Analysis of Higgs bosons decaying to two photons at CMS

L. D. Corpe

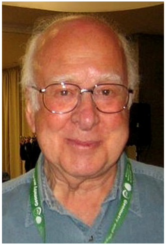
Imperial College London
Blackett Laboratory
London

PG Initial Report Talks, 2014

Outline

1. Introduction
   - The SM Higgs Boson
   - LHC, CMS and ECAL
2. $H \to \gamma\gamma$
   - Photon and Vertex Identification
   - Event Categorisation and Analysis
3. Outlook and future work

The Standard Model Higgs boson
History



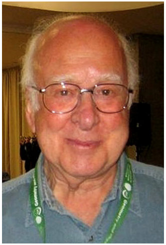
The authors of the "1964 PRL symmetry breaking papers" won the Sakurai Prize in 2010. Higgs and

Englert won the Nobel prize in 2013. Left: Kibble, Guralnik, Hagen, Englert,

Brout. Right: Higgs

The Higgs mechanism was independently formulated various theorists in 1964. Explains mass of $W^{\pm}$ and Z bosons via symmetry breaking in the electroweak interaction. Crucially, gauge invariance is conserved. Main properties of SM Higgs:

The Standard Model Higgs boson
History



The authors of the "1964 PRL symmetry breaking papers" won the Sakurai Prize in 2010. Higgs and

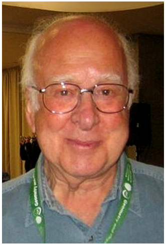
Englert won the Nobel prize in 2013. Left: Kibble, Guralnik, Hagen, Englert,

Brout. Right: Higgs

The Higgs mechanism was independently formulated various theorists in 1964. Explains mass of $W^{\pm}$ and Z bosons via symmetry breaking in the electroweak interaction. Crucially, gauge invariance is conserved. Main properties of SM Higgs:

- Massive and observable. Now known to be $\sim$ 125 GeV.

The Standard Model Higgs boson
History



The authors of the "1964 PRL symmetry breaking papers" won the Sakurai Prize in 2010. Higgs and

Englert won the Nobel prize in 2013. Left: Kibble, Guralnik, Hagen, Englert,

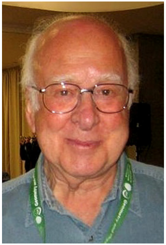
Brout. Right: Higgs

The Higgs mechanism was independently formulated various theorists in 1964. Explains mass of $W^{\pm}$ and Z bosons via symmetry breaking in the electroweak interaction. Crucially, gauge invariance is conserved. Main properties of SM Higgs:

- Massive and observable. Now known to be $\sim$ 125 GeV.
- Couples to particles proportional to their mass.

The Standard Model Higgs boson

History



The authors of the “1964 PRL symmetry breaking papers” won the Sakurai Prize in 2010. Higgs and

Englert won the Nobel prize in 2013. Left: Kibble, Guralnik, Hagen, Englert,

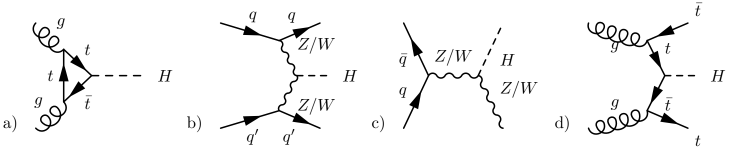
Brout. Right: Higgs

The Higgs mechanism was independently formulated various theorists in 1964. Explains mass of $W^{\pm}$ and Z bosons via symmetry breaking in the electroweak interaction. Crucially, gauge invariance is conserved. Main properties of SM Higgs:

- Massive and observable. Now known to be $\sim$ 125 GeV.
- Couples to particles proportional to their mass.
- Only one Higgs boson in SM, while other BSM theories predict more.

The Standard Model Higgs boson
Production and decay at LHC

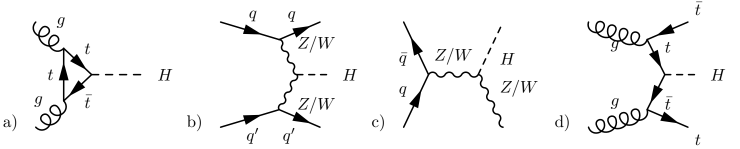
- H couples to particles $\propto$ m, so main production modes at LHC are:



a) gg fusion via t loop, b) Vector Boson Fusion (VBF), c) Assoc. Z, W production, d) Assoc. $t\bar{t}$ production.

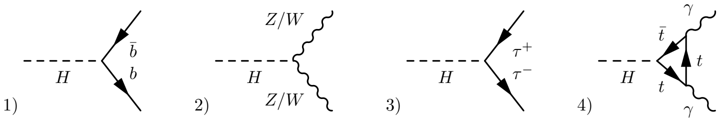
The Standard Model Higgs boson
Production and decay at LHC

- H couples to particles $\propto m$, so main production modes at LHC are:



a) gg fusion via t loop, b) Vector Boson Fusion (VBF), c) Assoc. Z, W production, d) Assoc. $t\bar{t}$ production.

- By the same token, it decays mostly to heavy particles:

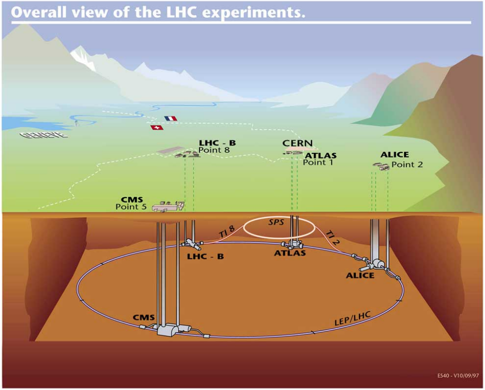


Decay to 1) $b\bar{b}$ pair, 2) vector boson pair, 3) τ^+, τ^-, 4) two photons via t loop (can also be W).

- t, $\bar{t}$ pair kinematically forbidden. $H \rightarrow \gamma\gamma$ is rare, but one of the most sensitive channels at the LHC.

LHC, CMS and the ECAL

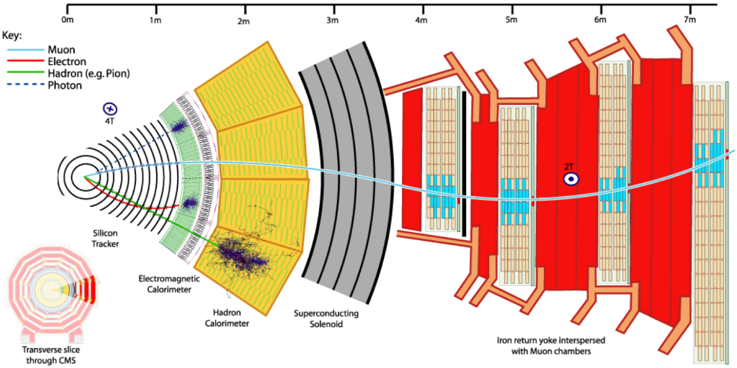
The Large Hadron Collider



- The LHC is a 27km circumference synchrotron at CERN, as explained by my colleagues.

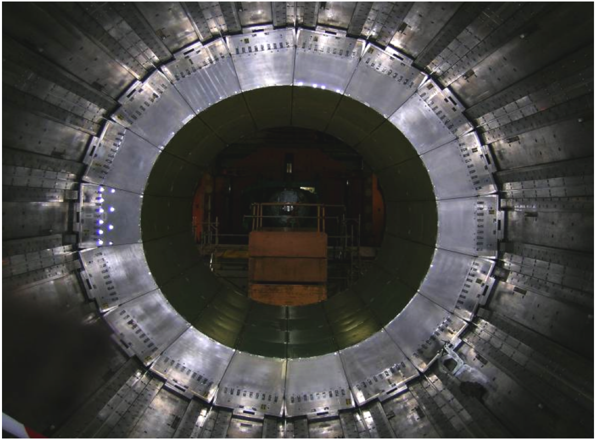
LHC, CMS and the ECAL

The Compact Muon Solenoid



- Explained already by previous talks - I will focus on ECAL layer.

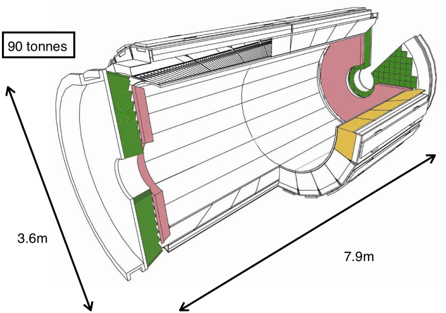
LHC, CMS and the ECAL
The Electromagnetic Calorimeter



A view of the inside of the ECAL Barrel.

LHC, CMS and the ECAL
The Electromagnetic Calorimeter

The CMS ECAL is composed of an array of $PbWO_4$ crystals.
The Crystals are offset by an angle of 3^o from the vertex to avoid particles going through the gaps in between.



- 62,100 crystals in 36 supermodules
- Supermodule containing 4 modules
- Endcaps containing 14,648 crystals
- Preshower for π^0 ID.

Photon and Vertex Identification

Initial event selection and mass reconstruction

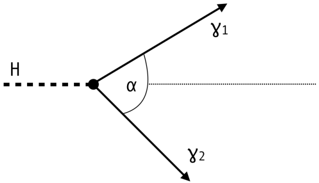
- Initial trigger identifies γs from ECAL isolation and shower shape. A loose E_T cut is also made, although a tougher one is imposed later to find Higgs decay candidates.

Photon and Vertex Identification

Initial event selection and mass reconstruction

- Initial trigger identifies γs from ECAL isolation and shower shape. A loose E_T cut is also made, although a tougher one is imposed later to find Higgs decay candidates.
- Higgs mass reconstructed using the following formula (simple 4-momentum conservation):

$$m_H = m_{\gamma\gamma} = \sqrt{2E_{\gamma 1}E_{\gamma 2}(1 - \cos\alpha)}$$

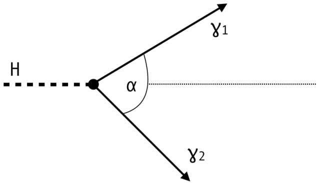


Photon and Vertex Identification

Initial event selection and mass reconstruction

- Initial trigger identifies γs from ECAL isolation and shower shape. A loose E_T cut is also made, although a tougher one is imposed later to find Higgs decay candidates.
- Higgs mass reconstructed using the following formula (simple 4-momentum conservation):

$$m_H = m_{\gamma\gamma} = \sqrt{2E_{\gamma 1}E_{\gamma 2}(1 - \cos\alpha)}$$



- $E_{\gamma 1}, E_{\gamma 2}$ dominate mass resolution if primary interaction vertex is identified. Thankfully ECAL has excellent E resolution.
- However, diphoton interaction vertex must be correctly identified to measure α.

Photon and Vertex Identification

Vertex ID and Pair Conversion

- If the diphoton vertex is reconstructed with 10mm of true position then the mass resolution is dominated by the E_γ resolution.

Photon and Vertex Identification

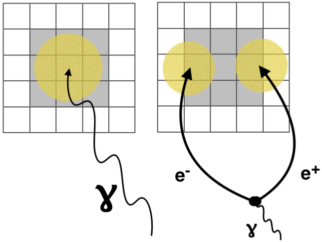
Vertex ID and Pair Conversion

- If the diphoton vertex is reconstructed with 10mm of true position then the mass resolution is dominated by the E_γ resolution.
- A BDT is used to identify vertex using kinematic properties as inputs. Also makes use of extra information from tracker if γ has converted to e^+e^-.

Photon and Vertex Identification

Vertex ID and Pair Conversion

- If the diphoton vertex is reconstructed with 10mm of true position then the mass resolution is dominated by the E_γ resolution.
- A BDT is used to identify vertex using kinematic properties as inputs. Also makes use of extra information from tracker if γ has converted to e^+e^-.
- We can tell if γ has converted using $R_9 \equiv \frac{E_{3x3}}{E_{SuperCluster}} < 0.94$.



- If γ hits, most of the energy is deposited within 3x3 array, so $E_{3x3} \simeq E_{5x5}$ so $R_9 \simeq 1$
- If γ has converted, less energy will be focused within 3x3, so $R_9 < 1$

Photon and Vertex Identification

Higgs decay candidates

- Not all diphoton events are of interest! We only want those which are Higgs decay candidates.
- Higgs decay photons should be highly energetic, so impose:

$$E^{T}_{\gamma 1} > \frac{m_{\gamma\gamma}}{3} \text{ and } E^{T}_{\gamma 2} > \frac{m_{\gamma\gamma}}{4}$$

- A further BDT is used to remove “non-prompt” photons and particles misidentified as photons, as they are of no interest.

Event Categorisation and Analysis

- Events are segmented into categories based on expected signal to background ratio and mass resolution using a BDT.
- This increases the overall sensitivity of the analysis.
- The background is modelled using data rather than Monte Carlo.

Event Categorisation and Analysis

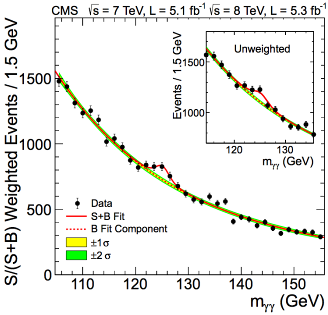
- Events are segmented into categories based on expected signal to background ratio and mass resolution using a BDT.
- This increases the overall sensitivity of the analysis.
- The background is modelled using data rather than Monte Carlo.
  - For each category, the $m_{\gamma\gamma}$ distribution is fitted. Candidate fitting functions include exponentials, power laws, Bernsteins (polynomials) and Laurent series.

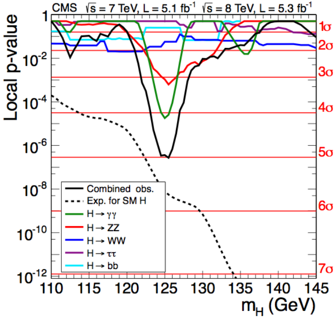
Event Categorisation and Analysis

- Events are segmented into categories based on expected signal to background ratio and mass resolution using a BDT.
- This increases the overall sensitivity of the analysis.
- The background is modelled using data rather than Monte Carlo.
  - For each category, the $m_{\gamma\gamma}$ distribution is fitted. Candidate fitting functions include exponentials, power laws, Bernsteins (polynomials) and Laurent series.
  - Fitting function chosen based on bias minimisation. Bias is negligible for all categories when Bersteins of order 3-5 (depending on category) are used.

Analysis

- The mass distribution is plotted for each category and compared to the background prediction. The categories are then combined to form the global analysis.
- In 2012, this method yielded an observed local significance of 4σ at $\sim$ 125 GeV. Combined with other analyses, the total local significance was 5σ, allowing a discovery to be claimed by CMS (and ATLAS).





Outlook

- A final legacy paper using all data from run 1 is being prepared, currently under approval.

Outlook

- A final legacy paper using all data from run 1 is being prepared, currently under approval.
- In 2015, the LHC will re-start collisions, hopefully ramping up towards design value of 14 TeV.

Outlook

- A final legacy paper using all data from run 1 is being prepared, currently under approval.
- In 2015, the LHC will re-start collisions, hopefully ramping up towards design value of 14 TeV.
- This will allow more precise measurements of couplings, differential cross-sections and J^P.

Outlook

- A final legacy paper using all data from run 1 is being prepared, currently under approval.
- In 2015, the LHC will re-start collisions, hopefully ramping up towards design value of 14 TeV.
- This will allow more precise measurements of couplings, differential cross-sections and J^P.
- Any deviation from the SM could yield insight on nature or existence of BSM physics, e.g. a 2nd Higgs, or increased cross-section due to heavy BSM particles.

Outlook

- A final legacy paper using all data from run 1 is being prepared, currently under approval.
- In 2015, the LHC will re-start collisions, hopefully ramping up towards design value of 14 TeV.
- This will allow more precise measurements of couplings, differential cross-sections and J^P.
- Any deviation from the SM could yield insight on nature or existence of BSM physics, e.g. a 2nd Higgs, or increased cross-section due to heavy BSM particles.
- For first time in history, we have found what we believe to be a scalar fundamental particle. Implications unclear.

Outlook

- A final legacy paper using all data from run 1 is being prepared, currently under approval.
- In 2015, the LHC will re-start collisions, hopefully ramping up towards design value of 14 TeV.
- This will allow more precise measurements of couplings, differential cross-sections and J^P.
- Any deviation from the SM could yield insight on nature or existence of BSM physics, e.g. a 2nd Higgs, or increased cross-section due to heavy BSM particles.
- For first time in history, we have found what we believe to be a scalar fundamental particle. Implications unclear.
- Although we have found the H, further studies are not only desirable but imperative.

Questions

Thanks for listening!
Questions?