Measuring the mass of the Higgs Boson at the ATLAS detector in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel using an analytic signal model

Tom Powell

University of Sheffield

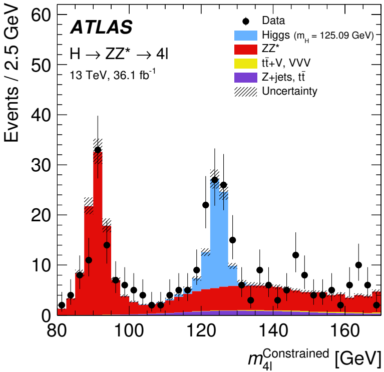
April 2019

Why measure the mass of the Higgs Boson?

- The Standard Model does not predict the Higgs Boson mass, but the Higgs branching ratio depends on mass
- Measurement of both of these properties serves as a test of the Standard Model.

Why use the $H \to ZZ^* \to 4\ell$ channel?

- Electrons and muons are very well reconstructed by ATLAS
- The channel has a smooth background with a sharp peak
- Large signal/background ratio



Plot from JHEP 03 (2018) 095

Currently, ATLAS uses two methods to perform this measurement

1. Per lepton response
   - Build a model of the $m_{4\ell}$ distribution using individual energy response distributions
   - Each lepton in each event requires 3 Gaussians, which are convoluted in each event to give a total of 81 Gaussians per event. These are then reduced down to 4 using Gaussian mixture reduction
   - See arXiv:1806.00242 for more details
2. Template model
   - Smooth Monte Carlo $H \to ZZ^* \to 4\ell$ distributions at various m_H values
   - Interpolate these to give a continuous model

Why create a new method?

An analytic model has advantages over the current methods

1. Simplicity
   - In the per-event method, there is no average m_H model, so there is no asimov dataset.
2. Flexibility
   - In the template method, each addition of a parameter of interest (e.g. natural width) requires another dimension of interpolation
   - These can be added much more easily with an analytic model

This method has been used before

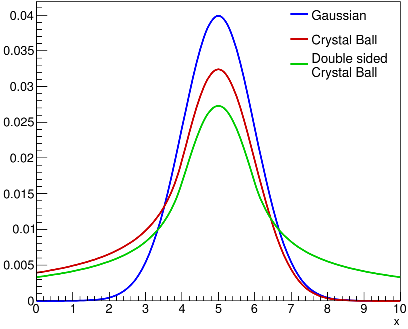
- CMS uses an analytic model to measure m_H in $H \to ZZ^* \to 4\ell$
- ATLAS uses an analytic model to measure m_H in $H \to \gamma\gamma$

Two models were considered

1. Sum of a Gaussian and Crystal Ball function
   - A Crystal ball function is a function with a Gaussian core and a power law tail
2. A double-sided Crystal Ball function
   - A double-sided Crystal Ball function is the same but with different power laws for the two tails

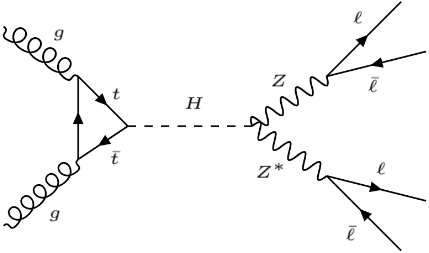
The tail shapes are determined by two parameters:

- α controls where the tail begins
- n is the exponent of the tail



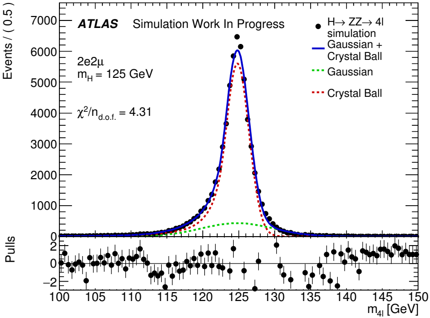
$$DoubleCB(x;\mu,\sigma,\alpha_1,n_1,\alpha_2,n_2,) = \begin{cases} A\cdot\left(\frac{n_1}{|\alpha_1|} - |\alpha_1| - \frac{x-\mu}{\sigma}\right)^{-n_1} & \text{for } \frac{x-\mu}{\sigma} \geq -\alpha_1 \\ B\cdot\left(\frac{n_2}{|\alpha_2|} - |\alpha_2| - \frac{x-\mu}{\sigma}\right)^{-n_2} & \text{for } \frac{x-\mu}{\sigma} \geq \alpha_2 \\ G(x;\sigma,\mu) & \text{else} \end{cases}$$

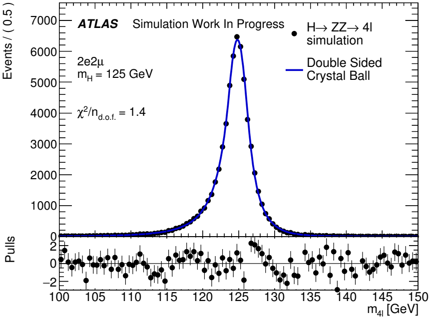
- For now, only using *ggF* Monte Carlo, other production modes will be included in the future
- Considering only the case where final state is two pairs of same-flavour opposite sign electrons or muons.
- Classify events in four channels by final state: 4μ, $4e$, $2e2\mu$ and $2\mu 2e$.



First, decide which model to use

Fit per-channel to $m_H = 125\ \mathrm{GeV}$ mass point and use $\chi^2/n_{d.o.f.}$ to asses the goodness of fit





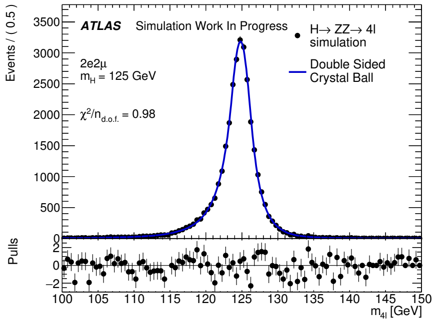
Fits in $2e2\mu$ channel

Double sided CB provides a better fit than CB + Gaussian

Check the DCB works using a simple model

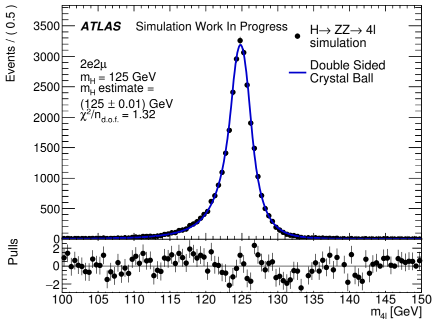
- Split the MC set for $m_H = 125\ \mathrm{GeV}$ in half
- Fit the model, per channel, to the first half and reserve the second half for validation

Fits to each channel are good, now perform validation



Fit to 125 GeV mass point in $2e2\mu$ channel

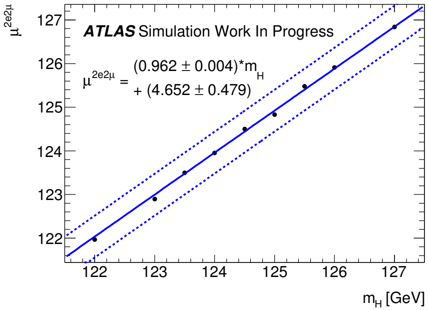
- Parameterise the mean of each channel, i, as $\mu^i = m_H - c^i$ where c^i are offsets
- Fit the value of m_H to the other half of the MC, simultaneously across all four channels.
- All parameters other than m_H are fixed for the validation fit



Validation plot in $2e2\mu$

- Result m_H $= 125.00 \pm 0.01\ \mathrm{GeV}$
  - Note, this uncertainty is due to simulation statistics and is not normalised to the expectation
- Parameterisation shows closure, the simple model works!
- Now build a more complicated model

Why build a more complicated model?

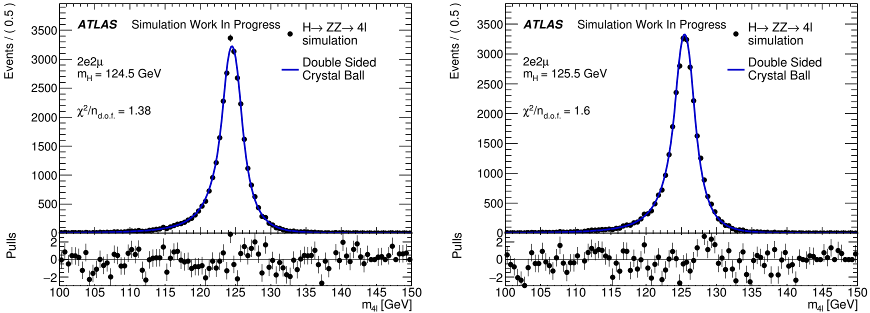


Fitted μ vs true m_H in $2e2\mu$

- m_H is not exactly 125 GeV so parameterising m_H as μ + offset is not exact
- Slope of μ vs $m_H < 1$
- A linear parameterisation is needed
- Can do a fit (as in figure opposite) or better still, simultaneously fit to each mass point

First, build the parameterisation

- Simultaneously fit, per channel, across several MC datasets of varying m_H
  - Mass points used are $m_H = 124, 124.5, 125.5, 126\ \mathrm{GeV}$
  - The mass point $m_H = 125\ \mathrm{GeV}$ is omitted from this fit and reserved for validation later
- Parameters of the fit are parameterised vs m_H
  - As mentioned previously, parameterise μ to be linear vs m_H
  - For now, all others are kept constant vs m_H to aid convergence of fit



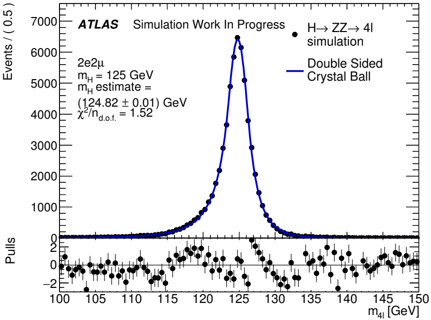
Fits to $2e2\mu$ channel for 124.5 and 125.5 GeV mass points

Fits are good, now perform a validation

Procedure for validation

- Using the parameterisations for each channel, fit m_H simultaneously to the $m_H = 125\ \mathrm{GeV}$ MC set.
- All parameters fitted in previous step have uncertainties, so apply Gaussian constraints to these

Validation & future work



Validation plot in $2e2\mu$

Model does not yet work perfectly, currently working to improve this with two approaches:

1. Parameterise variables differently. E.g. σ is better parameterised linearly
2. Currently, validation fit assumes parameters are uncorrelated, which is not the case. Correlation matrices from the fits need to be analysed to work out the best way to parameterise variables

Conclusions

- An analytical model for $H \rightarrow ZZ^* \rightarrow 4\ell$ is currently under development
- Currently working to improve model by accounting for correlations between parameters and parameterising variables differently.
- Also planned to be added in the future
  - Other production modes (e.g. VBF, $t\bar{t}H$ etc)
  - Per event errors

Backup

Validation plots