbb$, $b\tau\tau$, $b\gamma\gamma$, $bbWW^*$
- No signal observed yet
Combination of di-Higgs searches

- Channels included: bbbb, bbττ, bbγγ
- Integrated luminosity: 36 fb⁻¹
CMS combination
Electroweak fits

- But... are all the pieces of the SM fitting correctly???
Corrections to Electroweak observables

Electroweak observables are sensitive to masses of top quark and Higgs through radiative corrections

\[ M_W^2 = \rho M_Z^2 \cos^2 \theta_W \]

\[ (\rho - 1) \sim M_{\text{top}}^2 \]

\[ (\rho - 1) = \ln M_H \]

Sensitivity to Higgs mass is only logarithmic: Need ultra-precise measurements!

Precise measurements of electroweak observables can be used to constraint the Higgs boson mass or test internal coherence of the model!!
W boson mass measurement

- High precision measurement
  Data from 2011 only!
- Consistency test of the SM
\(m_W, m_t, m_H\)

- Long list of parameters used

- Best fit mass for Higgs boson:
  \[M_H = 90^{+21}_{-18} \text{ GeV}\]

- Compatible with observation within 1.7\(\sigma\)
Future perspectives

LHC / HL-LHC Plan

Run I
- Run 1
  - LS1: splice consolidation button collimators R2E project
  - experiment beam pipes
  - L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}
  - \mu = 27
  - 30 \text{ fb}^{-1}

Run II (LHC)
- Run 2
  - EYETS
  - 13-14 \text{ TeV}
  - 2011-2015

Run III
- Run 3
  - LS2: injector upgrade cryo Point 4 Civil Eng. P1-P5
  - experiment upgrade phase 1
  - L = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}
  - \mu = 55
  - 150 \text{ fb}^{-1}

Run IV
- Run 4 - 5...
  - LS3: HL-LHC installation
  - L = 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}
  - \mu = 140
  - 300 \text{ fb}^{-1}

Here we are 2037!!!

Run I
Run II
Run III
Run IV

7 TeV 8 TeV


0.75\% nominal luminosity

13-14 \text{ TeV}

experiment pipes

nominal luminosity

14 \text{ TeV}

nominal luminosity

radiation damage

2 x nominal luminosity

5 to 7 \times nominal luminosity

HL-LHC installation

energy

integrated luminosity

150 \text{ fb}^{-1}

30 \text{ fb}^{-1}

300 \text{ fb}^{-1}

2037!!!
Huge pile-up!!

- Will require upgraded detectors!!
High-Lumi LHC perspectives

- Uncertainties below 10% for most channels
- Continue to probe SM predictions
  or... find new physics!!
Conclusions

- The Higgs boson provides an optimal ground to probe the SM predictions and search for new physics!
- Outstanding performance of the LHC and the CMS and ATLAS detectors
  - Large increase in the available pp collisions
- A wealth of new results on SM Higgs boson studies
  - Main decay and production modes now observed in each experiment!!
    - Direct observation of the Higgs coupling to top and bottom quarks
    - Observation of VH, VBF production
- All results are compatible with SM predictions
- Searches for new physics and additional Higgs bosons continue
  - Much more data to come!
Thanks!

Acknowledgments
Backup
ATLAS observation of \( H \rightarrow \tau\tau \)

- 13 different signal regions considering
  - Final state of the \( \tau \) decays
  - VBF optimised category
  - Boosted \( H (p_{T\tau}>100 \text{ GeV}) \) category, dominated by ggF

\[ v_S = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]

- Run 1+Run2 combined significance: 6.4\( \sigma \) observed (5.4\( \sigma \) expected)
Search for \(ttH\) production

Direct probe of the top Yukawa coupling

Very difficult channel: many possible final states, many particles, combinatorics, ...

ATLAS EXPERIMENT

Run: 310341
Event: 3252230282
2016-10-11 03:50:46 CEST
Observation of $ttH$ production

- Direct probe of the top Yukawa coupling
- Use all available final states:
  - $H \rightarrow bb$, $H \rightarrow \gamma\gamma$, multi-leptons ($H \rightarrow \tau\tau$, $H \rightarrow ZZ^* \rightarrow 4\ell$)
- Combined Run 1 & Run 2 significance:
  - Expected: 5.1$\sigma$
  - Observed: 6.5$\sigma$
- Dominant systematic uncertainties
  - $tt+HF$ background in $H \rightarrow bb$
  - Non-prompt/fake lepton in multi-lepton channel
  - Signal modelling
  - Jet energy scale


FÍSICA DE PARTÍCULAS

Bosão de Higgs revela que relação mantém com o quark $top$

Investigadores portugueses participaram na descoberta.