Exclusive and rare Higgs boson decays

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University of Birmingham
on behalf of the ATLAS and CMS Collaborations

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Higgs-fermion interactions: Yukawa couplings

- Higgs interactions to vector bosons: defined by electroweak symmetry breaking
- Higgs interactions to fermions: ad-hoc hierarchical Yukawa couplings $\propto m_f$

\[ g_{hVV} = \frac{2m_V^2}{v} \]
\[ g_{hff} = \frac{m_f}{v} \]

- Yukawa couplings not imposed by fundamental principle
- Probing fermion mass generation scale→independent task
- Fermion mass generation scale from unitarity bounds:

\[ \Lambda \approx 23, 31, 52, 77, 84 \text{ TeV} \]


- Modified Higgs-fermion couplings in BSM scenarios
  - Concise summary in LHC Higgs Cross-section WG YR4 [arxiv:1610.07922]
  - Effects suppressed $1/\Lambda^2$ or proportional to mixing angles with extra scalars.
Higgs-fermion interactions: The story so far

Progress in Higgs boson properties:
- **mass** known to better than 0.19%
- **bosonic decays** measured to ~10-20%

For 3rd generation fermions:
- **t-quark**: several significant ttH excesses; indirect evidence
- **b-quark**: evidence for $h \rightarrow bb$ at LHC and Tevatron
- **τ-lepton**: $h \rightarrow \tau\tau$ observation established

For 1st/2nd generation fermions, different picture:
- **e/µ**: no evidence yet → established non-universality
- **c-quark**: no direct evidence, loose bounds from $h \rightarrow bb$
- **u/d/s-quarks**: no inclusive searches available

Higgs couplings: margin for undetected/unobserved decays

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Exclusive Decays $h \rightarrow Q\gamma$

- **h→Qγ decays: clean probe** for Higgs-quark couplings for 1st/2nd generation quarks
  - Q is a vector meson or quarkonium state
- **Two contributions**: direct and indirect amplitude
  - **Direct amplitude**: provides sensitivity to Higgs-quark couplings
  - **Indirect amplitude**: insensitive to Higgs-quark couplings; larger than direct amplitude
  - Destructive interference

\[
\Gamma(H \rightarrow J/\psi + \gamma) = \left| (11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c \right|^2 \times 10^{-10} \text{ GeV}
\]

Substantial interest from theory community on branching ratio estimates and feasibility

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Br(h → ργ)</td>
<td>19.0 ± 1.5</td>
<td></td>
<td>16.8 ± 0.8</td>
<td></td>
</tr>
<tr>
<td>Br(h → ωγ)</td>
<td>1.60 ± 0.17</td>
<td></td>
<td>1.48 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>Br(h → φγ)</td>
<td>3.00 ± 0.13</td>
<td></td>
<td>2.31 ± 0.11</td>
<td></td>
</tr>
<tr>
<td>Br(h → J/ψγ)</td>
<td>2.79 ±0.16</td>
<td></td>
<td>2.95 ± 0.17</td>
<td></td>
</tr>
<tr>
<td>Br(h → Υ(1S)γ)</td>
<td>(0.61 ±0.61) \cdot 10^{-3}</td>
<td></td>
<td>(4.61 ±1.76) \cdot 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>Br(h → Υ(2S)γ)</td>
<td>(2.02 ±1.28) \cdot 10^{-3}</td>
<td></td>
<td>(2.34 ±0.76) \cdot 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>Br(h → Υ(3S)γ)</td>
<td>(2.44 ±1.75) \cdot 10^{-3}</td>
<td></td>
<td>(2.13 ±0.76) \cdot 10^{-3}</td>
<td></td>
</tr>
</tbody>
</table>

Z → Qγ decays also interesting

- Experimentally unconstrained
  - LEP: accurately measured b-/c-quark couplings (~1%)
  - Light quark couplings less constrained
- Sensitive to BSM contributions
Dataset and pile-up

Z →μμ candidate with 25 reconstructed vertices from the 2012 run. Only good quality tracks with pT>0.4GeV are shown.
First search, with 2.7 fb⁻¹ at 13 TeV collected in 2015

h→φγ sensitive to strange quark Yukawa coupling
- challenging to access with inclusive h→ss decays!

Looking for new physics through anomalous couplings
- possible in various BSM scenarios, modifies BR(h→φγ)

Z→φγ not directly constrained by existing measurements

<table>
<thead>
<tr>
<th>Branching Fraction Limit (95% CL)</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>B(H → φγ) [10⁻³]</td>
<td>1.5⁺0.7₋0.4</td>
<td>1.4</td>
</tr>
<tr>
<td>B(Z → φγ) [10⁻⁶]</td>
<td>4.4⁺2.0₋1.2</td>
<td>8.3</td>
</tr>
</tbody>
</table>

New results for Summer 2017!
- updated h/Z→φγ
- added h/Z→ργ probing up- and down quark couplings to Higgs boson
**Analysis Strategy**

- **Exclusive decays** → distinct experimental signature
  - Pair of collimated high-pT isolated tracks recoils against high-pT isolated photon

- **Meson decays:**
  - \( \phi \rightarrow K^+K^- \), \( \text{BR}=49\% \)
  - \( \rho \rightarrow \pi^+\pi^- \), \( \text{BR} \approx 100\% \)

- **Small opening angles between decay products**
  - Particularly for \( \phi \rightarrow K^+K^- \)
  - Tracking in dense environments

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**Physics Overview**

- **ATLAS Simulation**
  - \( H \rightarrow \phi \gamma \)
  - Events / 0.01

- **ATLAS Simulation**
  - \( s=13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)
  - Statistical Uncertainty
  - Total Uncertainty
  - Data 2015

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Trigger Strategy

- Two-level trigger system
  - Level-1: Hardware-based
  - HLT: Software-based

Enabled by dedicated trigger items
- Modified $\tau$-lepton algorithms
- Activated: 9/2015 ($\varphi\gamma$) and 5/2016 ($\rho\gamma$)
- Efficiency $\sim$80% w.r.t offline selection

Level-1: Isolated EM object
- Lowest $p_T$ unprescaled EM object

HLT: Collimated/isolated high-$p_T$ track pair recoiling against high-$p_T$ photon
- Isolated di-track (leading $p_T>$15 GeV)
  consistent with $m_{\text{Meson}}$
- Photon ($p_T>$35 GeV)

Efficiency $\sim$80% w.r.t offline selection

ATLAS Trigger Operation
- L1 Group Rates (with overlaps)
  pp Data July 2016, $\sqrt{s}$= 13 TeV

ATLAS Trigger Operation
- HLT Physics Group Rates (with overlaps)
  pp Data July 2016, $\sqrt{s}$= 13 TeV

Triggers:
- Level-1: Isolated EM object
- HLT: Collimated/isolated high-$p_T$ track pair recoiling against high-$p_T$ photon

Efficiency $\sim$80% w.r.t offline selection

Small angular separation of decay products

Higgs
photon
meson
decay products

ATLAS-CONF-2017-061

ATLAS

Data 2015 $\sqrt{s}$ = 13 TeV
offline track $p_T >$ 1 GeV
25 GeV Tau Trigger
- Fast Track Finder (Stage 1)
- Fast Track Finder (Stage 2)
- Precision Tracking (Stage 2)

Efficiency

Offline track $p_T$ [GeV]
Event Selection

**Tracks**
- No particle identification available at momentum range, all tracks considered K/π
- Two opposite charged tracks
- Leading $p_T > 20$ GeV, sub-leading $p_T > 15$ GeV
- di-track consistent to $m_\phi \pm 8$ MeV or $m_\rho \pm 140$ MeV
- track-based isolation
- di-track system must satisfy:
  \[
  p_T^M > \begin{cases} 
  40 \text{ GeV}, & \text{for } m_{M\gamma} \leq 91 \text{ GeV} \\
  40 + 5/34 \times (m_{M\gamma} - 91) \text{ GeV}, \quad \text{for } 91 \text{ GeV} < m_{M\gamma} < 140 \text{ GeV} \\
  47.2 \text{ GeV}, \quad \text{for } m_{M\gamma} \geq 140 \text{ GeV}
  \end{cases}
  \]

**Photons**
- “Tight” identification criteria
- $p_T^\gamma > 35$ GeV
- $|\eta| < 2.47$ and not in $1.37 < |\eta| < 1.52$
- Isolated (calorimeter- and track-based)
- $\Delta\phi(M,\gamma) > \pi/2$
- Total signal acceptance/efficiency
  - $h(Z) \rightarrow \phi \gamma \rightarrow K^+K^-\gamma \sim 17\% \ (8\%)$
  - $h(Z) \rightarrow \rho \gamma \rightarrow \pi^+\pi^-\gamma \sim 10\% \ (0.4\%)$
Efficiency and Resolution

- No categorisation
- Mass resolution ~1.8%
- Signal Model
  - Higgs: double Gauss
  - Z: double Voigt with eff. corr.
- Signal Systematic Uncertainty

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>Yield uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total $H$ cross section</td>
<td>6.3%</td>
</tr>
<tr>
<td>Total $Z$ cross section</td>
<td>2.9%</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>3.4%</td>
</tr>
<tr>
<td>Photon ID efficiency</td>
<td>2.5%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>2%</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>6%</td>
</tr>
</tbody>
</table>

Phys. Rev. Lett. 117, 111802 $m_{K\K\gamma}$ [GeV]
Background Modelling

- Dominated by QCD production $\gamma$+jet and multi-jet events
- Exclusive “peaking” backgrounds (e.g. $h/Z \rightarrow \mu\mu\gamma_{\text{FSR}}$) estimated to be negligible
- Non-parametric data-driven background model; common for ATLAS $Q\gamma$ searches
  - Begin with loose sample of candidates
  - Model kinematic and isolation distributions
  - Generate “pseudo”-background events
  - Apply selection to “pseudo”-candidates

- Background Normalisation: Directly from the data in the Signal Region
- Background Shape Uncertainty: Estimated from modifications to modelling procedure (e.g. shifting/warping input distributions), shape uncertainty included in likelihood as a shape morphing nuisance parameter

ATLAS Preliminary + Data $s = 13$ TeV, 32.3 fb$^{-1}$

Region : VR1

<table>
<thead>
<tr>
<th>ATLAS Preliminary + Data $s = 13$ TeV, 32.3 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region : VR2</td>
</tr>
<tr>
<td>Region : VR3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Meson $p_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\gamma\gamma}$ [GeV]</td>
</tr>
</tbody>
</table>

Data/Model

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Background validation in side-bands

**ATLAS Preliminary**

\[ \bar{\nu}s = 13 \text{ TeV}, \, 35.6 \text{ fb}^{-1} \]

- Data
- Fit Result
- \( \phi \to K^+K^- \)
- Total Background

**Sideband Region**

- Background Model
- Model Shape Uncertainty

**Data/Model**

ATLAS-CONF-2017-057

\[ m_{KK} \text{ [GeV]} \]

\[ m_{\pi\pi} \text{ [GeV]} \]

ATLAS-CONF-2017-057
Results

- **Final discriminant** is $m_{KK\gamma}$ and $m_{\pi\pi\gamma}$
- **No significant signal observed**
- **95% confidence level upper limit**
  - CLs with profile likelihood test statistic
  - Limit on production cross-section times branching ratio
    - $h\rightarrow\phi\gamma < 25.3$ fb
    - $h\rightarrow\rho\gamma < 45.5$ fb

<table>
<thead>
<tr>
<th>Branching Fraction Limit (95% CL)</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(H \rightarrow \phi\gamma)$ [10$^{-4}$]</td>
<td>4.2$^{+1.8}_{-1.2}$</td>
<td>4.8</td>
</tr>
<tr>
<td>$B(Z \rightarrow \phi\gamma)$ [10$^{-6}$]</td>
<td>1.3$^{+0.6}_{-0.4}$</td>
<td>0.9</td>
</tr>
<tr>
<td>$B(H \rightarrow \rho\gamma)$ [10$^{-4}$]</td>
<td>8.4$^{+4.1}_{-2.4}$</td>
<td>8.8</td>
</tr>
<tr>
<td>$B(Z \rightarrow \rho\gamma)$ [10$^{-6}$]</td>
<td>33$^{+13}_{-9}$</td>
<td>25</td>
</tr>
</tbody>
</table>

x3 improvement in expected limits with respect to 2.7/fb result [PRL 117, 111802]
**ATLAS search** for exclusive $h/Z \rightarrow Q\gamma$ decays
- $Q = \psi$ or $Y(nS)$, $n=1,2,3$

**Event Selection**
- single muon and dimuon trigger
- $|\eta_\mu|<2.5$, $p_{T\mu}>20$, $p_{T\mu\mu}>36$ GeV
- $|\eta_\gamma|<2.47$ (excluding $1.37<|\eta_\gamma|<1.52$), $p_{T\gamma}>36$ GeV
- $\mu\mu$ and $\gamma$ isolation,
- $|m_{\mu\mu} - m_{\psi}|<0.15$ (0.20) GeV barrel (endcap) $8<m_{\mu\mu}<12$ GeV
- $|L_{xy}/\sigma_{L_{xy}}|<3$
- $\Delta\phi(\mu\mu,\gamma)>0.5$

**Total efficiency**
- $h(Z) \rightarrow \psi\gamma \rightarrow \mu\mu\gamma\approx 22\%(12\%)$
- $h(Z) \rightarrow Y\gamma \rightarrow \mu\mu\gamma\approx 28\%$ (15%)
Mass Resolution

- Simple event categorisation
- 4 detector-driven categories
  - Muon pseudorapidity ($\times 2$)
  - Photon conversion ($\times 2$)
- Mass resolution ~1.2-1.8%

\[ s = 8 \text{ TeV} \int \text{L} \, \text{dt} = 19.2 \text{ fb}^{-1} \]

**ATLAS**

- Fit
- J/$\psi$
- Background

\[ \sigma = 44 \pm 1 \text{ MeV} \]

\[ m_{\mu^+\mu^-} [\text{GeV}] \]

\[ m_{Y(1S)} \quad m_{Y(2S)} \quad m_{Y(3S)} \]

\[ \text{Phys.Rev.Lett. 114 (2015) 121801} \]

**ATLAS Simulation**

- Barrel Unconverted H$\rightarrow$J/$\psi$ $\gamma$
  - Sigma = 1.50 ± 0.02 GeV
  - Mean = 124.85 ± 0.02 GeV
- EndCap Converted H$\rightarrow$J/$\psi$ $\gamma$
  - Sigma = 2.23 ± 0.04 GeV
  - Mean = 124.89 ± 0.04 GeV

unconverted/barrel

unconverted/end-cap
**Background Modelling**

- **Inclusive quarkonium** with jet "seen" as γ
  - combinatoric background: small contribution
  - contribution from Q+γ production
- **Nonparametric data-driven** background model
  - Similar to h/Z→φγ and h/Z→ργ analyses
- **Y(nS)γ**: also Z→μμγ_{FSR} from side-band fit

<table>
<thead>
<tr>
<th>Category</th>
<th>Observed (Expected Background)</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass Range [GeV]</td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>80–100</td>
<td>115–135</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>H</td>
</tr>
<tr>
<td>J/ψγ</td>
<td>5 (5.0±0.9)</td>
<td>1.29±0.07</td>
</tr>
<tr>
<td>BC</td>
<td>3 (5.5±0.6)</td>
<td>0.63±0.03</td>
</tr>
<tr>
<td>EU</td>
<td>10 (5.8±0.8)</td>
<td>1.37±0.07</td>
</tr>
<tr>
<td>EC</td>
<td>2 (3.0±0.4)</td>
<td>0.99±0.05</td>
</tr>
<tr>
<td>Y(nS)γ</td>
<td>16 (12.9±2.0)</td>
<td>1.67±0.09</td>
</tr>
<tr>
<td>BC</td>
<td>5 (9.7±1.2)</td>
<td>0.79±0.04</td>
</tr>
<tr>
<td>EU</td>
<td>16 (17.8±2.4)</td>
<td>2.24±0.12</td>
</tr>
<tr>
<td>EC</td>
<td>18 (12.3±1.9)</td>
<td>1.55±0.08</td>
</tr>
</tbody>
</table>

**Systematic Uncertainties**

<table>
<thead>
<tr>
<th>Source</th>
<th>Signal Yield Uncertainty</th>
<th>Estimated From</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total H cross section</td>
<td>12%</td>
<td>QCD scale variation and PDF uncertainties</td>
</tr>
<tr>
<td>Total Z cross section</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>Integrated Luminosity</td>
<td>2.8%</td>
<td>Calibration observable and vdM scan uncertainties</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>1.7%</td>
<td></td>
</tr>
<tr>
<td>Photon ID Efficiency</td>
<td>Up to 0.7%</td>
<td></td>
</tr>
<tr>
<td>Muon ID Efficiency</td>
<td>Up to 0.4%</td>
<td></td>
</tr>
<tr>
<td>Photon Energy Scale</td>
<td>0.2%</td>
<td></td>
</tr>
<tr>
<td>Muon Momentum Scale</td>
<td>Negligible</td>
<td></td>
</tr>
</tbody>
</table>
**Multi-observable fit**
- $m_{\mu\mu\gamma}$, $p_{T\mu\mu\gamma}$ for $J/\psi\gamma$
- $m_{\mu\mu\gamma}$, $p_{T\mu\mu\gamma}$, $m_{\mu\mu}$ for $\Upsilon(nS)\gamma$

**No significant excess**
above background observed

95% CL upper limits on decay Branching Ratios:

- \( \mathcal{O}(10^{-3}) \) for Higgs boson (SM production)
- \( \mathcal{O}(10^{-6}) \) for Z boson

Indicate non-universal Higgs boson coupling to quarks

CMS search for $h \to \gamma^* \gamma \to \ell \ell \gamma$ and $h \to J/\psi \gamma$
- used 19.7 fb$^{-1}$ at 8 TeV
- Event Selection [for $h \to J/\psi \gamma$]
  - single muon and a photon, both $p_T > 22$ GeV
  - $|\eta_\mu| < 2.4$, $p_T \mu > 23.4$ GeV, $p_T \mu > 40$ GeV
  - $|\eta_\gamma| < 1.44$, $p_T \gamma > 40$ GeV
  - $\mu \mu$ and $\gamma$ isolation,
  - $2.9 < m_{\mu\mu} < 3.3$ GeV
  - $\Delta R(\mu, \gamma) > 1$ for each muon
  - muon impact parameter requirements

- Source
<table>
<thead>
<tr>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity (ref. [37])</td>
</tr>
<tr>
<td>Theoretical uncertainties:</td>
</tr>
<tr>
<td>PDF</td>
</tr>
<tr>
<td>Scale</td>
</tr>
<tr>
<td>$H \to \gamma^* \gamma \to \ell \ell \gamma$ branching fraction</td>
</tr>
<tr>
<td>Experimental uncertainties:</td>
</tr>
<tr>
<td>Pileup reweighting</td>
</tr>
<tr>
<td>Trigger efficiency, $\mu$ (e) channel</td>
</tr>
<tr>
<td>Muon reconstruction efficiency</td>
</tr>
<tr>
<td>Electron reconstruction efficiency</td>
</tr>
<tr>
<td>Photon reconstruction efficiency</td>
</tr>
<tr>
<td>$m_{\ell \ell \gamma}$ scale, $\mu$ (e) channel</td>
</tr>
<tr>
<td>$m_{\ell \ell \gamma}$ resolution, $\mu$ (e) channel</td>
</tr>
</tbody>
</table>

- CMS Preliminary

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$h \to \gamma^* \gamma \to ll\gamma$ and $h \to J/\psi \gamma$

- $h \to J/\psi \gamma$: fit over the 110-150 GeV mass range
  - Background: 2$^{nd}$ degree polynomial
  - Signal: Crystal Ball + Gaussian
- **No excess** above background observed
- 95% CL upper limit $H \to \gamma^* \gamma \to ll\gamma$: $6.7(5.9) \times$SM
- 95% CL upper limit BR($H \to J/\psi \gamma$) < $1.5 \times 10^{-3}$
  - 540 times the SM prediction

### Table

<table>
<thead>
<tr>
<th>Sample</th>
<th>Signal events before selection $m_H = 125$ GeV</th>
<th>Signal events after selection $m_H = 125$ GeV</th>
<th>Number of events in data $120 &lt; m_{\mu\mu} &lt; 130$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\mu\gamma$</td>
<td>13.9</td>
<td>3.3</td>
<td>151</td>
</tr>
<tr>
<td>$ee\gamma$</td>
<td>25.8</td>
<td>1.9</td>
<td>65</td>
</tr>
<tr>
<td>($J/\psi \to \mu\mu)\gamma$</td>
<td>0.065($J/\psi$) + 0.32 (non-res.)</td>
<td>0.014($J/\psi$) + 0.078 (non-res.)</td>
<td>12</td>
</tr>
</tbody>
</table>

### Graphs

- **CMS**
  - **Data**
  - **Background model**
    - $\pm 1 \sigma$
    - $\pm 2 \sigma$
  - **500x SM $H \to (J/\psi)\gamma \to \mu\mu\gamma$**
    - background-only fit to the data

- **95% CL limit on $\sigma_{SM}$**
  - **Observed**
  - **Expected ± 1σ**
  - **Expected ± 2σ**
  - **10x SM $H \to \gamma^*\gamma \to \mu\mu\gamma$**
  - **ee\gamma**

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Search for $h \rightarrow Z\gamma$

- Modified BR($H \rightarrow Z\gamma$) predicted in several BSM scenarios
  - $H \rightarrow Z\gamma$ proceeds by loop diagrams similar to $H \rightarrow \gamma\gamma$
  - SM BR $\approx 1.5 \times 10^{-3}$ ($m_H = 125$ GeV)
- Signal extracted by signal+background fit to $m_{Z\gamma}$
  - Mass resolution essential
  - $M_Z$ constraint improves $m_{\mu\mu\gamma}$ ($m_{ee\gamma}$) resolution by 7(13)%
  - FSR recovery in $\mu\mu\gamma$ channel 3% improvement
- 6 categories are used to enhance sensitivity

**Diagrams:**

- VBF BDT
- $p_T^\gamma / m_{Z\gamma}$
- Lepton flavour
- $p_T^l$
- $N_{jets}$
- ATLAS Simulation Preliminary
  - $\sqrt{s} = 13$ TeV
  - $pp \rightarrow H \rightarrow Z\gamma$
  - $m_H = 125$ GeV
  - $p_T^{\gamma}$
  - MC - Fit
  - ATLAS Preliminary
  - $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
  - $N_{jets} \geq 2, 115$ GeV $< m_{Z\gamma} < 170$ GeV
  - VBF $m_H = 125$ GeV
  - ggF $m_H = 125$ GeV

**Figures:**

- 1/N dN/d$m_{Z\gamma}$ [GeV$^{-1}$]
- 1/N dN/d m$_{Z\gamma}$ [GeV$^{-1}$]
- 1/N dN/d (BDT output)
Search for \( h \to Z\gamma \)

- Fit over the 115-150 GeV mass range.
  - Signal Modelled by double sided Crystal-Ball
  - Background: Bernstein polynomials,
    - Shape studied on \( Z+\gamma \) (fast) simulation
    - Parameters extracted from fit to data
- Background composition (\( Z+jets, Z+\gamma \)) is estimated by data-driven method using looser isolation requirements
  - \( Z+jets<20\% \) in all categories
- 95\% CL upper limit 6.6(4.4)xSM observed(expected)
- Run 1 results:
  - ATLAS 11(9)xSM (\( m_H=125.5 \) GeV) [Phys. Lett. B 732C (2014) 8-27]
h/\rightarrow Z\gamma$: in the future

- HL-LHC is a Higgs boson factory
  - \(\mathcal{O}(200M)\) Higgs bosons produced
- HL-LHC projections for \(h \rightarrow Z\gamma\)
  - Significance 3.9\(\sigma\) \(\delta\mu/\mu \sim 25\) (30%)
  - [ATL-PHYS-PUB-2014-006]
- HL-LHC projections for \(h/\rightarrow J/\psi\gamma\)
  - Simple and, relatively, clean final state
  - Small branching ratio, few events expected
  - At SM sensitivity \(h \rightarrow \mu\mu_{\text{FSR}}\)
    - contribution \(\sim 3\times h \rightarrow J/\psi\gamma\) and \((Z \rightarrow \mu\mu_{\text{FSR}}\) for Z)
- Sensitive to “anomalous” \(h \rightarrow \gamma\gamma\); use ratio
- Future colliders: leap in Higgs production
  - FCC-hh 100 TeV 20/ab: \(\mathcal{O}(15G)\) Higgs bosons

### ATLAS Simulation

<table>
<thead>
<tr>
<th>(E_\text{T}) (TeV)</th>
<th>(m_{h/\gamma}) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>14</td>
<td>50</td>
</tr>
</tbody>
</table>

**Preliminary**

- Data (Bkg. Only)
- S+B Fit
- Background
- H Signal \(\times 100\)
- Z Signal \(\times 10\)

### ATLAS-Phys-PUB-2015-043

<table>
<thead>
<tr>
<th>Expected branching ratio limit at 95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B (H \rightarrow J/\psi\gamma) [10^{-6}])</td>
</tr>
<tr>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>(300 \text{ fb}^{-1})</td>
</tr>
<tr>
<td>Cut Based: (185^{+81}_{-52})</td>
</tr>
<tr>
<td>(55^{+24}_{-15})</td>
</tr>
</tbody>
</table>

**Standard Model expectation**

| \(B (H \rightarrow J/\psi\gamma) [10^{-6}]\) | \(B (Z \rightarrow J/\psi\gamma) [10^{-7}]\) |
|-------------------------------------------|
| \(2.9 \pm 0.2\)                           | \(0.80 \pm 0.05\)                           |
HL-LHC upgrade proposed

Goal to collect 3000 fb^{-1} by 2035

Central feature of ATLAS upgrade programme: new, all silicon tracking system

Higgs boson-fermion interactions is the least explored (and motivated) part of the SM → Particularly 1^{st}/2^{nd} generation.

New Physics could be hiding here!

A number of complementary approaches appear currently in the literature: exclusive decays, inclusive (e.g. charm tagging), Higgs boson kinematic properties (somewhat less direct), etc.

New field of study in Higgs sector; novel ideas available to elucidate this corner of the SM!
Additional Slides
Background: $\phi\gamma$

- Dominated by QCD production $\gamma + \text{jet}$ and multi-jet events
- Exclusive “peaking” backgrounds (e.g. $h/Z \rightarrow \mu\mu\gamma_{\text{FSR}}$) estimated to be negligible
- Nonparametric data-driven model; same procedure as in $h/Z \rightarrow J/\psi\gamma$

![Graphs showing data and model for $pTM$, $\gamma$-isolation, and $M$-isolation](Image)
h/Z → J/ψγ and h/Z → Y(nS)γ: Mass Resolution


mass resolution
~1.2-1.8%
h/Z → J/ψγ and h/Z → Y(nS)γ: Mass Resolution

ATLAS

$h/Z \rightarrow J/\psi \gamma$ and $h/Z \rightarrow Y(ns)\gamma$