Search for the Higgs boson decaying into $Z\gamma$

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On Behalf of ATLAS and CMS

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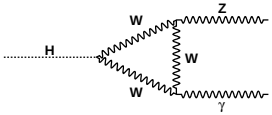
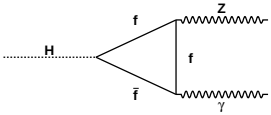
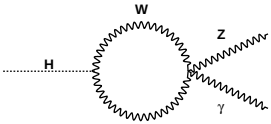
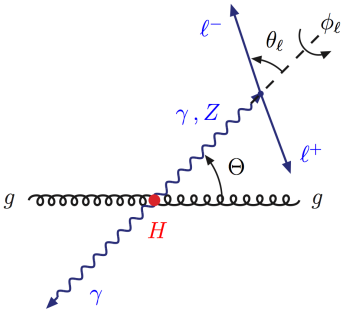
Introduction



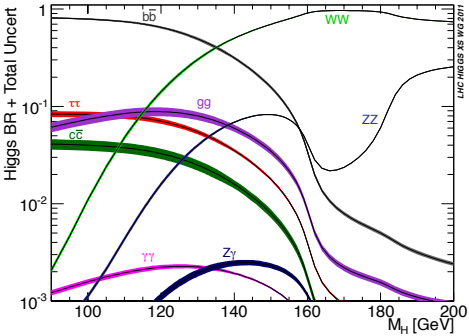






- Publications from ATLAS and CMS, searching for $H \to Z\gamma \to \ell\ell\gamma$:
  - ATLAS 8 TeV (20.3 fb^{-1}) + 7 TeV (4.5 fb^{-1}) with $m_{\ell\ell} > m_Z - 10$ GeV, $120 < m_{\ell\ell\gamma} < 150$ GeV : Phys. Lett. B 732 (2014), pp. 8-27
  - CMS 8 TeV (19.6 fb^{-1}) + 7 TeV (5.0 fb^{-1}) with $m_{\ell\ell} > 50$ GeV, $120 < m_{\ell\ell\gamma} < 160$ GeV : Phys. Lett. B 726 (2013) pp. 587-609
- Sensitive to physics beyond the SM, e.g. a composite model Ref.
- Extend our understanding of the Higgs picture
- Also a preliminary result searching for $H \to \gamma^*\gamma \to \mu\mu\gamma$ using 8 TeV data, with $m_{\mu\mu} < 20$ GeV, $120 < m_{\mu\mu\gamma} < 150$ GeV : CMS-PAS-HIG-14-003

Signal



- For a SM Higgs boson with $m = 125.5$ GeV :
  - $B(H \to Z\gamma) = 1.6 \times 10^{-3}$
  - Similar to $B(H \to \gamma\gamma) = 2.3 \times 10^{-3}$
  - At 8 TeV ($\ell = e, \mu$):
  - $\sigma(pp \to H \to Z\gamma \to \ell\ell\gamma) = 2.3$ fb
  - Similar to $\sigma(pp \to H \to ZZ^* \to 4\ell) = 2.8$ fb, 4.7% of $\sigma(pp \to H \to \gamma\gamma)$

- More information about the inclusive && differential cross sections, decay branching ratios and properties of Higgs can be found in **Handbooks of LHC Higgs Cross Sections** 1, 2, 3
- Generators of $pp \to H \to Z\gamma \to \ell\ell\gamma$:
  - ggF,VBF : POWHEG + PYTHIA 8.170 (ATLAS), 6.4 (CMS); CT10 PDFs
  - WH,ZH,$t\bar{t}H$: PYTHIA 8.170 (ATLAS), 6.4 (CMS); CTEQ6L1 (ATLAS), CTEQ6L (CMS) PDFs
- Cross sectons are computed at NNLO in QCD α_s, NLO in EW α; except for $t\bar{t}H$ (at NLO in QCD α_s)

Backgrounds

- Dominant backgrounds :
  - $Z(\rightarrow \ell\ell) + \gamma$ (including photon from fragmentation of quark or gluon) and $Z \rightarrow \ell\ell\gamma$
  - $Z(\rightarrow \ell\ell)$+jets with jet faking photon
  - Obtained by background-only fit to data mass spectrum
  - Choice of fitting functions :
    - ATLAS (fit mass range 115-170 GeV) : bias study based on simulated background MC, sensitivity study based on data
    - CMS (fit mass range 100-190 GeV): convolution of a Gaussian with a step function multiplied by a polynomial, degree of polymonial in turn based on bias study using pseudo-data generated from background-only fit to data
- ATLAS also consider $t\bar{t}$ and WZ, based on MC prediction, estimated to be 1% of total background

Event Selections

- ATLAS :
- lepton $p_T > 10$ GeV, except for calorimeter-tagged muon ($p_T > 15$ GeV)
- photon $p_T > 15$ GeV
- electron (muon) $|\eta| < 2.47(2.7)$
- photon $|\eta| < 2.37$, excluding $1.37 < |\eta| < 1.52$
- lepton and photon need to be isolated
- lepton must be from primary vertex
- electron and photon satisfy shower shape criteria measured in calorimeter
- $\Delta R(\ell, \gamma) > 0.3$
- $m_{\ell\ell} > m_Z - 10$ GeV, $115 < m_{\ell\ell\gamma} < 170$ GeV
- Events triggered by single-lepton || dilepton triggers
- Acceptance $\times$ Efficiency for $m_H = 125.5$ GeV at 8 TeV is 27% (33%) for electron (muon) channel.

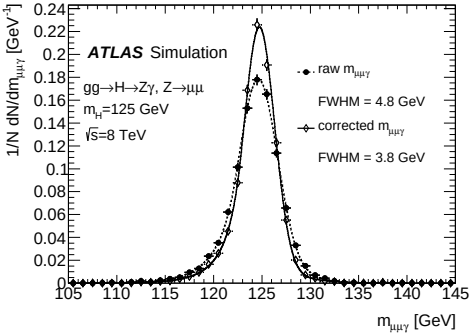
- CMS :
- leading (subleading) lepton $p_T > 20(10)$ GeV
- photon $p_T > 15$ GeV
- electron (muon) $|\eta| < 2.5(2.4)$
- photon $|\eta| < 2.5$, excluding $1.44 < |\eta| < 1.57$
- lepton and photon need to be isolated
- lepton must be from primary vertex
- electron and photon satisfy shower shape criteria measured in calorimeter
- $\Delta R(\ell, \gamma) > 0.4$
- $m_{\ell\ell} > 50$ GeV, $100 < m_{\ell\ell\gamma} < 190$ GeV
- $E_T^{\gamma}/m_{\ell\ell\gamma} > 15/110$
- $m_{\ell\ell} + m_{\ell\ell\gamma} > 185$ GeV
- Events triggered by dilepton triggers

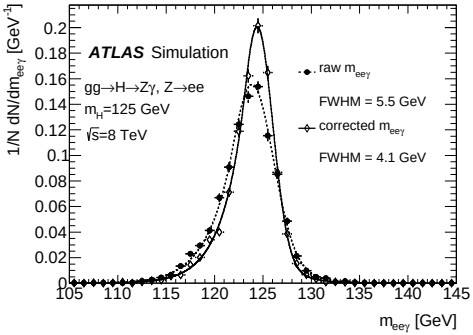
To Improve the Sensitivity I

- Event categories :
  - Based on signal-to-background ratios and invariant-mass resolutions
  - ATLAS :
    - $\Delta\eta_{Z\gamma}$ between photon and Z (smaller $\Delta\eta_{Z\gamma}$ for signal)
    - $p_{\mathrm{Tt}} = |(\vec{p}_{\mathrm{T}}^{\,\gamma} + \vec{p}_{\mathrm{T}}^{\,Z}) \times \hat{t}|$ where $\hat{t} = (\vec{p}_{\mathrm{T}}^{\,\gamma} - \vec{p}_{\mathrm{T}}^{\,Z})/|\vec{p}_{\mathrm{T}}^{\,\gamma} - \vec{p}_{\mathrm{T}}^{\,Z}|$ (larger p_{Tt} for signal)
  - CMS :
    - η of lepton and photon (small $|\eta|$ for signal)
    - photon conversion (better signal-to-background ratio with unconverted photon)
    - separate VBF category, obtained by dijet-tagging (though small statistics, signal-to-background ratio more than an order of magnitude larger than other categories)

To Improve the Sensitivity II

- ATLAS employs several methods to improve the $\ell\ell\gamma$ mass resolution
  - photon η^γ and $E_T^\gamma = E^\gamma / \cosh \eta^\gamma$ recalculated w.r.t. primary vertex ($\sim 1\%$ improvement on resolution)
  - muon momenta corrected for FSR ($\sim 1\%$ improvement on resolution)
  - lepton momenta recomputed by Z-mass-constrained kinematic fit ($\sim 15\% - 20\%$ improvement on resolution)





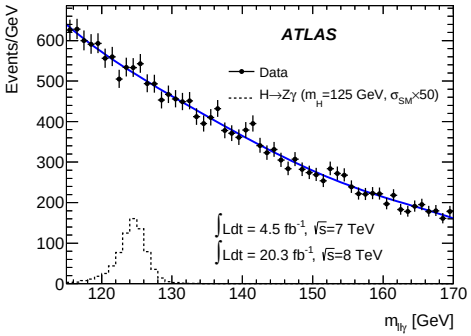
Event Yields

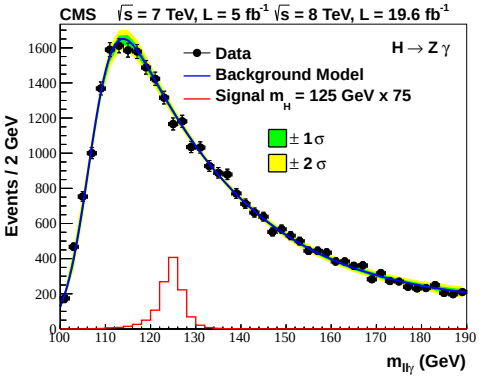
- Event yields for each category (ATLAS) :

$\sqrt{s}$ [TeV]	ℓ	Category	N_S	N_B	N_D	$\frac{N_S}{\sqrt{N_B}}$	FWHM [GeV]
8	μ	high p_{Tt}	2.3	310	324	0.13	3.8
8	μ	low p_{Tt}, low $\Delta\eta$	3.7	1600	1587	0.09	3.8
8	μ	low p_{Tt}, high $\Delta\eta$	0.8	600	602	0.03	4.1
8	e	high p_{Tt}	1.9	260	270	0.12	3.9
8	e	low p_{Tt}, low $\Delta\eta$	2.9	1300	1304	0.08	4.2
8	e	low p_{Tt}, high $\Delta\eta$	0.6	430	421	0.03	4.5
7	μ	high p_{Tt}	0.4	40	40	0.06	3.9
7	μ	low p_{Tt}	0.6	340	335	0.03	3.9
7	e	high p_{Tt}	0.3	25	21	0.06	3.9
7	e	low p_{Tt}	0.5	240	234	0.03	4.0

- Within ± 5 GeV mass window around $m_H = 125$ GeV

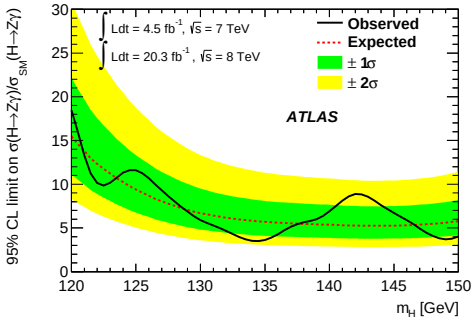
Uncertainties and $m_{\ell\ell\gamma}$ Spectrum

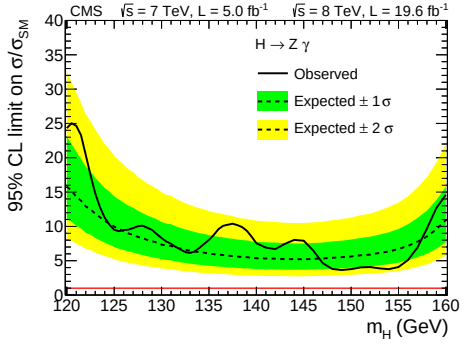




- The uncertainty on the limit is dominated by the size of the data sample (background is obtained from data).
- Systematic uncertainties on signal modeling have negligible impact
  - Experimental systematic uncertainties on signal yield and mass distribution.
  - Theoretical systematic uncertainties on signal cross section
  - Additional 5% accounts for the bias on signal modeling due to contamination from $H \to \ell\ell\gamma$ ($H \to \gamma^*\gamma \to \ell\ell\gamma$ or $H \to \ell\ell^* \to \ell\ell\gamma$)

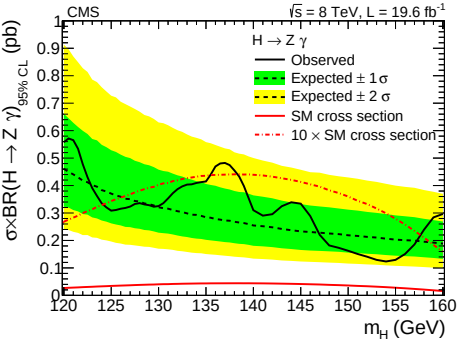
Results I





- 95% CL upper limit on signal strength :
  - ATLAS for $m_H = 125.5$ GeV : 9 (11) for expected (observed) limit
  - CMS for $m_H = 125$ GeV : 10 (9.5) for expected (observed) limit

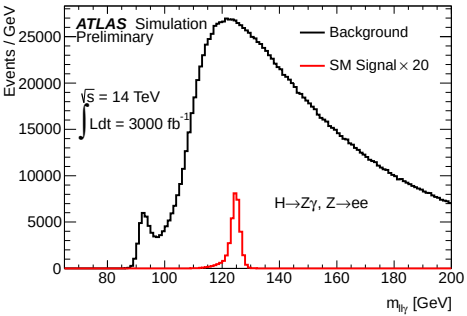
Results II

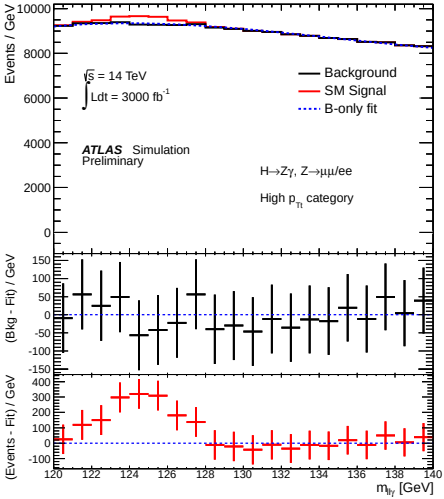


- 95% CL upper limit on $pp \to H \to Z\gamma$ cross section :
  - ATLAS : at 8 TeV, ranging between 0.13 and 0.5 pb for m_H between 120 to 150 GeV, for $m_H = 125.5$ GeV is 0.33 (0.45) pb for expected (observed) limit
  - CMS : shown in the plot, models predicting $\sigma(pp \to H \to Z\gamma)$ larger than one order of magnitude of SM prediction are excluded for most of the 125-157 GeV mass range

Towards High-Luminosity LHC

- Prospects for the $H \to Z\gamma$ search at the High-Luminosity LHC : ATL-PHYS-PUB-2014-006





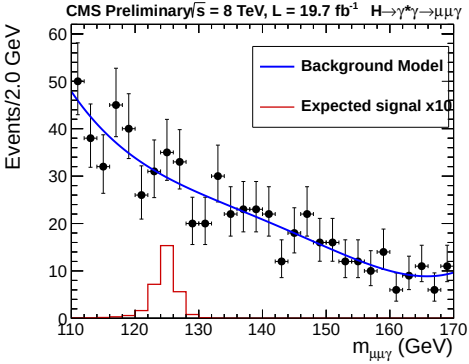
- With 3000 fb^{-1} data at 14 TeV, for $m_H = 125$ GeV, expected p-value is 3.9σ, expected limit is $0.52 \times \sigma_{SM}$; with 300 fb^{-1}, expected p-value is 2.3σ

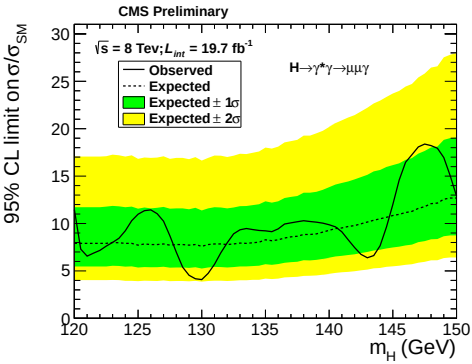
Search for $H \to \gamma^*\gamma$ I

Requirement	Observed event yield	Expected number of signal events for $m_{\mathrm{H}} = 125$ GeV
Trigger, photon selection, $p_T^{\gamma} > 25$ GeV	0.6M	6.2
Muon selection, $p_T^{\mu 1} > 23$ GeV and $p_T^{\mu 2} > 4$ GeV	55836	4.7
110 GeV $< m_{\mu\mu\gamma} <$170 GeV	7800	4.7
$m_{\mu\mu} < 20$ GeV	1142	3.9
$\Delta \mathrm{R}(\gamma, \mu) > 1$	1138	3.9
Removal of resonances	1020	3.7
$p_T^{\gamma}/m_{\mu\mu\gamma} > 0.3$ and $p_T^{\mu\mu}/m_{\mu\mu\gamma} > 0.3$	665	3.3
122 GeV $< m_{\mu\mu\gamma} <$ 128 GeV	99	2.9

- Similar background estimation method as in $H \to Z\gamma$ search.

Search for $H \to \gamma^*\gamma$ II





- The observed limit for $m_H = 125$ GeV is about ten times the SM prediction.

Conclusions

- Search for $H \to Z\gamma \to \ell\ell\gamma$ have been performed at ATLAS and CMS experiment, with 8 TeV + 7 TeV data.
- No excess above SM predictions has been found.
- Limits on $pp \to H \to Z\gamma$ signal strength and production cross section have been derived.

- HL-LHC will allow for evidence of $H \to Z\gamma \to \ell\ell\gamma$

- CMS also explored a search for $H \to \gamma^*\gamma \to \mu\mu\gamma$, with similar sensitivity to $H \to Z\gamma \to \ell\ell\gamma$