Akademia Górniczo-Hutnicza
im. Stanisława Staszica w Krakowie
AGH University of Science
and Technology

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

## Introduction to the Particle Physics Data Analysis

Aleksandra Poreba, Aleksandra Kukielka

# That's us!


Figure: That's Aleksandra P. and Aleksandra K.!

# Outline

# Physics motivation

AGH

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

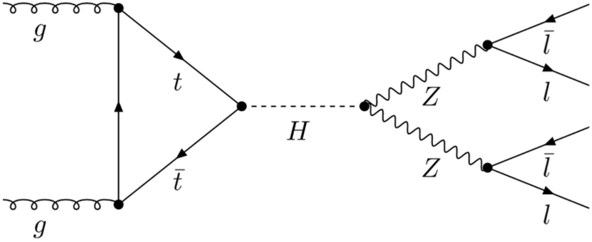



Figure: Feynman diagram for $H \to ZZ^* \to 4\ell$ decay [3].

# Background contributions



Processes constituting background of our analysis:

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

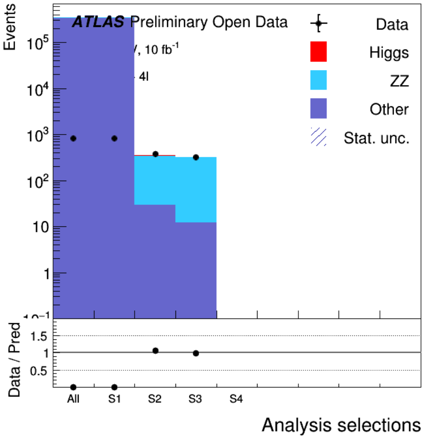
# Event selection

The final event-selection criteria:

- 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* [1] lepton pairs,
- the leading pair is defined as the *SFOS* 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

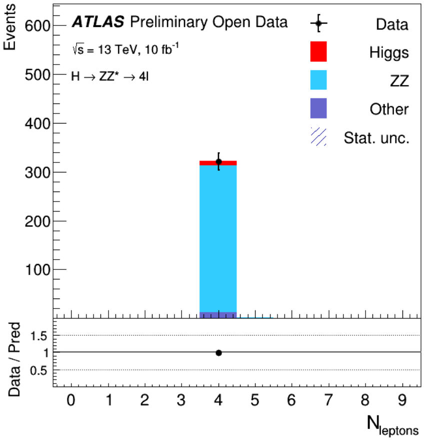
# Cutflow Histogram




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

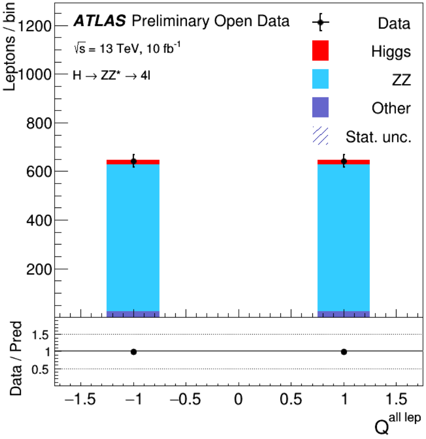
- $S1$ - single-electron or single-muon trigger satisfied,
- $S2$ - four leptons with $p_T > 25, 15, 10, 7 GeV$,
- $S3$ - two SFOS lepton pairs.

# 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

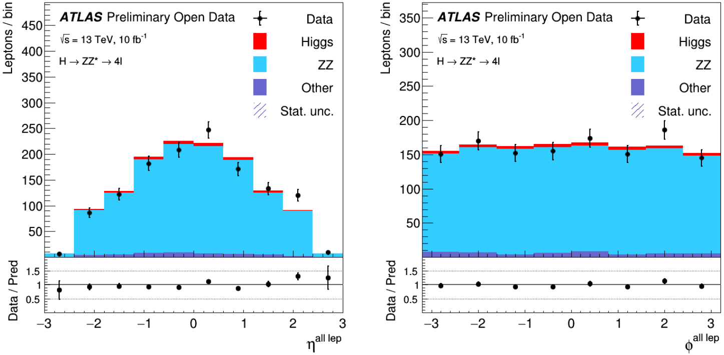



Figure: Pseudorapidity (on the left) and azimuthal angle (on the right) of selected leptons.

# Distribution of invariant masses of the reconstructed Z-boson candidates

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

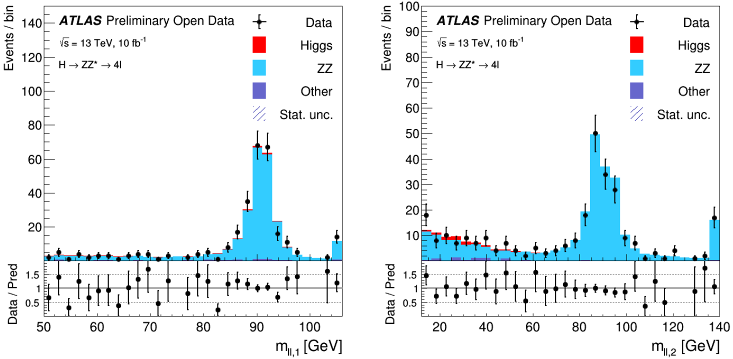



Figure: Distribution of invariant masses of leading and subleading SFOS pair.

# 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.

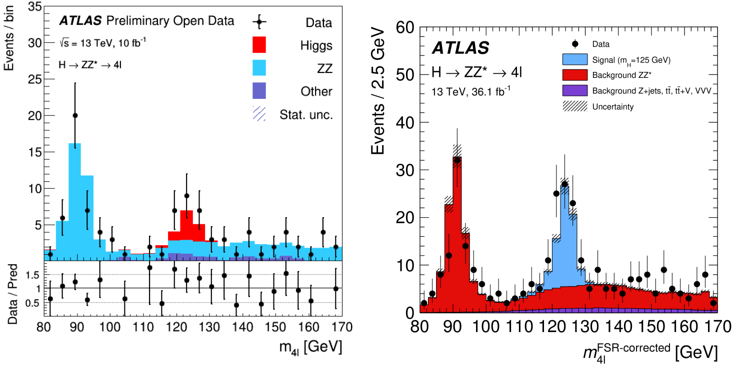



Figure: Distribution of four-lepton mass extreacted from our analysis (on the left) and the ATLAS publication (on the right) [2]. The ATLAS' histogram is corrected for final-state radiation.

# Traverse momentum of the four leptons

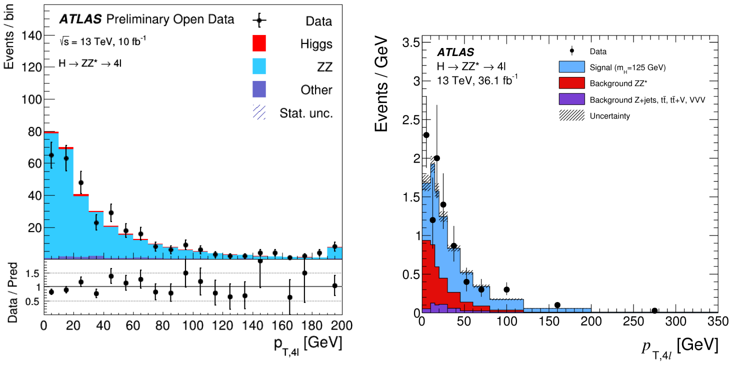
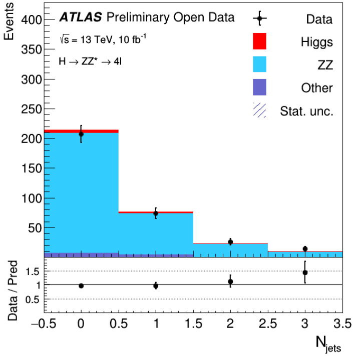



Figure: Distribution of traverse momentum for selected events extracted from out analysis (left) and the ATLAS publication (right) [2]. The background ZZ contribution in right histogram is much smaller.

# Jet multiplicity





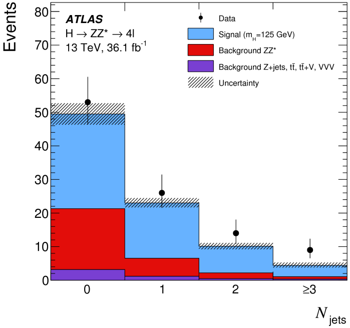




Figure: Jet multiplicity in selected events extracted from out analysis (left) and the ATLAS publication (right) [2]. The background ZZ contribution in right histogram is much smaller.

# 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:

$$\sigma_{incl}^{H\to ZZ^*\to 4\ell} = 3.62 \text{ fb},$$
$$L_{int} = 10.06 \text{ fb}^{-1}.$$

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

# C-factor

AGH

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; $C = 0.53$,
- $L_{int}$ - 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

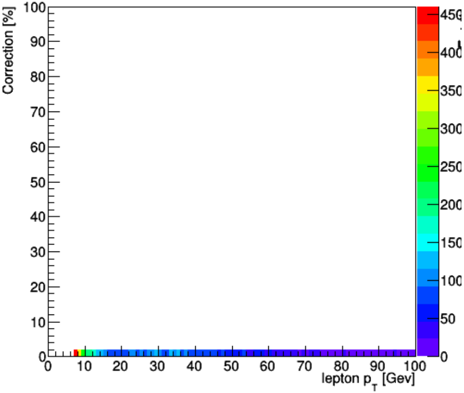



Figure: The histogram shows a size of correction in percentages for the data in the analysis.

# Systematic uncertainties for signal

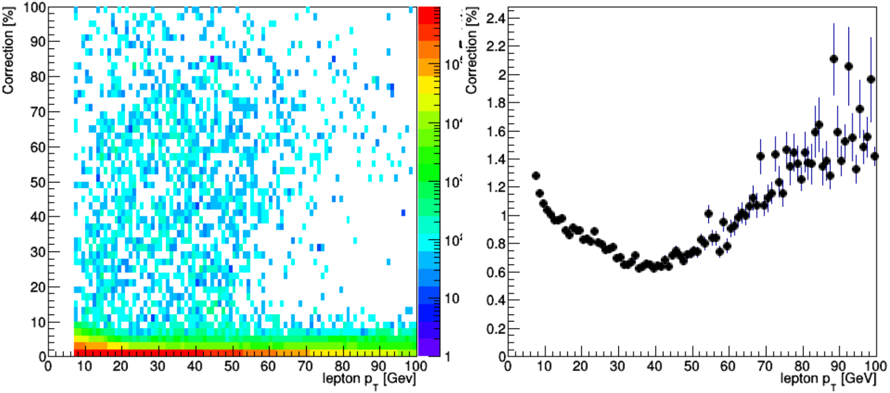



Figure: The histogram shows a size of correction in percentages for the MC data in the analysis. The correction is below 2.5%.

# Systematic uncertainties

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

Case 1: The systematic uncertainties were added to the leptons' traverse momenta. **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 momenta. **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:

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

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:

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

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 ☹.

# Cross section measurement comparison

Our analysis:

$$\sigma^{H\to ZZ^*\to 4\ell,\,\mathrm{nom}} = 1.14\ \pm 3.4\,(\mathrm{stat})\ \pm 0.98\,(\mathrm{syst})\ \pm 0.05\,(\mathrm{lumi})\,\mathrm{fb} \tag{11}$$

ATLAS publication [2]:

$$\sigma^{H\to ZZ^*\to 4\ell,\,\mathrm{nom}} = 3.62\ \pm 0.5\,(\mathrm{stat})\ \pm 0.25\,(\mathrm{syst})\,\mathrm{fb} \tag{12}$$

Standard Model prediction [2]:

$$\sigma^{H\to ZZ^*\to 4\ell,\,\mathrm{nom}} = 2.91\ \pm 0.13\,\mathrm{fb} \tag{13}$$

# Summary

AGH

- We cannot claim the Higgs boson discovery due to high uncertainties, especially statistical uncertainty.

- Ideas for possible measurement:
  - define more selection criteria for example for pseudorapidity

# Bibliography I

AGH


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 $s\sqrt{} = 13\,TeV$ with the ATLAS detector
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?