Higgs decay into a pair of Z bosons

A particle physics analysis using the 13TeV ATLAS Open Data release

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Outline

Motivation

- Higgs boson discovery was a remarkable milestone for particle physics.
- It was the missing piece to complete the **Standard Model** (a 48-year-long journey!).
- It taught us how to search for **new physics** at particle colliders.

Higgs mechanism in a nutshell

- The **Electroweak model** is based on the SU(2)$_L \times$U(1)$_Y$ gauge symmetry:

$$\mathcal{L}_{EW} = i\bar{\Psi}_L\gamma^\mu D_\mu \Psi_L + i\bar{\psi}_R\gamma^\mu D'_\mu \psi_R - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2}Tr[W_{\mu\nu}W^{\mu\nu}] \quad (1)$$

Where $D_\mu = \partial_\mu + igT^iW^i_\mu + ig'YB_\mu = igT^iW^i_\mu + D'_\mu$, is the covariant derivative.

- Two extra-terms are introduced to give mass to particles **without spoiling** the gauge symmetry:

$$\mathcal{L}_{Higgs} = (D^\mu\Phi)(D_\mu\Phi)^\dagger - V(\Phi^\dagger\Phi), \quad -\mathcal{L}_{Yukawa} = \bar{\Psi}_L\Phi\psi_R + h.c.$$

With Φ a complex scalar doublet, the **Higgs field**.

- But... where are the mass terms?
$\rightarrow$ After **spontaneous symmetry breaking (SSB)**:

$$\text{SU}(2)_L\times\text{U}(1)_Y \Longrightarrow \text{U}(1)_{EM}$$

Higgs mechanism in a nutshell

The **Higgs potential** in $\mathcal{L}_{Higgs}$ is given by:

$$V(\Phi^\dagger\Phi) = -\rho^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 \qquad (2)$$

With $\rho^2 > 0$ and $\lambda > 0$.

SSB arised from the choice of the unitary gauge ($v = \sqrt{\rho^2/\lambda}$):

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \qquad (3)$$

Considering just the cuadratic terms in vector bosons fields (from $\mathcal{L}_{Higgs}$):

$$\mathcal{L}_{m_V} = \frac{g^2v^2}{4}W^+_\mu W^{\mu-} + \frac{(g^2+g'^2)^2v^2}{8}Z_\mu Z^\mu + (0)A_\mu A^\mu \qquad (4)$$

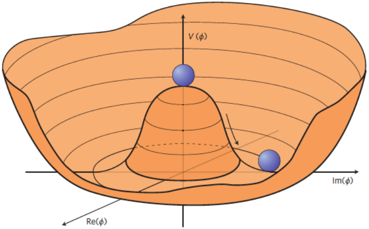

Figure 1: Higgs mechanism picture.

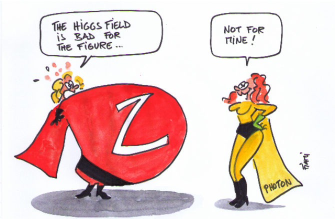

Figure 2: Z boson and photon cartoon.

Higgs and Z couplings

Other terms from $\mathcal{L}_{Higgs}$ are:

$$\mathcal{L}_{H,HV} = \frac{1}{2}(\partial_\mu H)^2 - \lambda v^2 H^2 + 4gH\left(M_W W_\mu^+ W^{\mu -} + \frac{M_Z}{2\cos\theta_W} Z_\mu Z^\mu\right) \quad (5)$$

Thus, from the above term and the Yukawa term, the **Higgs boson** has couplings to all the particles to which it gives mass:

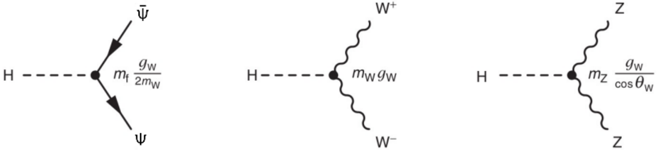

Figure 3: Feynmann diagrams for Higgs boson couplings.

On the other hand, **Z boson** couples to neutral currents:

$$\mathcal{L}_{int}^Z = \frac{-e}{2\sin\theta_W\cos\theta_W} Z_\mu \bar{\Psi}\gamma^\mu (V_f - A_f\gamma_5)\Psi \quad (6)$$

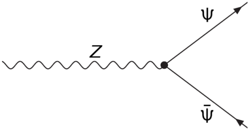

Figure 4: Z boson coupling to fermions.

Higgs production at ATLAS

- ATLAS is one of the 4 major experiments at the LHC.
- Proton-proton collisions take place in the LHC (a 27km circumference collider).
- ATLAS detector has a cylindrical shape.
- The Higgs boson is produced in the following modes:

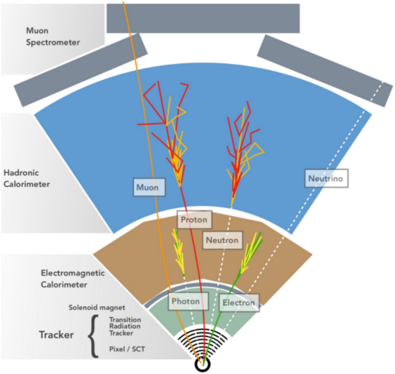

Figure 5: ATLAS detector slice.

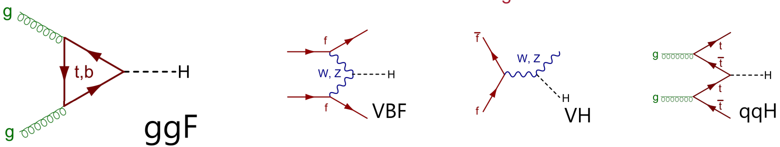

Figure 6: Higgs boson production modes.

Physics analysis: $H \to ZZ$ at ATLAS

- Let's consider the Higgs boson decay $H \to ZZ \to 4\ell$:

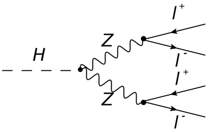

Figure 7: Feynman diagram of the Higgs boson decay to 4 leptons.

- The Higgs invariant mass can be computed as:

$$m_H = \sqrt{(E_{\ell_1} + E_{\ell_2} + E_{\ell_3} + E_{\ell_4})^2 - |\vec{p}_{\ell_1} + \vec{p}_{\ell_2} + \vec{p}_{\ell_3} + \vec{p}_{\ell_4}|^2} \qquad (7)$$

- Energy is measured in the calorimeters.
- Momentum is measured in the tracker.
- Pseudorapidity:

$$\eta = -\ln|\tan(\theta/2)| \qquad (8)$$

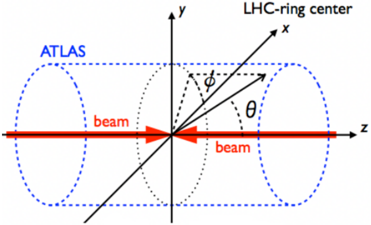

Figure 8: Lab frame at ATLAS.

Physics analysis: $H \rightarrow ZZ$ at ATLAS

- Data for the analysis was taken from the 13 TeV ATLAS Open Data release (2020).
- Because of the 4-lepton final state, variables were taken from the "**4lep**" sample (Data and Monte Carlo background).
- "Data" refers to the actual measurements (Run 2-2016), whereas "Monte Carlo background" refers to simulations.
- The MC background for $H \rightarrow ZZ$ corresponds to simulated processes whose final state is also a 4-lepton signal:

  \- **ZZ**, Z+jets, $t\bar{t}$, and single-top.
- The expected signal for the **Higgs boson** was simulated by its production modes.
- **Lepton** variables used:

  E, p_T, η, ϕ, charge, flavour, "$p_T cone30$" and "$etcone20$".
- **Tracker isolation**: $p_T cone30/p_T$
- **Calorimeter isolation**: $etcone20/p_T$

Final event-selection criteria and results

Based on the "Python uproot framework", it was implemented an analysis using **Google Colab**. The event-selection criteria was:

- Lepton trigger (e or μ) satisfied.
- "Loose lepton":
  - Tracker isolation (<0.3).
  - Calorimeter isolation (<0.3).
  - $|\eta| < 2.5$ for muons.
  - $|\eta| < 1.37$ and $1.52 < |\eta| < 2.47$ for electrons.
- Exactly four leptons with p_T >25GeV, 15GeV, 10GeV, and 7GeV respectively.
- Two pairs of same-flavour and opposite-charge leptons.

Statistics:

- Signal efficiency: $S/B \approx 0.70$
- Purity: $S/(S+B) \approx 0.41$

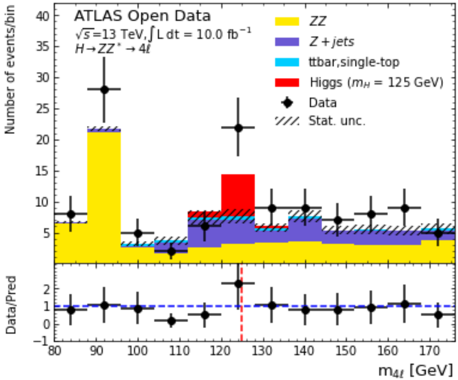

Figure 9: Four-lepton invariant mass distribution for selected events.

https://github.com/bcastiblancoo/HZZ-Analysis-13TeV-ATLAS-Open-Data

Conclusions

- An **excess of events** for the 4-lepton invariant mass was found around $m_{4\ell} \approx 125$ GeV, which agrees with the prediction of the **Higgs boson**.
- The **signal efficiency** was approximately 70%, and its **purity** about 41%.
- The main contribution for the background came from the ZZ process.
- A **notebook** in google colab was developed to analyze the data, optimizing the processing time. It can be modified and applied to other processes.

References I

[1] ATLAS Collaboration et al. **Review of the 13 TeV ATLAS Open Data release**. Tech. rep. Tech. Rep. ATLOREACH-PUB-2020-001, 2020.

[2] Valery Rubakov. **Classical theory of gauge fields**. Princeton University Press, 2009.

[3] Figures 1-5, and 8 were taken from:
CERN Document Server (https://cds.cern.ch)

[4] Images in Figure 6 were taken from:
https://commons.wikimedia.org/wiki/File:Higgs-gluon-fusion.svg
https://commons.wikimedia.org/wiki/File:Higgs-Higgsstrahlung.svg
https://commons.wikimedia.org/wiki/File:Higgs-WZ-fusion.svg
https://commons.wikimedia.org/wiki/File:Higgs-tt-fusion.svg

[5] Figure 7 is a free license image.

Thank you

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Appendix

Some more plots:

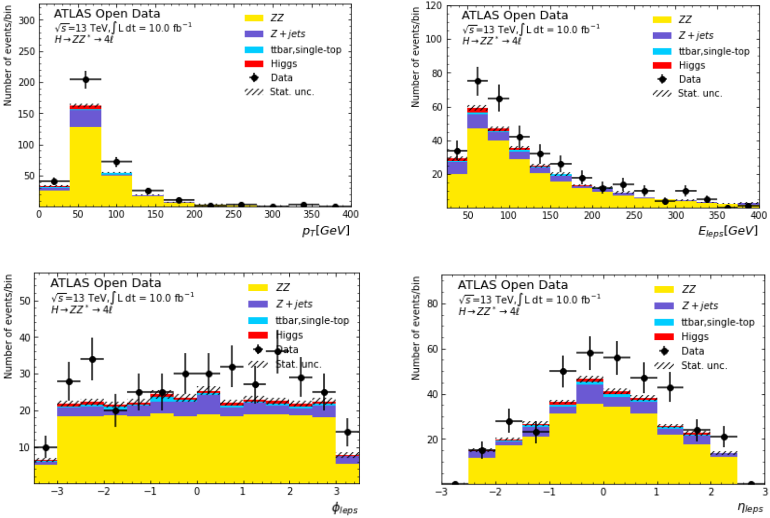

Figure 10: Distribution plots of lepton kinematic variables.

Appendix

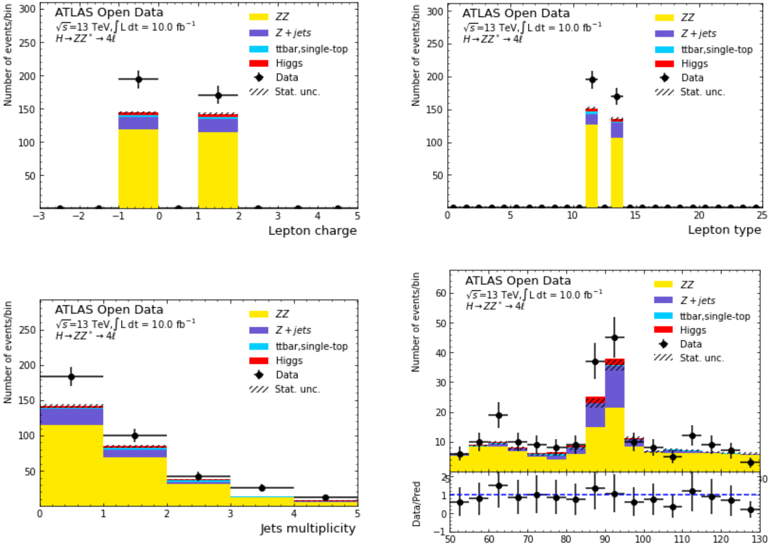

Figure 11: Distribution plots for other variables.