Search for non-standard and rare decays of the Higgs boson with the ATLAS detector

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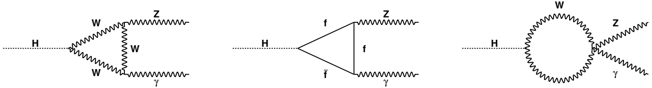
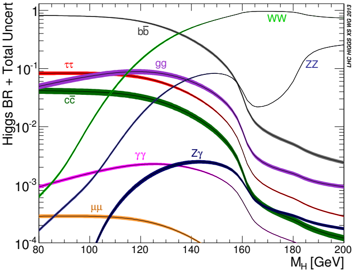
Introduction

- $H \to Z\gamma$:
  - Search for high-mass resonance $X \to Z\gamma$
  - Higgs decay to a Z boson and a photon
- $H \to \phi\gamma$ and $Z \to \phi\gamma$
- $H/Z \to J/\Psi\gamma$ and $H/Z \to \Upsilon(nS)\gamma$

$H/X \to Z\gamma$

- Search for $H \to Z\gamma \to \ell\ell\gamma$ ($\ell = e, \mu$) decays in mass range $m_H = 120$-150 GeV with the 20.3 (4.5) fb^{-1} at $\sqrt{s} = 8(7)$ TeV from 2012 (2011) data.

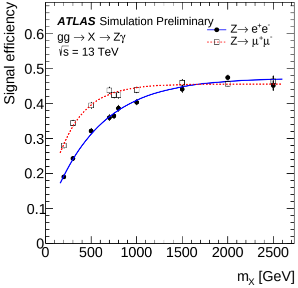


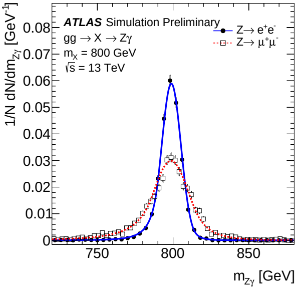


- Search for high-mass scalar spin-0 $X \to Z\gamma$:
  - using both leptonic and hadronic final state $Z \to \ell(\ell = e, \mu)$ ($BR = 6.7\%$) and $Z \to q\bar{q}$ ($BR = 70\%$) in boosted regime with th 3.2 fb^{-1} at $\sqrt{s} = 13$ TeV from 2015 data
  - update of the analysis $X \to Z(\to \ell\ell)\gamma$ with the 13.3 fb^{-1} at $\sqrt{s} = 13$ TeV from 2015-2016 data.

High mass $X \to Z\gamma$: Event Selection and Signal Model

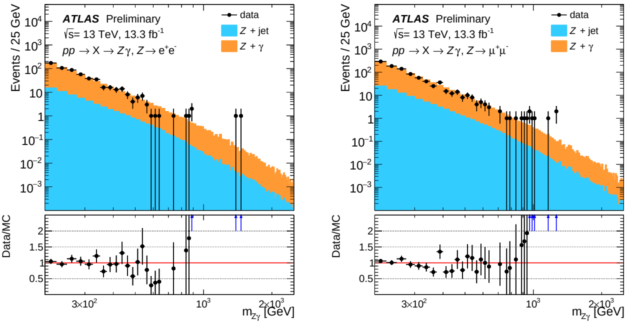
- Search for scalar spin-0 $X \to Z\gamma$ decays with 13.3 fb^{-1} of data collected at $\sqrt{s} = 13$ TeV in 2015 and 2016
- Event selection:
  - single and di-lepton triggers
  - two isolated, opposite-sign leptons ($p_T^e > 19$ GeV, $p_T^\mu > 24,10$ GeV) with $m_{\ell\ell} \sim m_Z$
  - one isolated photon, $p_T^\gamma / m_{\ell\ell\gamma} > 0.3$ (exploit spin-0 isotropic decay in X center-of-mass reference frame)
  - $m_{\ell\ell\gamma} > 200$ GeV
- Signal efficiency: 20–45%, parametrised as a function of the mass using MC samples generated at fixed masses (200<m_H<2500 GeV)
- Signal model:
  - Double-sided Crystal-Ball function (Gaussian with power-law tails)
  - Parameters described by polynomial functions of mass (simultaneous fit)
  - Resolution 1-0.6% ($ee\gamma$), 1-1.4% ($\mu\mu\gamma$)





High mass $X \to Z\gamma$: Background

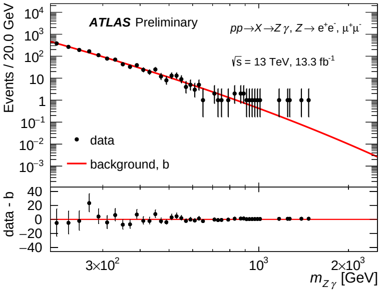
- Main contribution from $Z+\gamma$ and $Z+$jet events.
- Bkg composition studied with 2 data-driven methods based on identification and isolation of photon candidate $\to$ $Z+\gamma$ fraction $\sim$90% (not used in the final fit)

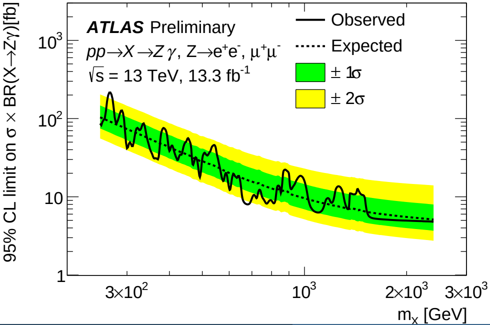


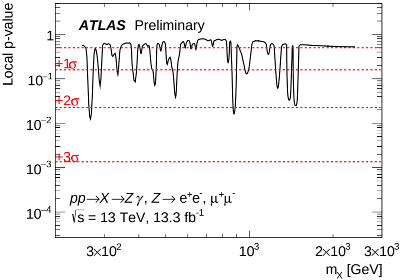
- Background model:
  - minimum number of free parameters
  - fit well a bkg-only control sample: small bias on signal, quantified as "spurious signal" in signal+bkg fit to high-statistics $(Z+\gamma)+(Z+\text{jet})$ bkg control sample
  - fit well the data (no significant improvement of fit quality when adding more degrees of freedom)

High mass $X \to Z\gamma$: Result

- No significant excess in $250 < m_X < 2400$ GeV
- Largest deviation from bkg-only hypothesis: local significance of $\sim 2.2\sigma$ at $m_X \sim 270$ GeV
- 95% CL upper limits set on $\sigma(pp \to X) \times BR(X \to Z\gamma)$ with CL_s method:
  - Expected: 5–105 fb
  - Observed: 5–215 fb

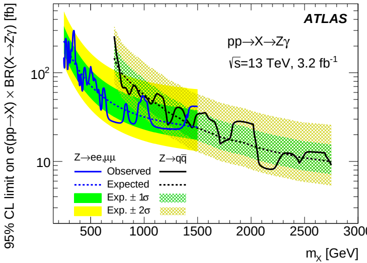


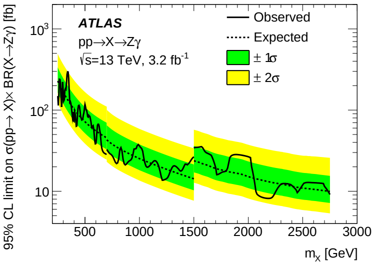




High mass $X \to Z\gamma$: Result 2015 only

- Search also for Z hadronic final state with 3.2 fb^{-1} at $\sqrt{s} = 13$ TeV
  - Complementary to leptonic analysis: worse purity, but $BR(Z \to qq) \sim 10 * BR(Z \to \ell\ell)$ leads to sensitivity at high mass where there are no events in leptonic analysis
  - $m_X > 700$ GeV: majority of events lead to overlapping quark-jets
  - p_T^γ>250 GeV, $|\eta^\gamma| < 2.37$ (excl. 1.32-1.57) $p_T^J > 200$ GeV, $|\eta^J| < 2$, $m_{J\gamma} > 640$ GeV
  - mass resolution $\sim$ 3-1.7%, signal efficiency 10–15% for m_X = 700-2750 GeV

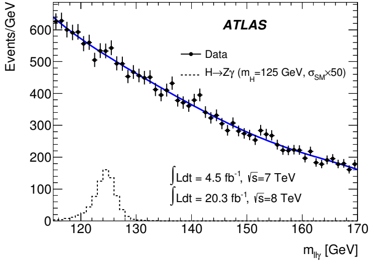


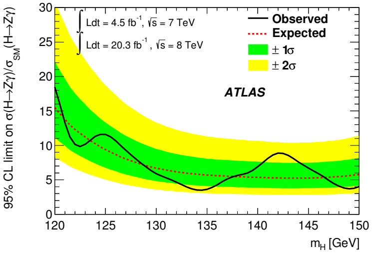


- Combination in overlapping range can improve single results by up to $\sim$ 40%
- At same lumi, highest masses probed by hadronic analysis only.

Run 1 $H \to Z\gamma$

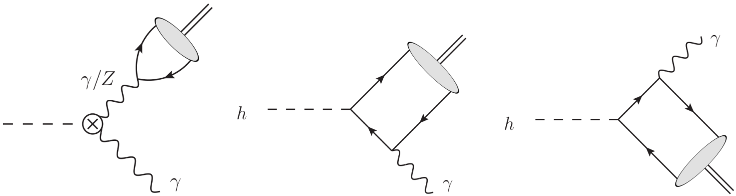
- Search for $H \to Z\gamma$ decays with the 20.3 (4.5) fb^{-1} at $\sqrt{s} = 8(7)$ TeV from 2012 (2011) data
- two isolated, opposite-sign leptons ($p_T^{\ell} > 10$ GeV) and one isolated photon ($p_T^{\gamma} > 15$ GeV)





- No significant excess with respect to the background is observed
- Maximum significance at 142 GeV: 1.6σ
- Observed (expected) upper limits vary between 3.5xSM (5.2xSM) and 18.5xSM (15.5xSM)
- At $m_H = 125.5$ GeV:
  - observed (expected) significance 0.6σ (0.2σ)
  - upper limit is 11xSM (9xSM)

$H/Z \to \phi\gamma$

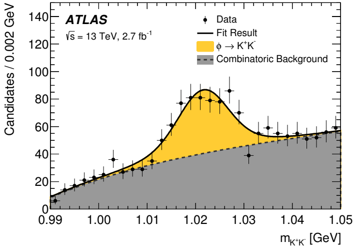


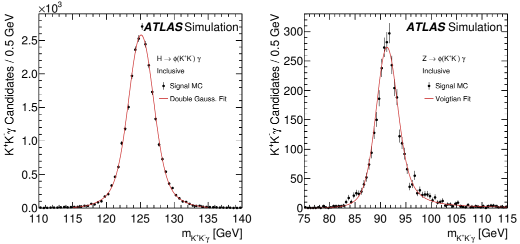
- First search for $H \to \phi\gamma$ decays with the 2.7 fb^{-1} at $\sqrt{s} = 13$ TeV from 2015 data
  - Sensitivity to strange-quark Yukawa coupling - almost entirely unconstrained
  - access to potential deviations from the SM expectation
- Search for the unobserved $Z \to \phi\gamma$ decay
  - test of the SM and the QCD factorisation approach
- Expected SM values:
  - $BR(H \to \phi\gamma) = (2.3 \pm 0.1) \times 10^{-6}$ †
  - $BR(Z \to \phi\gamma) = (1.17 \pm 0.08) \times 10^{-8}$ ‡
- Reconstruct only $\phi \to K^+K^-$ decays, $BR(\phi \to K^+K^-) = 49\%$
- Exploit the distinctive topology of a pair of high-p_T isolated tracks, with a very small opening angle ($\Delta R < 0.05$), recoiling against a hard isolated photon

† JHEP 1508 (2015) 012 (arXiv:1505.03870) ‡ Phys. Rev. D 92, 014007 (2015) (arXiv:1411.5924)

$H/Z \to \phi\gamma$: Event Selection and Signal Model

- Selection Requirements:
  - Tight isolated photon with p_T>35 GeV
  - Two high-p_T (>20 GeV, >15 GeV) opposite sign, isolated tracks
  - $|m_{KK} - m_{\phi}| < 20$ MeV
  - $\Delta\phi_{KK,\gamma} > 0.5$
  - $p_T^{KK} > 40 \to 45$ GeV based on $m_{KK\gamma}$
- $A \times \epsilon$ of ~18% for H and ~8% for the Z signals

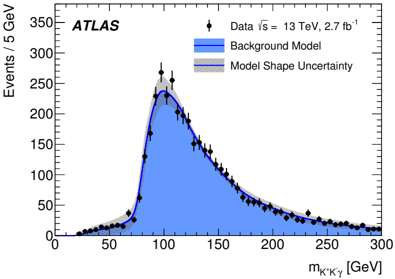


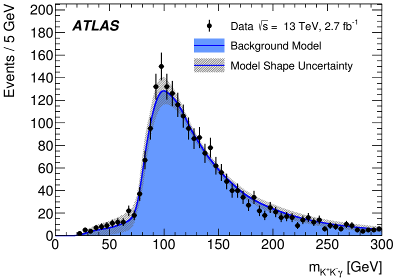


- Double Gaussian for Higgs and a Breit-Wigner $\otimes$ Gaussian for the Z
- Resolution of 2.1 GeV for Higgs boson and 1.6 GeV for Z boson signals

$H/Z \to \phi\gamma$: Background

- Main bkg. from random tracks and gamma combinations in multi-jet and gamma+jet
- Background modeled with non-parametric data-driven approach
  - Events from a loose selection are used to build templates for the kinematic distributions of the ϕ candidate and photon
  - Distributions are then sampled (retaining correlations with p_T^{γ}) and used to build pseudo-candidates
  - Large samples of pseudo-candidates are used to build background model templates
- Model validated in control regions with looser selection.
- Model shape uncertainty estimated from modifications to modeling procedure (e.g. shifting p_T^{KK} and neglecting the weakest correlation included in the model)



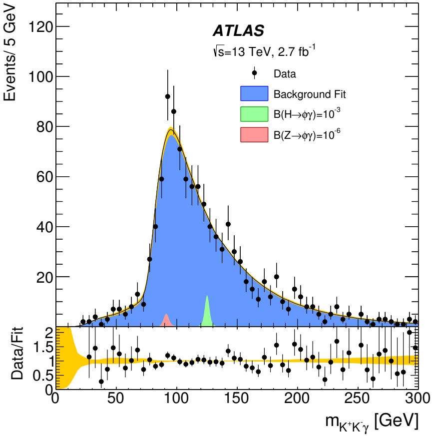


$H/Z \to \phi\gamma$: Result

- Unbinned maximum likelihood fit on $m_{K^+K^-\gamma}$
- Branching fraction limits at 95% CL:

	Exp.	Obs.
$BR(H \to \phi\gamma)[10^{-3}]$	$1.5^{+0.7}_{-0.4}$	1.4
$BR(Z \to \phi\gamma)[10^{-6}]$	$4.4^{+2.0}_{-1.2}$	8.3

- Expected SM values:
  - $BR(H \to \phi\gamma) = (2.3 \pm 0.1) \times 10^{-6}$
  - $BR(Z \to \phi\gamma) = (1.17 \pm 0.08) \times 10^{-8}$



→ First limits on these rare exclusive processes (~600/700 times the expected SM branching fraction)

$H/Z \to J/\Psi\gamma$ and $H/Z \to \Upsilon\gamma$

Phys. Rev. Lett. 114, 121801

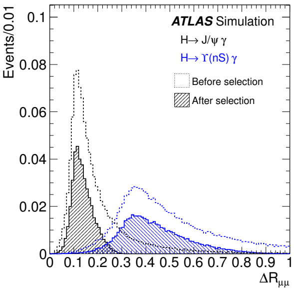
- Perform first search for $H \to J/\Psi\gamma$ and $H \to \Upsilon(nS)\gamma$ decays with the full 2012 dataset at $\sqrt{s} = 8$ TeV
  - Could provide a probe of the magnitude and sign of the $H \to c\bar{c}$ and $H \to b\bar{b}$ couplings
  - access to potential deviations from the SM expectation
- Search for $Z \to J/\Psi\gamma$ and $Z \to \Upsilon\gamma$
  - Can be used as a "standard candle" for the Higgs decay search
  - Available experimental limits only on the inclusive $Z \to QX$ (measured by LEP):
    - $BR(Z \to J/\Psi X) = (3.5 \pm 0.25) \times 10^{-3}$
    - $BR(Z \to \Upsilon(nS)X) < 4.4, 13.9, 9.4 \times 10^{5}$
- SM prediction:
  - $BR(H \to J/\Psi\gamma) = 2.8 \pm 0.2 \times 10^{-6}$ †
  - $BR(H \to \Upsilon(1S)\gamma) = 6.1^{+17.4}_{-6.1} \times 10^{-10}$ †
  - $BR(Z \to J/\Psi\gamma) = 9.96 \pm 1.86 \times 10^{-8}$ ‡
  - $BR(Z \to \Upsilon(1S)\gamma) = 4.93 \pm 0.51 \times 10^{-8}$ ‡
- Restrict the search to use $Q \to \mu^+\mu^-$ decays, where $Q = J/\Psi, \Upsilon(nS)$
  - $BR(J/\Psi \to \mu^+\mu^-) = 5.93 \pm 0.06\%$
  - $BR(\Upsilon(1S) \to \mu^+\mu^-) = 2.48 \pm 0.06\%$

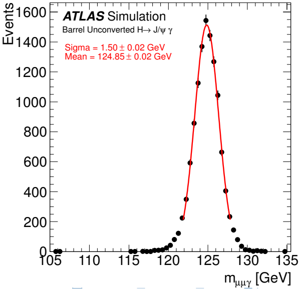
† Phys. Rev. D 90, 113010 (2014) (arXiv:1407.6695) ‡ Phys. Rev. D 92, 014007 (2015) (arXiv:1411.5924)

$H/Z \to J/\Psi\gamma$ and $H/Z \to \Upsilon(nS)\gamma$: Event Selection and Signal Model

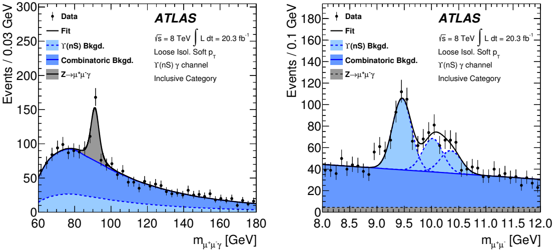
Phys. Rev. Lett. 114, 121801

- $J/\Psi\gamma$: single muon trigger ($\Delta R_{\mu\mu} \sim 0.1$)
- $\Upsilon\gamma$: single and double muon trigger ($\Delta R_{\mu\mu} \sim 0.35$)
- Muon:
  - Two high-p_T (>20 GeV, 3 GeV), opposite sign, isolated muons
  - $p_T^{\mu\mu} > 36$ GeV
  - Transverse decay length significance $L_{xy}/\sigma_{xy} < 3.0$
  - $J/\Psi\gamma$: $|m_{\mu\mu} - m_{J/\Psi}| < 0.15(0.20)$ GeV in the barrel (endcap)
  - $\Upsilon\gamma$: $8.0 < m_{\mu\mu} < 12.0$ GeV
- Photon: tight isolated photons with $p_T^{\gamma} > 36$ GeV
- $\Delta\phi(\mu\mu, \gamma) > 0.5$
- $J/\Psi\gamma$: total $A \times \epsilon$ of ~22% for H and ~12% for the Z signals
- $\Upsilon\gamma$: total $A \times \epsilon$ of ~28% for H and ~15% for the Z signals
- The $m_{\mu\mu\gamma}$ resolution varies between 1.2% and 1.8%.





- Inclusive QCD backgrounds:
  - Typically processes such as $pp \to QgX$ where the jet is identified as a photon
  - γ+jets and $b\bar{b}$ production with $b \to J/\Psi X$
  - Modelled together with a non-parametric data-driven method (as $H \to \phi\gamma$)
- Exclusive $Z \to \mu^+\mu^-\gamma$ background:
  - $Z \to \mu^+\mu^- \to \mu^+\mu^-\gamma$ decays with a catastrophic FSR can lead to $m_{\mu\mu}$ in $\Upsilon(nS)$ mass region $\to$ peaking bkg
  - Modelled with analytical template fitted to MC + data normalisation



- In the $J/\Psi\gamma$ channel 56% of the events originated from prompt J/Ψ production , 3% from J/Ψ non prompt production, 41% from combinatoric bkg.
- In the $\Upsilon(nS)\gamma$ channel non-resonant background account for 66% of the event, $Z \to \mu^+\mu^-\gamma$ 27%, inclusive $\Upsilon(nS)$ 7%.

$H/Z \to J/\Psi\gamma$ and $H/Z \to \Upsilon\gamma$: Result

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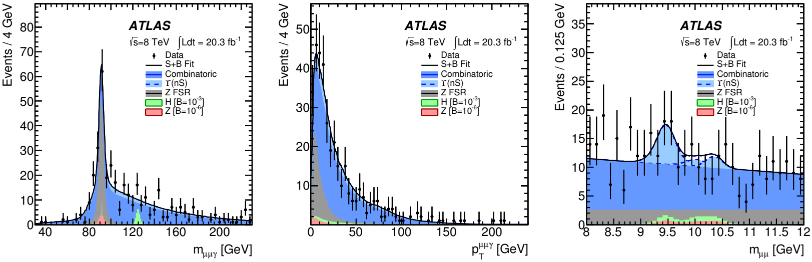
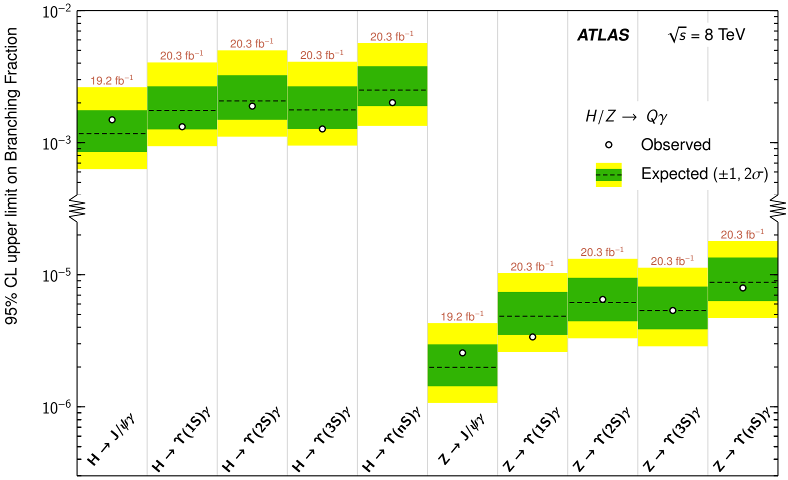
- Unbinned maximum likelihood fit:
  - $J/\Psi\gamma$: 2D fit $m_{\mu\mu\gamma}$ $p_T^{\mu\mu\gamma}$
  - $\Upsilon\gamma$: 3D fit $m_{\mu\mu\gamma}$ $p_T^{\mu\mu\gamma}$ $m_{\mu\mu}$
- Upper limit on $BR(H \to J/\Psi\gamma)$ corresponds to $\sim$ 540 the expected SM one
- Approaching to SM sensitivity for Z decays ($BR(Z \to J/\Psi\gamma) \sim 0.1 \times 10^{-6}$)

	95% CL_s Upper Limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum^n \Upsilon(nS)$
$\mathcal{B}(Z \to \mathcal{Q}\gamma)$ [10^{-6}]					
Expected	$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed	2.6	3.4	6.5	5.4	7.9
$\mathcal{B}(H \to \mathcal{Q}\gamma)$ [10^{-3}]					
Expected	$1.2^{+0.6}_{-0.3}$	$1.8^{+0.9}_{-0.5}$	$2.1^{+1.1}_{-0.6}$	$1.8^{+0.9}_{-0.5}$	$2.5^{+1.3}_{-0.7}$
Observed	1.5	1.3	1.9	1.3	2.0
$\sigma(pp \to H) \times \mathcal{B}(H \to \mathcal{Q}\gamma)$ [fb]					
Expected	26^{+12}_{-7}	38^{+19}_{-11}	45^{+24}_{-13}	38^{+19}_{-11}	54^{+27}_{-15}
Observed	33	29	41	28	44



$H/Z \to J/\Psi\gamma$ and $H/Z \to \Upsilon\gamma$: Result

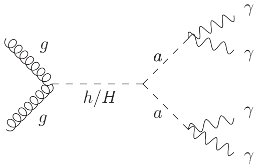


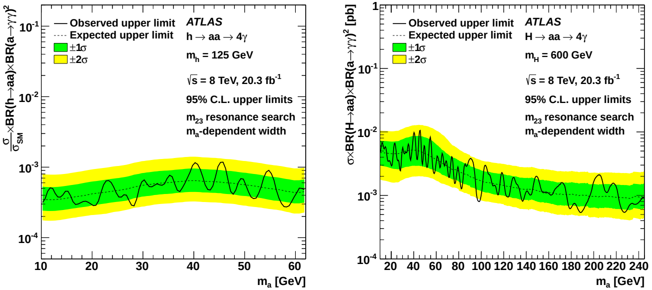
Conclusion

- Search for $H \to Z\gamma$ performed using 20.3 fb^{-1} + 4.5 fb^{-1} at $\sqrt{s} = 8$ and 7 TeV for m$_H$=120-150 GeV
  - No significant excess
  - Observed upper limits on $\sigma(H \to Z\gamma)/\sigma_{SM}(H \to Z\gamma)$ vary between 3.5xSM and 18.5xSM
  - At $m_H = 125.5$ GeV:
    - observed (expected) significance 0.6σ (0.2σ)
    - upper limit is 11xSM (9xSM)
- Search for $X \to Z\gamma$ performed using 13.3 fb^{-1} at $\sqrt{s} = 13$ TeV for m$_X$=250-2400 GeV
  - No significant excess
  - Upper limits set on $\sigma(pp \to X) \times BR(X\gamma)$ between 5–215 fb assuming spin-0 resonance produced in gluon fusion
- Search for $H \to \phi\gamma$ and $Z \to \phi\gamma$ performed using 2.7 fb^{-1} at $\sqrt{s} = 13$ TeV
  - First limit set on these exclusive processes
  - $BR(H \to \phi\gamma) < 4 \times 10^{-3}$ (SM: 2.3×10^{-6})
  - $BR(Z \to \phi\gamma) < 8.3 \times 10^{-6}$ (SM: 1.2×10^{-8})
- Search for $H \to J/\Psi\gamma$ ($\Upsilon(nS)\gamma$) and $Z \to J/\Psi\gamma$ ($\Upsilon(nS)\gamma$) performed using 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV
  - First limit set on these exclusive processes
  - $BR(H \to J/\Psi\gamma) < 1.5 \times 10^{-3}$ (SM: 2.8×10^{-6})
  - $BR(H \to \Upsilon(1S)\gamma) < 1.3 \times 10^{-3}$ (SM: 8.39×10^{-10})
  - $BR(Z \to J/\Psi\gamma) < 2.6 \times 10^{-6}$ (SM: 9.96×10^{-8})
  - $BR(Z \to \Upsilon(1S)\gamma) < 3.4 \times 10^{-6}$ (SM: 4.93×10^{-8})

Bonus Slides

- Search for new phenomena in events with at least three photons with 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV
- Extension of the Higgs sector include CP-odd particles (a) with coupling to the Higgs (h) or additional higher mass scalar (H) particle
- Three tight isolated γ with p_T^{γ}>22, 22, 17 GeV

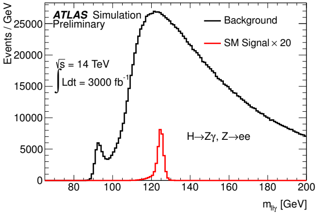


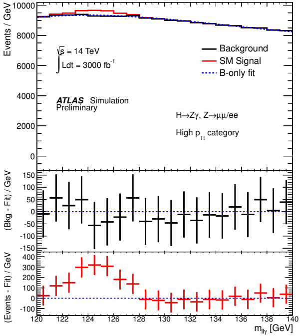


- $(\sigma/\sigma_{SM}) \times BR(h \to aa) \times BR(a \to \gamma\gamma)^2$<3-4$\times 10^{-4}$ for 10<m_a<62 GeV
- $\sigma \times BR(H \to aa) \times BR(a \to \gamma\gamma)^2$<0.02-0.001 pb for m_H up to 900 GeV

HL-LHC projection: $H \to Z\gamma$

- Projection of the results to HL-LHC: $\sqrt{s} = 14$ TeV, 300 fb^{-1} ($\mu = 60$) and 3000 fb^{-1} ($\mu = 140$)
- Same analysis structure as in Run 1
- Background: Z+γ contribution scaled by $\sigma^{14\text{TeV}}_{Z+\gamma}/\sigma^{8\text{TeV}}_{Z+\gamma} = 1.82$ and scaled by factors to correct from the Run I to the HL-LHC efficiencies.
- Result at 3000 (300) fb^{-1}:
  - The expected CL limit in the absence of a Higgs signal is $0.52\times\sigma_{SM}$
  - The expected p_0 with $m_H = 125$ GeV, is 3.9 (2.3) σ





HL-LHC projection: $H/Z \rightarrow J/\Psi\gamma$

- Projection of the results to HL-LHC: $\sqrt{s} = 14$ TeV, 300 fb^{-1} and 3000 fb^{-1} (with the overall assumption that the upgraded detector will exhibit the same performance as during LHC Run 1)
- Same event selection except for $p_T^{\mu\mu}$ raised to >40 GeV
- Also a multivariate analysis is introduce to enhance the sensitivity(BDT, with p_T^{γ} and $p_T^{\mu\mu}$ as input)
- Background evaluated scaling the observed yields in the $\sqrt{s} = 8$ TeV data by $\sigma^{14\text{TeV}}_{J/\Psi+X}/\sigma^{8\text{TeV}}_{J/\Psi+X}$

	Expected branching ratio limit at 95% CL		
	$\mathcal{B}(H \rightarrow J/\psi\gamma)$ [10^{-6}]		$\mathcal{B}(Z \rightarrow J/\psi\gamma)$ [10^{-7}]
	Cut Based	Multivariate Analysis	Cut Based
300 fb^{-1}	185^{+81}_{-52}	153^{+69}_{-43}	$7.0^{+2.7}_{-2.0}$
3000 fb^{-1}	55^{+24}_{-15}	44^{+19}_{-12}	$4.4^{+1.9}_{-1.1}$

	Standard Model expectation	
	$\mathcal{B}(H \rightarrow J/\psi\gamma)$ [10^{-6}]	$\mathcal{B}(Z \rightarrow J/\psi\gamma)$ [10^{-7}]
	2.9 ± 0.2	0.80 ± 0.05

- Limits on $BR(H \rightarrow J/\Psi X)$ and $BR(Z \rightarrow J/\Psi)$ 15 and 4 times the SM values,