

The case of Higgs boson
production in $H \rightarrow ZZ^*$ decay
Introduction to the Particle Physics Data
Analysis

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That's us!



Figure: That's Aleksandra P and Aleksandra K!

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Physics motivation



The physics motivation for the measurement:

- a good test for the SM,
- a measurement of inclusive and differential fiducial cross sections,
- test of perturbative QCD calculations.

The Feynman diagram

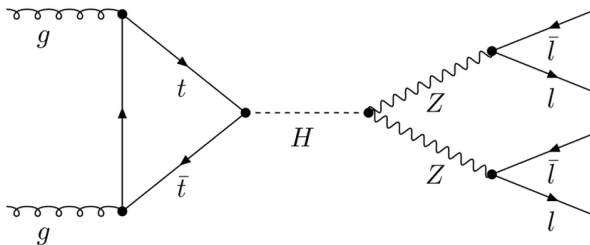


Figure: Feynman diagram for $H \rightarrow ZZ^* \rightarrow 4\ell$ decay [3].

Event selection

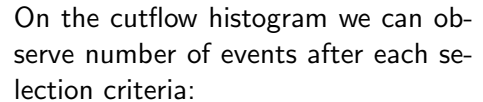


The final event-selection criteria for ZZ^* production:

- single-electron or single-muon trigger satisfied,
- exactly four leptons (electrons or muons) with $p_T > 25, 15, 10, 7 \text{ GeV}$, respectively,
- Higgs-boson candidates are formed by selecting two *SFOS* lepton pairs,
- the leading pair is defined as the *SFOS*¹ pair with the mass $m_{\ell\ell,1}$ closest to the Z boson mass m_Z , and the subleading pair is defined as the *SFOS* pair with the mass $m_{\ell\ell,1}$ second closest to m_Z [1].

¹*SFOS* - Same Flavour, Opposite Charge

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- S1 - single-electron or single-muon trigger satisfied,
- S2 - four leptons with $p_T > 25, 15, 10, 7 \text{ GeV}$,
- S3 - two SFOS lepton pairs.

Expected number of events



Expected number of events equals:

$$N_{exp}^{H \rightarrow ZZ^* \rightarrow 4\ell} = \sigma_{incl}^{H \rightarrow ZZ^* \rightarrow 4\ell} \cdot L_{int}, \quad (1)$$

where:

$$\sigma_{incl}^{H \rightarrow ZZ^* \rightarrow 4\ell} = 3,62 \text{ fb}^{-1},$$

$$L_{int} = 10,06 \text{ fb}^{-1}.$$

$$N_{exp}^{H \rightarrow ZZ^* \rightarrow 4\ell} = 3.62 \text{ fb} \cdot 10.06 \text{ fb}^{-1} = 36.42. \quad (2)$$

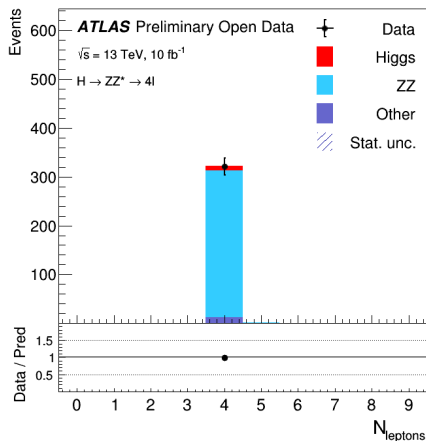
Background contributions



Processes constituting background of our analysis:

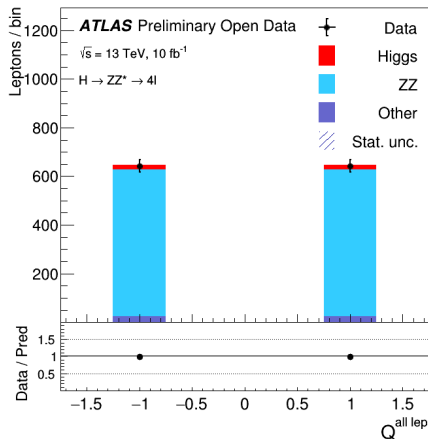
- non-resonant SM ZZ^* production,
- $t\bar{t}$ production,
- Z +jets production.

Number of Leptons



This histogram contains the number of leptons after all selection criteria. We can observe four leptons.

Charge of selected leptons



On the histogram we can observe agreement with the selection criteria. The same amount of leptons of opposite charges was selected.

Pseudorapidity and azimuthal angle of selected leptons

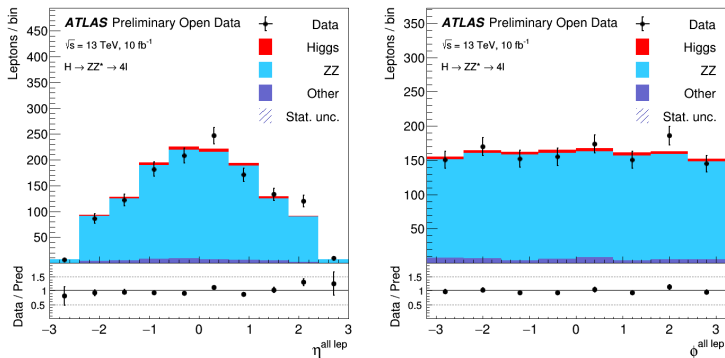


Figure: Pseudorapidity (on the left) and azimuthal angle (on the right) of selected leptons.

Distribution of invariant masses of the reconstructed Z-boson candidates

The histograms contains peaks for events with energy close to 90 GeV.

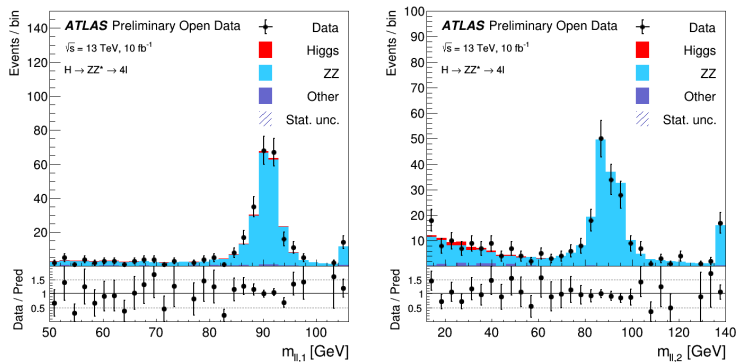


Figure: Distribution of invariant masses of leading and subleading SFOS pair.

Four-lepton mass distribution of selected events

On both histogram we can observe two peaks, one with $m_{4l} = 90$ GeV and other, the Higgs boson candidate with $m_{4l} = 125$ GeV.

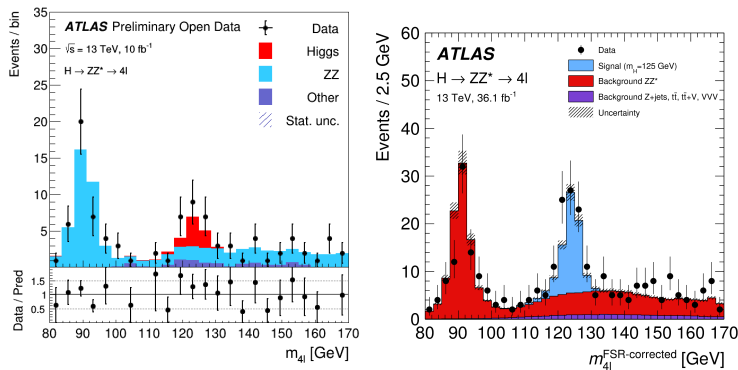


Figure: Distribution of four-lepton mass extracted from our analysis (on the left) and the ATLAS publication (on the right) [2]. The ATLAS' histogram is corrected for final-state radiation.

Transverse momentum of the four leptons

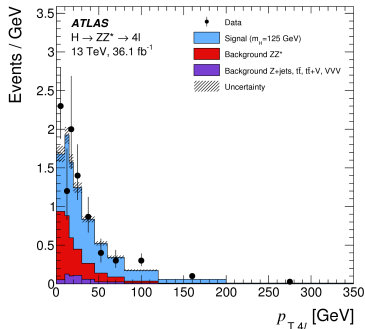
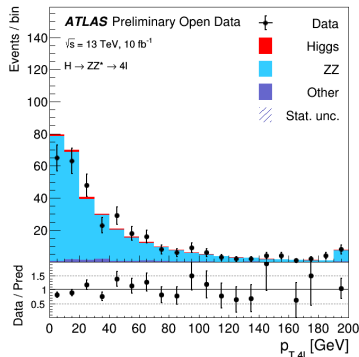


Figure: Distribution of transverse momentum for selected events extracted from our analysis (left) and the ATLAS publication (right) [2]. The background ZZ contribution in right histogram is much smaller.

Jet multiplicity

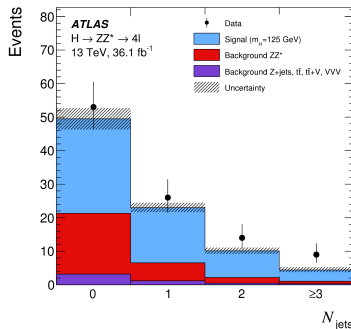
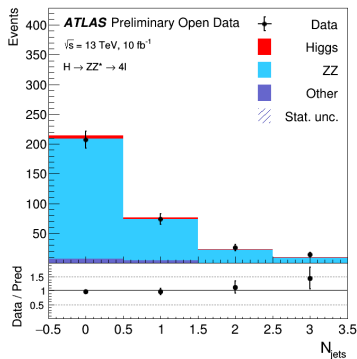


Figure: Jet multiplicity in selected events extracted from out analysis (left) and the ATLAS publication (right) [2]. The background ZZ contribution in right histogram is much smaller.

C-factor



In our analysis, there were **four** correction factors:

$$C_1 = C_{4\mu} = 0.64 \pm 0.04$$

$$C_2 = C_{2e2\mu} = 0.55 \pm 0.03$$

$$C_3 = C_{2\mu2e} = 0.48 \pm 0.05$$

$$C_4 = C_{4e} = 0.43 \pm 0.06$$

(3)

We took a "simplified approach" and used $C = \frac{1}{4} \sum_{i=1}^4 C_i = \mathbf{0.53}$

Cross-section measurement



Cross-section of $H \rightarrow ZZ^* \rightarrow 4\ell$ was calculated using the following formula:

$$\sigma^{H \rightarrow ZZ^* \rightarrow 4\ell} = \frac{N_{data} - N_{bkg}}{C \cdot L_{int}} = \frac{N_{obs}}{C \cdot L_{int}}, \quad (4)$$

where:

N_{data} - number of all events in data; $N_{data} = 321$,

N_{bkg} - number of background events; $N_{bkg} = 315$,

N_{obs} - number of observed $H \rightarrow ZZ^* \rightarrow 4\ell$; $N_{obs} = 6$,

C - correction factor; $C = 0.525$,

L_{int} - integrated luminosity; $L_{int} = 10.06 \text{ fb}^{-1}$.

$$\sigma^{H \rightarrow ZZ^* \rightarrow 4\ell} = \frac{321 - 315}{0.525 \cdot 10.06} = \frac{6}{0.525 \cdot 10.06} = 1.14 \text{ [fb]} \quad (5)$$

Systematic uncertainties for data

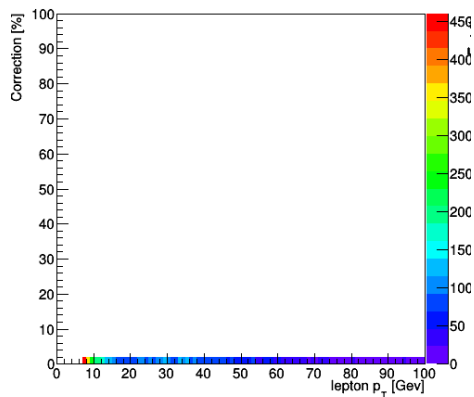


Figure: The histogram shows a size of correction in percentages for the data in the analysis.

Systematic uncertainties for signal

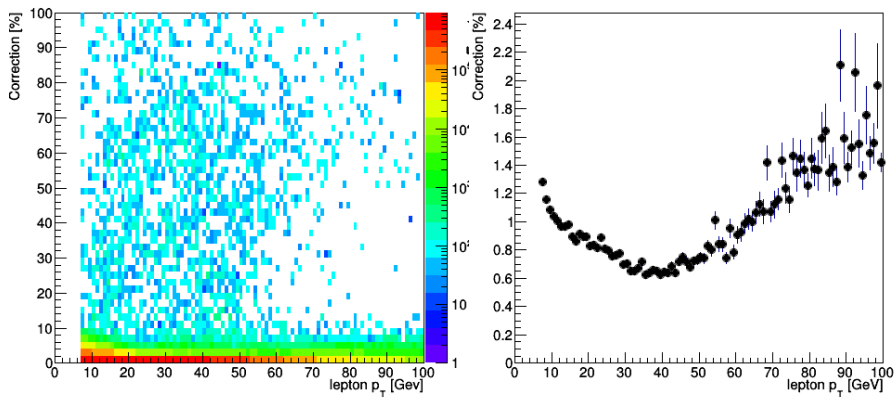


Figure: The histogram shows a size of correction in percentages for the MC data in the analysis. The correction is below 2.5%.

Systematic uncertainties



The cross-section measurement was repeated with correction on leptons' transverse momenta.

Case 1: The systematic uncertainties were added to the leptons' transverse momenta. **Four** events were observed.

$$\delta_{syst,1} = \sigma^{H \rightarrow ZZ^* \rightarrow 4\ell} - \sigma^1 = |1.136 - 0.757| = 0.379 \text{ [fb]} \quad (6)$$

Case 2: The systematic uncertainties were subtracted from the leptons' transverse momenta. **Eleven** events were observed.

$$\delta_{syst,2} = \sigma^{H \rightarrow ZZ^* \rightarrow 4\ell} - \sigma^2 = |1.136 - 2.083| = 0.946 \text{ [fb]} \quad (7)$$

As the final systematic uncertainty of the cross section measurement maximum value of $\delta_{syst,1}, \delta_{syst,2}$ was taken.

$$\delta_{systA} = 0.946 \text{ [fb]} \quad (8)$$

Statistical, systematic and luminosity uncertainties of cross-section

Error propagation rule was used in cross-section's uncertainty calculations:

$$\delta\sigma = \sqrt{\sum_i \left(\frac{\partial\sigma}{\partial x_i} \cdot \delta x_i \right)^2} \quad (9)$$

$$= \sqrt{\left(\frac{1}{C \cdot L_{int}} \cdot \delta N_{data} \right)^2 + \left(\frac{-N_{obs}}{C \cdot L_{int}^2} \cdot \delta L_{int} \right)^2 + \left(\frac{-N_{obs}}{C^2 \cdot L_{int}} \cdot \delta C \right)^2},$$

where:

$$\delta N_{data} = \sqrt{N_{data}} = 17.92,$$

$$\delta L_{int} = 0.37 \text{ fb}^{-1},$$

$$\delta C = \max(|C_i - C|) = 0.12, \quad i = 1, 2, 3, 4.$$

Statistical, systematic and luminosity uncertainties of cross-section



Based on the formula above, all required uncertainties were calculated:

$$\begin{aligned}\delta_{stat} &= 3.40 \\ \delta_{syst} &= \sqrt{\delta_{syst_A}^2 + \delta_{syst_B}^2} = 0.98 \\ \delta_{lumi} &= 0.05\end{aligned}$$

Eventually, cross-section value can be expressed as:

$$\sigma^{H \rightarrow ZZ^* \rightarrow 4\ell, \text{nom}} = \mathbf{1.14} \pm 3.4 \text{ (stat)} \pm 0.98 \text{ (syst)} \pm 0.05 \text{ (lumi) fb} \quad (10)$$

Due to very high value of uncertainties we cannot claim the Higgs boson discovery ☹.

Cross section measurement comparison



Our analysis:

$$\sigma^{H \rightarrow ZZ^* \rightarrow 4\ell, \text{nom}} = 3.62 \pm 3.4 \text{ (stat)} \pm 0.98 \text{ (syst)} \pm 0.05 \text{ (lumi) fb} \quad (11)$$

ATLAS publication [2]:

$$\sigma^{H \rightarrow ZZ^* \rightarrow 4\ell, \text{nom}} = 1.14 \pm 0.5 \text{ (stat)} \pm 0.25 \text{ (syst) fb} \quad (12)$$

Standard Model prediction [2]:

$$\sigma^{H \rightarrow ZZ^* \rightarrow 4\ell, \text{nom}} = 2.91 \pm 0.13 \text{ fb} \quad (13)$$

Ideas for possible measurement



- or change this frame to summary and then add ideas?

Bibliography I



The ATLAS collaboration

Review of the 13 TeV ATLAS Open Data release

<https://cds.cern.ch/record/2707171>



Aaboud, Morad and others

Measurement of inclusive and differential cross sections in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel in pp collisions at $s\sqrt{=} 13\text{ TeV}$ with the ATLAS detector

[http://dx.doi.org/10.1007/JHEP10\(2017\)132](http://dx.doi.org/10.1007/JHEP10(2017)132)



Passon, Oliver

On the interpretation of Feynman diagrams, or, did the LHC experiments observe the Higgs to gamma gamma decay?