Approval Talk [HIG-23-005]
"Search for rare decays of the Higgs boson into a photon and a ρ^0, ϕ or K^{*0} meson"

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Documentation

- Collaboration of **MIT** and **Torino** groups, targeting different categories.
- CADI HIG-23-005
- ARC: Anadi Canepa (chair), Stefan Spanier, Jian Wang, Angelo Giacomo Zecchinelli
- CCLE: Christoph Maria Ernst Paus
- Three analysis notes (two separate + one combined):
  AN-22-004 (MIT, v9), **AN-22-067** (Torino, v10), and **AN-23-004** (combined, v7)
- Q&A with ARC, L3, and L2 conveners: Twiki Q&A

Motivations

- SM prediction of branching ratios of $H \to \phi\gamma$ or $\rho\gamma$ within reasonable reach (??)
- ATLAS upper limit at 95% CL is $\mathcal{O}(10^{-4})$ to $\mathcal{O}(10^{-3})$.
- K_0^* channel added as an extension of ditrack + gamma final state analyses.

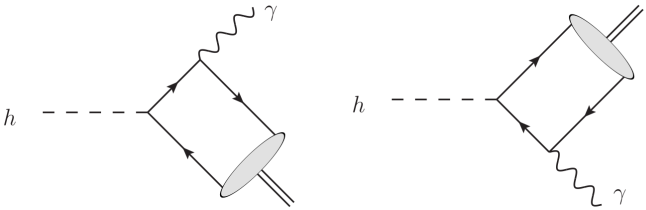
Channel	Coupling	SM $\mathcal{BR}(H \to M\gamma)$	Limits on $\mathcal{BR}$	Notes
$H \to \phi\gamma$	s	$(1.68 \pm 0.8) \times 10^{-5}$ [1]	Exp. $4.2^{+1.8}_{-1.2} \times 10^{-4}$ Obs. 5.0×10^{-4} [2]	ATLAS Run 2, $35.6\ \mathrm{fb}^{-1}$ $\phi\gamma \to K^+K^-\gamma$
$H \to \rho\gamma$	u, d	$(2.31 \pm 0.11) \times 10^{-6}$ [1]	Exp. $10.0^{+4.9}_{-2.8} \times 10^{-4}$ Obs. 10.4×10^{-4} [2]	ATLAS Run 2, $35.6\ \mathrm{fb}^{-1}$ $\rho\gamma \to \pi^+\pi^-\gamma$
$H \to K_0^*\gamma$	$d\&s$ (flavor-changing)	(Only available for $H \to d\bar{s} + \bar{d}s$) 1.19×10^{-11} [3]	Exp. $3.7^{+1.5}_{-1.0} \times 10^{-4}$ Obs. 2.2×10^{-4} [4]	ATLAS Run 2, $134\ \mathrm{fb}^{-1}$ $K_0^*\gamma \to K^\pm\pi^\mp\gamma$

Motivations

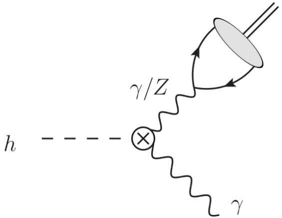
$H \to M\gamma$ [1]

- **Direct contribution**. The Higgs couples via Yukawa coupling to the quarks, one of which radiates a photon.
- **Indirect contribution**. The off-shell γ^* or Z^* produced in $H \to \gamma\gamma^*, \gamma Z^*$ *fragments* into a meson.

Direct and indirect contributions interfere destructively. Due to light quark masses, direct contribution is smaller than indirect. Direct contribution is sensitive to deviation from SM Higgs couplings. Branching ratios are $\mathcal{O}(10^{-5}\text{–}10^{-6})$.



(a) Direct contributions via Yukawa coupling to the light quarks.



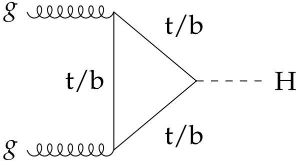
(b) Indirect contribution via a virtual photon or Z boson.

Figure 1: Leading order Feynman diagrams to the $H \to M\gamma$ processes. Image taken from Fig. 2 of [1].

Strategy

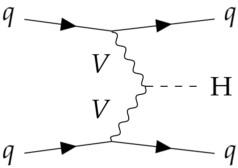
- **Final states**
  1. High energy **photon**
  2. High energy **ditrack** from meson
  3. FIX! Look for photon-meson inv. mass

- **Higgs Production Categories**



ggH

- No e/μ
- Veto events with $|\Delta\eta_{JJ}| > 3$

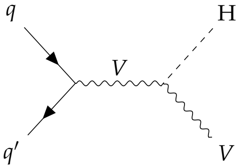


VBF high p_T^γ

- Barrel photon $p_T^\gamma > 75$ GeV
- No e/μ
- $|\Delta\eta_{JJ}| > 3$, $M_{JJ} > 400$ GeV

VBF low p_T^γ

- $40 < p_T^\gamma < 75$ GeV
- No e/μ
- $|\Delta\eta_{JJ}| > 3$, $M_{JJ} > 300$ GeV



VH ($\mathbf{Z_{ll}H, W_{l\nu}H}$)

- At least one l, ν
- Also included is $\mathbf{t\bar{t}H}$, accounting for $\sim 30\%$.

Triggers

- What to discuss?
- FIX! Trigger efficiency — how to measure (slide with plots)
  - $Z \to \mu^+\mu^-$ events data/MC
  - Measure photon leg & tau leg
  - Figs. 30 & 38

	ggH	**High-$\mathbf{p_T^\gamma}$ VBF**	**Low-$\mathbf{p_T^\gamma}$ VBF**	**VH**
Triggers	tau-like	VBF-like	tau-like	single/di-muon single/di-electron muon+gamma
Luminosity (fb^{-1})	39.50 (2018)	28.2 (2016) 7.7 (2017) 60 (2018)	39.50 (2018)	138 (2016–2018)

Simulated Samples

$$\phi(1020) \to K^+K^- \quad (\mathrm{BR} \sim 49\%)$$
$$\rho(770) \to \pi^+\pi^- \quad (\mathrm{BR} \sim 100\%)$$
$$K_0^*(892) \to K^\pm\pi^\mp \quad (\mathrm{BR} \sim 100\%)$$

FIX! Polarization reweighting (new slide if plot)

Event Selection

- **Photon selection**

	ggH	High-p_T^γ VBF	Low-p_T^γ VBF	VH
p_T^γ [GeV]	> 38	> 75	$38 < p_T^\gamma < 75$	> 40
$\lvert\eta^\gamma\rvert$	< 2.1	< 1.4	< 2.1	< 2.5
γ-ID signal eff.	80%	90%	80%	90%

Table 1: Photon selection criteria across different production categories.

- γ-ID signal eff. $=$ MVA-based selection ID [5]
- p_T^γ cut based on trigger
- Where is the information about di-photon veto for ggH? FIX! ggH & VH .
- ggH/VBF: conversion veto, VH: pixel veto.
- Highest-p_T^γ photon chosen as candidate.

Event Selection

- **Ditrack reconstruction**
  - Track selection
    1. Originate from PV
    2. Pass "high purity" criteria
  - Meson definition ($M = \phi, \rho^0, K_0^*$)
    1. Pair of oppositely charged tracks
    2. $p_T > 5$ GeV, $|\eta| < 2.5$
    3. At least one track $p_T > 20$ GeV
  - Invariant mass
    1. $\rho^0 : 0.62 < m_{\pi\pi} < 0.92$ GeV
       $\phi : 1.008 < m_{KK} < 1.032$ GeV
       $K_0^* : 0.84 < m_{K\pi} < 0.94$ GeV
    2. $m_{K\pi}$ closest to $m_{K_0^*}$ selected
    3. Reject events where m_{KK} consistent with m_ϕ and have higher p_T, vice versa.

Applies to all production categories.

Event Selection

FIX! mass sidebands

- **Di-track system**

  Define the relative **charged isolation** of the leading meson candidate,

$$I^{\mathrm{trk}}(M) = \frac{p_T^M}{p_T^M + \sum_{trk} |p_T^{trk}|},$$

and the **neutral isolation** as

$$I^{\mathrm{neu}}(M) = \frac{p_T^M}{p_T^M + \sum_{neu} |p_T^{neu}|}.$$

$\sum_{trk/neu} |p_T^{trk/neu}|$: sum of charged/neutral track p_T within $\Delta R = 0.3$ of meson candidate.

	ggH	High-$\mathbf{p_T^\gamma}$ VBF	Low-$\mathbf{p_T^\gamma}$ VBF	VH
p_T^M [GeV]	> 38	> 40	> 40	> 40
I_M^{trk}	> 0.9	> 0.9	> 0.9	> 0.8
I_M^{neu}	> 0.8	-	-	-

Table 2: Di-track system criteria across different production categories.

- Highest-p_T meson chosen as candidate.

- **Event tagging**

	ggH	High-p_T^{γ} VBF	Low-p_T^{γ} VBF	VH
Event tagging	Meson candidate within a jet with $p_T^{\mathrm{j}} > 40$ GeV, tracks with $\Delta R < 0.07$	2 jets with $p_T^{j} > 40$ GeV, $m_{jj} > 400$ GeV, $\eta_{jj} > 3$	2 jets with $p_T^{j} > 30, 20$ GeV, $m_{jj} > 300$ GeV, $\eta_{jj} > 3$	1 selected and isolated e/μ or 2 selected e/μ compatible with m_Z

Table 3: Event tagging selection criteria across different production categories.

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Event Selection

Summary of Event Selection

FIX! Take the version of the paper

	Common selections			
M selection	"high-purity" tracks, opposite sign $\|\eta^{\mathrm{trk}}\| < 2.5$, $p_T^{\mathrm{trk1}} > 20$ GeV, $p_T^{\mathrm{trk1}} > 5$ GeV, $\|\eta^M\| < 2.1$ $0.62 < m_{\pi\pi} < 0.92$ GeV, $1.008 < m_{KK} < 1.032$ GeV, $0.84 < m_{K\pi} < 0.94$ GeV			
	ggH	**High-$\mathbf{p_T^\gamma}$ VBF**	**Low-$\mathbf{p_T^\gamma}$ VBF**	**VH**
p_T^γ [GeV]	> 38	> 75	$40 < p_T^\gamma < 75$	> 40
$\|\eta^\gamma\|$	< 2.1	< 1.4	< 2.1	< 2.5
γ-ID signal eff.	80%	90%	80% (endcap), 90% (barrel)	90%
p_T^M [GeV]	> 38	> 40	> 40	> 40
I_M^{trk}	> 0.9	> 0.9	> 0.9	> 0.8
I_M^{neu}	> 0.8	-	-	-
Event tagging	Meson candidate within a jet with $p_T^{\mathrm{j}} > 40$ GeV, tracks with $\Delta R < 0.07$	2 jets with $p_T^j > 40$ GeV, $m_{jj} > 400$ GeV, $\eta_{jj} > 3$	2 jets with $p_T^j > 30, 20$ GeV, $m_{jj} > 300$ GeV, $\eta_{jj} > 3$	1 selected and isolated e/μ or 2 selected e/μ compatible with m_Z

Table 4: FIX! Taken from paper Summary of event selection before MVA.

MC/Data Background Comparison

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Event Selection (MVA)

- **Multivariate Analysis (MVA)**
  - BDT classifiers based on ROOT TMVA [6] for **ggH**, **low-$\mathbf{p_T^\gamma}$ VBF**, and **high-$\mathbf{p_T^\gamma}$ VBF**.
  - Training and validation samples defined by **meson mass SR & sidebands**.
  - Signal & Background events weighted by $1/(\sigma_M/M)$, where

$$\frac{\sigma_M}{M} = \sqrt{\left(\frac{\sigma_m}{m}\right)^2_{\mathrm{meson}} + \left(\frac{\sigma_E}{E}\right)^2_{\gamma}}$$

Event Selection (MVA)

- **Multivariate Analysis (MVA)**
  - Input variables used for ggH and VBF categories.

	ggH	**High-$\mathbf{p_T^{\gamma}}$ VBF**	**Low-$\mathbf{p_T^{\gamma}}$ VBF**
Kinematics	p_T^{γ} p_T^{M} η_M	$p_T^{M\gamma}$ p_T^{γ} $p_T^{M}/m_{M\gamma}$	$p_T^{M\gamma}$ p_T^{γ} $p_T^{M}/m_{M\gamma}$
Meson Isolation	$I^{\mathrm{trk}}(M)$	$I^{\mathrm{trk}}(M)$	$I^{\mathrm{trk}}(M)$
Jet-related		M_{JJ} $\Delta\phi_{JJ}$ FIX! zepVar	M_{JJ} $\Delta\phi_{JJ}$ FIX! zepVar

- **Multivariate Analysis (MVA): ggH category**
  - Input variables
  - SR & CR
  - Results.
  - MVAdisc
  - cat0 & cat1

Event Selection (MVA)

- **Multivariate Analysis (MVA): High-p_T^γ VBF category**
  - Input variables
  - SR & CR
  - Results.
  - MVAdisc

- **Multivariate Analysis (MVA): Low-p_T^γ VBF category**
  - Input variables
  - SR & CR
  - Results.
  - MVAdisc

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Systematic Uncertainties

FIX! Note: only for signal

1. **Integrated Luminosity**
2. **Total inelastic cross section** correcting PU profile in simulation to data.
3. **Trigger efficiencies**.
4. **Photon ID efficiencies**. Derived from $Z \to e^+e^-$.
5. **Tracking efficiency**.
6. **Muon/Electron ID**.
7. **Meson Charged/Neutral Isolation Efficiencies**.
8. **JEC & JES**

Theoretical:

9. **QCD renormalization and factorization**.
10. **PDF &** α_S.
11. **Parton shower modeling** from renormalization of QCD-induced ISR and FSR in `PYTHIA`.

Signal modeling

- $\mathbf{m_{M\gamma}}$. Distribution of the **reconstructed Higgs boson mass**.
- Analytic function: **two-tailed Crystal Ball(TTCB)**.

$$\mathrm{TTCB}(t) = \begin{cases} e^{-t^2/2}, & \text{for} \quad -\alpha_L < t < \alpha_R \\ (\frac{n_L}{|\alpha_L|})^{n_L} e^{-\alpha_L^2/2} (\frac{n_L}{|\alpha_L|} - |\alpha_L| - t)^{-n_L}, & \text{for} \quad t \leq -\alpha_L \\ (\frac{n_R}{|\alpha_R|})^{n_R} e^{-\alpha_R^2/2} (\frac{n_R}{|\alpha_R|} - |\alpha_R| + t)^{-n_R}, & \text{for} \quad t \geq \alpha_L \end{cases}$$

- Fitted via unbinned likelihood to simulated signal events.

Background modeling

- Analytic functions: **Chebychev** polynomials (main), **Bernstein** polynomials and **exponential** series (determination of shape uncertainties).
- Fitting region defined as $m_{M\gamma}$ sidebands.
  - ggH category: $110 < m_{M\gamma} < 120$ GeV & $130 < m_{M\gamma} < 160$ GeV.
  - VBF categories (high & low p_T^{γ}): $100 < m_{M\gamma} < 120$ GeV & $130 < m_{M\gamma} < 170$ GeV.
  - VH category: $100 < m_{M\gamma} < 120$ GeV & $130 < m_{M\gamma} < 150$ GeV.
- Degree of polynomial determined with **F-test**.
- **Bias test**.

Signal & Background Post-fit Distributions

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Results

- **Upper limits** on $\mathcal{B}(H \to \rho^0\gamma)$, $\mathcal{B}(H \to \phi\gamma)$, and $\mathcal{B}(H \to K_0^*\gamma)$ set at 95% CL.
- CLs profile-likelihood ratio used as test-statistics, with the asymptotic approximation.
- Systematic uncertainties treated as nuisance parameters.

Results

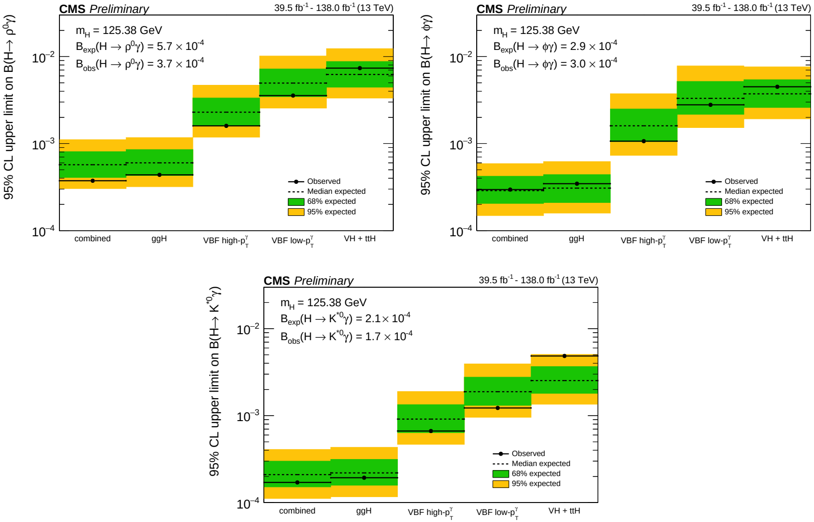

Figure 2: Expected and observed upper limits on $\mathcal{B}(H \to \rho^0\gamma)$ (top left), $\mathcal{B}(H \to \phi\gamma)$ (top right), and $\mathcal{B}(H \to K_0^*\gamma)$ (bottom) split by analysis categories and combined. Green and yellow bands correspond to 1 and 2σ confidence intervals in the expected upper limits.

Results

	U.L. $\mathcal{B}(H \to \rho^0\gamma)$		U.L. $\mathcal{B}(H \to \phi\gamma)$		U.L. $\mathcal{B}(H \to K_0^*\gamma)$	
category	Exp.(10^{-4})	Obs.(10^{-4})	Exp.(10^{-4})	Obs.(10^{-4})	Exp.(10^{-4})	Obs.(10^{-4})
VH	$62.3^{+25.6}_{-17.9}$	73.7	$37.3^{+16.9}_{-11.3}$	45.0	$25.3^{+11.4}_{-7.3}$	48.5
low-p_T^γ VBF	$49.6^{+22.5}_{-15.0}$	35.6	$33.1^{+18.7}_{-11.5}$	27.9	$18.8^{+8.90}_{-5.7}$	12.3
high-p_T^γ VBF	$22.9^{+10.5}_{-6.9}$	16.0	$16.0^{+9.0}_{-5.5}$	10.7	$9.13^{+4.25}_{-2.75}$	6.66
ggH	$6.01^{+2.53}_{-1.72}$	4.37	$3.08^{+1.33}_{-0.98}$	3.46	$2.20^{+0.94}_{-0.62}$	1.93
combined	$5.71^{+2.37}_{-1.63}$	**3.74**	$2.88^{+1.33}_{-0.83}$	**2.97**	$2.10^{+0.90}_{-0.58}$	**1.71**

Table 5: Exclusion limits at 95% CL on the branching fractions of the H boson decays. Observed and median expected limits with the upper and lower bounds in the expected 68% CL intervals are reported.

Bibliography

[1] M. König and M. Neubert, "*Exclusive radiative Higgs decays as probes of light-quark Yukawa couplings*", *Journal of High Energy Physics* **2015** (2015) .

[2] ATLAS collaboration, "*Erratum to: Search for exclusive Higgs and Z boson decays to $\phi\gamma$ and $\rho\gamma$ with the ATLAS detector*", *Journal of High Energy Physics* **2023** (2023) .

[3] J.I. Aranda, G. González-Estrada, J. Montaño et al., "*Revisiting the rare $H \to q_i q_j$ decays in the standard model*", *Journal of Physics G: Nuclear and Particle Physics* **47** (2020) 125001.

[4] ATLAS collaboration, "*Search for exclusive Higgs and Z boson decays to $\omega\gamma$ and Higgs boson decays to $K_0^*\gamma$ with the ATLAS detector*", *Physics Letters B* **847** (2023) 138292.

[5] CMS collaboration, "*Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC*", *Journal of Instrumentation* **16** (2021) P05014.

[6] A. Hoecker, P. Speckmayer, J. Stelzer et al., "*TMVA - Toolkit for Multivariate Data Analysis*", 2009.