COFUND. A project supported by
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Search for Higgs and Z Boson Decays to $\phi\gamma$ with the ATLAS Detector

Kaon 2016, University of Birmingham

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Introduction - Yukawa Couplings

“Yukawa” couplings between the Higgs (ϕ) and fermion (ψ) fields are possible:

$$\mathcal{L}_{fermion} = -y_f \cdot \left[\bar{\psi}_L \phi \psi_R + \bar{\psi}_R \bar{\phi} \psi_L\right]$$

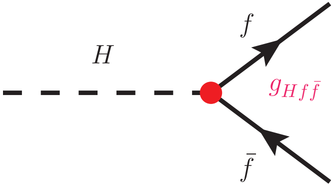
If ϕ has a non-zero VEV, expansion leads to:

$$\mathcal{L}_{fermion} = -\underbrace{\frac{y_f v}{\sqrt{2}} \cdot \bar{\psi}\psi}_{\text{mass term}} - \underbrace{\frac{y_f}{\sqrt{2}} \cdot h\bar{\psi}\psi}_{\text{Yukawa coupling term}}$$

where *h* is the physical Higgs boson field...

The End Result:

- Gauge invariant Fermion mass terms ✓
- Higgs–fermion coupling proportional to the fermion mass ($g_{Hf\bar{f}} = m_f/v$) ✓



While y_f are still free parameters in the model, $v \approx 246$ GeV is known from Electroweak measurements and we know the fermion masses...

We can predict the couplings in the SM!

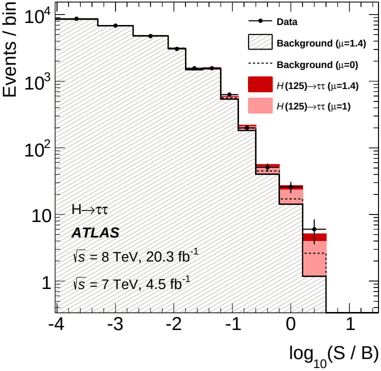
Yukawa Couplings - Experimental Status

What we know about the Higgs coupling to:

- ***t* quark:** No firm evidence for $t\bar{t}H$ production from LHC experiments
- ***b* quark:** No firm evidence for $H \to b\bar{b}$ decays from LHC experiments, only $1-2\sigma$ excesses
- ***c* quark:** No direct evidence, only loose bounds from $H \to b\bar{b}$ searches and limit on $H \to J/\psi\,\gamma$ (see later!)
- ***u*, *d*, *s* quarks:** Nothing! Huge challenge!
- **τ lepton:** Evidence for $H(125) \to \tau\tau$ decays from ATLAS and CMS!
- ***e*, μ leptons:** No evidence, but that shows the lepton Yukawa couplings are not universal!

Evidence for Higgs Yukawa couplings ($H \to \tau\tau$) from the LHC!

JHEP 04 (2015) 117 (arXiv:1501.04943)



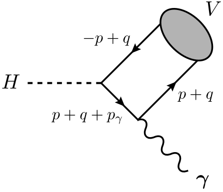
Data show lepton Yukawa couplings are present and non-universal...
But not too much else!

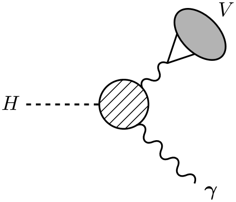
Introduction - $H \to \mathcal{Q}\,\gamma$

$H \to \mathcal{Q}\,\gamma$ decays could provide a clean probe of the light and charm quark Yukawa couplings

- $\mathcal{Q}$ is a vector ($J^{PC} = 1^{--}$) meson or quarkonium state (e.g. ϕ or J/ψ)
- Interference between direct (top) and indirect (bottom) contributions
- Indirect (bottom) amplitude provides dominant rate contribution
- Direct (top) amplitude provides sensitivity to $Hs\bar{s}$ and $Hc\bar{c}$ couplings in cases of $\mathcal{Q} = \phi$ and J/ψ, respectively
- Very rare decays in the SM!

$$\mathcal{B}(H \to \phi\,\gamma) = (2.6 \pm 0.1) \times 10^{-6\dagger}$$
$$\mathcal{B}(H \to J/\psi\,\gamma) = (2.8 \pm 0.2) \times 10^{-6\ddagger}$$



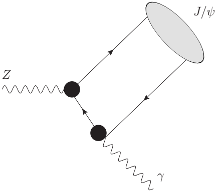


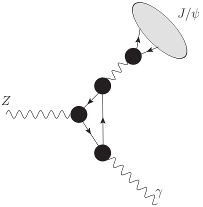
More details: † JHEP 1508 (2015) 012 (arXiv:1505.03870) and ‡ Phys. Rev. D 90, 113010 (2014) (arXiv:1407.6695)

Introduction - $Z \to \mathcal{Q}\,\gamma$

$Z \to \mathcal{Q}\,\gamma$ decays could provide a stepping stone towards the observation of the Higgs decays at the LHC

- Analogous to Higgs decay, could provide useful control channel
- Similar interference between direct (top) and indirect (bottom) contributions
- Indirect amplitude suppressed w.r.t. the Higgs decay case
- While these are rarer decays, Z bosons much more copiously produced than Higgs at the LHC...

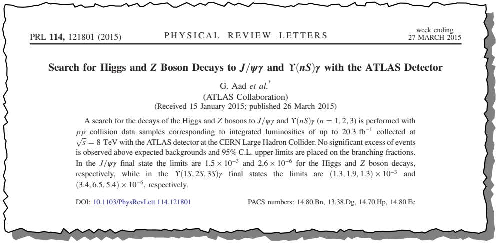




$$\mathcal{B}\,(Z \to \phi\,\gamma) = (1.2 \pm 0.1) \times 10^{-8\dagger}$$
$$\mathcal{B}\,(Z \to J/\psi\,\gamma) = (1.0 \pm 0.2) \times 10^{-7\dagger}$$

More details: † Phys. Rev. D 92, 014007 (2015) (arXiv:1411.5924)

Interlude - Existing Results



PRL **114,** 121801 (2015) PHYSICAL REVIEW LETTERS week ending 27 MARCH 2015

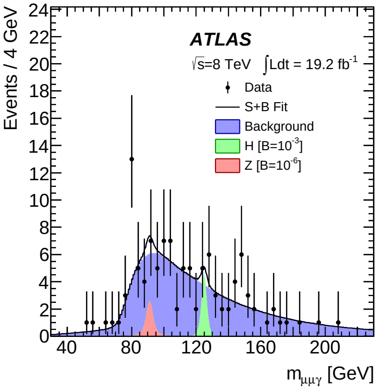
Search for Higgs and Z Boson Decays to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ with the ATLAS Detector

G. Aad *et al.*[*]
(ATLAS Collaboration)
(Received 15 January 2015; published 26 March 2015)

A search for the decays of the Higgs and Z bosons to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ ($n = 1, 2, 3$) is performed with pp collision data samples corresponding to integrated luminosities of up to 20.3 fb^{-1} collected at $\sqrt{s} = 8$ TeV with the ATLAS detector at the CERN Large Hadron Collider. No significant excess of events is observed above expected backgrounds and 95% C.L. upper limits are placed on the branching fractions. In the $J/\psi\gamma$ final state the limits are 1.5×10^{-3} and 2.6×10^{-6} for the Higgs and Z boson decays, respectively, while in the $\Upsilon(1S, 2S, 3S)\gamma$ final states the limits are $(1.3, 1.9, 1.3) \times 10^{-3}$ and $(3.4, 6.5, 5.4) \times 10^{-6}$, respectively.

DOI: 10.1103/PhysRevLett.114.121801 PACS numbers: 14.80.Bn, 13.38.Dg, 14.70.Hp, 14.80.Ec

- First search for such rare Higgs decays was performed by ATLAS with Run 1 dataset[†]
- Studied quarkonium decays, in particular $H \rightarrow J/\psi\,\gamma$ (with $J/\psi \rightarrow \mu^+\mu^-$)
- Very similar $H \rightarrow J/\psi\,\gamma$ limit subsequently deduced by CMS[‡]
- First direct information on decay modes sensitive to the $Hc\bar{c}$ coupling



Branching fractions limits (95% C.L.):

$$\mathcal{B}\left(H \rightarrow J/\psi\,\gamma\right) < 1.5 \times 10^{-3}$$
$$\mathcal{B}\left(Z \rightarrow J/\psi\,\gamma\right) < 2.6 \times 10^{-6}$$

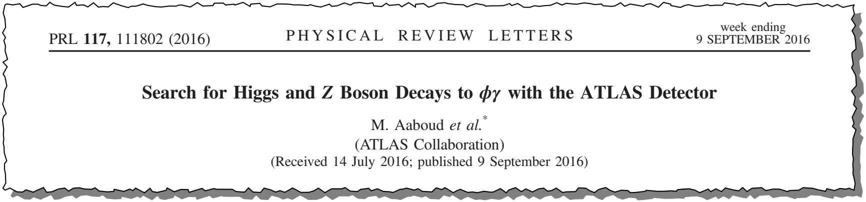
† Phys. Rev.Lett. 114 (2015), 121801 (arXiv:1501.03276)

‡ Phys. Lett. B753 (2016) 341 (arXiv:1507.03031)

Analysis Introduction

Search for the rare decay $H \to \phi\gamma$

- New analysis based on ATLAS 2015 dataset collected at $\sqrt{s} = 13$ TeV
- Analogous decay $Z \to \phi\gamma$ also considered



PRL **117,** 111802 (2016) PHYSICAL REVIEW LETTERS week ending 9 SEPTEMBER 2016

Search for Higgs and *Z* Boson Decays to *ϕγ* with the ATLAS Detector

M. Aaboud *et al.*[*]
(ATLAS Collaboration)
(Received 14 July 2016; published 9 September 2016)

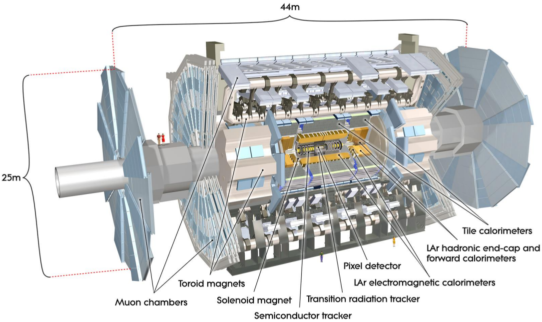
Phys. Rev. Lett. 117 (2016), 111802 (arXiv:1607.03400)

Supplementary Information: **http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-05/**

Motivation

- Higgs decay sensitive to the strange quark Yukawa coupling, very difficult to access with inclusive $H \to s\bar{s}$ decays!
- Anomalous $Hs\bar{s}$ couplings possible in various BSM scenarios (e.g. Minimal Flavour Violation or Froggatt-Nielsen mechanism) would modify $\mathcal{B}(H \to \phi\gamma)$
- $Z \to \phi\gamma$ poorly constrained by existing Z decay measurements

ATLAS Detector

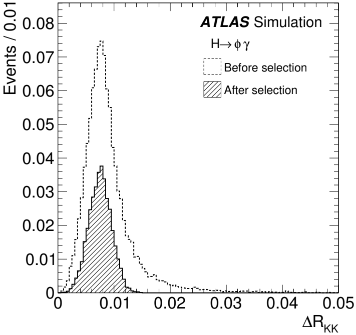


- **Inner Detector (ID):** Silicon Pixels and Strips (SCT) with Transition Radiation Tracker (TRT) $|\eta| < 2.5$
- **New for Run 2!** - "Insertable B-Layer" (IBL) - additional inner-most pixel layer ($r = 33$ mm) and lower x/X_0 beam pipe
- **LAr EM Calorimeter:** Highly granular + longitudinally segmented (3-4 layers)
- **Two Level Trigger:** Level 1 (Hardware) + High Level (Software) trigger

Analysis Stategy

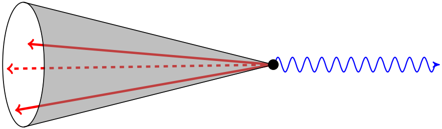
Reconstruction

- Reconstruct only $\phi \to K^+K^-$ decays, $\mathcal{B}(\phi \to K^+K^-) = 49\%$
- Distinctive topology - **pair of high p_T isolated tracks**, with a very small opening angle, recoiling against a **high p_T isolated photon**



Trigger

- A dedicated trigger was implemented in September 2015
- Requires both an isolated photon with $p_T^\gamma > 35$ GeV and an isolated pair of tracks loosely consistent with the ϕ meson mass, at least one of which has $p_T > 15$ GeV
- Trigger efficiency w.r.t. offline selection (described next) of around 80% (for both H and Z decays)
- Data sample corresponding to 2.7 fb^{-1} was collected towards the end of the 2015 LHC run



Event Selection I - $\phi \rightarrow K^+K^-$ Selection

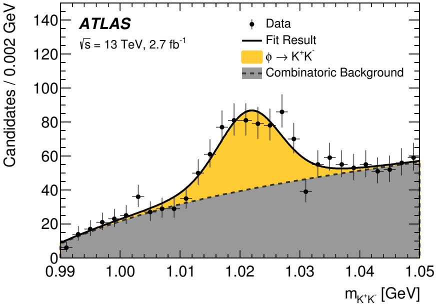
- No $\pi/K/p$ particle ID available for tracks in relevant p_T range - assume K hypothesis for all tracks
- Leading track $p_T > 20$ GeV and sub-leading track $p_T > 15$ GeV
- Require consistency with ϕ mass: $|m_{KK} - m_\phi| < 20$ MeV
- Track isolation: sum p_T of tracks within $\Delta R < 0.2$ must be less than $0.1 \times p_T^{KK}$
- The di-track system transverse momentum must satisfy:

$$p_T^{KK} > \begin{cases} 40\,\text{GeV}, & \text{for } m_{KK\gamma} \leq 91\,\text{GeV} \\ 40 + 5/34 \times (m_{KK\gamma} - 91)\,\text{GeV}, & \text{for } 91\,\text{GeV} < m_{KK\gamma} < 125\,\text{GeV} \\ 45\,\text{GeV}, & \text{for } m_{KK\gamma} \geq 125\,\text{GeV} \end{cases}$$

The “sliding” p_T^{KK} requirement ensures optimal sensitivity for both H and Z yet the gradient is small w.r.t. the scale of the $m_{KK\gamma}$ resolution

Event Selection II - Photon Selection

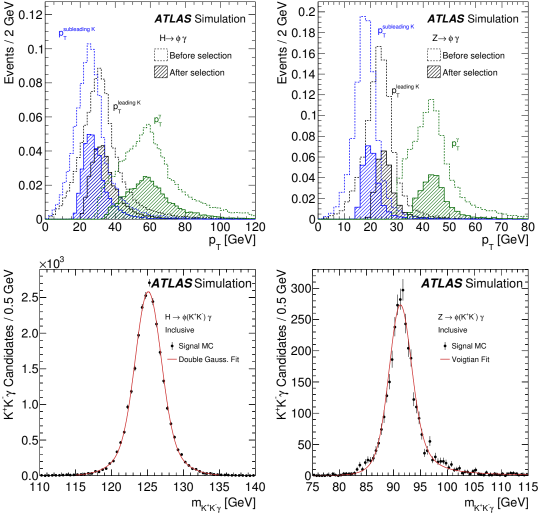
- Photons must satisfy the “Tight” γ identification criteria and $p_T^\gamma > 35$ GeV
- Photons must be within $|\eta^\gamma| < 2.47$ and outside of $1.37 < |\eta^\gamma| < 1.52$
- Calorimeter isolation: sum E_T of energy deposits within $\Delta R < 0.4$ must be less than $2.45 \text{ GeV} + 0.022 \times p_T^\gamma$
- Track isolation: sum p_T of tracks within $\Delta R < 0.2$ must be less than $0.05 \times p_T^\gamma$
- Require $\Delta\phi(K^+K^-, \gamma) > 0.5$ (removes $\sim$ collinear $\phi\gamma$ pairs)



Clear $\phi \to K^+K^-$ signal visible with full selection applied (no m_{KK} requirement)

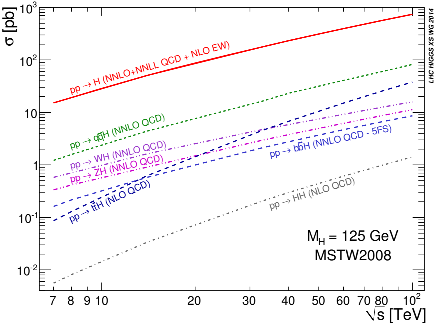
Acceptance, Efficiency and Mass Resolution

Total $A \times \epsilon$ of around 18% for Higgs signal and 8% for the Z signal



Mass resolution is around 1.8% at both m_H and m_Z

Signal Modeling



Composition of Higgs boson production with $m_H = 125$ GeV at $\sqrt{s} = 13$ TeV:

Channel	σ [pb]	Fraction
ggH	43.92	86%
VBF	3.748	7%
WH	1.380	3%
ZH	0.8696	2%
$t\bar{t}H$	0.5085	1%
$b\bar{b}H$	0.5116	1%

Source: LHCXSWG (arXiv:1307.1347)

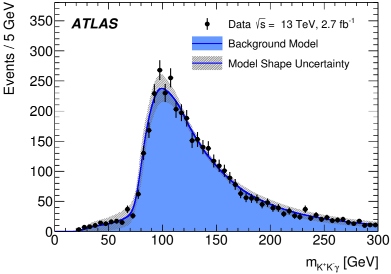
- $H, Z \to \phi\gamma$ signals are modeled with exclusive samples of simulated events
- POWHEG used to model Higgs (ggH and VBF) and Z boson production
- PYTHIA 8.1 used to model small WH and ZH contributions
- ggH sample is rescaled to model small $t\bar{t}H$ and $b\bar{b}H$ contributions
- Z boson simulation scaled to $\sqrt{s} = 13$ TeV cross section measured by ATLAS[†]
- PYTHIA 8.1 is used to simulate parton showering and hadronisation in all cases

[†] Phys. Lett. B 759 (2016) 601 (arXiv:1603.09222)

Background Modelling

Background Composition:

- Background dominated by QCD production of photon+jet and multi-jet events
- Exclusive "peaking" backgrounds (e.g. $Z \to \mu^+\mu^-\gamma$) estimated to be negligible



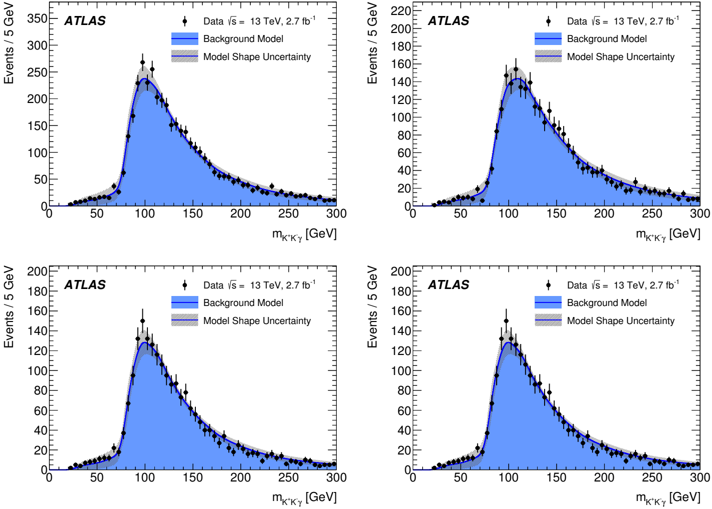
Data driven model of inclusive background:

- Begin with a very loose sample of $\phi\gamma$ events ($\nearrow$) with p_T and isolation cuts (on both ϕ and γ) relaxed w.r.t. nominal selection - high statistics background dominated data sample
- Model kinematic and isolation distributions of this background dominated sample and generate background $\phi\gamma$ pseudo-candidates
- Apply nominal selection (tight p_T and isolation cuts) to these pseudo-candidates to model the background in validation and signal regions

Model provides a good description of background shape (norm. from fit to data)

Background Modelling Validation

↖ Loose "generation region" (GR) sample ↗ GR + nominal p_T req.



↙ GR + nominal γ isolation req. ↘ GR + nominal ϕ isolation req.

Systematic Uncertainties

Signal Yield Uncertainty: **Several sources of systematic uncertainty on the H and Z signal yields are considered, all modeled with nuisance parameters in likelihood:**

Source	**H/Z Yield Uncertainty**	**Estimated From**
Total H cross section	**12%**	QCD scale + PDF uncertainties
Total Z cross section	**5.5%**	ATLAS Measurement
Integrated Luminosity	**5%**	Calibration observable and vdM scan uncertainties†
Photon ID Efficiency	**2.5%**	Data driven techniques with $Z \rightarrow \ell^+\ell^-$ and $Z \rightarrow \ell^+\ell^-\gamma$
Photon Energy Scale	**0.3%**	
Trigger Efficiency	**2%**	
Tracking Efficiency	**6%**	Tracking studies within dense jets

Background Shape Uncertainty: **Estimated from modifications to modeling procedure (e.g. shifting p^T_{KK} and neglecting the weakest correlation included in the model), shape uncertainty included in likelihood as a shape morphing NP**

† Method described in: EPJC 73 (2013) 2518 (arXiv:1302.4393)

Statistical Analysis and Results

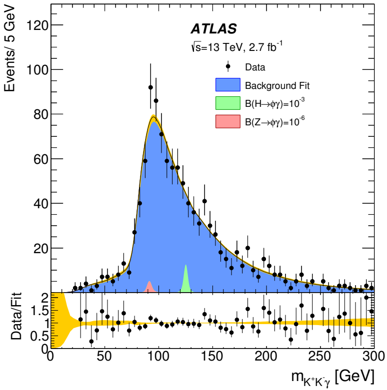
Limit Setting Procedure

- Final discriminant is $m_{KK\gamma}$ distribution
- Limits set using CL_s formalism with the profile likelihood ratio test statistic

Results

- Largest excess of events above background observed (around 100 GeV) is around a 2σ effect
- No significant H or Z signal observed, set branching fraction limits at the level of 10^{-3} (H) and 10^{-6} (Z)

Bkgd. only fit to observed data



Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)\,[10^{-3}]$	$1.5^{+0.7}_{-0.4}$	1.4
$\mathcal{B}(Z \to \phi\gamma)\,[10^{-6}]$	$4.4^{+2.0}_{-1.2}$	8.3

Summary

Conclusion

Exclusive radiative decays of the Higgs boson to a ϕ meson can be used to probe Higgs Yukawa couplings to the strange quark!

ATLAS have performed the first search for such Higgs decays and the analogous rare Z boson decays

First experimental information on such decays:

$$\mathcal{B}\,(H \to \phi\,\gamma) < 1.4 \times 10^{-3}$$
$$\mathcal{B}\,(Z \to \phi\,\gamma) < 8.3 \times 10^{-6}$$

This study and the associated theoretical work represent an important emerging subfield of Higgs physics!

We can expect other such rare decays to further elucidate light quark Yukawa couplings through LHC Run 2 and beyond!