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The case of Higgs boson production in $H \to ZZ^*$ decay

Introduction to the Particle Physics Data Analysis

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That's us!

Figure: That's Aleksandra P and Aleksandra K!

Outline

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

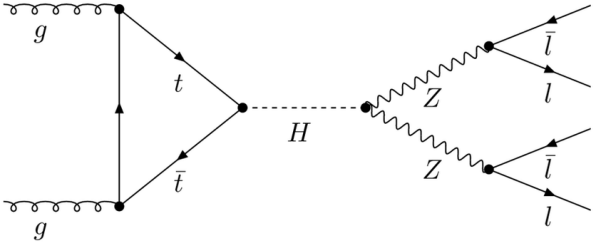


Figure: Feynman diagram for $H \to ZZ^* \to 4\ell$ decay [3].

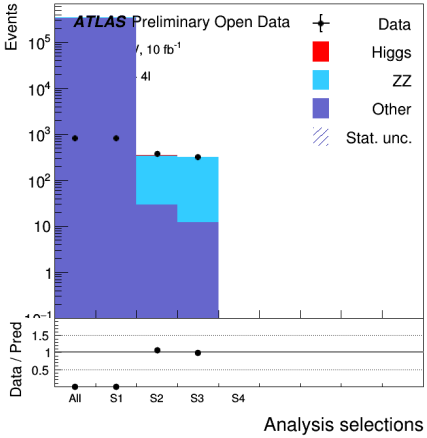
Event selection

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

- single-electron or single-muon trigger satisfied,
- exactly four leptons (electrons or muons) with $p_T > 25, 15, 10, 7 GeV$, 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

Cutflow Histogram



On the cutflow histogram we can observe number of events after each selection criteria:

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

Expected number of events

Expected number of events equals:

$$N_{exp}^{H\to ZZ^*\to 4\ell} = \sigma_{incl}^{H\to ZZ^*\to 4\ell} \cdot L_{int}, \tag{1}$$

where:

$$\sigma_{incl}^{H\to ZZ^*\to 4\ell} = 3{,}62\ fb^{-1},$$
$$L_{int} = 10{,}06\ fb^{-1}.$$

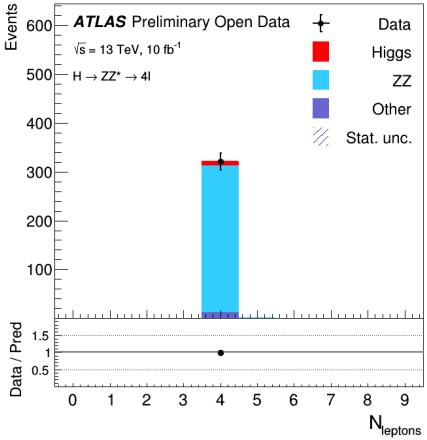
$$N_{exp}^{H\to ZZ^*\to 4\ell} = 3.62\,\mathrm{fb} \cdot 10.06\,\mathrm{fb}^{-1} = 36.42. \tag{2}$$

Background contributions

Processes constituting background of our analysis:

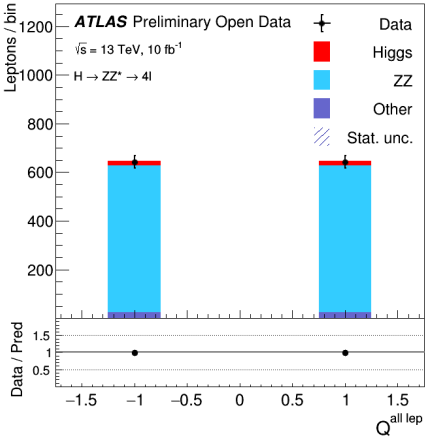
- non-resonant SM ZZ* production,
- $t\bar{t}$ production,
- Z+jets production.

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 leptions of opposite charges was selected.

Pseudorapidity and azimuthal angle of selected leptons

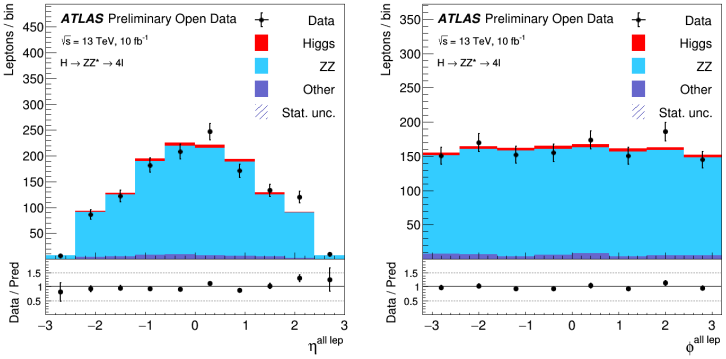


Figure: Pseudorapidity (on the left) and azimuthal angle (on the right) of selected leptons.

Distribution of invariant masses of the reconstructed Z-boson candidates

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

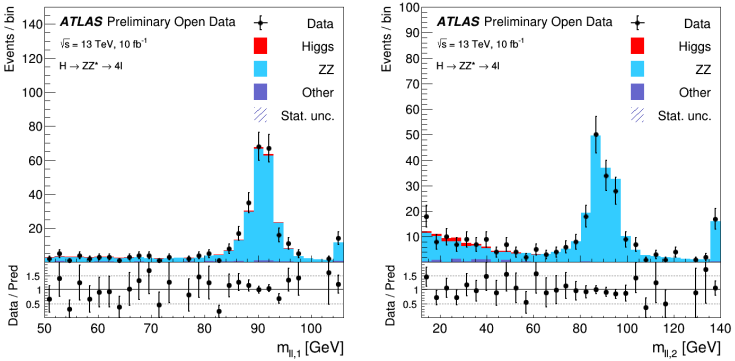


Figure: Distribution of invariant masses of leading and subleading SFOS pair.

Four-lepton mass distribution of selected events

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

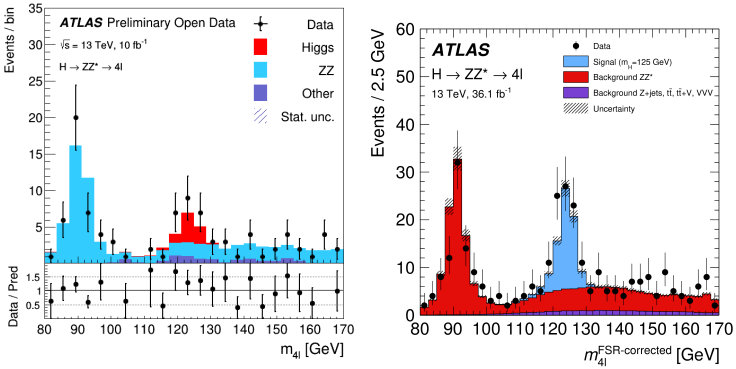


Figure: Distribution of four-lepton mass extreacted from our analysis (on the left) and the ATLAS publication (on the right) [2]. The ATLAS' histogram is corrected for final-state radiation.

Traverse momentum of the four leptons

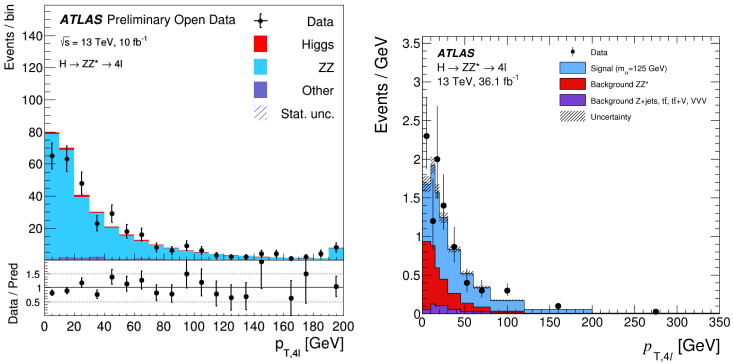


Figure: Distribution of traverse momentum for selected events extracted from out analysis (left) and the ATLAS publication (right) [2]. The background ZZ contribution in right histogram is much smaller.

Jet multiplicity

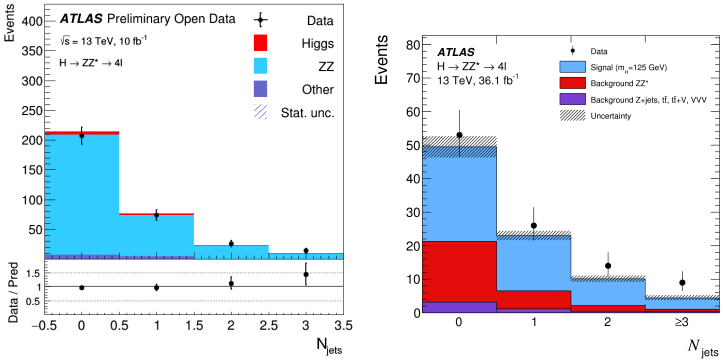


Figure: Jet multiplicity in selected events extracted from out analysis (left) and the ATLAS publication (right) [2]. The background ZZ contribution in right histogram is much smaller.

C-factor

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

$$\begin{aligned} C_1 &= C_{4\mu} = 0.64 \pm 0.04 \\ C_2 &= C_{2e2\mu} = 0.55 \pm 0.03 \\ C_3 &= C_{2\mu 2e} = 0.48 \pm 0.05 \\ C_4 &= C_{4e} = 0.43 \pm 0.06 \end{aligned} \tag{3}$$

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 $H \to ZZ^* \to 4\ell$ was calculated using the following formula:

$$\sigma^{H\to ZZ^*\to 4\ell} = \frac{N_{data} - N_{bkg}}{C \cdot L_{int}} = \frac{N_{obs}}{C \cdot L_{int}}, \tag{4}$$

where:

- N_{data} - number of all events in data; $N_{data} = 321$,
- N_{bkg} - nubmer of background events; $N_{bkg} = 315$,
- N_{obs} - number of observed $H \to ZZ^* \to 4\ell$; $N_{obs} = 6$,
- C - correction factor; $C = 0.525$,
- L_{int} - integrated luminosity; $L_{int} = 10.06\,\mathrm{fb}^{-1}$.

$$\sigma^{H\to ZZ^*\to 4\ell} = \frac{321 - 315}{0.525 \cdot 10.06} = \frac{6}{0.525 \cdot 10.06} = 1.14\ [\mathrm{fb}] \tag{5}$$

Systematic uncertainties for data

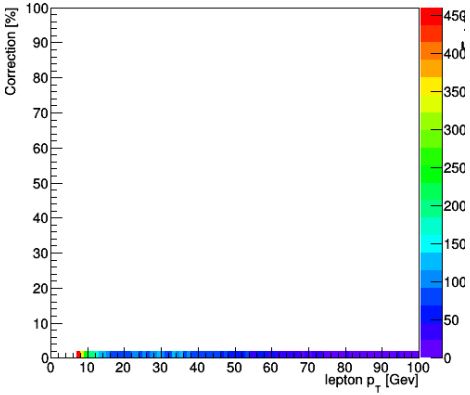


Figure: The histogram shows a size of correction in percentages for the data in the analysis.

Systematic uncertainties for signal

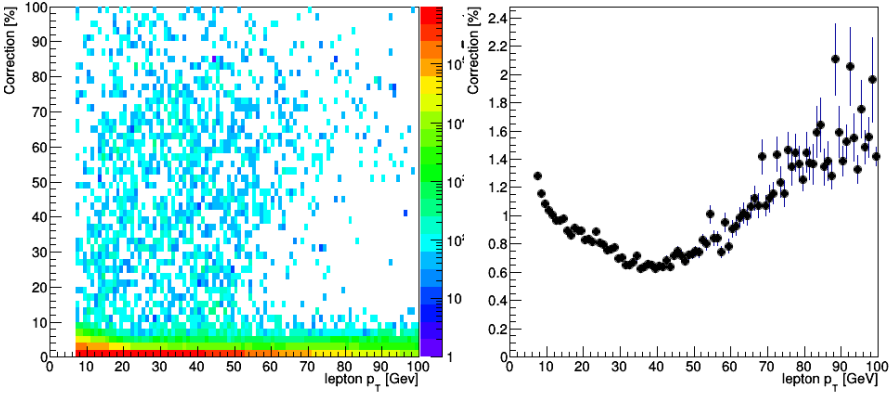


Figure: The histogram shows a size of correction in percentages for the MC data in the analysis. The correction is below 2.5%.

Systematic uncertainties

The cross-section measurement was repeated with correction on leptons' traverse momentums.

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

$$\delta_{syst,1} = \sigma^{H\to ZZ^*\to 4\ell} - \sigma^1 = |1.136 - 0.757| = 0.379\ [\mathrm{fb}] \tag{6}$$

Case 2: The systematic uncertainties were subracted from the leptons' traverse momentums. **Eleven** events were observed.

$$\delta_{syst,2} = \sigma^{H\to ZZ^*\to 4\ell} - \sigma^2 = |1.136 - 2.083| = 0.946\ [\mathrm{fb}] \tag{7}$$

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

$$\delta_{syst_A} = 0.946\ [\mathrm{fb}] \tag{8}$$

Statistical, systematic and luminosity uncertainties of cross-section

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

$$\delta_\sigma = \sqrt{\sum_i \left(\frac{\partial \sigma}{\partial x_i} \cdot \delta_{x_i}\right)^2}$$
$$= \sqrt{\left(\frac{1}{C \cdot L_{int}} \cdot \delta_{N_{data}}\right)^2 + \left(\frac{-N_{obs}}{C \cdot L_{int}^2} \cdot \delta_{L_{int}}\right)^2 + \left(\frac{-N_{obs}}{C^2 \cdot L_{int}} \cdot \delta_C\right)^2}, \quad (9)$$

where:

$$\begin{aligned} \delta_{N_{data}} &= \sqrt{N_{data}} = 17.92, \\ \delta_{L_{int}} &= 0.37\ \mathrm{fb}^{-1}, \\ \delta_C &= \max(|C_i - C|) = 0.12,\ i = 1, 2, 3, 4. \end{aligned}$$

Statistical, systematic and luminosity uncertainties of cross-section

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

$$\delta_{stat} = 3.40$$
$$\delta_{syst} = \sqrt{\delta^2_{syst_A} + \delta^2_{syst_A}} = 0.98$$
$$\delta_{lumi} = 0.05$$

Eventually, cross-section value can be expressed as:

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

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

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