Observation of $H \rightarrow bb$
In CMS with VHbb

May 2nd, 2019
Game of Flavours

Chris Palmer
Princeton University

VHbb motivation/history

CMS VHbb 2017 data analysis

CMS Hbb Observation

Outlook
SM Higgs Production at LHC

![Graph and diagrams showing Higgs production mechanisms at LHC, including Gluon Fusion (87%), Vector Boson Fusion (7%), Higgsstrahlung (4%), and t\(\bar{t}\) Production (1%).]
SM Higgs Boson Decay

### Channel BR Resolution S/B

<table>
<thead>
<tr>
<th>Channel</th>
<th>BR</th>
<th>Resolution</th>
<th>S/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow bb$</td>
<td>0.58</td>
<td>10-15%</td>
<td>low</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>0.063</td>
<td>15-20%</td>
<td>med</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>0.0002</td>
<td>1-3%</td>
<td>low</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4$ leptons</td>
<td>2.7e-4</td>
<td>1-4%</td>
<td>high</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow 2l2\nu$</td>
<td>0.022</td>
<td>15%</td>
<td>med</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>0.002</td>
<td>0.8-2%</td>
<td>low</td>
</tr>
</tbody>
</table>

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**Plot Description:**

- **Higgs BR + Total Uncert:**
  - The plot illustrates the branching ratio (BR) of Higgs boson decays as a function of the Higgs boson mass ($M_H$) in GeV.
  - Channels include $bb$, $\tau\tau$, $\mu\mu$, $ZZ$, and $WW$.
  - The $Z\gamma$ channel is also shown.

- **Fermion and Gauge:**
  - The plot uses different colors to represent various fermion and gauge interactions.
  - The decay channels are color-coded for clarity.

- **S/B:**
  - The signal-to-background (S/B) ratio is indicated for each channel.
July 4th, 2012: Higgs boson discovery

- Fully reconstructed Higgs boson decay channels with excellent mass resolution drove the discovery.

- Peter Higgs and François Englert won the 2013 Nobel Prize in physics.

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Peter Higgs and François Englert won the 2013 Nobel Prize in physics. (Peter Higgs and François Englert are shown in the image.)

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Chris Palmer (Princeton)

BTV GoF - Hbb Observation in CMS

2 May 2019
The Importance of $H \rightarrow bb$

- The $H \rightarrow bb$ final state uniquely measures the coupling with down-type quarks
- Largest branching fraction $\sim 58\%$
  - Will drive total uncertainty of the total Higgs boson width and thus on the measurement of absolute couplings
  - Important for constraining BSM coupling of the Higgs.
Pre-LHC VHbb

LEP


Tevatron


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BTV GoF – Hbb Observation in CMS

2 May 2019
Expectations for (V)Hbb at LHC

- With backgrounds—like ttbar—growing faster than VHbb by:
  - 2.5 at 8 TeV
  - 8 at 13 TeV
- ttHbb was the most hopeful channel.
Expectations for (V)Hbb at LHC

- With backgrounds—like ttbar—growing faster than VHbb by:
  - 2.5 at 8 TeV
  - 8 at 13 TeV
- ttHbb was the most hopeful channel.

uncertainty of ± 5 %. on the shape of the Wb\bar{b} background in the H → b\bar{b} signal region. In conclusion, the extraction of a signal from H → b\bar{b} decays in the WH channel will be very difficult at the LHC, even under the most optimistic assumptions for the b-tagging performance and calibration of the shape and magnitude of the various background sources from the data itself.

— SNOWMASS-2001-P111

http://www.hep.ph.ic.ac.uk/~wstirlin
Jet substructure as a new Higgs search channel at the LHC

Jonathan M. Butterworth, Adam R. Davison
Department of Physics & Astronomy, University College London.

Mathieu Rubin, Gavin P. Salam
LPTHE; UPMC Univ. Paris 6; Univ. Denis Diderot; CNRS UMR 7589; Paris, France.

In this letter we investigate $VH$ production in a boosted regime, in which both bosons have large transverse momenta and are back-to-back. This region corresponds to only a small fraction of the total $VH$ cross section (about 5% for $p_T > 200$ GeV), but it has several compensating advantages: (i) in terms of acceptance, the

- Boosting has indeed been critical to LHC VHbb searches.
- Jet substructure is a powerful tool employed in CMS’s ggHbb search.

Evidence of VH(bb) at LHC

- VH(bb) evidence at LHC established with 2016 data by both ATLAS and CMS
- Detectors clearly demonstrated ability to deal with very high pile-up in such complex analyses
- Signal strength uncertainty ~40%

<table>
<thead>
<tr>
<th></th>
<th>signal strength</th>
<th>significance (exp)</th>
<th>significance (obs)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS Run 1</strong></td>
<td>0.52±0.40</td>
<td>2.6σ</td>
<td>1.4σ</td>
</tr>
<tr>
<td><strong>CMS Run 1</strong></td>
<td>0.89±0.47</td>
<td>2.5σ</td>
<td>2.1σ</td>
</tr>
<tr>
<td><strong>ATLAS+CMS Run 1</strong></td>
<td>0.79±0.29</td>
<td>3.7σ</td>
<td>2.6σ</td>
</tr>
<tr>
<td><strong>ATLAS 2015+2016</strong></td>
<td>1.20±0.42</td>
<td>3.0σ</td>
<td><strong>3.5σ</strong></td>
</tr>
<tr>
<td><strong>CMS 2016</strong></td>
<td>1.19±0.40</td>
<td>2.8σ</td>
<td><strong>3.3σ</strong></td>
</tr>
</tbody>
</table>

As in many searches for the Higgs boson, S/B is increases with the Higgs’ $P_T$.

Given the correlation between the $P_T$ of the $V$ and $H$, requiring $V$ to be transversely boosted gets into the most sensitive phasespace.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Boosting</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \nu\nu$ (0-lep)</td>
<td>$P_{T,Z} &gt; 170$ GeV</td>
</tr>
<tr>
<td>$W \rightarrow l\nu$ (1-lep)</td>
<td>$P_{T,W} &gt; 150$ GeV</td>
</tr>
<tr>
<td>$Z \rightarrow ll$ (2-lep)</td>
<td>$P_{T,Z} &gt; 150$ GeV $50 &lt; P_{T,Z} &lt; 150$ GeV</td>
</tr>
</tbody>
</table>
VHbb Backgrounds

- **ttbar**
  - Diagram showing quark and antiquark interactions

- **Z+jets**
  - Diagram showing parton-level processes

- **VV**
  - Diagram showing vector boson interactions

- **Single top**
  - Diagram showing top quark and antiquark interactions

- **W+jets**
  - Diagram showing W boson and jet interactions

2 May 2019
VHbb Analysis Strategy

- Start with boosted W or Z
- 3 channels with 0, 1, and 2 leptons and 2 b-tagged jets
  - Targeting Z(νν)H(bb), W(lν)H(bb), and Z(νν)H(bb) processes
- Signal region designed to increase S/B
  - Multivariate analysis exploiting the most discriminating variables (m_{bb}, P_{T,V}, b-tagging discriminator values)
- Control regions to validate analysis variables and control/constrain background normalizations
- Simultaneous fit of signal regions and control regions
  - Background normalization and signal extracted in one fit.

1-lepton channel

For 2-lepton channel use M_z veto

* Number of additional jets in the event
2017 analysis improvements

- Improved b-tagging
  - New pixel detector (additional barrel layer)
  - New algorithm (deep neural network)

- Improving mass resolution
  - Better b-jet energy regression
  - Introduction of kinematic fit in 2-lepton channel
  - Final state radiation (FSR) jet recovery

- Improved background discrimination in vector boson plus heavy flavor targeted control regions
Continuous effort to improve b-tagging algorithms

- New pixel detector, new algorithm with track-level info (DeepCSV)
- 2016 analysis was the same but used cMVA.
Some of the best

- Very well separated secondary vertices in our more signal-like events

Charged tracks and reconstructed vertices in a 0-lepton $H \rightarrow bb$ candidate event.
B-tagging efficiency measured in 2-lepton ttbar control region

Applied as a re-weighting per jet as function of $\eta$, $P_T$ and tagging score.

We validate these re-weightings in all of our control regions.
Improved energy regression for b-jets

- Improved energy regression for b-jets
- Inputs include jet kinematics and b-tagging variables
- Extended inputs: lepton flavor, energy rings, and more
- Switch from BDT to DNN algorithm

In 2-lepton channel kinematic fit using constraint of vector sum of transverse momentum being 0.

- Effectively constraining jet resolution using superior lepton resolution.
Validating mass resolution

- Regression validated using dedicated Z+1jet analysis
- 10% uncertainty applied (conservative)
- Visual validation using $p_{T, jj}/p_{T, ll}$ in 2-lepton system
- Data/MC is very good at each step
- Distribution narrows as expected with regression and kinematic fit.

**Resolution 10-13%**

<table>
<thead>
<tr>
<th>$p_T(V)$</th>
<th>#ISR Jets</th>
<th>$\sigma_{std}$</th>
<th>$\sigma_{reg}$</th>
<th>$\sigma_{fit}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 150</td>
<td>0</td>
<td>17.4</td>
<td>14.9</td>
<td>9.9</td>
</tr>
<tr>
<td>&gt; 150</td>
<td>1</td>
<td>17.9</td>
<td>15.4</td>
<td>12.4</td>
</tr>
<tr>
<td>&gt; 150</td>
<td>&gt; 1</td>
<td>18.9</td>
<td>15.9</td>
<td>14.4</td>
</tr>
</tbody>
</table>

No reg, no kin fit

B-jet reg, no kin fit

B-jet reg, kin fit

Chris Palmer (Princeton)

BTV GoF – Hbb Observation in CMS

2 May 2019
Heavy Flavor control region discriminators

- Reminder: leading systematic uncertainty from normalization of V+(b)b

- 2-lepton channel control region very pure
  - Fit b-tag shape (DeepCSV) to discriminate processes

- 0- and 1-lepton channel control regions less pure
  - Fit DNN multi-categorizer to distinguish among background components
  - Use same input variables as Signal vs Background discriminator
Signal vs Background discriminator

- DNN discriminator used to extract signal
- Input variables:
  - b-jet properties
  - H, V candidate kinematics
  - Carefully validated through data/MC comparisons
- Optimized separately in each channel
- Performance optimization with blind analysis

1-lepton ($\mu$)
Systematic uncertainties

- Total uncertainty ~34%, statistically dominated
- Major sources of systematic uncertainties from background normalization and modeling, b-tagging, MC sample size

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Statistical</strong></td>
<td>+0.26 -0.26</td>
</tr>
<tr>
<td>Normalization of backgrounds</td>
<td>+0.12 -0.12</td>
</tr>
<tr>
<td><strong>Experimental</strong></td>
<td>+0.16 -0.15</td>
</tr>
<tr>
<td>b-tagging efficiency and misid</td>
<td>+0.09 -0.08</td>
</tr>
<tr>
<td>V+jets modeling</td>
<td>+0.08 -0.07</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>+0.05 -0.05</td>
</tr>
<tr>
<td>Lepton identification</td>
<td>+0.02 -0.01</td>
</tr>
<tr>
<td>Luminosity</td>
<td>+0.03 -0.03</td>
</tr>
<tr>
<td>Other experimental uncertainties</td>
<td>+0.06 -0.05</td>
</tr>
<tr>
<td><strong>MC sample size</strong></td>
<td>+0.12 -0.12</td>
</tr>
<tr>
<td><strong>Theory</strong></td>
<td>+0.11 -0.09</td>
</tr>
<tr>
<td>Background modeling</td>
<td>+0.08 -0.08</td>
</tr>
<tr>
<td>Signal modeling</td>
<td>+0.07 -0.04</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>+0.35 -0.33</td>
</tr>
</tbody>
</table>
Validation: VZ(bb)

- VZ analysis using Z(bb) standard candle next to H(bb) peak

- Same “technology” used for VH(bb) fit
  - Same DNN inputs (but dedicated training), same Control Regions, VH(bb) normalized to SM and left free to float
  - Larger m(bb) window in Signal Region to fully include Z(bb) peak

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**Significance**

5.0σ expected

5.2σ observed

**Signal strength**

$\mu = 1.05 \pm 0.22$
Putting all 2017 channels together

- Discriminator (DNN) distributions with systematic uncertainties from signal extraction fit.
- Coarsely one can see that the data to simulation agreement is very good after fitting with shape systematics.

<table>
<thead>
<tr>
<th>Channel</th>
<th># Signal Regions</th>
<th># Control Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-lep</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>1-lep</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>2-lep</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>21</td>
</tr>
</tbody>
</table>

Chris Palmer (Princeton)
Putting all 2017 channels together

- Zooming into high sensitivity region.
- Overall visually compatible with S+B hypothesis.

Chris Palmer, Princeton

BTV GoF – Hbb Observation in CMS

2 May 2019
Results constitute standalone evidence for the VH\(bb\) process

<table>
<thead>
<tr>
<th>Data set</th>
<th>Expected</th>
<th>Observed</th>
<th>Signal strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-lepton</td>
<td>1.9</td>
<td>1.3</td>
<td>0.73 ± 0.65</td>
</tr>
<tr>
<td>1-lepton</td>
<td>1.8</td>
<td>2.6</td>
<td>1.32 ± 0.55</td>
</tr>
<tr>
<td>2-lepton</td>
<td>1.9</td>
<td>1.9</td>
<td>1.05 ± 0.59</td>
</tr>
<tr>
<td>Combined</td>
<td>3.1</td>
<td>3.3</td>
<td>1.08 ± 0.34</td>
</tr>
</tbody>
</table>

\[ \mu = 1.08 \pm 0.34 \]

\[ 3.3\sigma \]

\[ \mu = 1.08 \pm 0.26 \text{ (stat.)} \pm 0.23 \text{ (syst.)} \]
“Run 2”: 2016+2017 VHbb

- Combining with published 2016 results with 2017 VHbb
  (AKA “Run 2”)

- Cross-check mjj analysis
  - Categorize events with “mass-blind” DNN (four categories per channel)
  - Plot categories weighted by S/(S+B)

### Plot

**CMS Supplementary**

- Data
- Background
- VH,H→b\bar{b}
- Background uncertainty
- Signal + Background

**Observation in CMS**

- Combining with published 2016 results with 2017 VHbb
  (AKA “Run 2”)

- Cross-check mjj analysis
  - Categorize events with “mass-blind” DNN (four categories per channel)
  - Plot categories weighted by S/(S+B)

**4.4σ**

**μ = 1.06 ± 0.26**
“Run 2”: 2016+2017 VHbb

- Combining with published 2016 results with 2017 VHbb
- (AKA “Run 2”)

Cross-check mjj analysis

- Categorize events with “mass-blind” DNN (four categories per channel)

Plot categories weighted by $S/(S+B)$

CMS Supplementary

77.2 fb\(^{-1}\) (13 TeV)

Entries

$4.4\sigma$

$\mu = 1.06 \pm 0.26$

Data / Bkg
### Significance ($\sigma$)

<table>
<thead>
<tr>
<th>Data set</th>
<th>Expected</th>
<th>Observed</th>
<th>Signal strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>3.1</td>
<td>3.3</td>
<td>$1.08 \pm 0.34$</td>
</tr>
<tr>
<td>Run 2</td>
<td>4.2</td>
<td>4.4</td>
<td>$1.06 \pm 0.26$</td>
</tr>
<tr>
<td>Run 1 + Run 2</td>
<td>4.9</td>
<td>4.8</td>
<td>$1.01 \pm 0.23$</td>
</tr>
</tbody>
</table>

5.1 fb$^{-1}$ (7 TeV) + 18.9 fb$^{-1}$ (8 TeV) + 77.2 fb$^{-1}$ (13 TeV)

**Combined**

$4.8 \sigma$

$\mu = 1.01 \pm 0.23$

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**CMS**

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

- **Data**
- Background
- VH, $H \rightarrow b\bar{b}$
- Background uncertainty
- Signal + Background

---

**Observed**

- Run 2
  - $1.06 \pm 0.20$ (stat) ± $0.17$ (syst)
- 2016
  - $1.19 \pm 0.39$
- 2017
  - $1.08 \pm 0.34$
- Run 1
  - $0.89 \pm 0.38$ (stat) ± $0.24$ (syst)
- Combined
  - $1.01 \pm 0.17$ (stat) ± $0.14$ (syst)

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**Significance ($s$)**

- Run 2
  - 3.1
- 2016
  - 3.3
- 2017
  - 4.9
- Combined
  - 4.8

---

**Best fit $\mu$**

- Run 2
  - $0.89 \pm 0.38$ (stat) ± $0.24$ (syst)
- 2016
  - $1.19 \pm 0.39$
- 2017
  - $1.08 \pm 0.34$
- Combined
  - $1.01 \pm 0.17$ (stat) ± $0.14$ (syst)

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**Chris Palmer (Princeton)**

**BTV GoF – Hbb Observation in CMS**

2 May 2019
Combination of $H \rightarrow bb$ measurements

Theory uncertainties are correlated between all processes and data sets. (Most others uncorrelated)

**5.6σ (5.5σ)**

$\mu = 1.04 \pm 0.20$

**Observation of the $H \rightarrow bb$ decay**

by the CMS Collaboration

Chris Palmer (Princeton)
Combination of $H \rightarrow bb$ measurements

Dragons alone do not win the iron throne!

Chris Palmer (Princeton)
BTV GoF – Hbb Observation in CMS
Higgs’ Quest

- LEP (Geneva, Switzerland)
- Fermilab (Chicago, USA)

LEP Dismantling
November 2000

6 years

Tevatron Run II
In progress

Startup of LHC
2006 or later

Chris Tully, LEP Higgs Search Results @ Weak Interactions and Neutrinos Workshop 2002
As we approach precision higgs boson measurements, the LHC Higgs Cross Section Working Group devised a framework that should

1. Reduce the impact of theoretical uncertainties on CMS and ATLAS measurements
2. Improve the accessibility/utility of Higgs cross sections to theorists such that they can constrain their BSM models based on data.

Independent analysis bins are made in variables that are both useful for the analysis and so that theory systematic impact can be reduced.
CMS and ATLAS have both independently observed the decay of the Higgs boson with signal strength compatible with SM and 20% uncertainty.

In each case multiple production tag searches were combined with combo dominated by VHbb (~90% of sensitivity).

The Higgs boson’s Yukawa coupling to bottom quarks is firmly and directly established.

The shoulders of giants is a wonderful place to stand.

LEP and tevatron pioneered VHbb searches and their work deserves note and praise.

Of course none of this could be possible without the excellent performance of the LHC.
Thank you! Questions?
Higgs sector of SM Lagrangian

Why do Yukawa couplings matter?

(1) A part of the Higgs sector that’s unlike any other experimentally-probed interaction

\[ V(\phi) = -\mu^2 \phi^2 + \lambda \phi^4, \ \text{HHH} \]

the keystone of the Higgs mechanism and Standard Model, familiar as QFT toy model, never probed in nature

\[ D_m \phi^2 \]

(HWW, HZZ): A gauge interaction, with scalars rather than fermions; much like what we’ve seen before

\[ x_i y_{ij} x_j \phi \]

(Hbb, Htt, etc.): not a gauge interaction, and unlike anything we’ve probed before

G. Salam, LHCP ‘18
Using the same tunnel used for LEP in the 1990s.

Colliding protons (and heavier ions)

Build for finding the Higgs boson and discovering new particles up to the few TeV scale.
Excellent LHC performance in data delivery in Run 2

Running now at TWICE design rate!

CMS and ATLAS are able to reach numerous milestone measurements with 2016+2017 data.

~80 fb$^{-1}$ of recorded data for each experiment

The CMS Integrated Luminosity graph shows data included from 2010-03-30 11:22 to 2018-10-24 04:00 UTC.
Muons, electrons, b-jets, and missing energy are necessary components for the VHbb analysis.

Particle flow algorithm reconstructs all objects coherently.
**CMS Detector**

- **SCINTILLATING PbWO$_4$ CRYSTALS**
  - ~13000 tonnes
- **SILICON TRACKER**
  - Pixels (100 x 150 μm$^2$)
  - ~1m$^2$ ~66M channels
  - Microstrips (80-180μm)
  - ~200m$^2$ ~9.6M channels
- **STEEL RETURN YOKE**
- **HADRON CALORIMETER (HCAL)**
  - Brass + plastic scintillator
  - ~7k channels
- **SILICON TRACKER**
  - Pixels (100 x 150 μm$^2$)
  - ~1m$^2$ ~66M channels
  - Microstrips (80-180μm)
  - ~200m$^2$ ~9.6M channels
- **FORWARD CALORIMETER**
- **SUPERCONDUCTING SOLENOID**
  - Niobium-titanium coil
  - carrying ~18000 A
- **CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
  - ~76k scintillating PbWO$_4$ crystals
- **PRESHOWER**
  - Silicon strips
  - ~16m$^2$ ~137k channels

**CMS Detector**

- **Pixels**
- **Tracker**
- **ECAL**
- **HCAL**
- **Solenoid**
- **Steel Yoke**
- **Muons**

**Upgrades**

- **2017**
  - Outer rings
  - Inner rings
- **2016**
  - Inner rings

**Announcement**

- BTV GoF – Hbb Observation in CMS
- 2 May 2019

Chris Palmer (Princeton)
- Each particle’s coupling is proportional to its mass.
- Gauge/Yukawa for bosons/fermions
- Combination of big five (+μμ) yields bosonic and fermionic Higgs boson couplings within 1σ of SM expectations.

![Diagram showing Higgs couplings (LHC Run 1)]
Higgs boson summary

Properties
- Spin 0 / parity + (SM)
- Signal strength near SM expectations (1.09±0.11)
- SM compatible couplings
- Mass precision of 0.2%

Established Higgs production
- Gluon fusion
- Vector boson fusion
- VH (2018!)
- ttH (2018!)

Established Higgs decays
- ZZ, γγ, WW (Run 1)
- ττ (2017)
- bb (2018!)
For low Higgs masses $bb$ is the dominant decay channel.
Combined with $\tau \tau$ and WW channels, the mass of the Higgs boson was excluded less than 114.4 GeV at 95% confidence level.
D0 and CDF combined analyses very similar to those performed at LHC to provide the first hints of this process.

- Sharpen the mass resolution
- Multi-variate discriminant

The hbb searches are the most significant components of the final combination with WW and $\tau\tau$.

More proton-proton collisions

More instantaneous luminosity means more collisions per crossing

Run 2 and Run 3 have between 20-50 simultaneous pp collisions

Like top left

At HL-LHC it will be more like 100-200.

The right plot is from a special high “pile-up” fill with luminosity more like HL-LHC.

Chris Palmer (Princeton)
Further CMS Hbb Searches

- Trigger strategies based on two b-jets are overwhelmed by QCD and ttbar backgrounds at LHC.

- All Hbb analyses in CMS are based (at least in part) on other decay products recoiling against the Higgs boson.
Higgs properties measurements

- How SM is this Higgs boson?
- Using only 4-lepton events with full Run 1 dataset, the favored spin-parity was clear.
- SM: $0^+$
Observations of lepton coupling

- Tree-level lepton coupling to Higgs boson observed in CMS with Higgs to $\tau\tau$ search!
- 2016 data plus Run 1 combination: 5.9$\sigma$ observed

Chris Palmer (Princeton)
BTV GoF – Hbb Observation in CMS
2 May 2019
ttH Production Observed!

The news of the past 12 months

A few weeks ago:
CMS >5-sigma ttH

This week:
ATLAS >5-sigma ttH
The volume of background events is a bit staggering.
The transverse momentum of the vector boson is one of the more important variables in this analysis.

\[ P_{T,V} \text{-dependent electroweak correction uncertainties on signal and background} \]

In W+Jets (Madgraph) and ttbar (Powheg) \( P_{T,W} \) must be corrected.

Empirical approaching: derive correction by fitting data/MC in control regions.

The size of V+Jets samples in the highest \( P_{T,V} \) bins are limited.

Normalization uncertainties impacted.
Heavy Flavor control region discriminators

- Reminder: leading systematic uncertainty from normalization of V+(b)b

- 2-lepton channel control region very pure
  - Fit b-tag shape (DeepCSV) to discriminate processes

- 0- and 1-lepton channel control regions less pure
  - Fit DNN multi-categorizer to distinguish among background components
  - Use same input variables as Signal vs Background discriminator

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Chris Palmer (Princeton)

BTV GoF - Hbb Observation in CMS

2 May 2019
For the triggers focus on the vector boson decay products

0-lepton (targeting $Z \rightarrow \nu \nu$)
- Large missing transverse energy or missing hadronic energy (only jets)

1-lepton (targeting $W \rightarrow l \nu$)
- Single lepton triggers

2-lepton (targeting $Z \rightarrow ll$)
- Double lepton triggers

Offline selection mirrors online

<table>
<thead>
<tr>
<th>Channel</th>
<th>Online</th>
<th>Offline</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-lepton (MET)</td>
<td>120 GeV</td>
<td>170 GeV</td>
</tr>
<tr>
<td>1-muon</td>
<td>22 GeV</td>
<td>25 GeV</td>
</tr>
<tr>
<td>1-electron</td>
<td>32 GeV</td>
<td>30 GeV</td>
</tr>
<tr>
<td>2-muons</td>
<td>17,8</td>
<td>20,20</td>
</tr>
<tr>
<td>2-electrons</td>
<td>23,12</td>
<td>25,20</td>
</tr>
</tbody>
</table>
Background normalizations

- After fitting control regions and signal regions the following scale factors are derived per process per channel.

- Fitting control regions only yield very similar results.

- Note: TTbar and V+light flavor control regions are fit to yield only

<table>
<thead>
<tr>
<th>Process</th>
<th>$Z(\nu\nu)H$</th>
<th>$W(\ell\nu)H$</th>
<th>$Z(\ell\ell)H$ low-$p_T$</th>
<th>$Z(\ell\ell)H$ high-$p_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W + udscg$</td>
<td>$1.04 \pm 0.07$</td>
<td>$1.04 \pm 0.07$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$W + b$</td>
<td>$2.09 \pm 0.16$</td>
<td>$2.09 \pm 0.16$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$W + b\bar{b}$</td>
<td>$1.74 \pm 0.21$</td>
<td>$1.74 \pm 0.21$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$Z + udscg$</td>
<td>$0.95 \pm 0.09$</td>
<td>$-$</td>
<td>$0.89 \pm 0.06$</td>
<td>$0.81 \pm 0.05$</td>
</tr>
<tr>
<td>$Z + b$</td>
<td>$1.02 \pm 0.17$</td>
<td>$-$</td>
<td>$0.94 \pm 0.12$</td>
<td>$1.17 \pm 0.10$</td>
</tr>
<tr>
<td>$Z + b\bar{b}$</td>
<td>$1.20 \pm 0.11$</td>
<td>$-$</td>
<td>$0.81 \pm 0.07$</td>
<td>$0.88 \pm 0.08$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$0.99 \pm 0.07$</td>
<td>$0.93 \pm 0.07$</td>
<td>$0.89 \pm 0.07$</td>
<td>$0.91 \pm 0.07$</td>
</tr>
</tbody>
</table>
Normalizations factors are generally independent per channel. They float freely just like the signal strength.

Uncertainties on the heavy flavor components come both from the size of the V+Jets samples and from systematic errors on kinematics of vector boson.

Example 2-muon, high $p_T$ channel.

- Data
- ZH(b$\bar{b}$) 125
- ggZH(b$\bar{b}$) 125
- Z + b$\bar{b}$
- Z + b
- VVHF
- VVLF
- Single top
- VH(bb) 125
- MC Unc. (Stat.)
- MC Unc. (Stat. + Postfit Syst.)

BDT Output

$\chi^2$/dof = 0.73
MC Unc. (Stat.)
MC Unc. (Stat. + Postfit Syst.)

Example 2-muon, high $p_T$ channel.

Chris Palmer (Princeton)
Putting all 2016 channels together

Discriminator (BDT) distributions that are fit with control regions.

Coarsely one can see that the data to simulation agreement is very good after the fitting with shape systematics.

<table>
<thead>
<tr>
<th>Channel</th>
<th># Signal Regions</th>
<th># Control Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-lep</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>1-lep</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>2-lep</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>23</td>
</tr>
</tbody>
</table>
Putting all 2016 channels together

¬ Zooming into high sensitivity region.

¬ Overall visually compatible with S+B hypothesis.

2-lepton

1-lepton

0-lepton

BDT bins converted into S/B bins and summed
Validating with VZbb in 2016

- Take advantage of similar process with much larger cross section.
- Shift mass window down to Z
- Strikingly consistent!

<table>
<thead>
<tr>
<th>Channels</th>
<th>Signal strength observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-lepton</td>
<td>0.57 ± 0.32</td>
</tr>
<tr>
<td>1-lepton</td>
<td>1.67 ± 0.47</td>
</tr>
<tr>
<td>2-lepton</td>
<td>1.33 ± 0.34</td>
</tr>
<tr>
<td>Combined</td>
<td>1.02 ± 0.22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channels</th>
<th>Significance expected</th>
<th>Significance observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-lepton</td>
<td>3.1</td>
<td>2.0</td>
</tr>
<tr>
<td>1-lepton</td>
<td>2.6</td>
<td>3.7</td>
</tr>
<tr>
<td>2-lepton</td>
<td>3.2</td>
<td>4.5</td>
</tr>
<tr>
<td>Combined</td>
<td>4.9</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Significance
2.8σ expected
3.3σ observed!

Signal strength relative to SM
\[ \mu = 1.19^{+0.21}_{-0.20} \text{(stat)}^{+0.34}_{-0.32} \text{(syst)} \]
Fair compatibility between channels in the VH fits

- the 3 channels are contributing almost equally to sensitivity

<table>
<thead>
<tr>
<th>Channels</th>
<th>Significance expected</th>
<th>Significance observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-lepton</td>
<td>1.5</td>
<td>0.0</td>
</tr>
<tr>
<td>1-lepton</td>
<td>1.5</td>
<td>3.2</td>
</tr>
<tr>
<td>2-lepton</td>
<td>1.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Combined</td>
<td>2.8</td>
<td>3.3</td>
</tr>
</tbody>
</table>

The probability for these channels to be compatible with the combined $\mu$ is 6%.