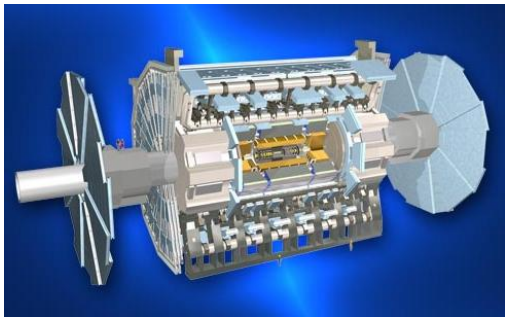
$H \rightarrow ZZ^* \rightarrow 4\ell$ search at the ATLAS experiment

Karoline Selbach
University of Edinburgh

IOP meeting

April 9, 2013

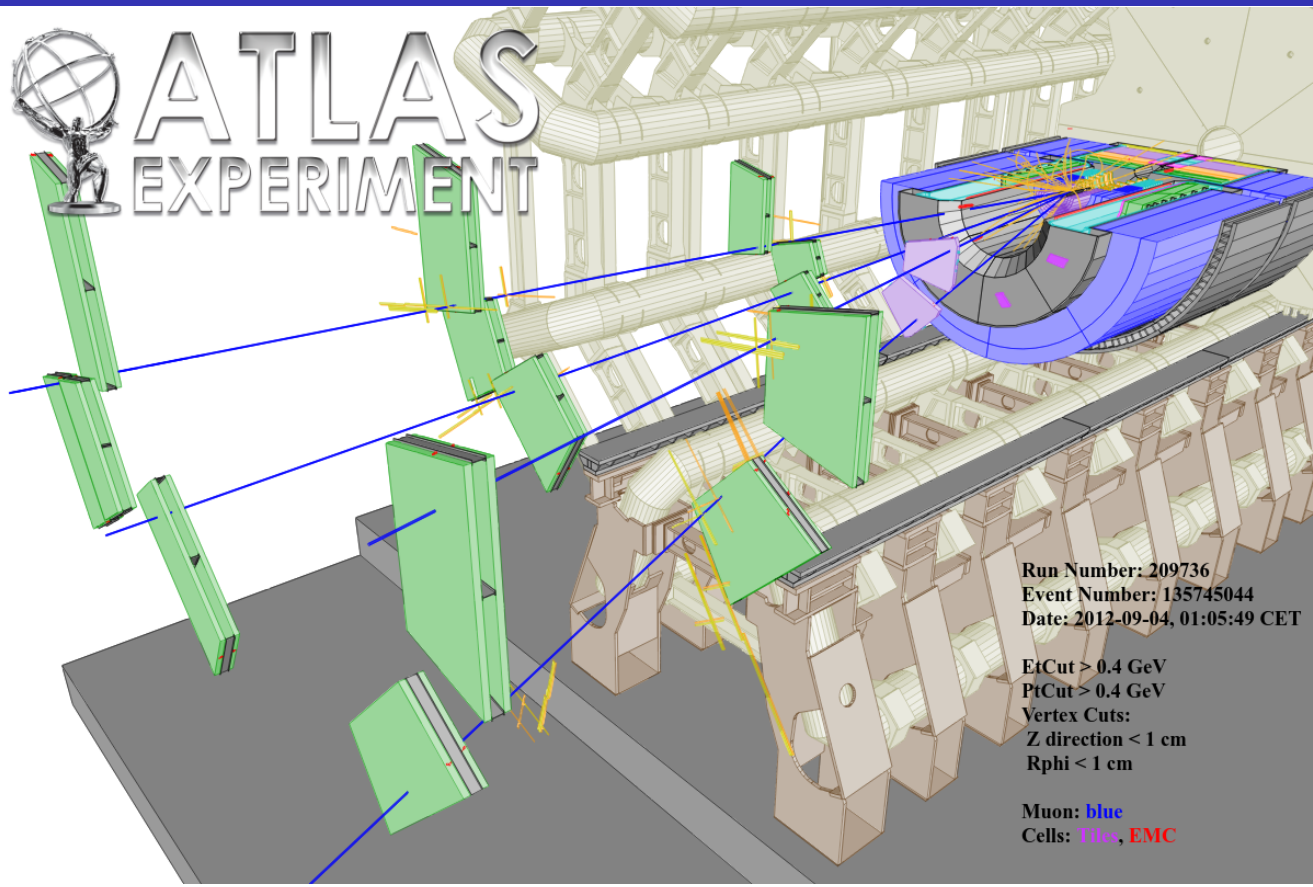


Many greetings from...

Many greetings from...

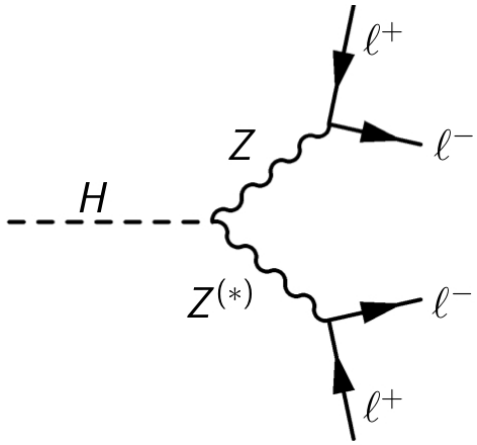
Structure

- Introduction
- Fitting framework
- Fitting procedure
- Per-event errors
- Mass measurement
- Conclusion



$H \to ZZ^* \to 4\ell$ with its **good mass resolution** is an ideal channel for the mass measurement.

Introduction



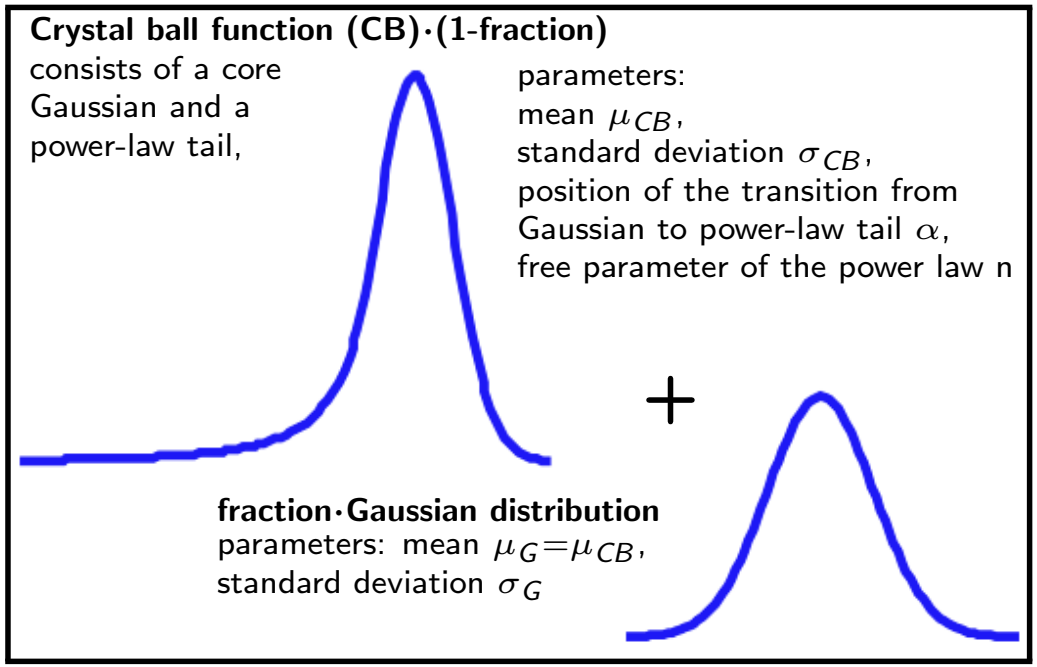
- **Four final states:** 4μ, 4e, 2e2μ and 2μ2e
- Signal:
  - **Production modes: gg, VBF, ZH, WH & ttH**
  - Shapes as a function of the Higgs mass by interpolating between simulation samples of discrete mass points
- Backgrounds:
  - **Irreducible: $ZZ^{(*)}$**
    Taken from MC simulation normalised to the theoretical cross section
  - **Reducible: Zbb, Z+jets and $t\bar{t}$**
    - Evaluated by data-driven procedure
    - Suppressed with isolation and impact parameter cuts

Fitting the mass of $H \to ZZ^{(*)} \to 4\ell$

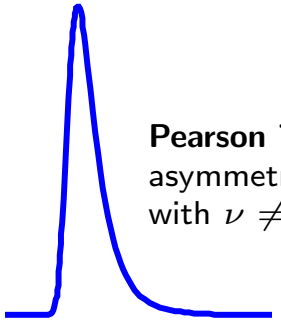
- **New machinery for fitting** the data has been developed
- Consists of a "workspace" based on RooFit containing data events, systematics and probability density functions (p.d.f.s) for signal and background
- **Created for the needs** of this analysis and **flexible to use** additional models
- Helps facilitate the Higgs combination results
- **Rigorously validated** against the results published at ICHEP 2012 and used for the publications since then
- By using the new fitting machinery it was observed that splitting the analysis into different final states results in a gain of $\sim$7%
- The systematic uncertainties have been parametrised depending on m_H

Analytical models

- **Analytical functions** have been developed to model the background and signal e.g. the sum of a **Crystal ball** and Gaussian function (CB+GA)
- The **Pearson Type IV distribution** is a continuous probability function where k is a normalization constant and m, ν, a and λ are real-valued parameters:



$$f(x) = k\left[1 + \left(\frac{x-\lambda}{a}\right)^2\right]^{-m} \exp\left[-\nu \arctan\left(\frac{x-\lambda}{a}\right)\right]$$
$$\text{for } -\infty < x < \infty \text{ where } m < \frac{1}{2}$$



Pearson Type IV: asymmetric tails with $\nu \neq 0$

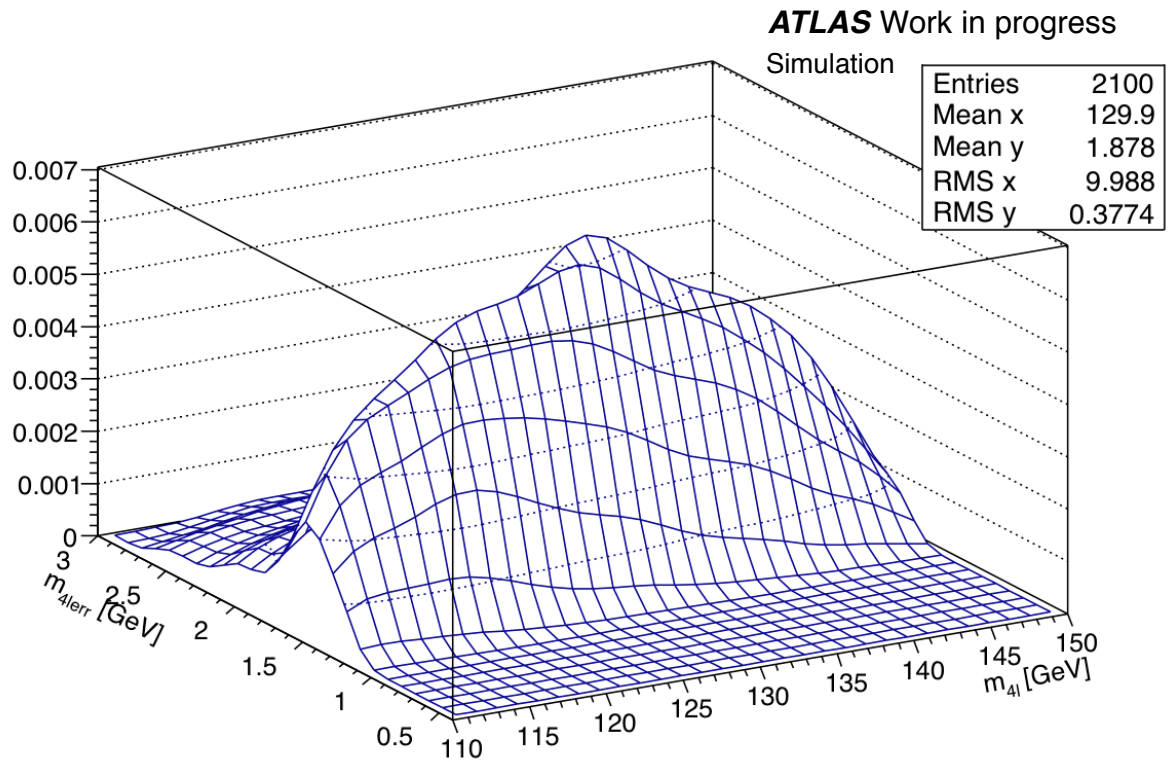
- The Pearson Type IV distribution models the error of the invariant mass of the 4 leptons allowing for an **asymmetric tail**

Per-event error for $H \to ZZ^{(*)} \to 4\ell$

- Implementation of **per-event errors** for the reconstructed mass ($m_{4\ell}$) and the corresponding error ($m_{4\ell err}$) to take advantage of resolution information
- **Conditional p.d.f.** is applied to ensure correlation due to differing signal and background shape is taken into account:

$$P_k(m_{4\ell}|m_{4\ell err})P_k(m_{4\ell err}) = P_k(m_{4\ell err}|m_{4\ell})P_k(m_{4\ell})$$

- For the mass measurement applied to the low mass region 110 GeV$<m_H<$150 GeV

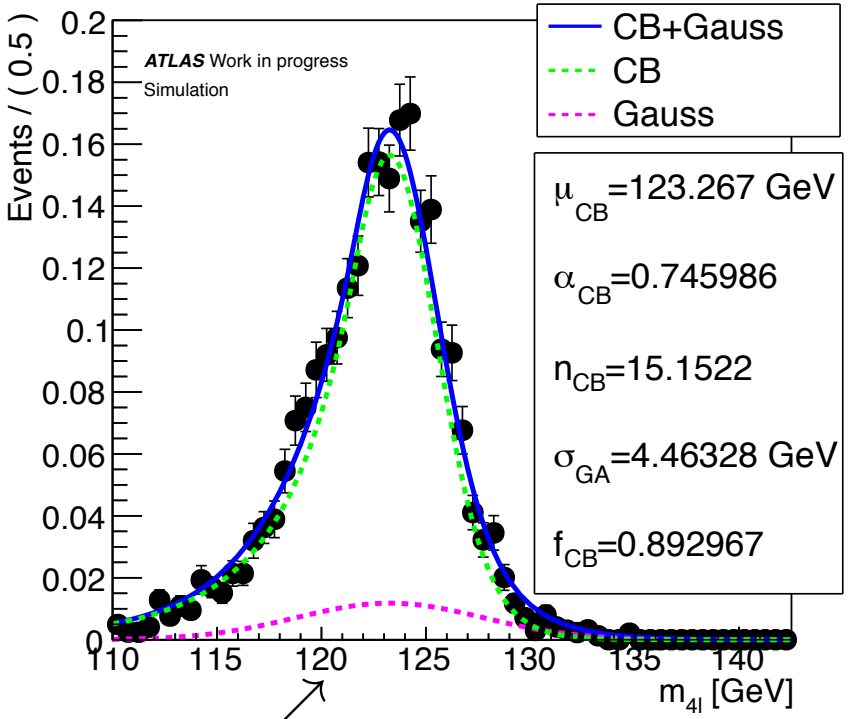


Simulated **$ZZ^{(*)}$ background** in the $4e$ channel modeled by a smoothed function in $m_{4\ell}$ and $m_{4\ell err}$

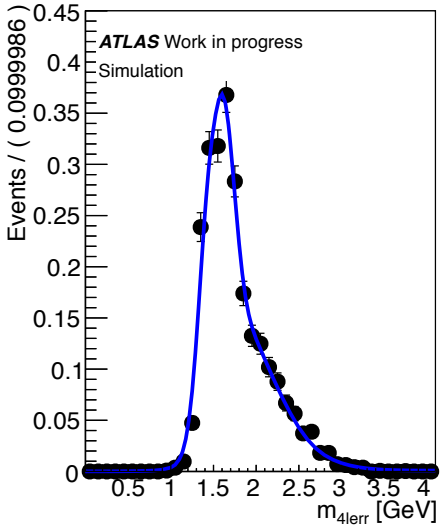
Conditional p.d.f. for $H \to ZZ^{(*)} \to 4\ell$

Models for the reconstructed mass $m_{4\ell}$ and the error on the reconstructed mass $m_{4\ell err}$.:

- Signal:
  - $P_k(m_{4\ell}|m_{4\ell err})$: **Crystal ball** or sum of Crystal ball and Gaussian distribution
  - $P_k(m_{4\ell err})$: **Pearson Type IV distribution** or smoothed histogram
- Background:
  - $P_k(m_{4\ell})$: Polynomial function
  - $P_k(m_{4\ell err}|m_{4\ell})$: Pearson Type IV distribution



Signal model with sum of Crystal ball and Gaussian for $P_k(m_{4\ell}|m_{4\ell err})$ and smoothed histogram for $P_k(m_{4\ell err})$

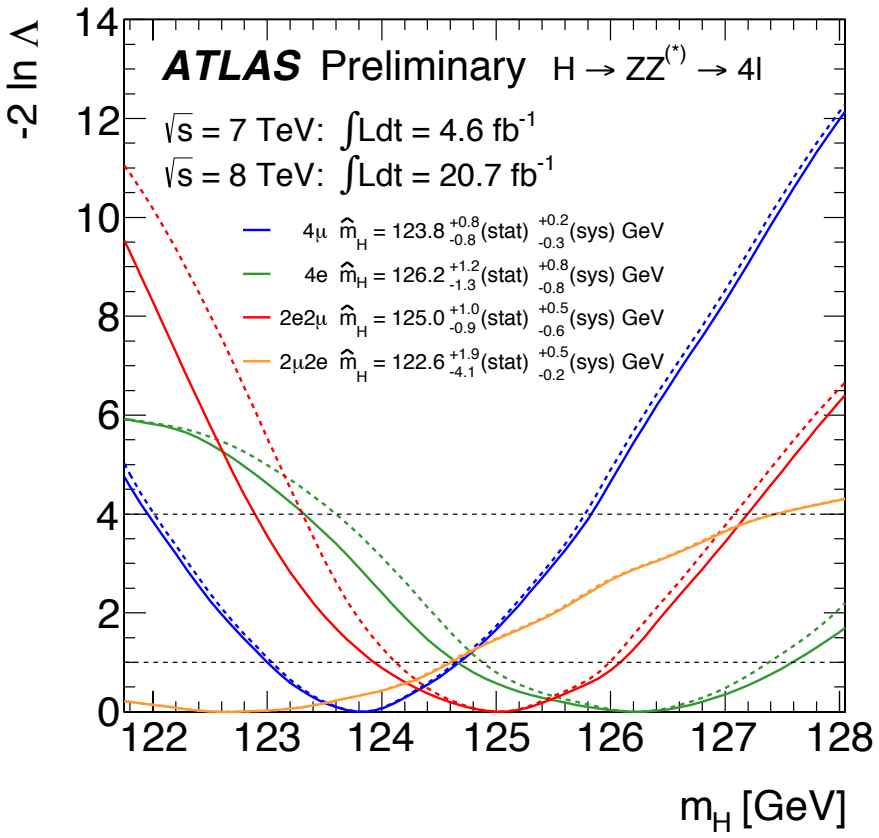


$\Rightarrow$ With the per-event error implementation the **resolution** is **improved by $\sim$ 0.1 GeV**

Mass measurement results (released 05.03.13) ATLAS-CONF-2013-013

- **Profile likelihood** shown with mass scale systematics (solid curve) and without (dashed curve)
- Observed and expected signal and background events in [120 GeV, 130 GeV] show in table below
- Strong contribution of 4μ channel with **most expected signal events**

$\Rightarrow$ **4μ** channel is **most sensitive**



	Expected:				Observed:
	Signal (m_H=125 GeV)	ZZ^*	Z+jets, $t\bar{t}$	Sum	
4μ	6.3±0.8	2.8±0.1	0.55±0.15	9.6±1.0	13
$2\mu 2e$	3.0±0.4	1.4±0.1	1.56±0.33	6.0±0.8	5
$2e2\mu$	4.0±0.5	2.1±0.1	0.55±0.17	6.6±0.8	8
$4e$	2.6±0.4	1.2±0.1	1.11±0.28	4.9±0.8	6
total	15.9±2.1	7.4±0.4	3.74±0.93	27.1±3.4	32

Mass and signal strength

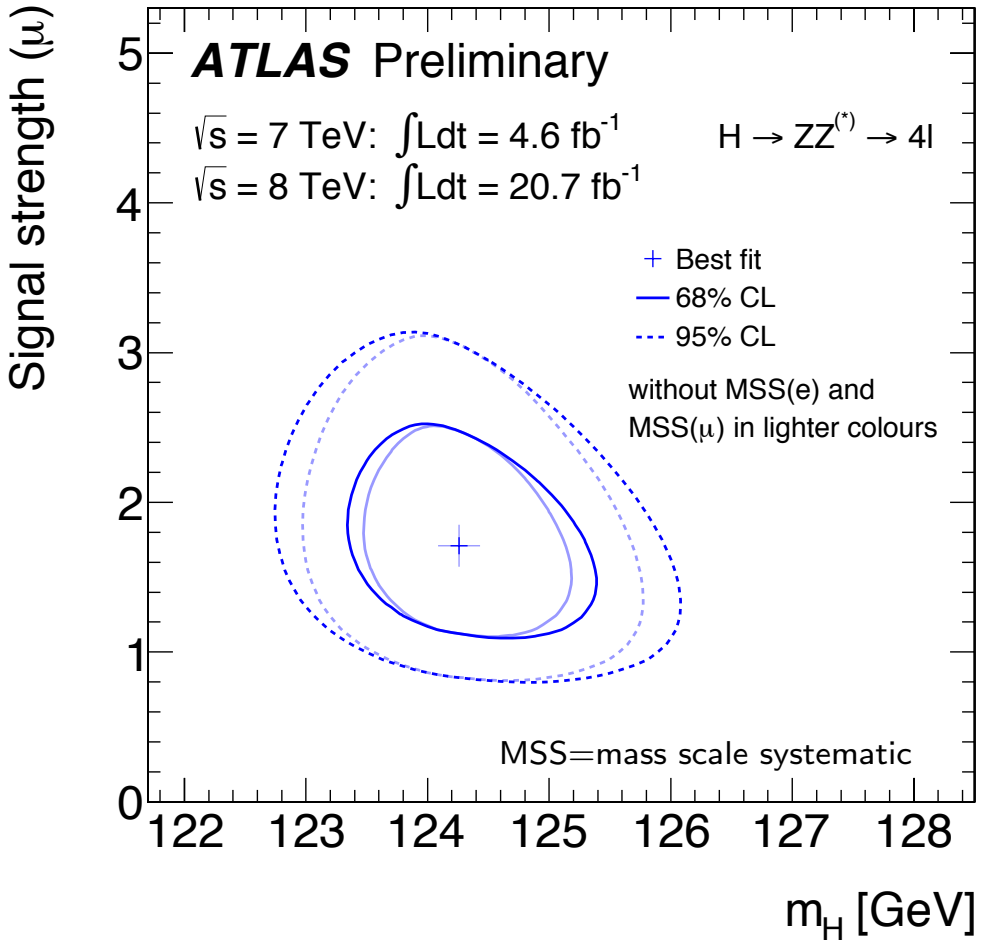
- Results are based on **4.6 fb^{-1}** at $\sqrt{s} = 7$ TeV and **20.7 fb^{-1}** at $\sqrt{s} = 8$ TeV

- Best fitted mass of

$$\mathbf{m_H = 124.3^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(syst)\ GeV}$$

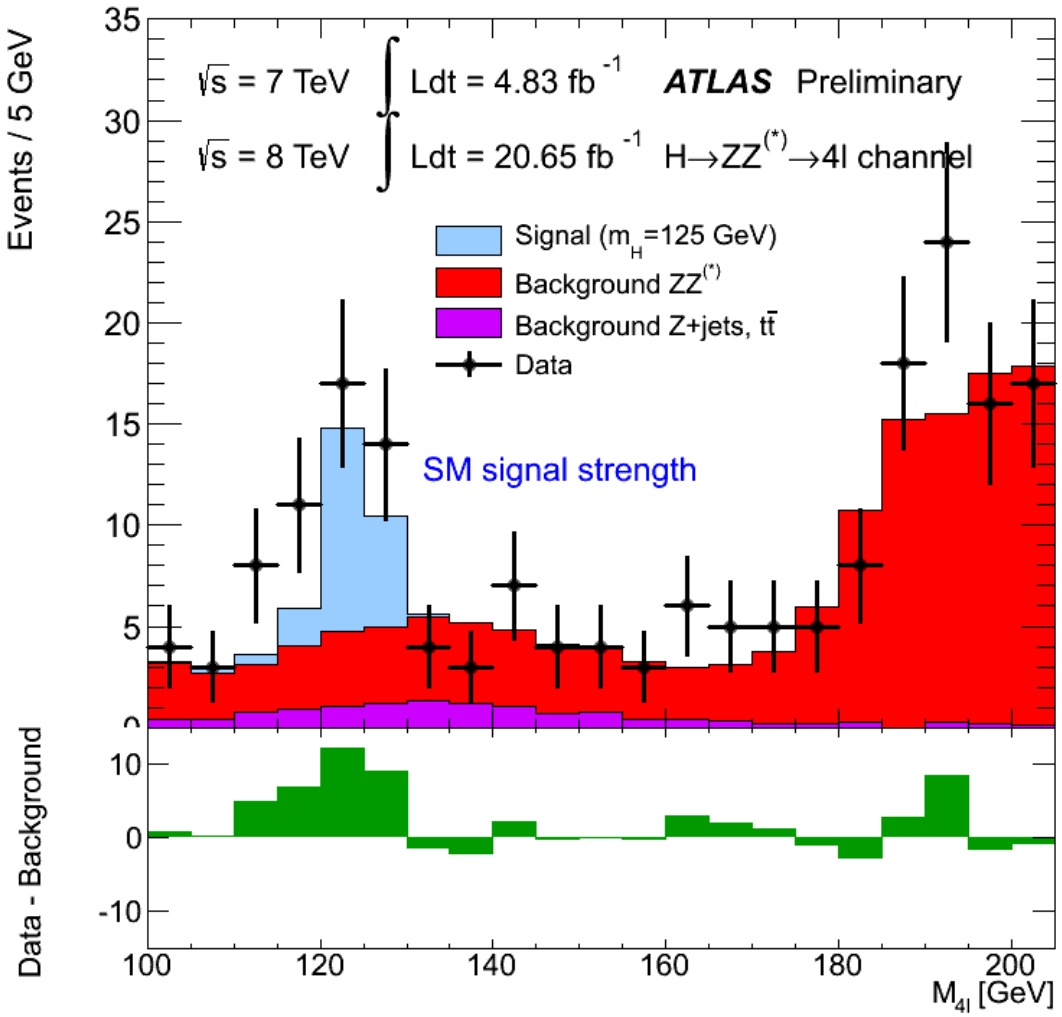
- Excess of background with a significance of 6.6 standard deviations
- With a signal strength factor (fitted signal strength divided by expected SM strength):

$$\boldsymbol{\mu = 1.7^{+0.5}_{-0.4}}$$



Conclusion

- **New fitting framework** created exactly for $H \to ZZ^* \to 4\ell$ needs
- Results from **per-event error mass fit** and the standard fit are compatible
- **Improved resolution by $\sim$ 0.1 GeV** with the per-event error implemented



$H \to ZZ^* \to 4\ell$ fit results:

$\mu = 1.7^{+0.5}_{-0.4}$

$m_H = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})\ \text{GeV}$

Acknowledgement

I want to thank especially the following people for their work:

- Pierluigi Catastini[1]
- Phil Clark[2]
- Francisca Garay[2]
- Robert Harrington[2]
- Ben Wynne[2]

1 2

Backup Slides

H→ZZ* → 4ℓ systematic uncertainties

- Experimental systematic uncertainties:

Systematic uncertainties	Value (%)
Luminosity	1.8 (2011)/3.6 (2012)
Muon efficiency	0.4-0.8
Muon momentum scale	0.1-0.2
Electron efficiency	1.6-9.4
Electron energy scale	0.2-0.4

- Theoretical systematic uncertainties:

Process	QCD Scale (depend of m_H) in %	PDF+α_S in %	Total in %
ggF	+12/–7	±8	+20/-15
VBF	±1	±4	±5
WH/ZH	±1	±4	±5
$t\bar{t}$	±4	±4	±1
ZZ (SM)	±5 +10 (gg→ZZ)+shape	±4	±12

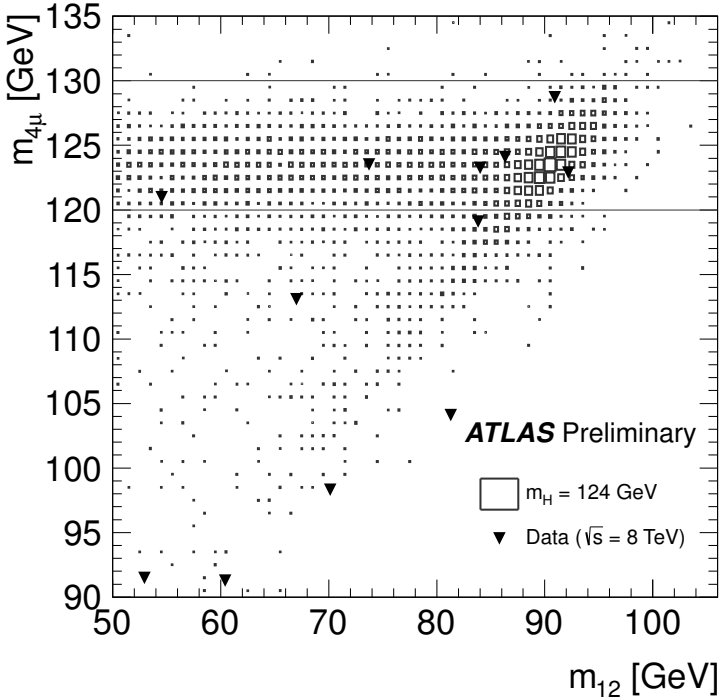
Cross checks

- Investigate systematic effects in the dominant muon channels:
  Using the redundancy of the muon momentum measurement
  - Comparing mass measurement results of muons only reconstructed by the ID to the results of combined muon measurement

    $\Rightarrow$ Consistent results

- Check the leading lepton pair distribution in the 4μ channel:
  $m_{4\mu}$ vs m_{12} distribution for data and expected MC response for $m_H = 124$ GeV
  - Without Z-mass constraint (kinematic fit to the leading lepton pair for $m_{4\ell}<190$ GeV)
  - Populated band, shown by horizontal lines (120 -130 GeV), with both Z bosons off-shell and particularly populated where m_{12} is on-shell

    $\Rightarrow$ Data and MC agree well within the statistical uncertainty



References

SM $H \rightarrow ZZ^* \rightarrow 4\ell$ results released:

- ATLAS-CONF-2013-013 (March 2013)
- ATLAS-CONF-2012-162 (December 2012)
- ATLAS-CONF-2012-092 (July 2012)

All available at
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults