Probing Higgs Yukawa Couplings with Rare Decays

Birmingham HEP Seminar

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13th May 2015

This project has received funding from the European Union's 7th Framework Programme for research, technological development and demonstration under grant agreement number 334034 (EWSB)

Higgs Boson Yukawa Couplings

- What is the Higgs boson and Yukawa coupling?
- How can we study them through rare Higgs decays?

Experimental Investigations

- How can we study these rare decays at the LHC?
- First search: Phys. Rev. Lett. 114 (2015) 121801 (arXiv:1501.03276)

Discussion

- What have we learnt from this search?
- What can we expect from future studies?

Introduction - **The “BEH” Mechanism**

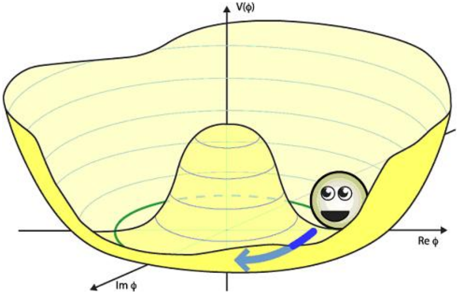


Figure from Philip Tanedo

- Complex scalar SU(2) doublet ϕ introduced to SM, “The Higgs field” (4 real d.o.f.)
- Then consider the symmetry spontaneously broken
- Potential of the field has non-zero VEV, 3 d.o.f. become Goldstone bosons
- Three Goldstone bosons mix with $W^{\pm}, Z$ fields
- Provides gauge invariant mass terms (and longitudinal pol) to the $W^{\pm}$ and Z
- The fourth d.o.f. is a scalar “Higgs” boson!

Provides masses to the $W^{\pm}$ and Z bosons!

Now we have a Higgs field, "Yukawa" couplings between the Higgs and Fermion fields are possible:

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

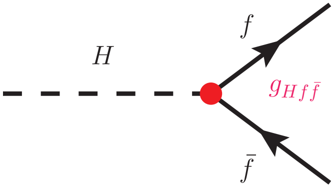
If ϕ has a non-zero VEV, expansion leads to:

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

where h is the physical Higgs boson field...

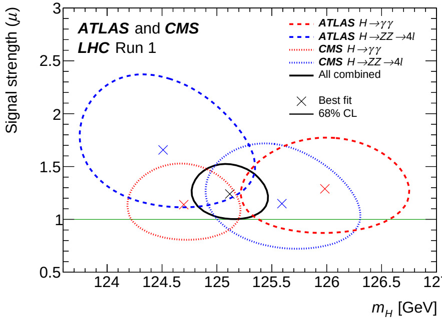
The End Result:

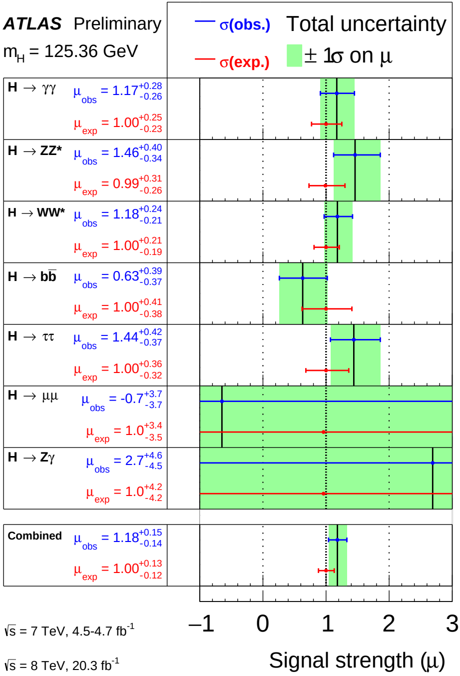
- Gauge invariant Fermion mass terms ✓
- Higgs-Fermion coupling proportional to the Fermion mass ($g_{Hf\bar{f}} = m_f/v$) ✓



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!

In 2012, the ATLAS and CMS experiments discovered a new boson, with a mass of around 125 GeV





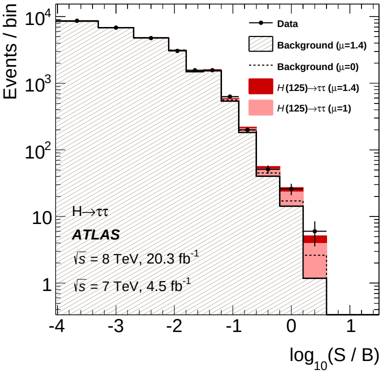
All subsequent measurements suggest compatibility with the Higgs boson of the Standard Model...

What do we know about Higgs couplings to:

- ***t* quark:** No <u>firm</u> evidence for $t\bar{t}H$ production from LHC experiments
- ***b* quark:** No <u>firm</u> 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
- **u, d, s quarks:** Nothing!
- **τ lepton:** Evidence for $H(125) \to \tau\tau$ decays from ATLAS and CMS!
- **e, μ leptons:** No evidence, but that suggests lepton coupling isn't universal!

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

JHEP 04 (2015) 117 (arXiv:1501.04943)

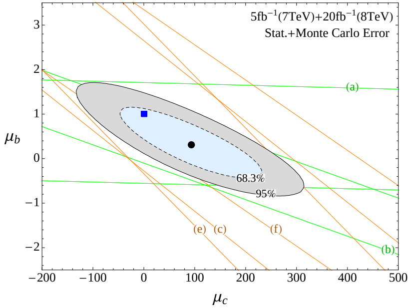


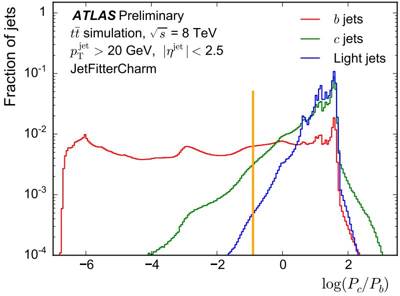
Data suggest lepton Yukawa couplings are present and non-universal...
But not too much else!

Introduction - **Charm Quark Yukawa Coupling**

The "traditional" approach is to search for inclusive $H \to c\bar{c}$ decays

- Direct searches suffer from very large backgrounds from inclusive jet production
- Recent dedicated efforts to develop charm tagging! **(ATL-PHYS-PUB-2015-001)**
- Not yet applied to $H \to c\bar{c}$ searches...



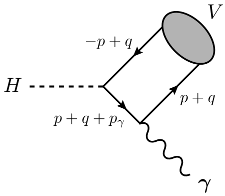


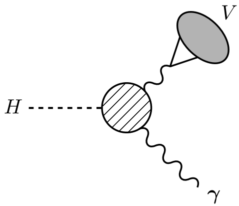
† See arXiv:1503.00290 for details

- Existing $H \to b\bar{b}$ searches an be reinterpreted to include the possibility of anomalous $H \to c\bar{c}$ production
- Exploit the non-zero rate of charm quarks mistagged as bottom
- ATLAS and CMS data provide $\boldsymbol{\kappa_c} < \mathbf{234}$ at 95% CL upper bound†

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

- $\mathcal{Q}$ is a vector ($J^{PC} = 1^{--}$) quarkonium state
- Interference between direct (top) and indirect (bottom) contributions
- Indirect (bottom) amplitude provides dominate rate contribution
- Direct (top) amplitude provides sensitivity to $Hc\bar{c}$ and $Hb\bar{b}$ couplings
- Very rare SM decay (c.f. $\mathcal{B}(H \to \gamma\gamma) \approx 2 \times 10^{-3}$)
- Will need a HL-LHC with (at least) 3000 fb^{-1} to approach observation





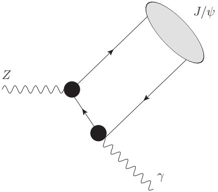
$$\mathcal{B}(H \to J/\psi\,\gamma) = 2.8 \times 10^{-6\dagger}$$
$$\mathcal{B}(H \to \Upsilon(1S, 2S, 3S)\,\gamma) = \{0.6, 2.0, 2.4\} \times 10^{-9\dagger}$$

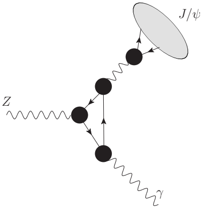
More details: Phys. Rev. **D 88**, 053003 (2013) (arXiv:1306.5770) and † Phys. Rev. **D 90**, 113010 (2014) (arXiv:1407.6695)

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. Higgs case
- While a rarer decay in the J/ψ case, Z bosons much more copiously produced than Higgs at the LHC, better prospects for observation





$$\mathcal{B}\,(Z \to J/\psi\,\gamma) = 1.0 \times 10^{-7\dagger}$$
$$\mathcal{B}\,(Z \to \Upsilon(1S)\,\gamma) = 4.9 \times 10^{-8\dagger}$$

More details: † (arXiv:1411.5924)

Further work: Nucl. Phys. B 174, 317 (1980), Theor. Math. Phys. 170, 39 (2012), arXiv:1501.06569

Experimental limits on $Z \to \mathcal{Q}\,\gamma$ decays

- Only information from LEP measurements of inclusive $Z \to \mathcal{Q}\,X$ decays
- LEP "only" produced around 17 million Z bosons...
- Can expect only around one $Z \to J/\psi\,\gamma$ decay in the dataset!
- Existing knowledge on these exclusive decays is in the form of upper bounds from inclusive $Z \to \mathcal{Q}\,X$ measurements/limits

Combined (PDG) LEP Measurements:

$$\mathcal{B}(Z \to J/\psi\,X) = \left(3.5^{+0.23}_{-0.25}\right) \times 10^{-3}$$

$$\mathcal{B}(Z \to \Upsilon(nS)\,\gamma) = (1.0 \pm 0.5) \times 10^{-4}$$

Nearly 4 orders of magnitude away from SM branching fraction!

Experimental limits on $H \to \mathcal{Q}\,\gamma$ decays

- Nothing known, until now...

The first experimental information on $H/Z \to \mathcal{Q}\,\gamma$ decays, from the ATLAS experiment!

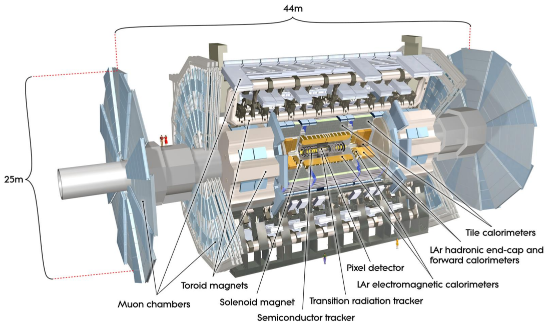
PRL **114,** 121801 (2015) PHYSICAL REVIEW LETTERS week ending 27 MARCH 2015

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



- **Muon Spectrometer (MS):** Triggering $|\eta| < 2.4$ and Precision Tracking $|\eta| < 2.7$
- **Inner Detector (ID):** Silicon Pixels and Strips (SCT) with Transition Radiation Tracker (TRT) $|\eta| < 2.5$
- **LAr EM Calorimeter:** Highly granular + longitudinally segmented (3-4 layers)
- **Muon Trigger:** Single and di-muon triggers - several p_T^{μ} thresholds (4–40 GeV)
- **Resolution in $m_{\mu^+\mu^-}$:** Around 50 MeV at J/ψ and 150 MeV at $\Upsilon(nS)$

Analysis - **Overview**

Experimental Signature

- High p_T isolated photon recoiling against a high p_T isolated quarkonium state

Analysis Aim

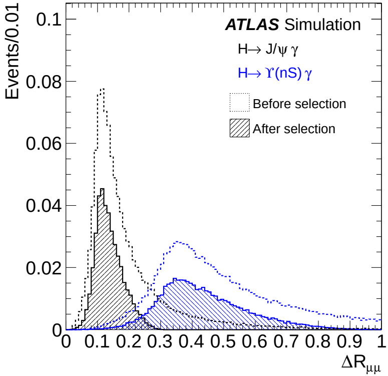
- Search for both Higgs and Z boson decays
- Study both $J/\psi\,\gamma$ and $\Upsilon(nS)\,\gamma$ decay channels
- Exploit full ATLAS data sample collected at $\sqrt{s} = 8$ TeV, around 20 fb^{-1}

How to reconstruct the quarkonium?

Decay	Rate	Background	Trigger	Reconstruction
$\mathcal{Q} \rightarrow$ hadrons	✓ $\mathcal{B} = 80 - 90\%$	✗	✗	?
$\mathcal{Q} \rightarrow e^+e^-$	✗ $\mathcal{B} = 2 - 6\%$	?	✓	✗
$\mathcal{Q} \rightarrow \mu^+\mu^-$	✗ $\mathcal{B} = 2 - 6\%$	✓	✓	✓

Of the several options, choose to reconstruct $\mathcal{Q} \rightarrow \mu^+\mu^-$ only...

- Photon is too soft (by single photon trigger standards) to provide a trigger
- The $\mathcal{Q}$ produced in a H/Z boson decay is often highly boosted ($< p_T > \approx 50$ GeV)
- The opening angle between muons in such boosted $\mathcal{Q} \to \mu^+\mu^-$ decays is very small
- **This presents a challenge when using muons to trigger such events!**



$J/\psi\,\gamma$ Channel:

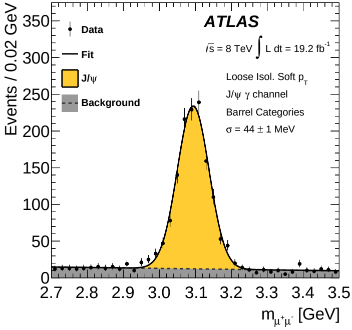
- With $< \Delta R_{\mu^+\mu^-} > \approx 0.1$, dimuon or isolated muon triggers have low efficiency
- Use single non-isolated high p_T muon trigger

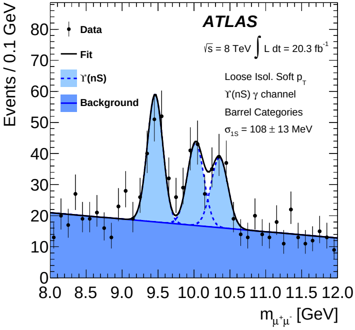
$\Upsilon(nS)\,\gamma$ Channel:

- Broader $< \Delta R_{\mu^+\mu^-} >$ distribution
- Can use an isolated single high p_T muon trigger with a lower threshold dimuon trigger

Oppositely charged dimuon pairs with $|\eta^\mu| < 2.5$ and $p_T^\mu > 3.0$ GeV that are:

- **Hard:** At least one muon must have $p_T^\mu > 20$ GeV, require $p_T^{\mu^+\mu^-} > 36$ GeV
- **Isolated:** Require the sum p_T of tracks and calo. deposits within $\Delta R < 0.2$ of the leading p_T muon to be less than 10% of its p_T
- **Prompt:** Transverse decay length significance $L_{xy}/\sigma_{L_{xy}} < 3.0$ to reject $b \to J/\psi$
- **The correct mass:** $|m_{\mu^+\mu^-} - m_{J/\psi}| < 0.15(0.20)$ GeV in barrel(endcap) OR $8.0 < m_{\mu^+\mu^-} < 12.0$ GeV

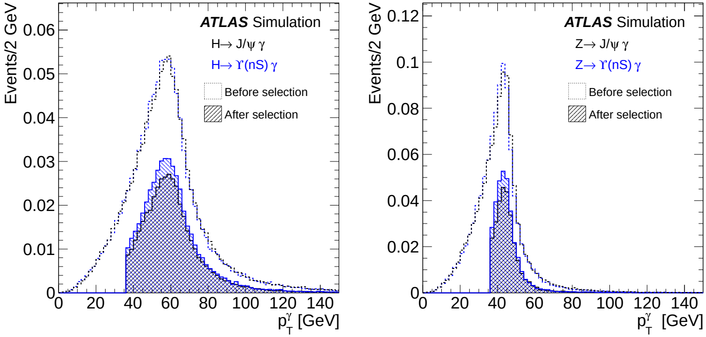




Event Selection - **Photon Selection**

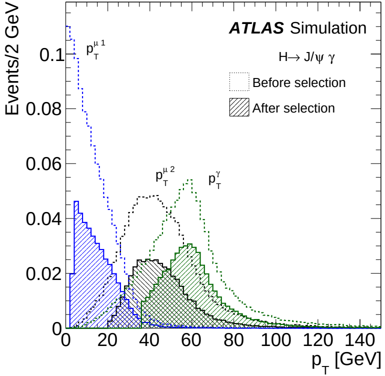
Select converted and unconverted photons within $|\eta^{\gamma}| < 2.47$ and outside of $1.37 < |\eta^{\gamma}| < 1.52$ that are:

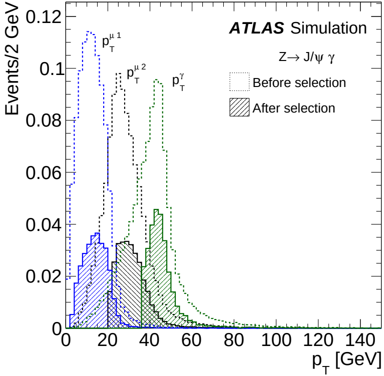
- **Unlikely a Jet:** Require "tight" γ shower shape identification criteria
- **Hard:** Require $p_T^{\gamma} > 36$ GeV
- **Isolated:** Require the sum p_T of tracks and calo. deposits within $\Delta R < 0.2$ of the photon to be less than 8% of its p_T
- **Recoiling against $\mathcal{Q}$:** Require $\Delta\phi(\mu^+\mu^-, \gamma) > 0.5$



Overall acceptance $\times$ efficiency (including trigger):

Channel	$H \to J/\psi\,\gamma$	$H \to \Upsilon(nS)\,\gamma$	$Z \to J/\psi\,\gamma$	$Z \to \Upsilon(nS)\,\gamma$
$A \times \epsilon$	22%	28%	12%	15%

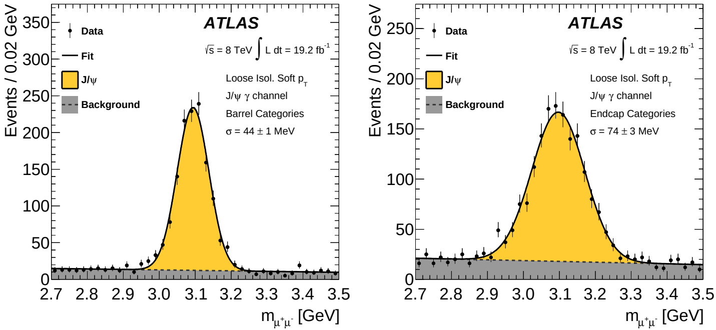




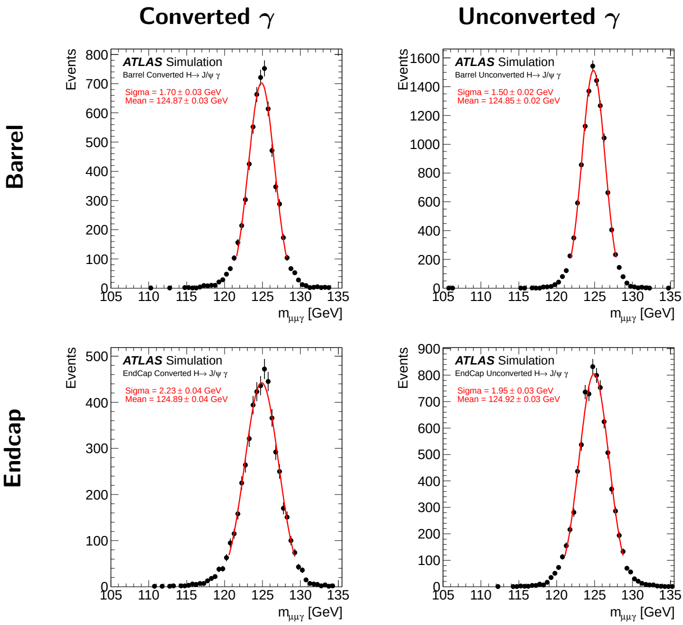
Lepton and photon p_T distributions in fiducial volume ($|\eta^\gamma| < 2.47$ and $|\eta^\mu| < 2.5$) and after all selection, final state particles slightly softer in Z decays...

Events are split into four individual categories based on η^{μ} and photon conversion status (i.e. converted or unconverted):

- `B_UNCONV`: Both muons within $|\eta^{\mu}| < 1.05$ and an unconverted photon
- `B_CONV`: Both muons within $|\eta^{\mu}| < 1.05$ and an converted photon
- `EC_UNCONV`: Either muon with $|\eta^{\mu}| > 1.05$ and an unconverted photon
- `EC_CONV`: Either muon with $|\eta^{\mu}| > 1.05$ and an converted photon

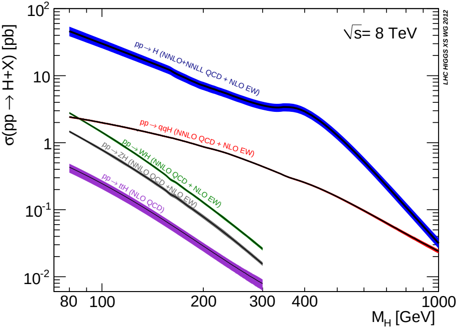


Resolution and S/B vary across categories, separate treatment enhances sensitivity



Three body $m_{\mu^+\mu^-\gamma}$ mass resolution varies from 1.2% (barrel) to 1.8% (endcap)

Analysis - **Signal Modeling**



Composition of Higgs boson production with $m_H = 125$ GeV at $\sqrt{s} = 8$ TeV:

Channel	σ [pb]	Fraction
ggH	19.27	87%
VBF	1.58	7%
WH	0.70	3%
ZH	0.42	2%
$t\bar{t}H$	0.13	1%

Source: LHCXSWG (arXiv:1307.1347)

The POWHEG MC generator is used to model Higgs and Z boson production:

- All $H, Z \to \mathcal{Q}\gamma$ signals are modeled with exclusive samples of simulated events
- Separate samples of gluon fusion and VBF production are used for Higgs channels
- VBF sample is rescaled to model ZH, $W^{\pm}H$ and $t\bar{t}H$ production contributions (accounting for small acceptance differences)

PYTHIA 8.1 is used to simulate parton showering and hadronisation while PHOTOS used to simulate QED final state effects (e.g. FSR)

"Exclusive" Backgrounds

Electroweak production of an isolated dimuon pair and isolated photon

- $Z \to \mu^+\mu^- \to \mu^+\mu^-\gamma$ decays with a "catastrophic" FSR, effect depends strongly on $m_{\mu^+\mu^-}$ region of interest
- Important in $\Upsilon(nS)\gamma$ channel BUT negligible for $J/\psi\,\gamma$ channel
- Other Higgs decays e.g. $H \to \mu^+\mu^-\gamma$ - Negligible at current sensitivity...

Small, but "peaking" backgrounds, modeled with MC simulation

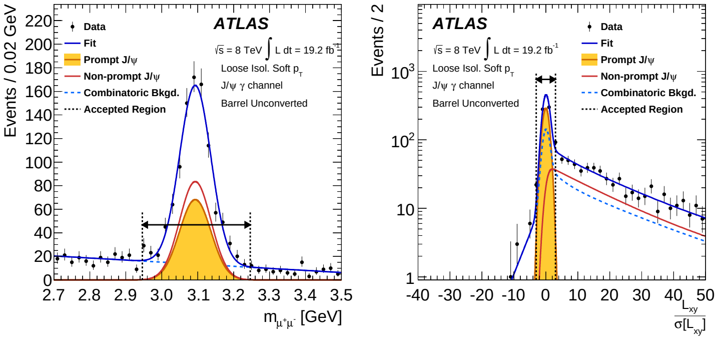
"Inclusive" Backgrounds

QCD production of quarkonia, jets and photons

- Processes such as $pp \to \mathcal{Q}\,g\,X$ where jet is identified as a photon
- Smaller contributions such as γ+jets, $b\bar{b}$ production (with $b \to J/\psi X$)

Large, but "smooth" backgrounds, modeled with a data-driven approach

The $m_{\mu^+\mu^-}$ and $L_{xy}/\sigma_{L_{xy}}$ requirements are removed to study the background dimuon composition

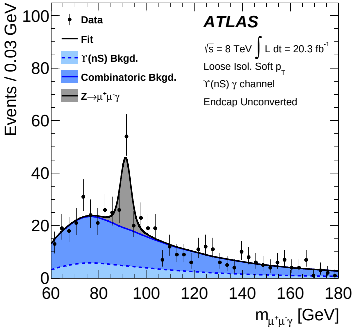


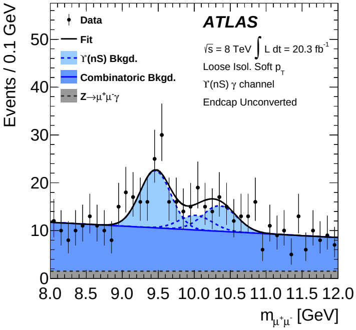
- Composition estimated from simultaneous fit to $m_{\mu^+\mu^-}$ and $L_{xy}/\sigma_{L_{xy}}$ distributions, an example fit shown for relaxed control region (not full event selection)

Background dimuon composition for full selection:

56% prompt J/ψ, 3% non-prompt J/ψ and 41% combinatoric dimuons

Similarly, the background composition of the $\Upsilon(nS)\gamma$ channel can be studied





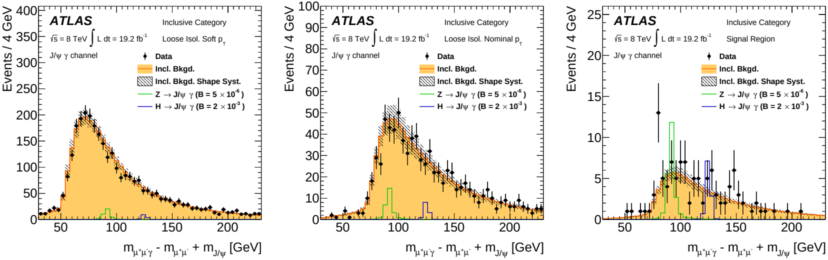
- Composition estimated from simultaneous fit to $m_{\mu^+\mu^-\gamma}$ and $m_{\mu^+\mu^-}$ distributions, an example fit shown for relaxed control region (not full event selection)

Background dimuon composition for full selection:

7% $\Upsilon(nS)$, 27% $Z \to \mu^+\mu^-\gamma$ and 66% combinatoric dimuons

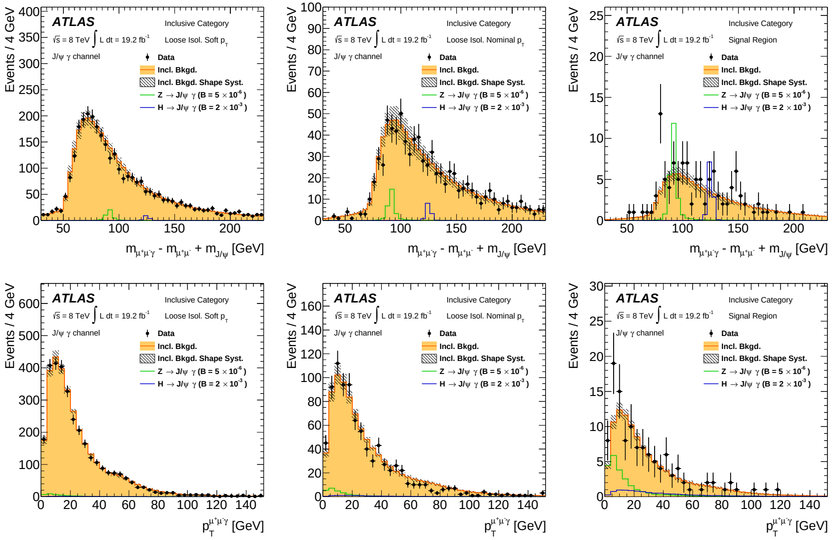
Event mixing model for "Inclusive" backgrounds:

- Start with a very loose sample of $\mathcal{Q}\gamma$ events with p_T and isolation cuts significantly relaxed w.r.t. nominal selection - high statistics data sample dominated by background events
- Use the kinematic and isolation distributions of this background dominated sample to generate "toy" background $\mathcal{Q}\gamma$ candidates
- Can apply nominal selection (tight p_T and isolation cuts) to these "toy" candidates to model the background in the signal region



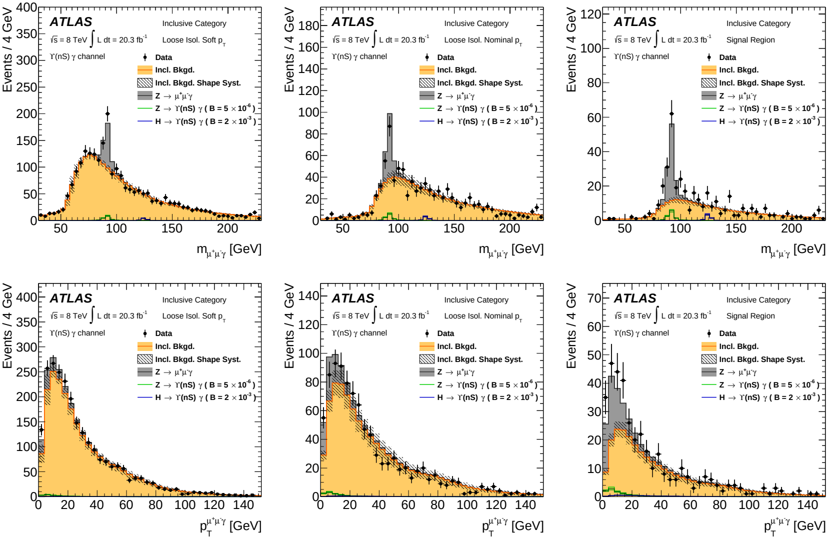
Provides good description of the shape and normalisation of inclusive background contribution to important kinematic distributions

Backgrounds - **Inclusive Background Model: $J/\psi\,\gamma$ Channel**



Loose Selection **Validation Selection** **Final Selection**

Backgrounds - **Inclusive Background Model: $\Upsilon(nS)\,\gamma$ Channel**



Loose Selection **Validation Selection** **Final Selection**

Systematics Uncertainties - **Signal and Background**

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	Signal Yield Uncertainty	Estimated From
Total H cross section	**12%**	QCD scale variation and PDF uncertainties
Total Z cross section	**4%**	
Integrated Luminosity	**2.8%**	Calibration observable and vdM scan uncertainties†
Trigger Efficiency	**1.7%**	Data driven techniques with $Z \to \ell^+\ell^-$, $Z \to \ell^+\ell^-\gamma$ and $J/\psi \to \mu^+\mu^-$ events
Photon ID Efficiency	**Up to 0.7%**	
Muon ID Efficiency	**Up to 0.4%**	
Photon Energy Scale	**0.2%**	
Muon Momentum Scale	**Negligible**	

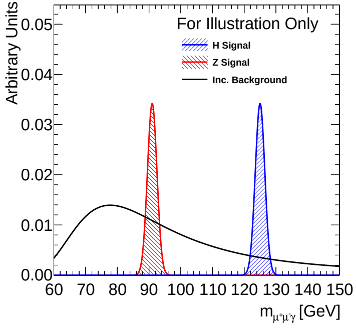
Background Shape Uncertainty: **Estimated from modifications to modeling procedure (e.g. shifting/warping input distributions), shape uncertainty included in likelihood as a shape morphing nuisance parameter**

† See EPJC 73 (2013) 2518 (arXiv:1302.4393) for details

Limit Setting Procedure

- Limits set using CLs modified frequentist formalism with the profile likelihood ratio test statistic
- Unbinned likelihood built from multi dimensional PDFs
- Systematic uncertainties included in likelihood as nuisance parameters

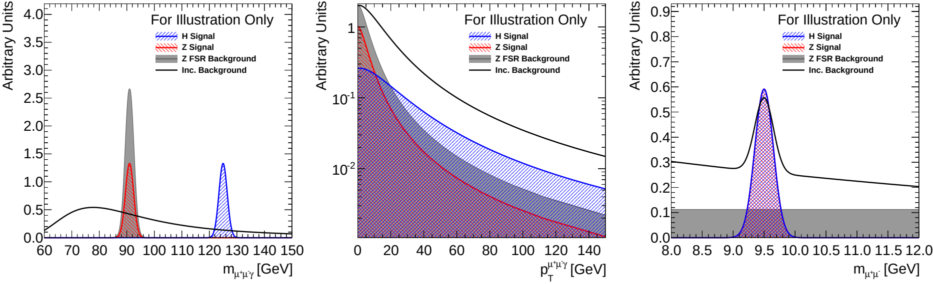
$J/\psi\,\gamma$ Channel: Simultaneous fit to $m_{\mu^+\mu^-\gamma}$ and $p_T^{\mu^+\mu^-\gamma}$ distributions



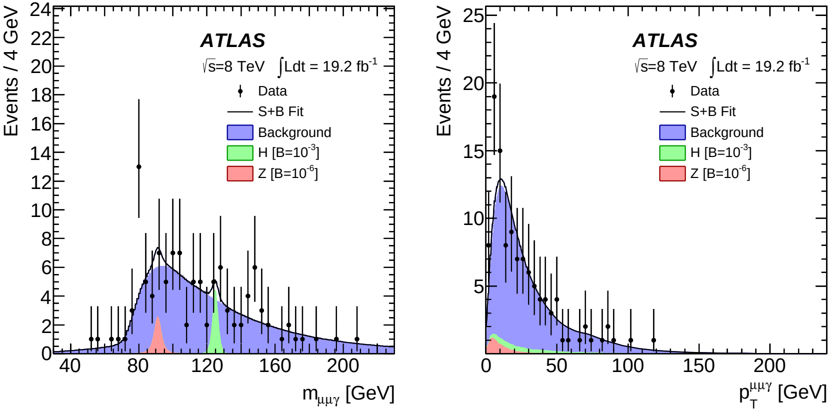
$p_T^{\mu^+\mu^-\gamma}$ information provides further discrimination between signal and background

Statistical Analysis - $\Upsilon(nS)\,\gamma$ Channel Model

Simultaneous fit to $m_{\mu^+\mu^-\gamma}$, $p_T^{\mu^+\mu^-\gamma}$ and $m_{\mu^+\mu^-}$ distributions

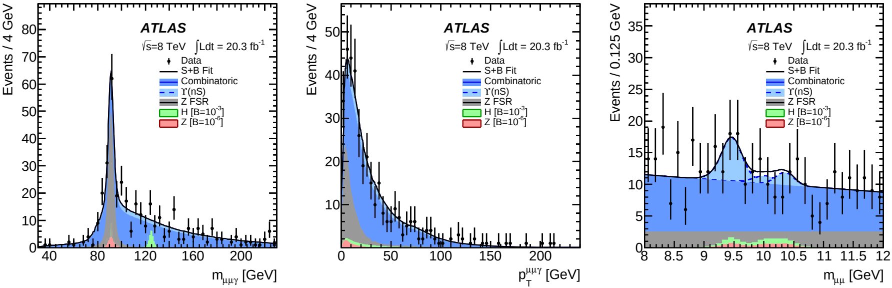


Addition of $m_{\mu^+\mu^-}$ distribution provides discrimination between $Z \to \Upsilon(nS\,\gamma)$ signal and $Z \to \mu^+\mu^-\gamma$ FSR. Also allows $Z \to \mu^+\mu^-\gamma$ FSR normalisation to be reliably fitted directly with data!



No significant Higgs or Z boson signals observed...

Fit Results - $\Upsilon(nS)\,\gamma$



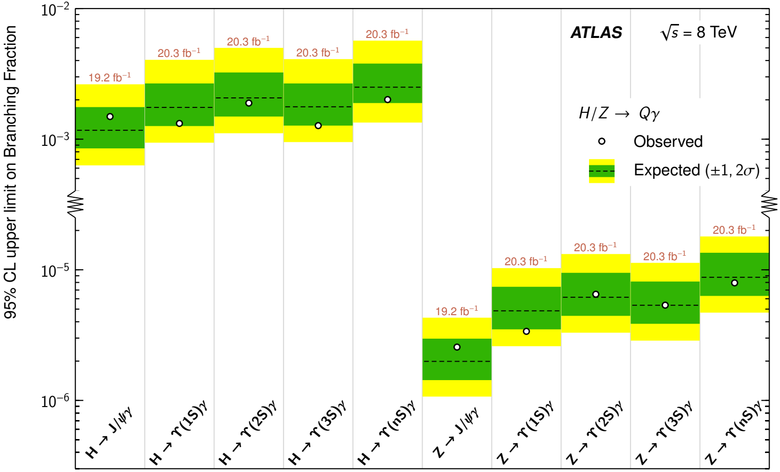
No significant Higgs or *Z* boson signals observed...

Limits are set on the branching fractions and $\sigma \times \mathcal{B}$ for each decay channel:

	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

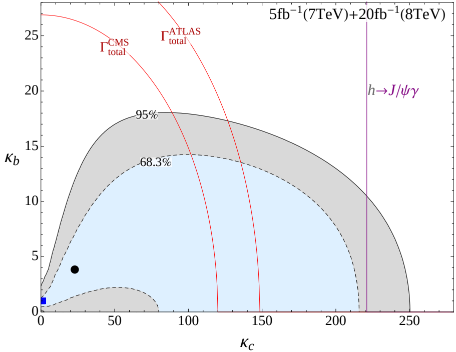
- Upper limit of around 540×SM rate for $H \to J/\psi\,\gamma$ decay
- Upper limit of around 26×SM rate for $Z \to J/\psi\,\gamma$ decay

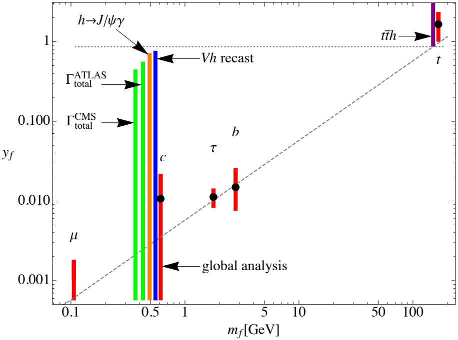
Upper limits set on Higgs decays at the level of 10^{-3}!
Remember, this is at the level of the $H \to \gamma\gamma$ decay rate! (2×10^{-3})



Upper limits set on Z decays rule out several predictions in the literature!
e.g. Theor. Math. Phys. 170, 39 (2012) (up to 10^{-5} predicted!)

The limit on $\sigma \times \mathcal{B}$ for the $H \to J/\psi\,\gamma$ channel was recently reinterpreted as a constraint on the charm Yukawa coupling (arXiv:1503.00290):





- In the SM the ratio of $y_t/y_c \approx 280$...
- Exploiting measured ATLAS $H \to ZZ^* \to 4\ell$ rate (to cancel Γ_H dependence), obtain a bound of $\kappa_c \leq 220$

Suggests that limit on $H \to J/\psi\,\gamma$ (with world data on $t\bar{t}H$) can exclude universal quark Yukawa couplings!

What could one expect with $3000fb^{-1}$ at $\sqrt{s} = 14$ TeV?

- For a total Higgs cross section of around 57 pb at $\sqrt{s} = 14$ TeV, can expect around 480 $H \to J/\psi\,\gamma$ decays to occur within each experiment
- Accounting for $\mathcal{B}\left(J/\psi \to \mu^+\mu^-\right)$ gives around 29 signal events...
- Assume $A \times \epsilon = 22\%$ from existing result...

Expect around 6 reconstructed $H \to J/\psi\,\gamma \to \mu^+\mu^-\gamma$ events!

- Expected number of events far from the whole story, existing result demonstrates backgrounds can be formidable!
- One would surely have to consider $J/\psi \to e^+e^-$ or even $J/\psi \to$ hadrons along with a combination of ATLAS and CMS!
- Can expect improvements such as multivariate techniques and exploitation of angular distributions, all combined upgraded detectors!

Clearly a challenge, but there are many possibilities to explore!

Will certainly be very complimentary to direct $H \to c\bar{c}$ search!

Conclusion

Exclusive rare decays of the Higgs boson to quarkonia can be used to probe Higgs Yukawa couplings to the charm quark!

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

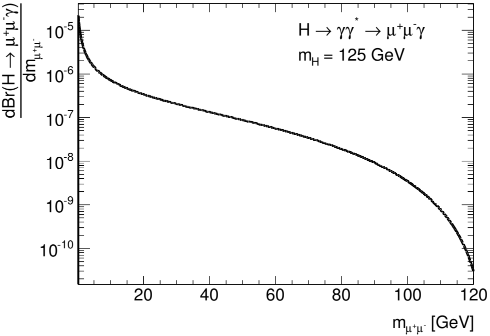
The existing constraints experimentally establish the non-universality of Higgs couplings to quarks

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!

$H \to \gamma^*(Z^*)\gamma \to \mu^+\mu^-\gamma$:

- $H \to \gamma^*\gamma \to \mu^+\mu^-\gamma$ branching fraction around 1.7% relative to $H \to \gamma\gamma$ [1]
- Model decay distribution with calculation from [1] (right plot)
- Contributions from Z^* are small and populate high $m_{\mu^+\mu^-}$ region close to Z pole [2]
- Two orders of magnitude below γ^* for $m_{\mu^+\mu^-} < 12.0$ GeV [2]



- Effective branching fractions (integrate right plot within J/ψ or $\Upsilon(nS)$ mass regions used in analysis) calculated to be $\mathbf{8.3 \times 10^{-7}}$ ($J/\psi\,\gamma$) and $\mathbf{2.9 \times 10^{-6}}$ ($\boldsymbol{\Upsilon(nS)}\,\gamma$)

[1] Phys. Rev. D76 057301 (arXiv:0704.3987)

[2] JHEP 1305 (2013) 061 (arXiv:1303.2230)

Category	Observed (Expected Background)					Signal	
		Mass Range [GeV]				Z	H
	All	80–100		115–135		$\mathcal{B}$ $[10^{-6}]$	$\mathcal{B}$ $[10^{-3}]$
				$J/\psi\,\gamma$			
BU	30	9	(8.9±1.3)	5	(5.0±0.9)	1.29±0.07	1.96±0.24
BC	29	8	(6.0±0.7)	3	(5.5±0.6)	0.63±0.03	1.06±0.13
EU	35	8	(8.7±1.0)	10	(5.8±0.8)	1.37±0.07	1.47±0.18
EC	23	6	(5.6±0.7)	2	(3.0±0.4)	0.99±0.05	0.93±0.12
				$\Upsilon(nS)\,\gamma$			
BU	93	42	(39±6)	16	(12.9±2.0)	1.67±0.09	2.6±0.3
BC	71	32	(27.7±2.4)	5	(9.7±1.2)	0.79±0.04	1.45±0.18
EU	125	49	(47±6)	16	(17.8±2.4)	2.24±0.12	2.5±0.3
EC	85	31	(31±5)	18	(12.3±1.9)	1.55±0.08	1.60±0.20