Search for rare radiative decays of the Higgs boson with the CMS experiment

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Higgs rare decays

Are the properties of the Higgs boson exactly as foreseen by the Standard Model?

A way to test it ➔ **Higgs boson rare decays**

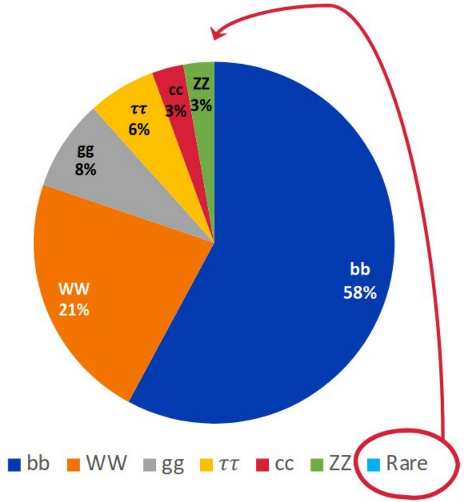
- Rare decays: experimentally challenging
  - Small branching ratios
  - Low signal/background

- Higgs boson production at LHC:
  - Small cross section (~ 50 pb)
  - Different production modes with different signatures

- This talk: search for rare decays of the Higgs boson into a light meson and a photon
  - **H ➔ Mγ**, where M = ρ, ϕ, K^{*0}
    - H couplings to **light quarks**

Decay channel	Branching fraction (%)
bb	57.63 ±0.70
WW	22.00 ±0.33
gg	8.15 ±0.42
ττ	6.21 ±0.09
cc	2.86 ±0.09
ZZ	2.71 ±0.04
γγ	0.227 ±0.005
Zγ	0.157 ±0.009
ss	0.025 ±0.001
μμ	0.0216 ±0.0004

Nature 607 (2022) 60



Meson	Composition	Mass (GeV)
ρ	u, d	0.776
ϕ	s	1.020
K^{*0}	d, s	0.892

Motivations

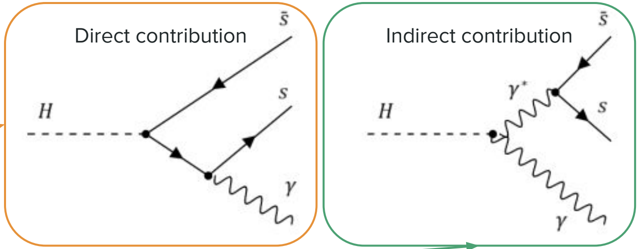
- Higgs boson **couplings with u, d, s quarks** still to be confirmed experimentally

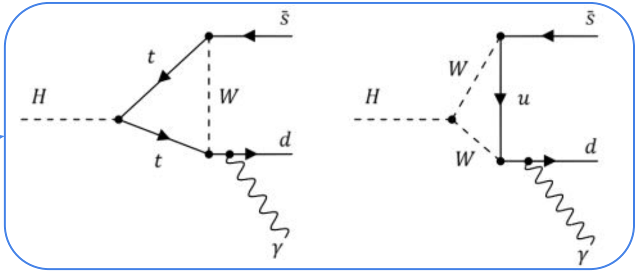
- Theoretical calculation of branching ratios for $\rho\gamma$ and $\phi\gamma$ channels: **QCD factorization approach** and **LCDA** (Light Cone Distribution Amplitudes) to take into account bound state effects of the hadrons
  - $\mathcal{B}(H \to \rho\gamma) = (1.68 \pm 0.08) \times 10^{-5}$ [1]
  - $\mathcal{B}(H \to \phi\gamma) = (2.31 \pm 0.08) \times 10^{-6}$ [1]
- **EFT + LCDA** framework for $K^{*0}\gamma$ channel:
  - $\mathcal{B}(H \to K^{*0}\gamma) = 1.0 \times 10^{-19}$ [2]

- **Flavor-conserving probes**
  - ϕ: s quark coupling

    ρ: u and d quark coupling
- **Flavor-changing probes**
  - K^{*0} : flavor-changing s and d quarks via weak interaction

- **ATLAS** upper limit at 95% CL on observed BR:
  - $\mathcal{B}(H \to \rho\gamma) < 10.4 \times 10^{-4}$ [3]
  - $\mathcal{B}(H \to \phi\gamma) < 5.0 \times 10^{-4}$ [3]
  - $\mathcal{B}(H \to K^{*0}\gamma) < 2.2 \times 10^{-4}$ [4]





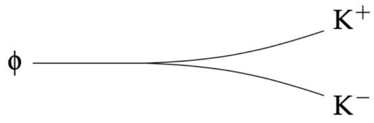
Phys. Lett. B 862 (2025) 139296

[1] J. High Energ. Phys. 2016, 37 (2016)
[2] J. Phys. G: Nucl. Part. Phys. 52 053001
[3] J. High Energ. Phys. 2018, 127 (2018)
[4] Phys. Lett. B. 847 (2023) 138292

Strategy

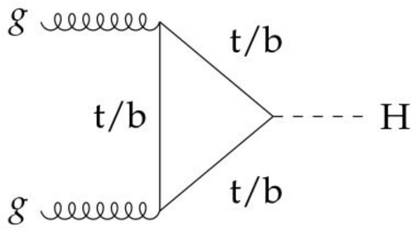
Search for a **photon** and a **meson** compatible with a Higgs boson decay

- **Final state**
  - **High energy photon**
  - **High energy di-track system from meson**
    - $\phi \rightarrow K^+K^-$ (49%)
    - $\rho \rightarrow \pi^+\pi^-$ (100%)
    - $K^{*0} \rightarrow K^{\pm}\pi^{\mp}$ (67%)

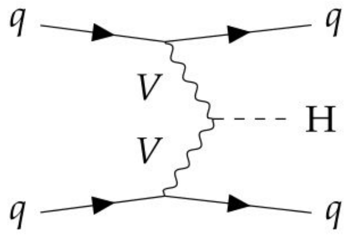


- Different **Higgs production modes** targeted: gluon fusion, vector boson fusion, associated production with a vector boson

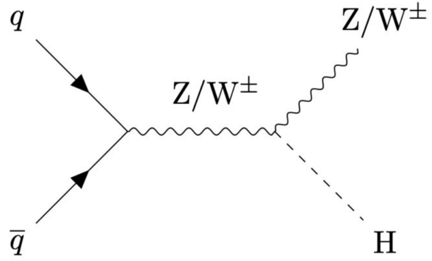
ggH



VBF



VH



Dataset & simulated samples

Data RunII dataset, 13 TeV, (40 – 138) fb^{-1}

- Data samples depending on **High-Level Triggers** considered (software online selection, up to 10 kHz rate of events)

Target signal	**HLT**	**Trigger selection**	**Luminosity (fb^{-1})**
VH	single/di muon single/di electron	• at least one **isolated e/μ** • p^{ℓ}_{T} **threshold** between 24 and 35 GeV (depending on ℓ and data-taking period)	138
VBF high-p^{γ}_{T}	VBF-like	• p^{γ}_{T} **> 75 GeV** • **di-jet pair** with $\|\Delta\eta_{jj}\| > 3$ and $m_{jj} > 400$ GeV	28.2 (2016) 7.7 (2017) 60.0 (2018)
VBF low-p^{γ}_{T}	tau-like	• same trigger of ggH category (to recover VBF events with p^{γ}_{T} **< 75 GeV**)	39.5 (2018 only)
ggH	tau-like	• p^{γ}_{T} **> 35 GeV** • tau-like jet p^{j}_{T} **> 35 GeV** (jet signature similar to isolated di-track system)	39.5 (2018 only)

MC signal ~2 millions of events centrally produced per decay channel

- **Powheg** for Higgs production, **Pythia8** for Higgs decays

Event reconstruction

Reconstruction via a **single photon** + **2 decay products** compatible with the decay of a ρ, ϕ, or K^{*0}

- **High-energy photon selection**
  - requirements on several variables, most relevant:
    - p_T
    - η
- **Meson selection** (focus in next slide)
  - ρ, ϕ, K^{*0} decay respectively to $\pi^+\pi^-$, K^+K^-, $K^\pm\pi^\mp$
    - **hadron decay**
- Further selection based on **MVA**, using a **BDT**
  - **2 categories** of classification, to improve the statistics

		Common selections		
M selection	2 "high-purity" tracks, opposite charge			
	$\lvert\eta^{trk}\rvert < 2.5$, $p_T^{trk1} > 20\,GeV$, $p_T^{trk2} > 5\,GeV$, $\lvert\eta^M\rvert < 2.1$			
	$0.62 < m_{\pi\pi} < 0.92\,GeV$ (ρ^0) / $1.008 < m_{KK} < 1.032\,GeV$ (ϕ) / $0.84 < m_{K\pi} < 0.94\,GeV$ (K^{*0})			
Category	ggH	VBF High-p_T^γ	VBF Low-p_T^γ	VH
$\mathcal{L}$	$39.5\,fb^{-1}$	$86.9\,fb^{-1}$	$39.5\,fb^{-1}$	$138\,fb^{-1}$
Trigger	γ + jet with τ-ID	High-p_T γ + VBF-like jets	γ + jet with τ-ID	Double or single e/μ
p_T^γ (GeV)	>38	>75	>38 and <75	>40
$\lvert\eta^\gamma\rvert$	<2.5	<1.4	<2.1	<2.5
γ-ID (eff.)	80%	90%	80%	90%
p_T^M (GeV)	>38	>30	>38	>40
$I^{ch}(M)$	>0.9	>0.9	>0.9	>0.8
$I^{neu}(M)$	>0.8	—	—	—
Event tagging	Meson candidate within a jet with $p_T^j > 40\,GeV$, tracks with $\Delta R < 0.07$	2 jets with $p_T^j > 40\,GeV$ $m_{jj} > 400\,GeV$ $\lvert\Delta\eta_{jj}\rvert > 3$	2 jets with $p_T^j > 30/20\,GeV$ $m_{jj} > 300\,GeV$ $\lvert\Delta\eta_{jj}\rvert > 3$	1 selected and isolated e/μ or 2 selected e/μ $\lvert M_{\ell\ell} - M_Z\rvert < 15\,GeV$
Veto	e/μ, VBF-like jets	e/μ	e/μ	—
		BDT categories		
cat0	BDT > 0.55	BDT > 0.7	BDT > 0.7	—
cat1	−0.4 < BDT < 0.55	−0.6 < BDT < 0.7	−0.6 < BDT < 0.7	—

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Meson selection

- First, select **jet**
  - Used for identifying di-track system candidates
  - Tracks from meson decay in a narrow cone ➔ classified as a jet
- Then, select the **di-track system**
  - Pair of **oppositely charged tracks**
  - Requirements on several variables (p_T, ΔR, ecc)
  - Must fall in a range compatible with **rest mass of the meson**
  - Define **isolation** of the meson candidate $\mathrm{Iso} = \dfrac{p_{\mathrm{T}}^{\mathrm{meson}}}{p_{\mathrm{T}}^{\mathrm{meson}} + \sum_{\mathrm{trk}} \left| p_{\mathrm{T}}^{\mathrm{trk}} \right|}$

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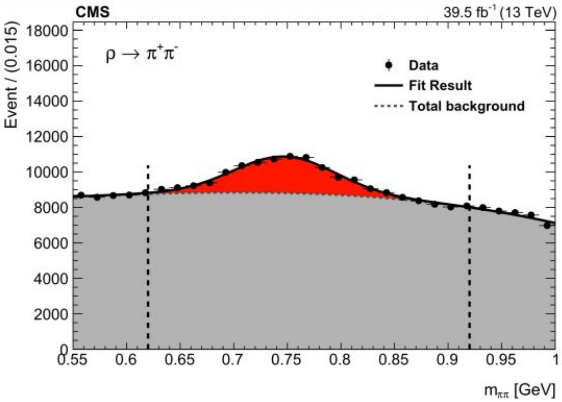
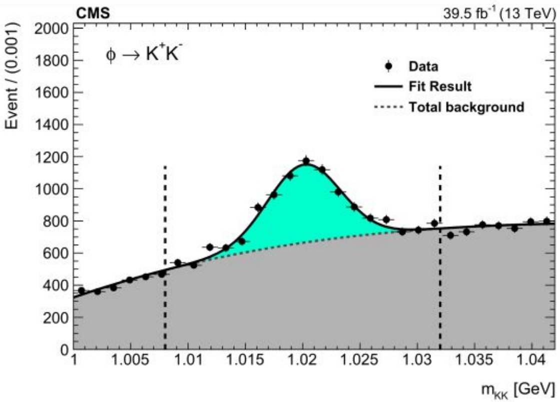
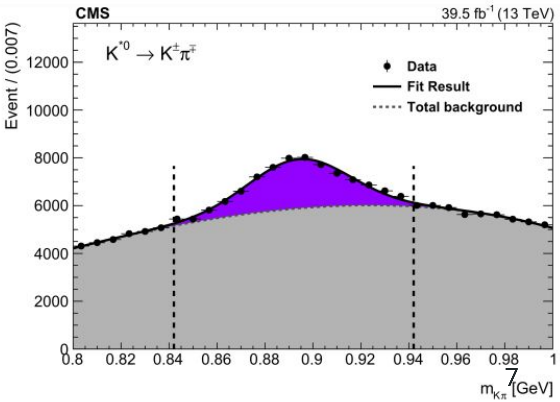






Signal & background modelling

Signal modelled fitting the distribution of the **reconstructed Higgs boson mass** from the **MC signal samples**

- Analytic function: **Double-Sided Crystal Ball**:
  - gaussian core
  - left and right power-law tail

$$
\mathrm{DCB} = \begin{cases} e^{-(m_{\mathrm{ditrk}\gamma}-\hat{m})^2/2\sigma^2}, & -\alpha_L < \frac{m_{\mathrm{ditrk}\gamma}-\hat{m}}{\sigma} < \alpha_R \\ \left(\frac{n_L}{|\alpha_L|}\right)^{n_L} e^{-\alpha_L^2/2} \left(\frac{n_L}{|\alpha_L|} - |\alpha_L| - \frac{m_{\mathrm{ditrk}\gamma}-\hat{m}}{\sigma}\right)^{-n_L}, & \frac{m_{\mathrm{ditrk}\gamma}-\hat{m}}{\sigma} \leq -\alpha_L \\ \left(\frac{n_R}{|\alpha_R|}\right)^{n_R} e^{-\alpha_R^2/2} \left(\frac{n_R}{|\alpha_R|} - |\alpha_R| + \frac{m_{\mathrm{ditrk}\gamma}-\hat{m}}{\sigma}\right)^{-n_R}, & \frac{m_{\mathrm{ditrk}\gamma}-\hat{m}}{\sigma} \geq \alpha_L \end{cases}
$$

Background modelled fitting the **sidebands** of the distribution of the **reconstructed Higgs boson mass** from the **data samples**

- Analytic functions:
  - Chebychev pdf
  - Bernstein pdf
  - Exponential

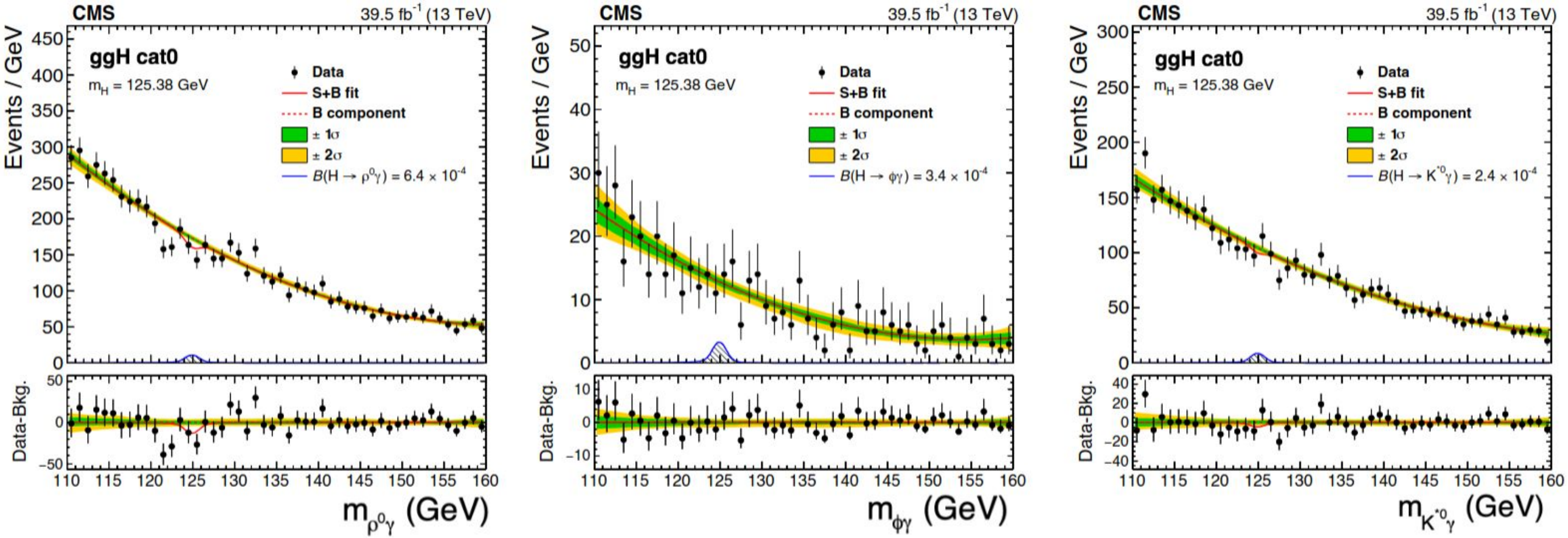
Statistical analysis

- **Fit** the **signal+background** distributions (i.e. the whole dataset) with the PDFs obtained from the signal and background modelling
- Obtain the **branching ratio** of H → Mγ from

$$N_{sig} = \mathcal{L}_{int} \times \epsilon \times \sigma^{H}_{13TeV} \times \mathcal{B}(H \rightarrow M\gamma) \times \mathcal{B}(M \rightarrow Daughter^{+}Daughter^{-})$$

- In case of BR **compatible with 0** perform the **upper limit calculation**:
  - **CLs** (Confidence Level Signal) profile likelihood ratio as **test statistics**
  - **Upper limit** set requiring CLs < α=5%

Results: fits



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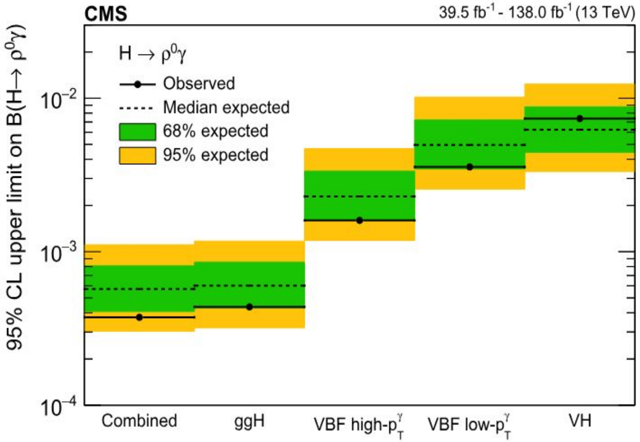
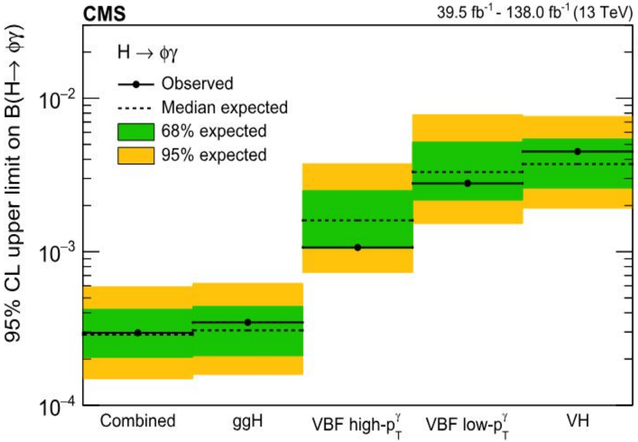
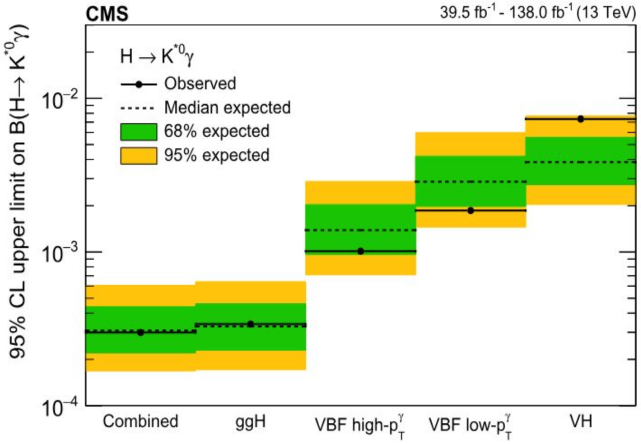
Results: upper limits







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Results: summary

Channel	Coupling	Theoretical BR	ATLAS limits (10^{-4})	CMS limits (10^{-4})
$H\to\rho\gamma$	u, d	$(1.68\pm0.08)\cdot10^{-5}$ [1]	exp. $10.0^{+4.9}_{-2.8}$ obs. 10.4 [3]	exp. $5.7^{+2.4}_{-1.6}$ obs. 3.7 [5]
$H\to\phi\gamma$	s	$(2.31\pm0.08)\cdot10^{-6}$ [1]	exp. $4.2^{+1.8}_{-1.2}$ obs. 5.0 [3]	exp. $2.9^{+1.3}_{-0.8}$ obs. 3.0 [5]
$H\to K^{*0}\gamma$	d&s (flavour changing)	$1.0\cdot10^{-19}$ [2]	exp. $3.7^{+1.5}_{-1.0}$ obs. 2.2 [4]	exp. $3.1^{+1.3}_{-0.9}$ obs. 3.0 [5]

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Conclusions

Summary

- Search for Higgs boson rare decays into a light meson and a photon presented
  - Published in Phys. Lett. B 862 (2025) 139296
- **Most stringent limits** to the branching ratios of H ➔ $\rho\gamma$ and H ➔ $\phi\gamma$ to date

A glimpse into the future...

- **HL-LHC**: factor **~100 more statistics** wrt ggH dataset ➔ exploring 10^{-5} region
- Investigation on New Physics effects enhancing the BRs of factor > 10 [1 , 2]
- Current plans: **Run3** version of the analysis:
  - More statistics
  - Including Z boson decays (same channels)