Optimisation of the Higgs boson mass measurement in the diphoton channel with the ATLAS detector

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The Higgs boson

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About the Higgs

- Particle in the SM
  - Theory of elementary particles and their interactions
- Discovered in 2012 by ATLAS and CMS collaborations
- Responsible for giving mass to all elementary particles
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Masses are not predicted by SM $\Rightarrow$ measure m_H

- Higgs properties $(\sigma, \mathrm{BR} \dots)$ are given as function of its mass
  - Compare them with predictions
- m_H, m_W, m_t are related
  - TEST SM consistency

Higgs boson @ LHC

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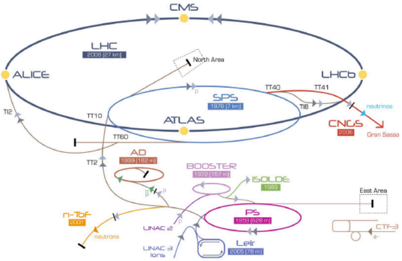
The LHC is a *pp* collider at CERN

- Operates at 13 TeV
- Higgs production achieved in 4 main ways



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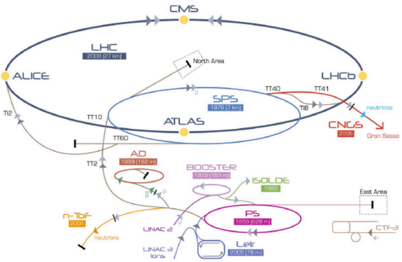
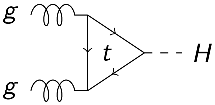
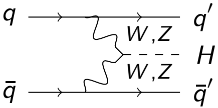
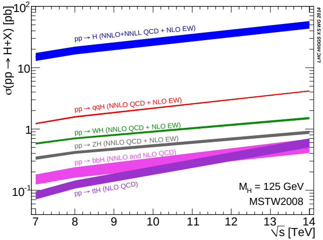


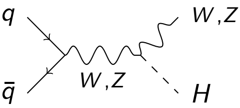


ggH



VBF





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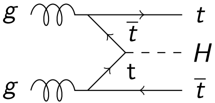

$t\bar{t}H$

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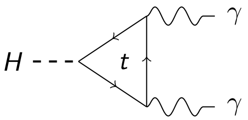

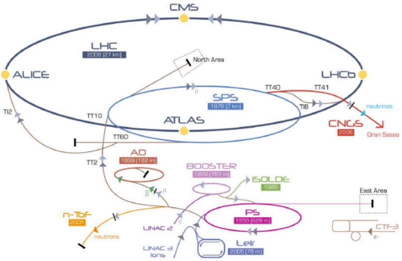

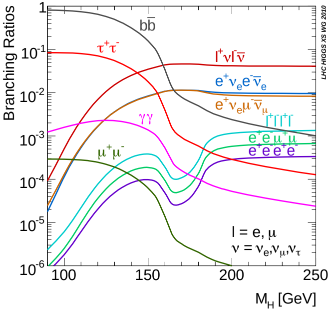

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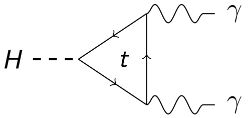
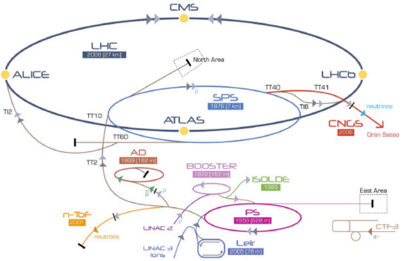
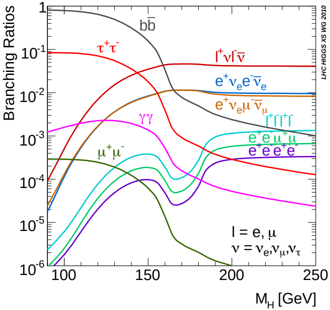


- At ATLAS m_H is measured with $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$
  - Great resolution $\sim$1 GeV
  - Low background





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Latest mass measurement from ATLAS @ 36.1 fb^{-1}

$$H \to \gamma\gamma \qquad m_H = 124.93 \pm 0.21(\text{stat}) \pm 0.34(\text{syst})\,\text{GeV}$$
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$\to$ **Main focus of this thesis**

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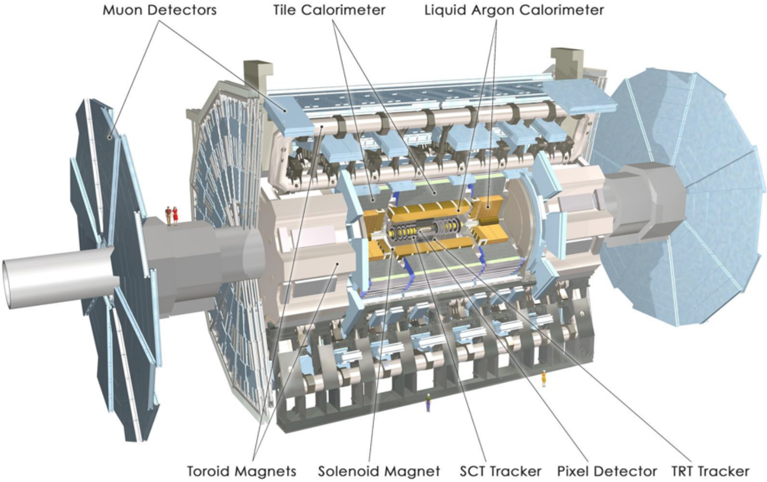

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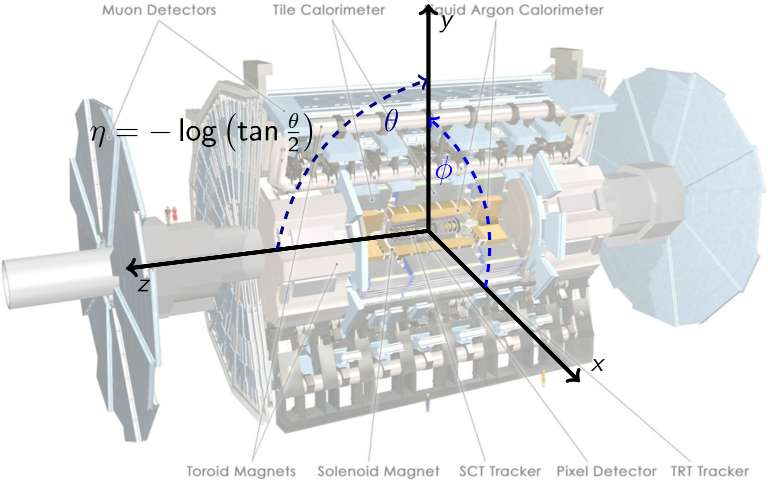

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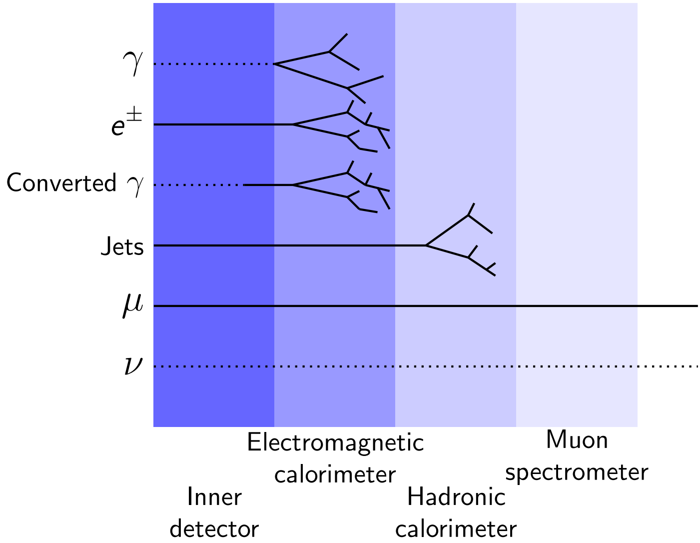

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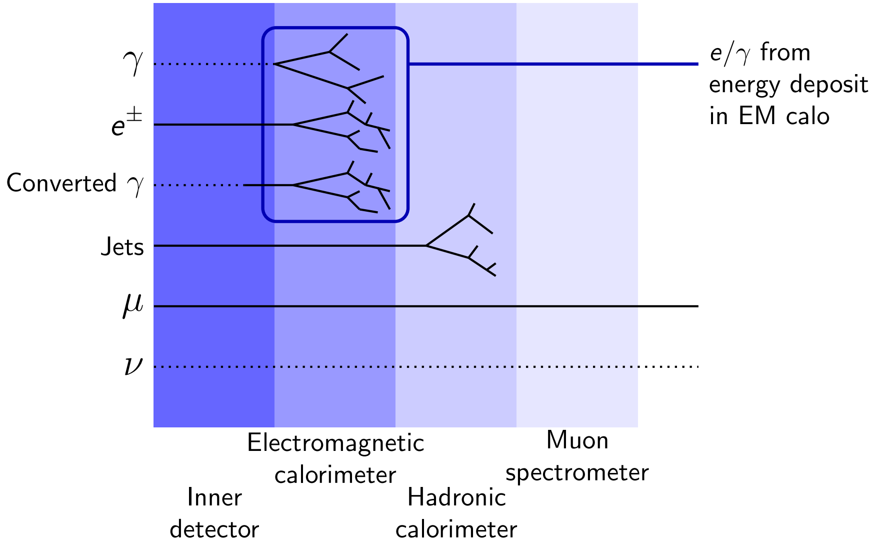

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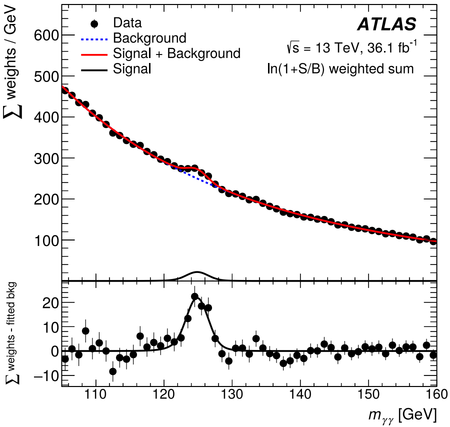
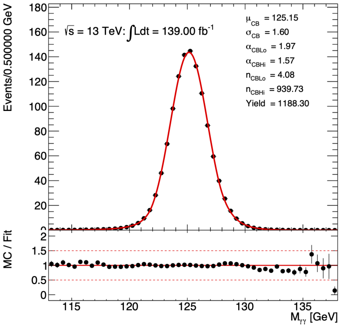


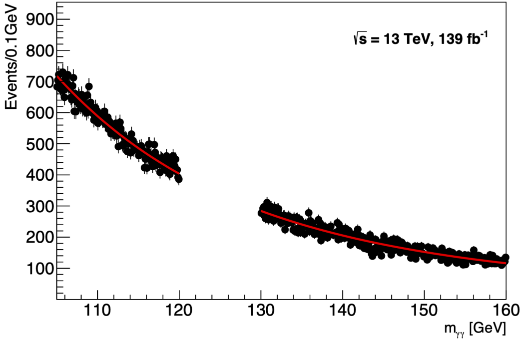
Fit result

Result for Signal and Background Fit in one event category

Signal Fit



Background Fit



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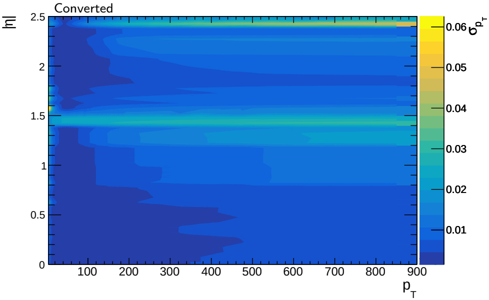
  - From maps $f(p_{\text{T}}, \eta, \text{conv}) = \sigma_{p_{\text{T}}}$



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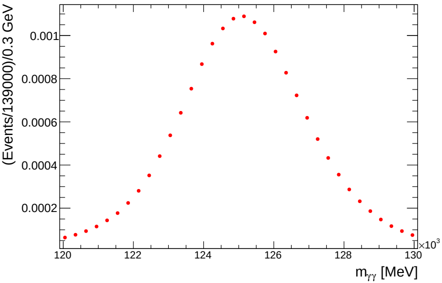

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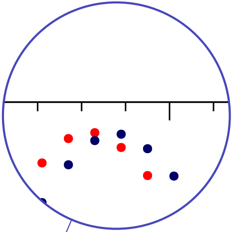

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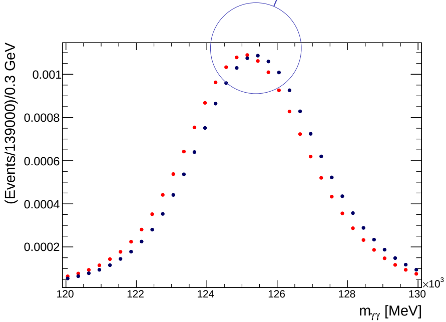
- Evaluate

$$\delta = \frac{\langle m_{\gamma\gamma}^{\text{var}} \rangle}{\langle m_{\gamma\gamma} \rangle} - 1$$



Likelihood Fit

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Statistical strategy is based on the definition of likelihood function

$$\mathcal{L}\left(m_H, \boldsymbol{\theta}; \boldsymbol{n}_c, \boldsymbol{m}_{\gamma\gamma}\right) = \prod_{c=1}^{N_{\text{cat}}} P\left(n_c | s_c(m_H, \boldsymbol{\theta}) + b_c\right) \prod_{i=1}^{n_c} f_c\left(m^i_{\gamma\gamma}, m_H, \boldsymbol{\theta}\right) K(\boldsymbol{\theta})$$

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  - Diphoton mass probability density function f_c
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- $K(\boldsymbol{\theta}) = \prod_i \frac{1}{\sqrt{2\pi}} e^{-\frac{\theta_i}{2}}$ are a set of gaussian constraints for NPs
  - A systematic uncertainty affecting quantity X, enters with a parameter δ in the likelihood as

$$X(\theta_i) = X \cdot r(\theta_i) = X \cdot \begin{cases} 1 + \delta\theta_i \\ e^{\delta\theta_i} \end{cases}$$

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- Higgs mass m_H is the POI
  - Value and **uncertainty** are extracted with likelihood maximisation
- Test Statistic is the **PLR**

$$\lambda(m_H) = -2\log\left(\frac{\mathcal{L}(m_H, \hat{\boldsymbol{\theta}}_{m_H})}{\mathcal{L}(\hat{m}_H, \hat{\boldsymbol{\theta}})}\right)$$

  - May be interpreted as change of χ^2 wrt minimum
- Performed on an Asimov dataset

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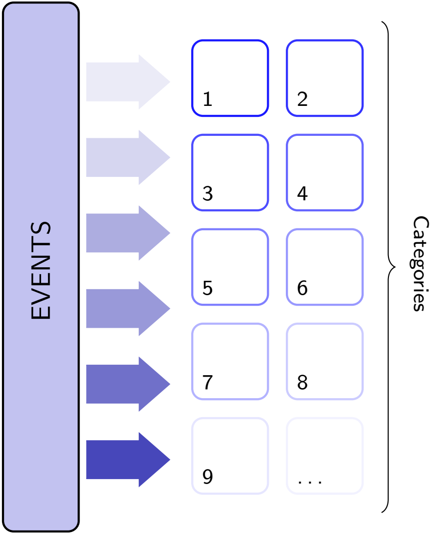

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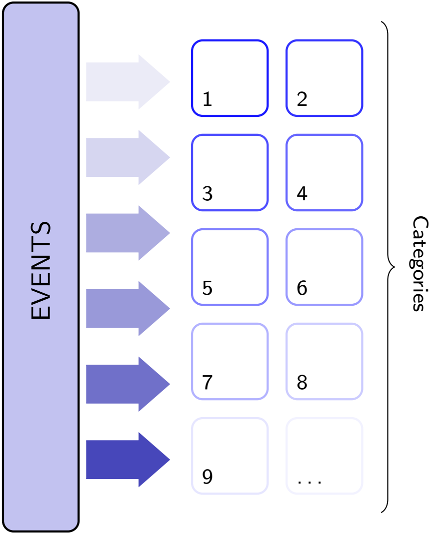

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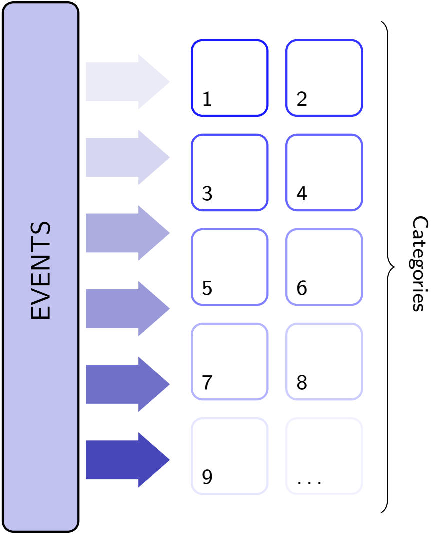

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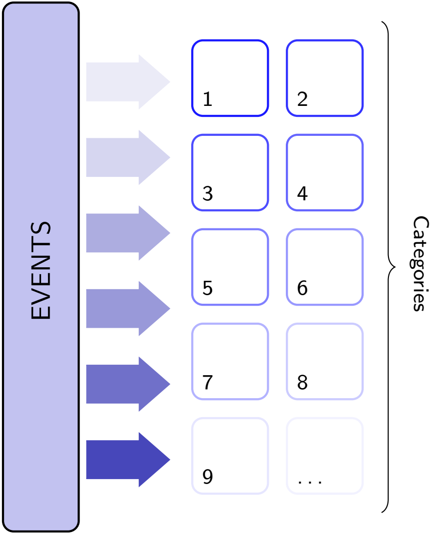

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By means

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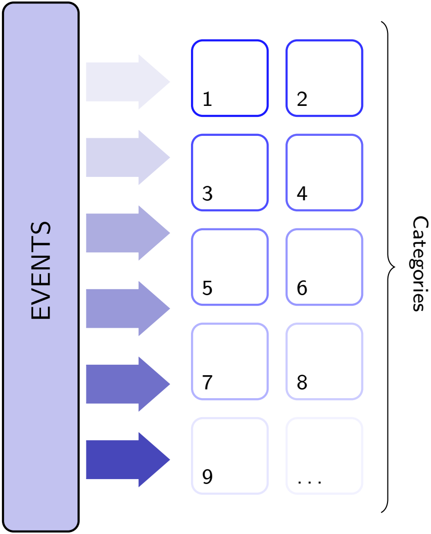
- Build a **systematic uncertainty oriented** categorisation
  - Select events with low systematic value
- Suitable choice can reduce the systematic uncertainty
- 4 different categorisation are studied



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Attempt to optimise the uncertainty on coupling categorisation

- Analyse 2 *ggH* categories
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  - ggH 0J Cen is sharply peaked
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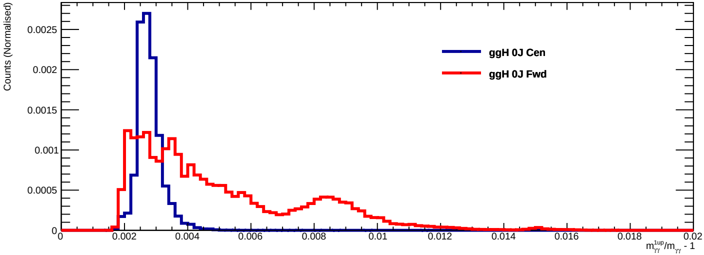

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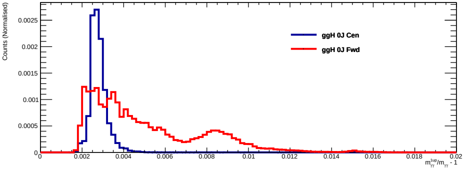

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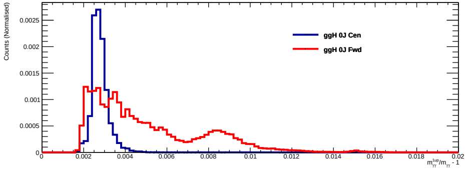
- Higher systematic values are seen in
  - Unconverted photons
  - Photons at $|\eta| \sim 1.5$



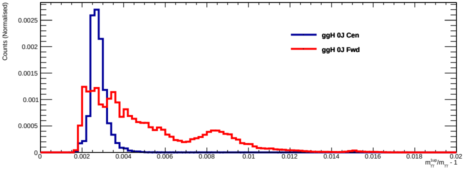
Coupling analysis

First categorisation tested is the one used for the 2018 Higgs Coupling analysis

- 29 categories built to target different Higgs boson production modes

Attempt to optimise the uncertainty on coupling categorisation

- Analyse 2 *ggH* categories
- $m_{\gamma\gamma}^{\text{var}}/m_{\gamma\gamma} - 1$ distribution, for total systematic variation
  - ggH 0J Cen is sharply peaked
  - ggH 0J Fwd is broader
- Address a new categorisation according to systematic value
- Higher systematic values are seen in
  - Unconverted photons
  - Photons at $|\eta| \sim 1.5$
- The division follows those criteria
- 4 new categories are introduced



Production mode categorisation

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A different approach in categorising events

- Aiming to reduce systematic uncertainty as well
- Based on Higgs production mode

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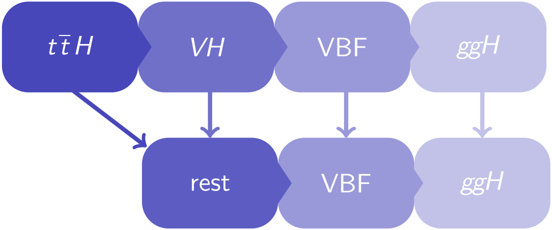

- ggH being the most populated

Production mode and systematic value categorisation

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Natural subdivision of production mode categorisation

- Focus on total systematic uncertainty
- Create 3 subcategories

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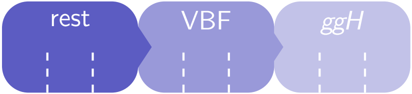

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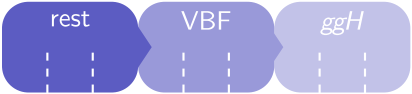
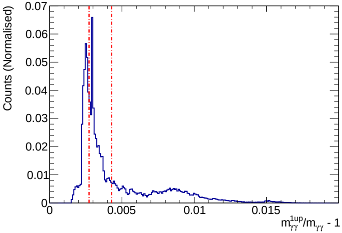
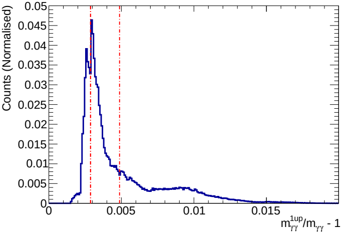


Total systematic value distribution



ggH



VBF

Production mode and systematic value categorisation

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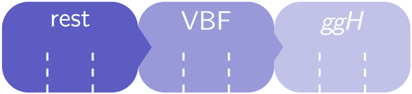
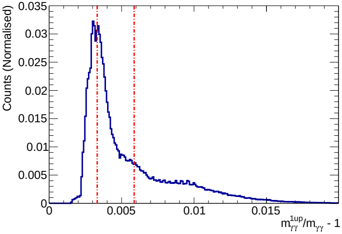


Total systematic value distribution



rest

Results

For every categorisation

- Models are re–built (Signal, Background, Systematics)
- Asimov fit is performed
  - $\Rightarrow$ extract the expected uncertainty on m_H

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Coupling	298	129	268
Split “ggH 0J FWD”	294	126	266
Production mode	325	155	286
Production mode and systematic	280	152	235

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Reduction of the total (systematic) uncertainty by 6 % (12 %)

Conclusion

I performed an optimisation of the Higgs boson mass analysis

The last ATLAS measurement showed a significant contribution from systematic uncertainty

I addressed the optimisation of the event category

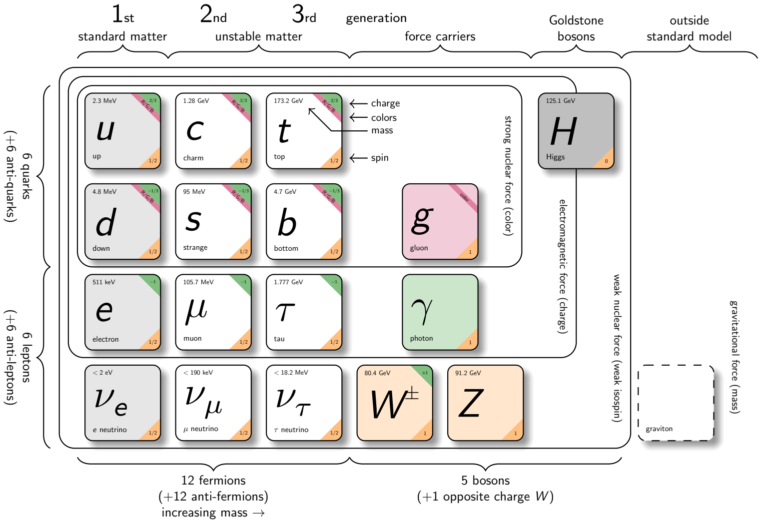
- Event division according to systematic value
- I noticed a possible improvement wrt the actual categorisation
  - Reduction of the systematic uncertainty of 12 %
  - Reduction of the total uncertainty of 6 %

Future improvements will include

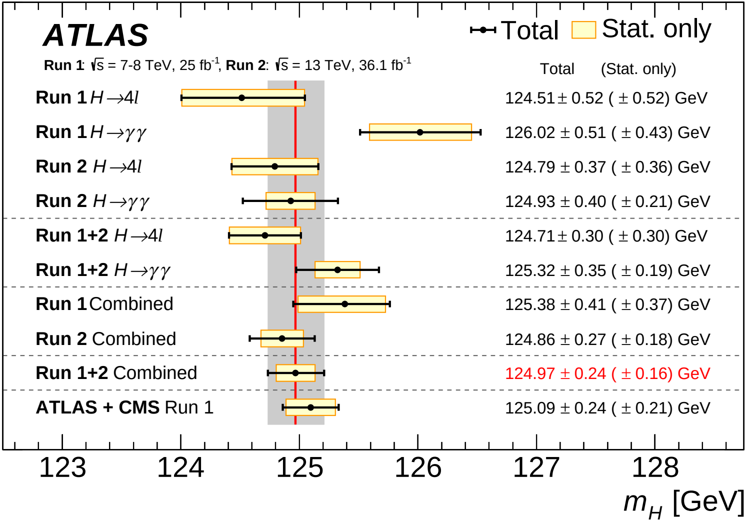
- Reduction of statistical uncertainty
  - Increasing number of categories
- Optimisation of boundaries between them

Backup

The Standard Model



Higgs boson mass



ggH 0J FWD division

From analysis of the systematic value as a function of kinematic variables

- Converted photons have lower systematic
- Higher systematic within the barrel–endcap EM calorimeter transition

Division proposed

ggH 0J FWD CC | ggH 0J FWD | ggH 0J FWD UC

ggH 0J FWD UU GR | ggH 0J FWD UU BR

ggH 0J FWD CC
- Both photons converted

ggH 0J FWD UC
- Only one photon converted

ggH 0J FWD UU GR
- Both photons unconverted
- Both photons away of the transition region

ggH 0J FWD UU BR
- Both photons unconverted
- At least on photons in the transition region

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ggH 0J FWD CC | ggH 0J FWD | ggH 0J FWD UC

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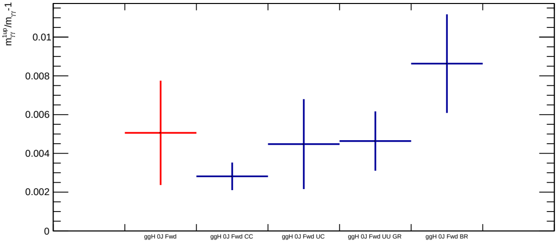
Total systematic, mean and RMS



EM calibration