

# Energy calibration of electrons and photons in ATLAS and impact on precision measurements of the Higgs boson properties in the diphoton channel

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Journées de Rencontre de Jeunes Chercheurs  
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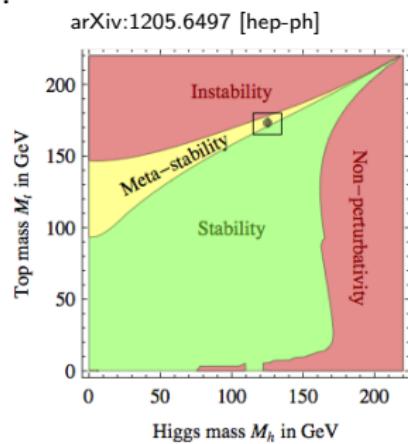


# Outline

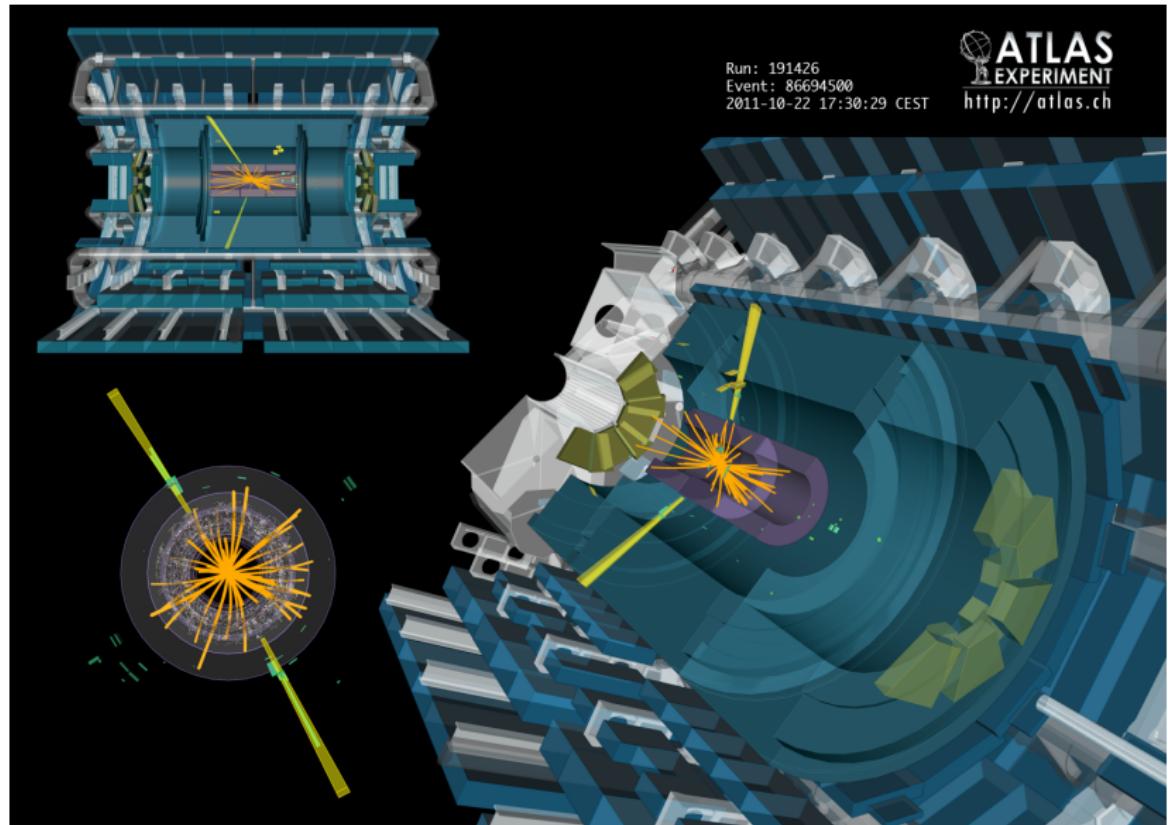
- ① Introduction: Higgs to diphoton in ATLAS
- ② Electron & photon energy calibration
- ③ Higgs mass measurement
- ④ Conclusion & Outlook

# Introduction: why to measure the Higgs properties

- Is the particle discovered in 2012 the Standard Model Higgs boson?
  - precision measurement of couplings and cross-sections
  - use  $H \rightarrow \gamma\gamma$  channel: clean, easy to trigger
- Alternative theories:
  - light boson of a two-Higgs-doublet-model?
  - composite particle?
- What is the **mass** of the new particle?
  - is our universe stable or meta-stable?
  - only free parameter in the couplings prediction; can be used as input for measurements (also in other channels)
- Good **photon energy calibration** needed to measure Higgs properties!



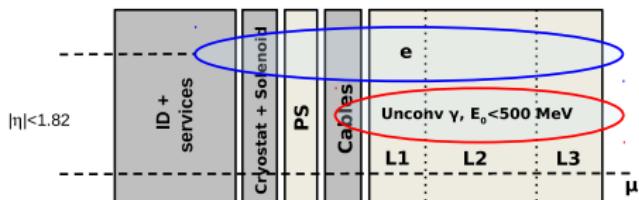
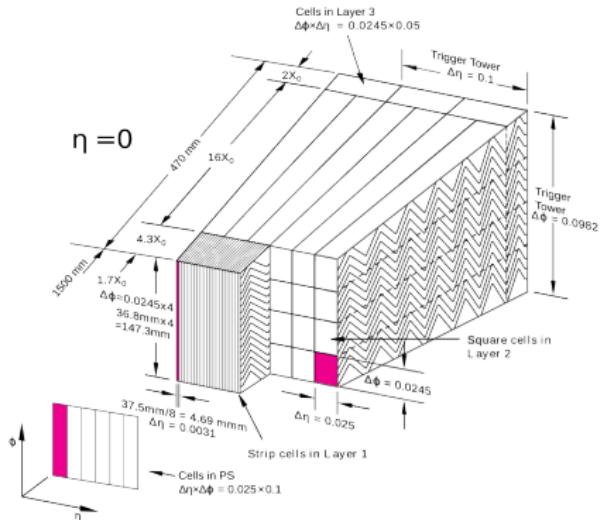
# How to measure $H \rightarrow \gamma\gamma$ with ATLAS?



# Electron & photon reconstruction

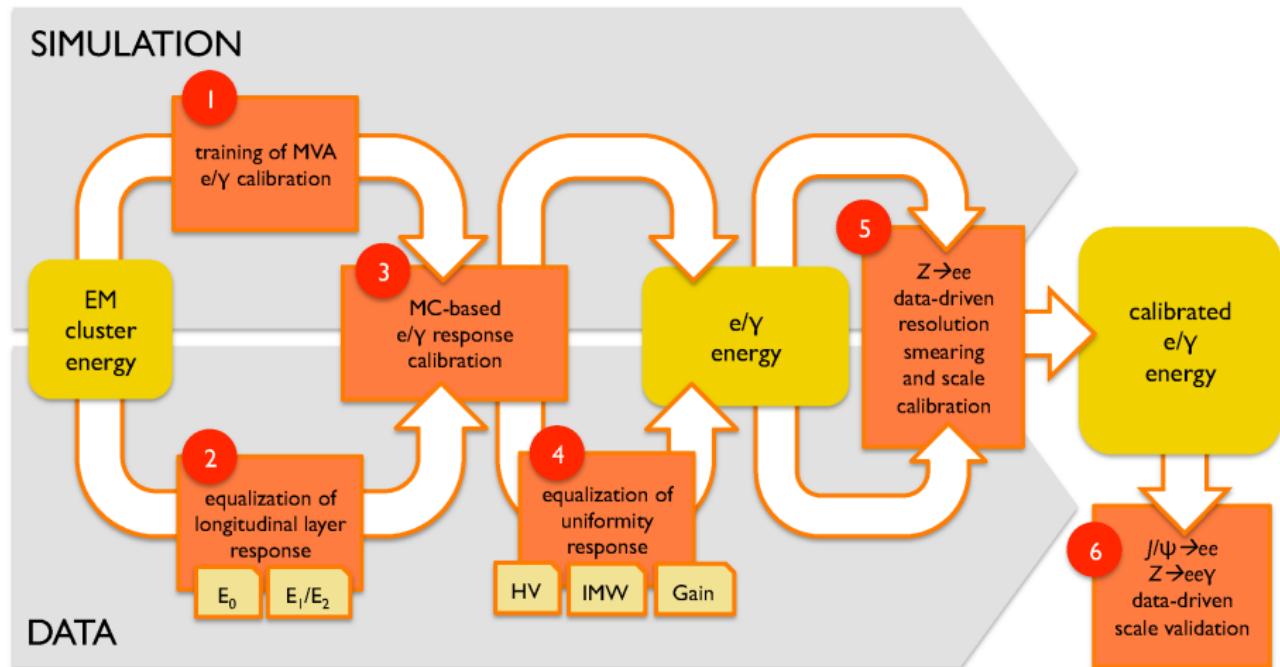
**Electron:** track + cluster in electromagnetic calorimeter

**Photon:** only cluster in electromagnetic calorimeter (unconverted)  
cluster with conversion vertex and track(s) (converted)

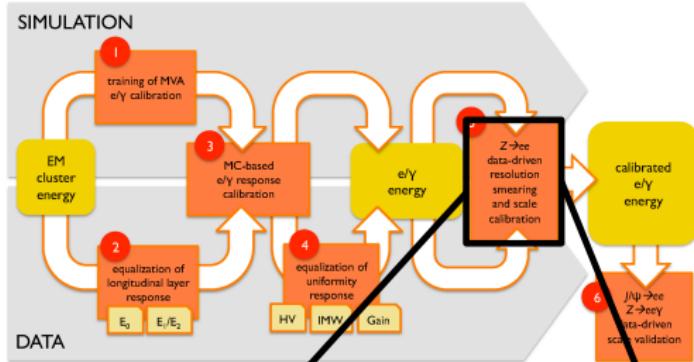


# Electron and photon energy calibration

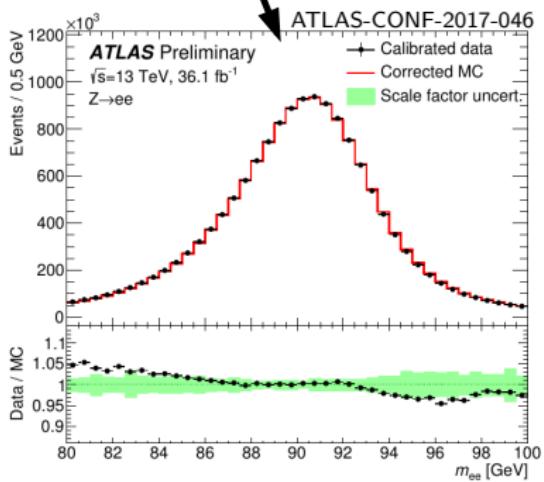
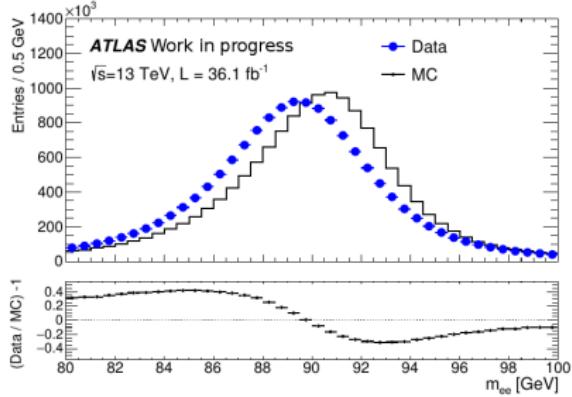
- Calorimeter showers of **electrons** and **photons** are very similar:  
calibrated using mainly same procedure



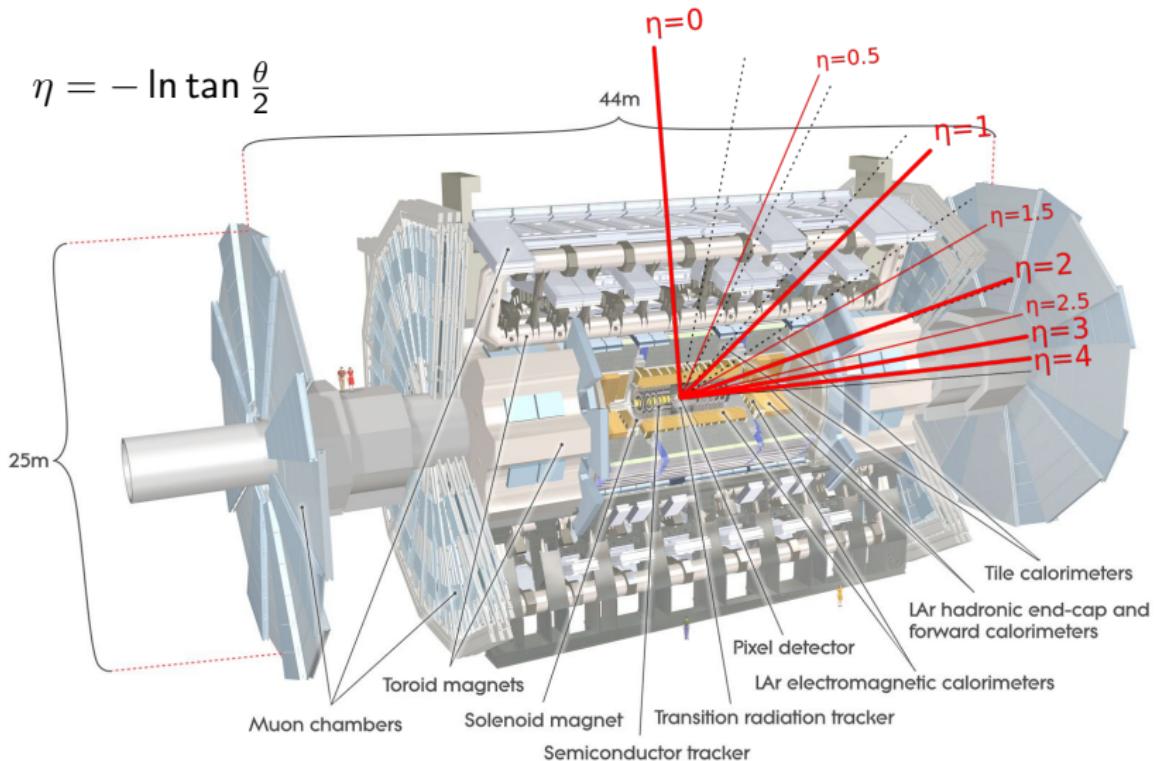
# Effect of the calibration



Consider the different y-scales in the ratio plot!

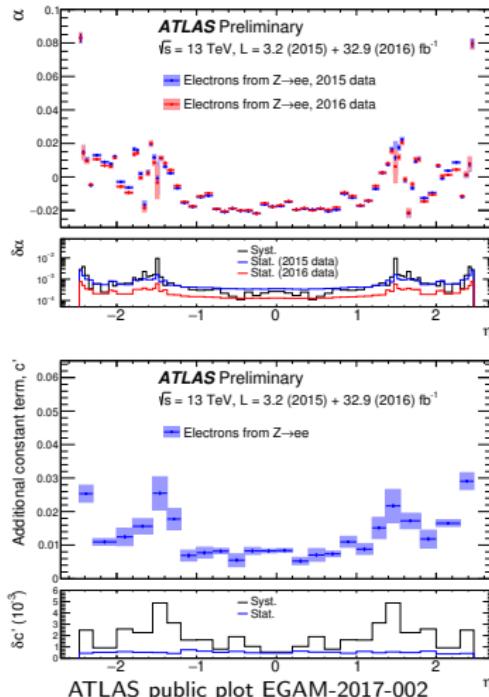


# Pseudorapidity



# In situ calibration from $Z \rightarrow e^+ e^-$ events

- Smearing of MC to match resolution in data
- Correct in bins of electron  $\eta_{\text{calo}}$



## Energy scales

$$E_i^{\text{data}} = E_i^{\text{MC}} \cdot (1 + \alpha_i)$$

$$m_{ij}^{\text{data}} = m_{ij}^{\text{MC}} \cdot \sqrt{(1 + \alpha_i)(1 + \alpha_j)}$$

## Additional constant term

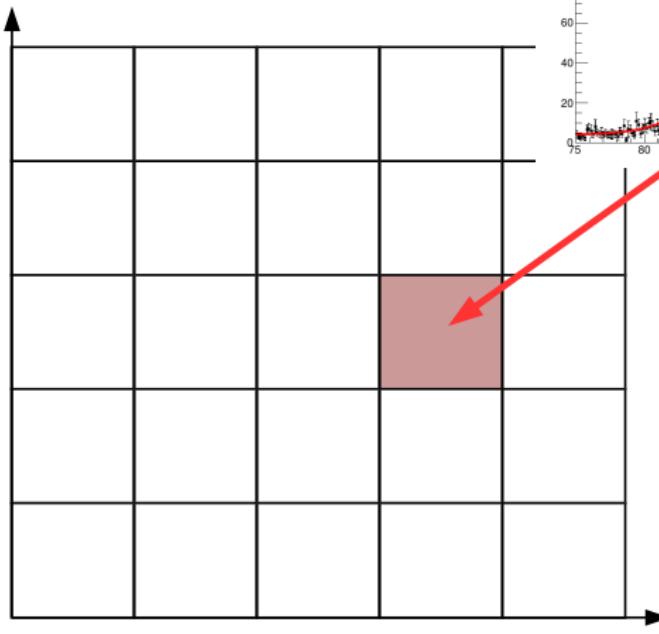
$$E_i^{\text{data}} = E_i^{\text{MC}} \cdot (1 + N(0, c_i))$$

$$m_{ij}^{\text{data}} = m_{ij}^{\text{MC}} \sqrt{(1 + N_i(0, c_i))(1 + N_j(0, c_j))}$$

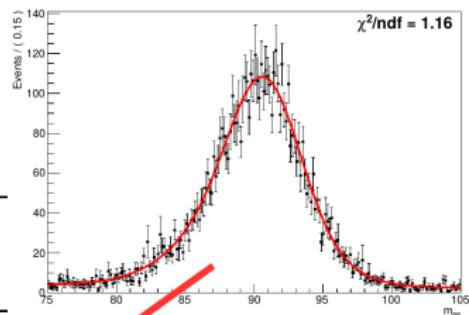
# How to get scales for single electrons from invariant mass?

$\eta$  of electron 1

$\rightarrow \alpha_1, c'_1$



$\eta$  of electron 2  
 $\rightarrow \alpha_2, c'_2$

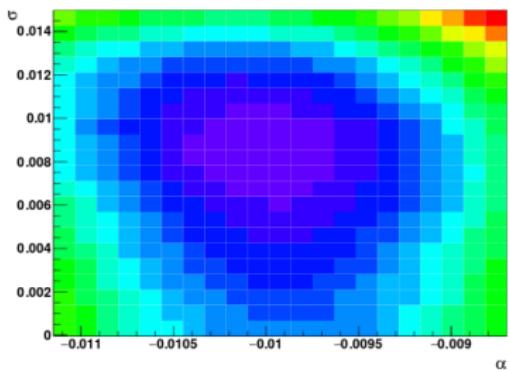
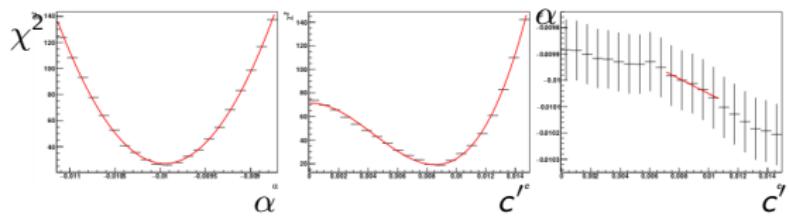


# Template method: baseline method

- Build distorted MC templates with known values of  $\alpha_i$  and  $c_i$
- Compute  $\chi^2$  of each of these templates with data  $Z$  mass distribution

Fit  $\chi^2$ -distribution in each  $\eta_{ij}^{\text{calo}}$ -bin to get

$$\text{minimum } \alpha_{ij} := \frac{\alpha_i + \alpha_j}{2} \text{ and } c_{ij} := \frac{c_i^2 + c_j^2}{2}$$

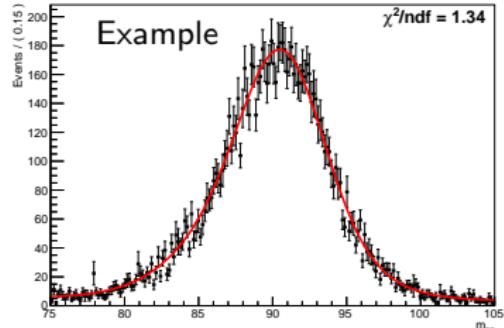


- Invert equation system to obtain single-electron correction factors  $\alpha_i$  and  $c_i$  using a  $\chi^2$ -minimisation

# Direct fit of scale factors using a lineshape method

Lineshape based fit:

- $Z$ -mass distribution described by sum of 3 Gaussians ( $n = 1, 2, 3$ )
- Shape fixed from fit to MC



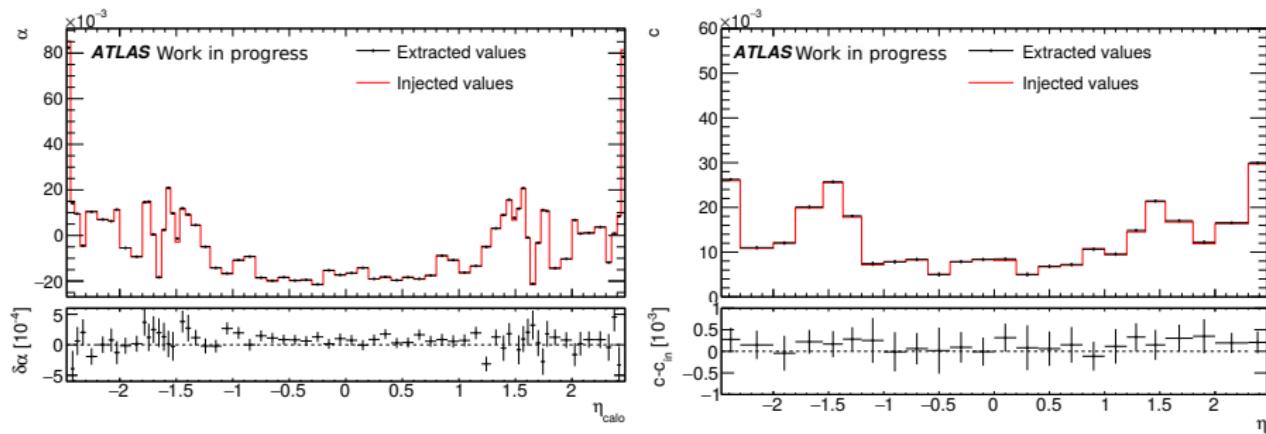
Parametrisation of data relative to MC modified my scale factors

$$\begin{aligned}\mu_{\text{data}}^n &= \left(1 - \frac{1.8}{8}(c_i^2 + c_j^2)\right) \sqrt{(1 + \alpha_i)(1 + \alpha_j)} \cdot \mu_{\text{MC}}^n \\ \sigma_{\text{data}}^n &= \sqrt{(1 + \alpha_i)(1 + \alpha_j) \left[ (\sigma_{\text{MC}}^n)^2 + \frac{(\mu_{\text{MC}}^n)^2}{4} \cdot (c_i^2 + c_j^2) \right]}\end{aligned}$$

- Simultaneous fit to all  $\eta_{\text{calo}}^{ij}$ -bins: direct extraction of single electron scale factors

# Performance of the lineshape method

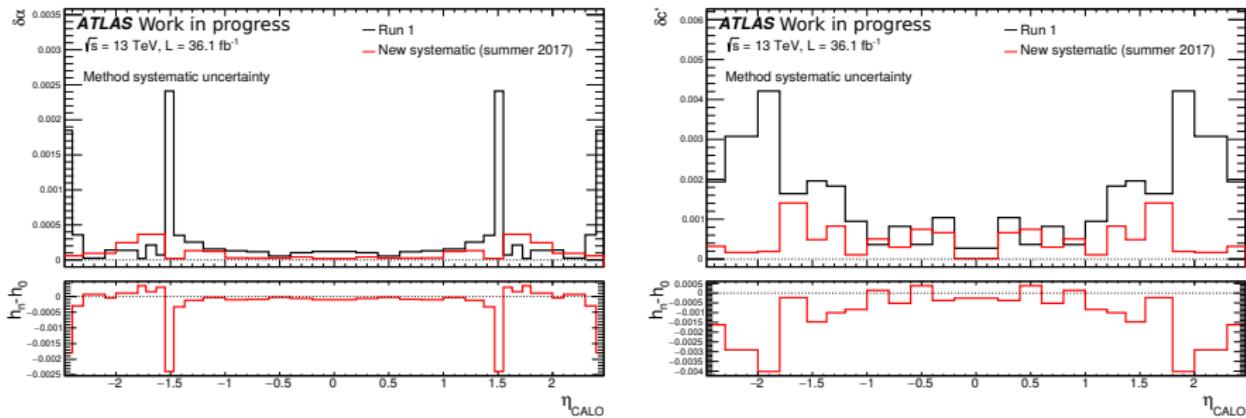
Closure test on MC with known injected scale factors



- Similar to closure of template method

# Method systematics

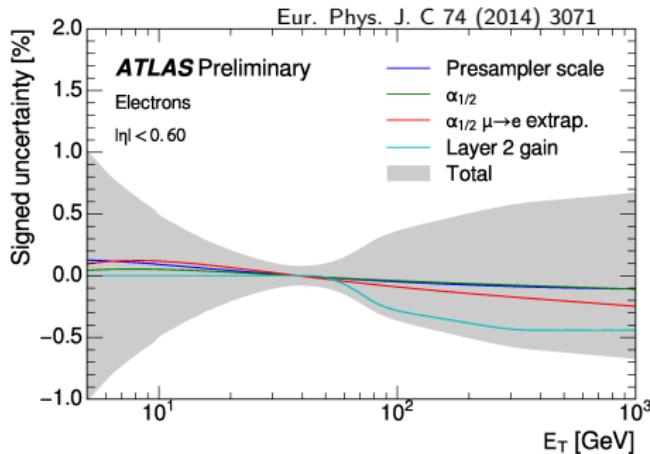
- Have 2 independent methods with good closure each
- Difference taken as systematic uncertainty



N.B.: lineshape method allows easy expansion of scale factors in more dimensions

# Energy dependent scale factors

- Scale factors from  $Z \rightarrow ee$  with typical electron energy of 40 GeV
- By definition, systematics most constrained there; then extrapolated

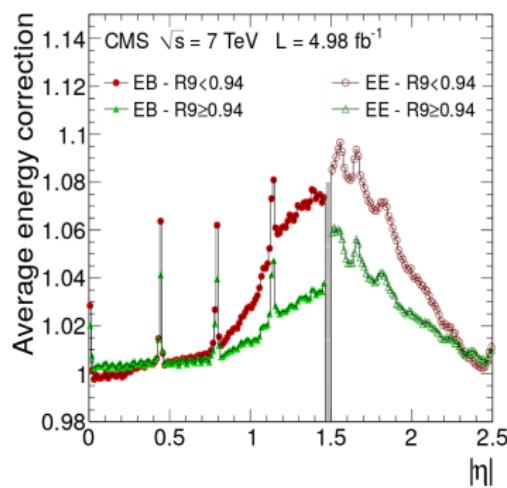


- Idea: consider energy dependence of scales to constrain systematics
- Would be helpful for precision measurement of  $W$ -mass

# Shower shape dependent scales

- Additional systematics in extrapolation from electrons to photons
- Mainly due to differences in the shower shape
- Constrain systematics with shower shape dependent scale factors?

arXiv:1306.2016 [hep-ex]



Example from CMS:

$$R_9 = \frac{E_{3\times 3 \text{ around } E_{\max}}}{E_{\text{tot,supercluster}}}$$

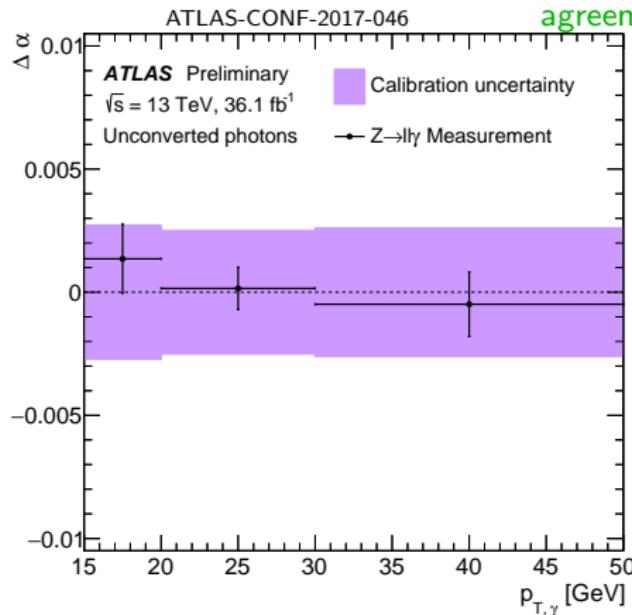
Typical values:

- converted photons:  $R_9 < 0.94$
- unconverted photons:  $R_9 \geq 0.94$

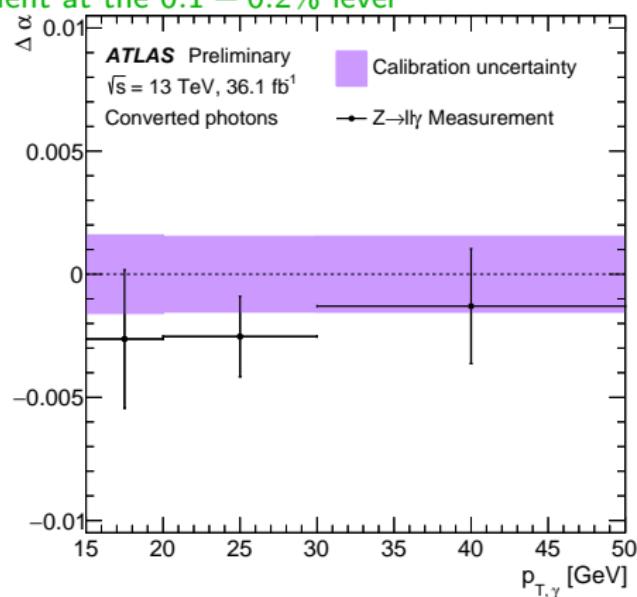
Correction with electron from  $W$  decay (could be done using  $Z \rightarrow ee$ )

# Cross-check of the energy calibration for photons

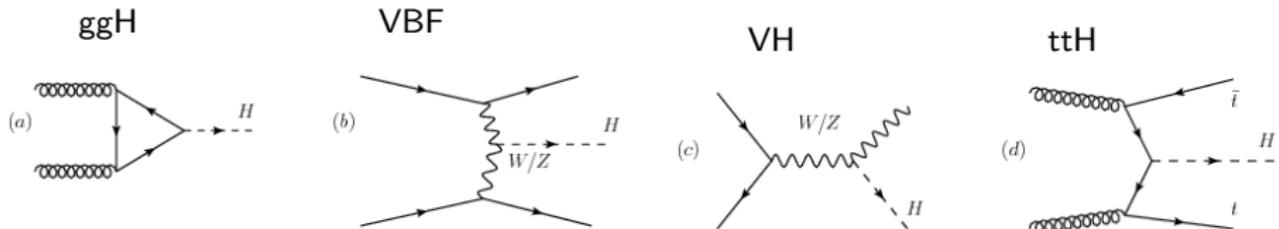
- Same calibration used to calibrate photon energy
- Some additional photon-specific systematics
- Cross-check validity of calibration for photons using radiative  $Z \rightarrow \ell\ell\gamma$  ( $\ell = e, \mu$ ) events



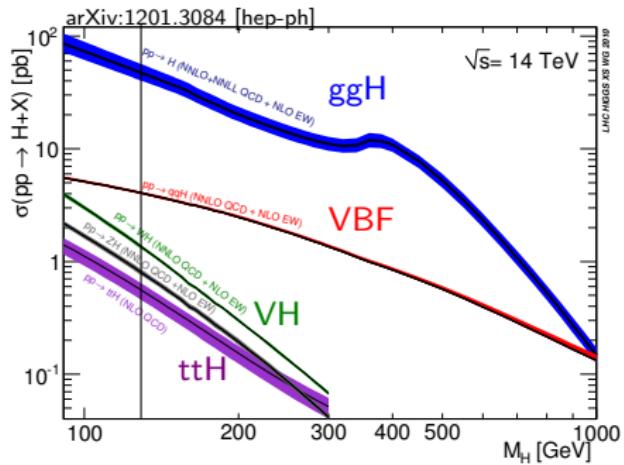
agreement at the 0.1 – 0.2% level



# Higgs production modes at the LHC

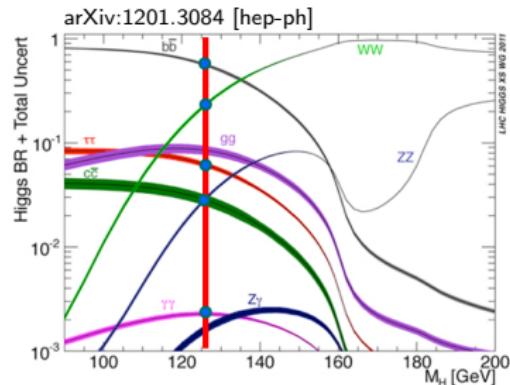


- ggH: gluon-gluon fusion
- VBF: vector boson fusion
- VH: Higgs strahlung
- ttH: ass. top quark production

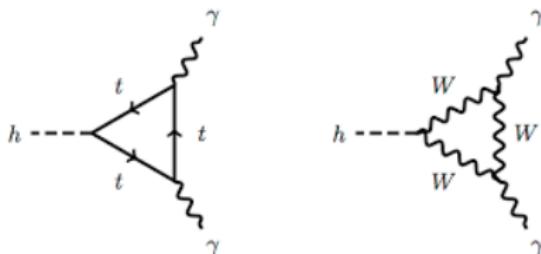


# The Higgs boson decay into a pair of photons

- Higgs boson coupling to elementary particles goes with their mass
- $H \rightarrow \gamma\gamma$ : small branching fraction



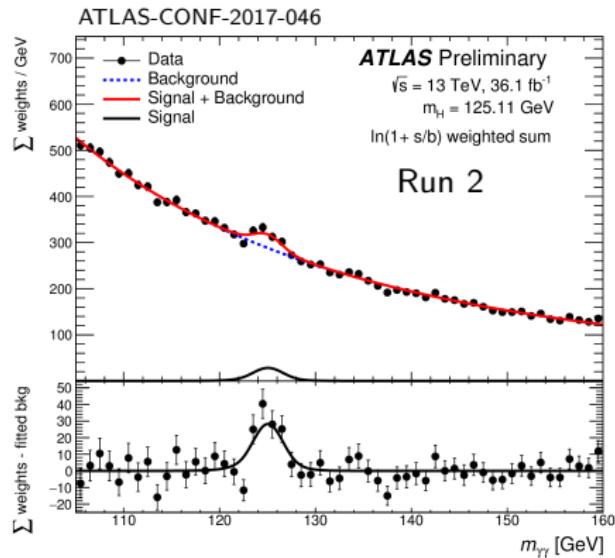
Does not couple directly to massless photons; only via loop processes:



- Good/clean reconstruction
  - easy to trigger and select
  - lead to discovery (together with  $H \rightarrow ZZ^* \rightarrow 4\ell$ ,  $\ell = e, \mu$ )
  - one of the best channels for precision measurements

# Higgs mass measurement in $H \rightarrow \gamma\gamma$

- Run 1: combination of  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ^* \rightarrow 4\ell$  stat. dominated:  
 $m_H = 125.36 \pm 0.37 \text{ (stat)} \pm 0.18 \text{ (syst)} \text{ GeV}$
- Run 2: higher int. lumi. and higher cross-section  $\rightarrow$  reduced stat. error



# Signal and background model

- Fit range: [105, 160] GeV
- Signal (from MC): double-sided Crystal-Ball with

$$\mu_{CB} = \mu_{CB}(m_H = 125 \text{ GeV}) + s_{\mu_{CB}}(m_H - 125 \text{ GeV})$$

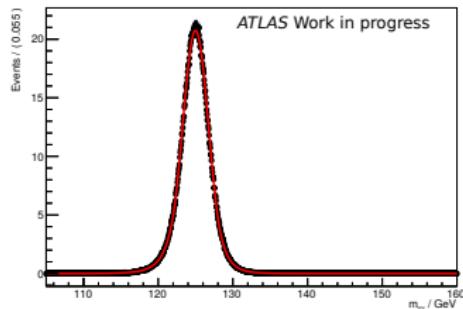
$$\sigma_{CB} = \sigma_{CB}(m_H = 125 \text{ GeV}) + s_{\sigma_{CB}}(m_H - 125 \text{ GeV})$$

$\alpha_{low}, \alpha_{high} = \text{const.}$

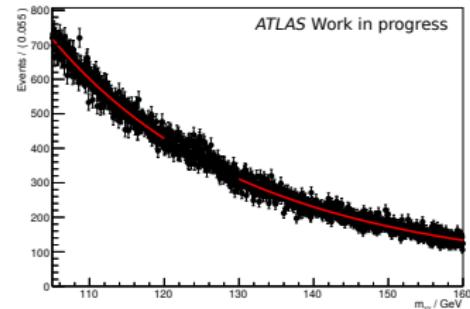
$n_{low} = n_{high} = 10$

- Background from spurious signal test (mostly exponential with 2<sup>nd</sup> order polynomial)

Signal



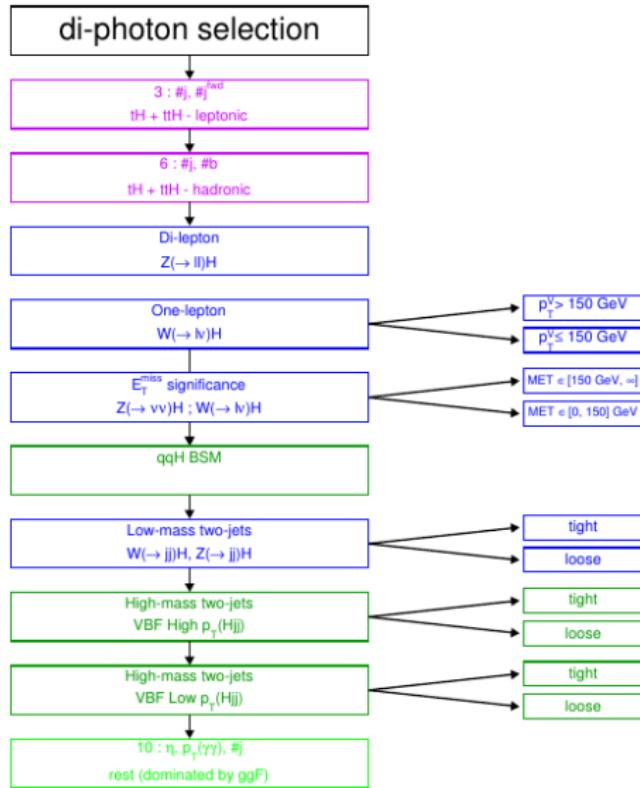
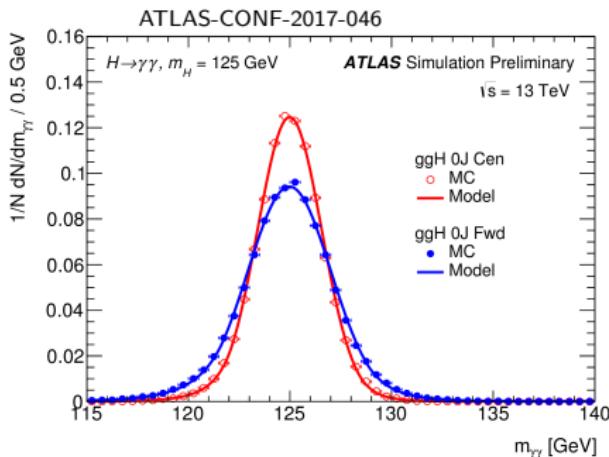
Background



Example:  
GGH\_0j\_CEN

# Optimisation of the event categorisation

- Use event categories to optimise signal significance and resolution
- Several categorisations tested using Asimov dataset



# Systematic uncertainties

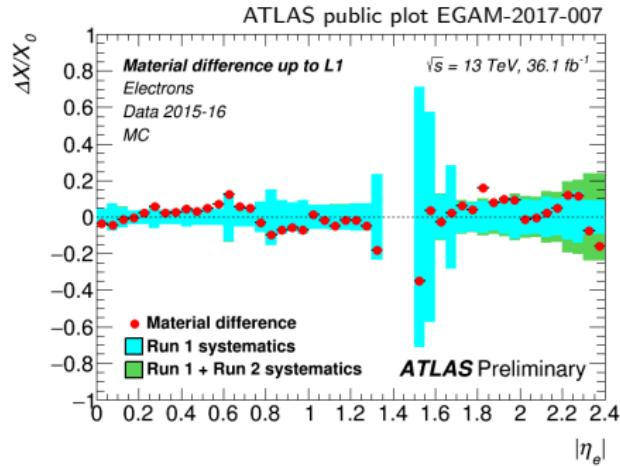
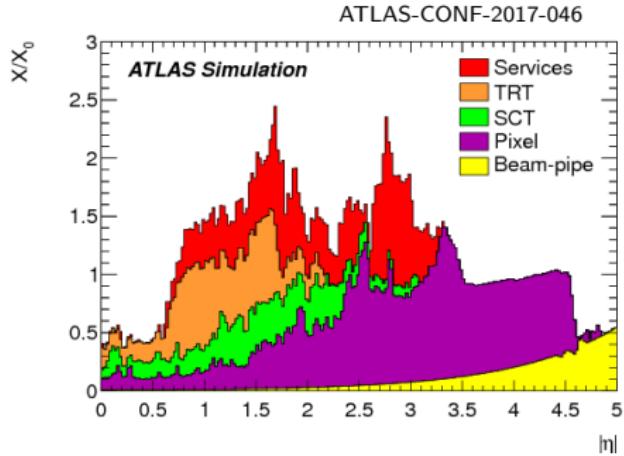
Dominant uncertainty: photon energy calibration uncertainties

Source	Systematic uncertainty on $m_H^{\gamma\gamma}$ [MeV]
Photon energy calibration	LAr cell non-linearity $\pm 200$
	LAr layer calibration $\pm 190$
	Non-ID material $\pm 120$
	Lateral shower shape $\pm 110$
	ID material $\pm 110$
	Conversion reconstruction $\pm 50$
	$Z \rightarrow ee$ calibration $\pm 50$
	Background model $\pm 50$
	Primary vertex effect on mass scale $\pm 40$
	Resolution $^{+20}_{-30}$
	Signal model $\pm 20$

ATLAS-CONF-2017-046

# Main sources of photon energy scale uncertainties

Material:

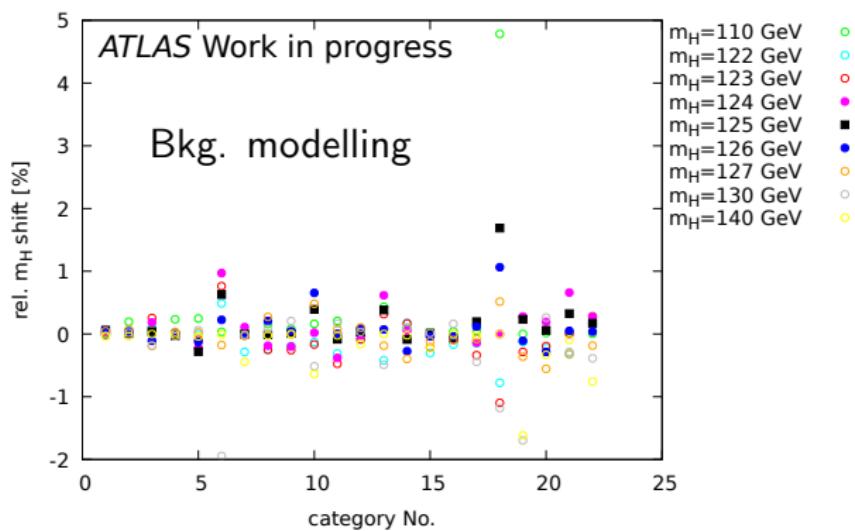


Cell non-linearity: detector response for different reconstruction gains  
(depending on energy deposit)

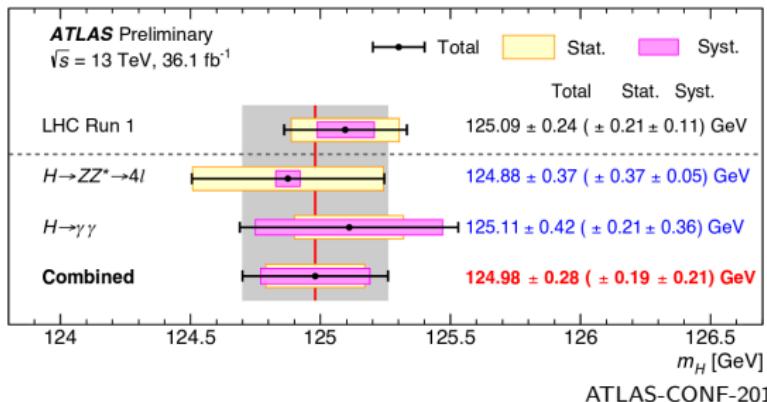
Layer inter-calibration: relative calibration of different calorimeter layers  
(see Antoine's talk)

# Uncertainty from signal and background modelling

- Study bias on  $m_H$  from chosen model
- Background modelling: background from MC and signal from Asimov
- Signal modelling: vice-versa
- Fit with nominal model → compute shift in each category
- Limited background MC statistics



# Result of the mass measurement



Combination of  $H \rightarrow \gamma\gamma$  &  $H \rightarrow 4l$ :

- result dominated by  $H \rightarrow 4l$
- however, the diphoton channel has larger stat.

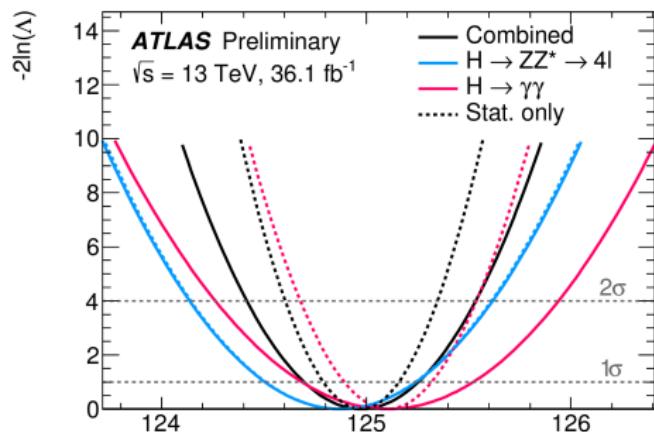
Compare run 1:

$H \rightarrow ZZ^* \rightarrow 4l$ :

$$m_H = 124.51 \pm 0.52 \pm 0.06 \text{ GeV}$$

$H \rightarrow \gamma\gamma$ :

$$m_H = 125.98 \pm 0.42 \pm 0.28 \text{ GeV}$$

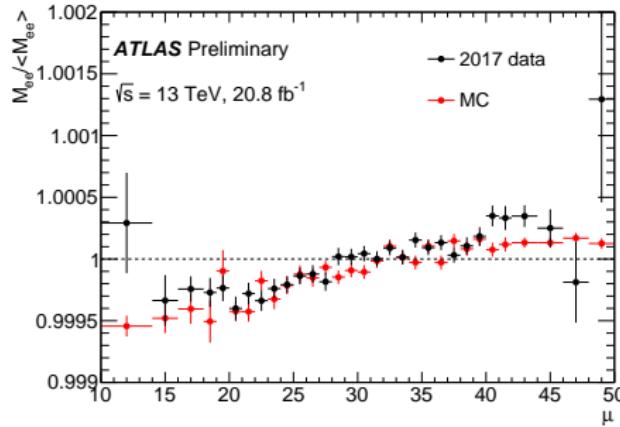


# Conclusion

- Precision measurement of Higgs properties important to test Standard Model
- Higgs to diphoton is very clean and has good resolution
- Need an excellent energy calibration of photons
- Use  $Z \rightarrow ee$  decay, taking advantage of similarity between electrons and photons
- Serves as input for other measurement such as couplings

We are well prepared to analyse our 2017 data!

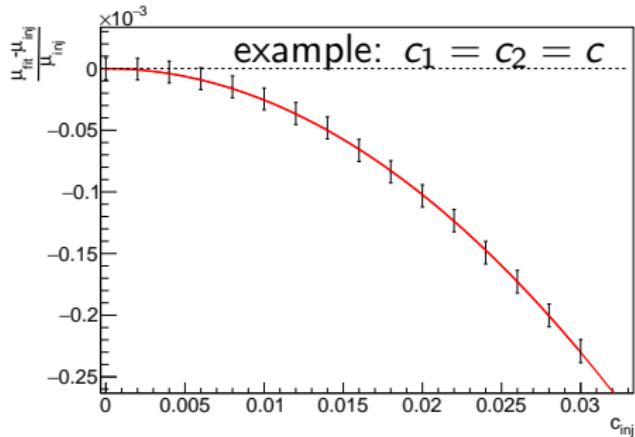
Thanks for your attention!



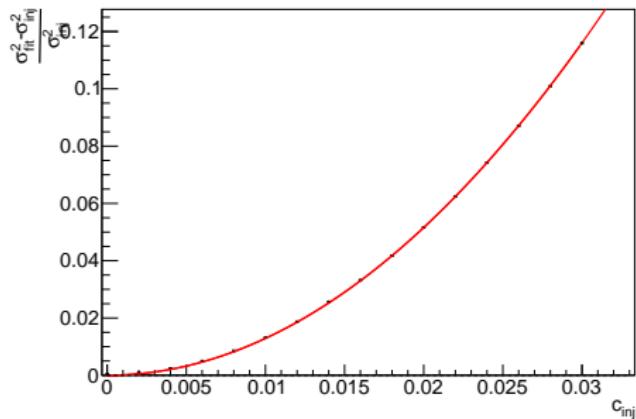
# Backup

# Studies of the bias

- Simplified Gaussian invariant mass: shift of the mean with injected values of  $c_{i/j}$  parametrisable



$$\mu_{\text{smear}} = \mu \cdot \left[ 1 - \frac{1}{8} (c_1^2 + c_2^2) \right]$$

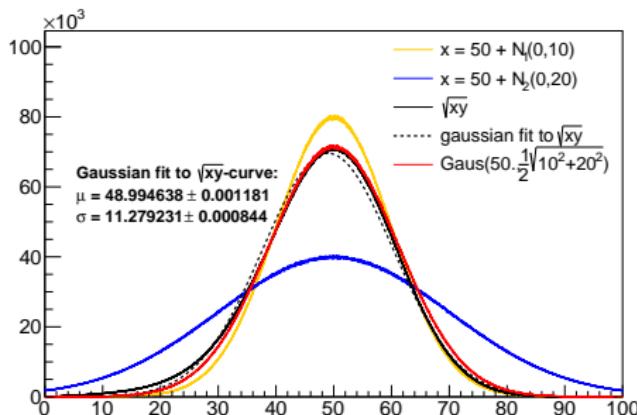
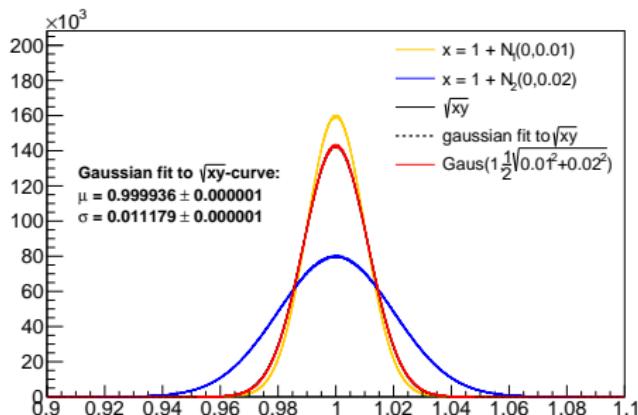


$$\sigma_{\text{smear}}^2 = \sigma^2 + \frac{\mu^2}{4} \cdot (c_1^2 + c_2^2)$$

- Sum of 3 Gaussians:  $\frac{1}{8} \rightarrow \frac{x}{8}$  found from toy experiment; optimisation of MC closure gives  $x = 1.8$
- Remark: the fit is not very sensitive to the exact value of  $x$

# Studies of the bias

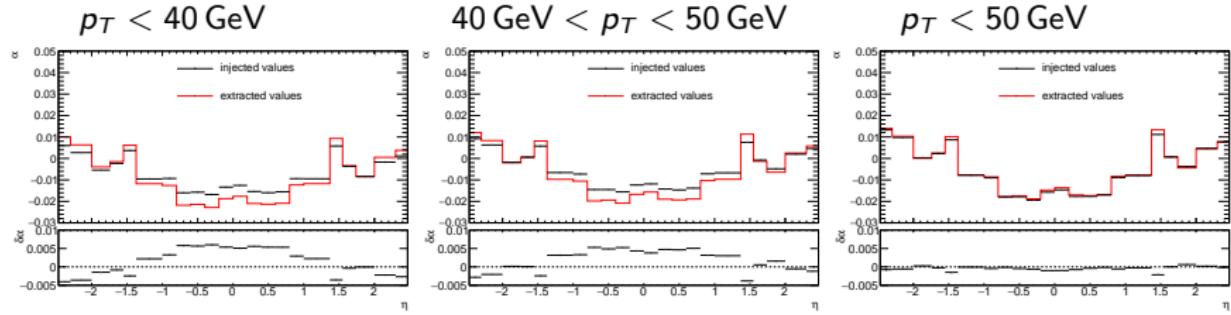
- Smearing of mass:  $m_{12}^{smear} = m_{12} \cdot \sqrt{(1 + N_1(0, c_1))(1 + N_2(0, c_2))}$
- NOT a Gaussian smearing of the mass and  $\sigma_{smear} \neq \frac{c_1^2 + c_2^2}{2} = c_{12}^2$



- Leads to shift of mean of mass distribution when folding

# $p_T$ dependent scale factors

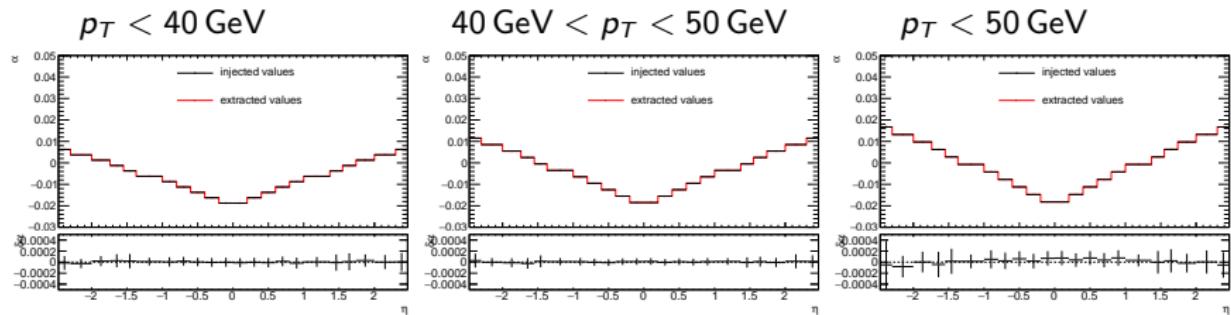
MC closure test: pseudo-data with injected energy dependent scale factors



- strong bias observed
- due to migration between  $p_T$ -bins from scale factors

# Origin of the bias

No redetermination of event  $p_T$ -bin after injection of scale factors



- Events shifted out of true  $p_T$ -bin due to scale → do not compare compatible events in data and MC
- Not easy to correct: event information is lost in lineshapes
- No bias in template method: binning after injection of scales