中國科學院高能物理研究所
Institute of High Energy Physics
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HIGGS POTENTIAL 2024
HIGGS POTENTIAL AND BSM OPPORTUNITIES

ATLAS EXPERIMENT

Rare Decays from Higgs Boson Including 2nd generation fermions

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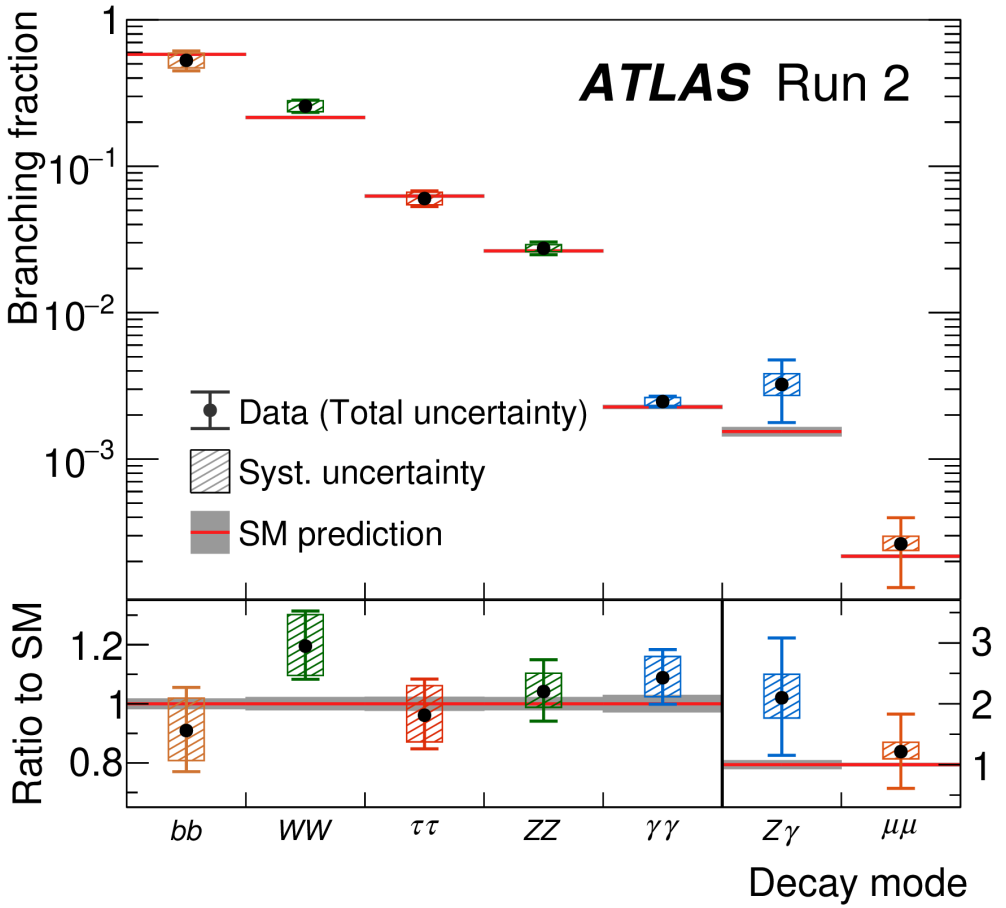
Higgs Potential 2024, Hefei, Anhui
2024-12-20

Overview and Motivation

- **About 7.7M Higgs bosons** produced at the LHC for the **full Run2**.
- Higgs decays properties studied by ATLAS and CMS Collaborations
  - **Coupling to 3rd generation fermions and bosons observed (*O*~10%)**
    - Quite consistent with SM predictions
  - **Rare channels** (i.e coupling to 2nd generation fermions or radiative decays) are **possible**.
    - **Experimentally challenging** (smaller BR)
    - Techniques to reduce relatively large backgrounds to improve signal efficiency
    - Any deviations? → hints toward Physics Beyond SM

- Overview of the talk:
  - **Higgs rare decay**, **2nd generation fermions**, **mesons + γ**.

Nature 607 52 (2022)

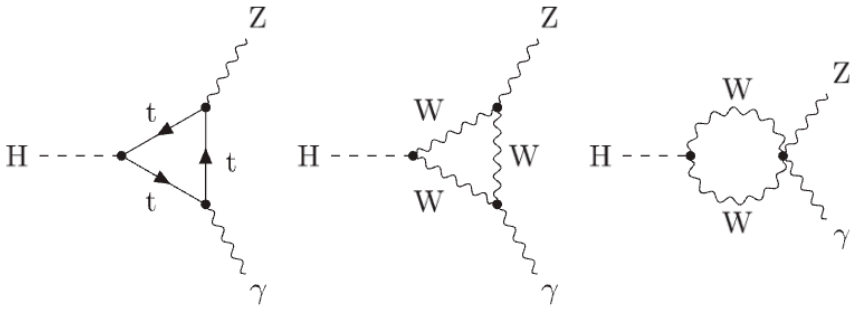


$$H \rightarrow ll\gamma \ (\ Z\gamma \ \textbf{and} \ \gamma\gamma^{*}\ )$$

$H \to Z\gamma$ Analysis: Overview

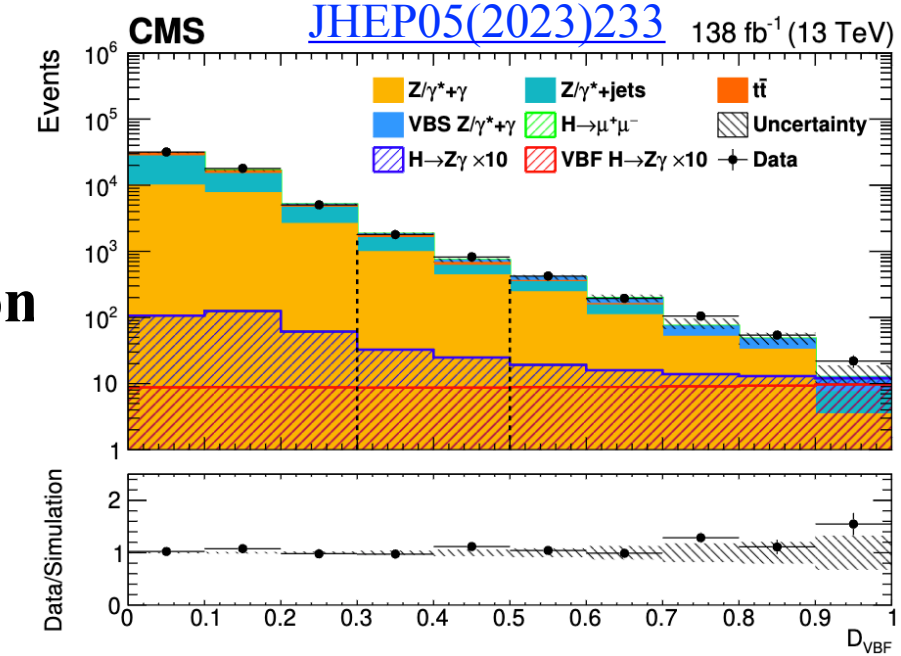
PhysRevLett.132.021803

- $H \to Z\gamma$ **rare decay** via **loop diagrams** → sensitive to new physics
  - Relatively **small branching fraction**: $Br \approx 1.54 \times 10^{-3}$
- Final state with **one photon** and **two same-flavour opposite charge leptons** ($l = e, \mu$)
  - Additional requirements depending on the production modes



- Major backgrounds: **Drell-Yan with ISR photon** or **Drell-Yan with jet** (misidentified as γ)
- **Events categorized** to target **the different H production modes**
  - In some categories, **BDT score** used to define **analysis regions** with **various S/B ratios**

JHEP05(2023)233

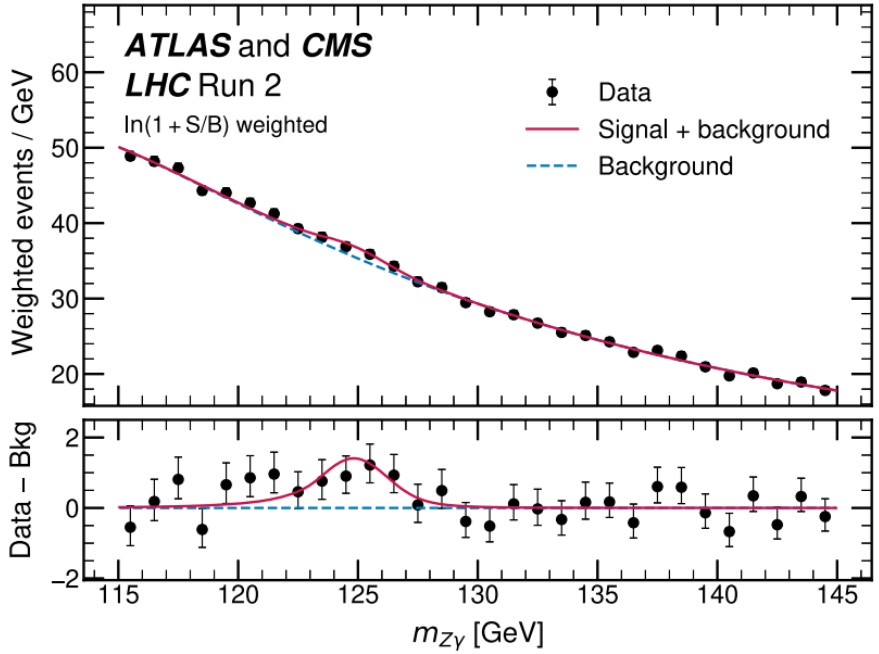


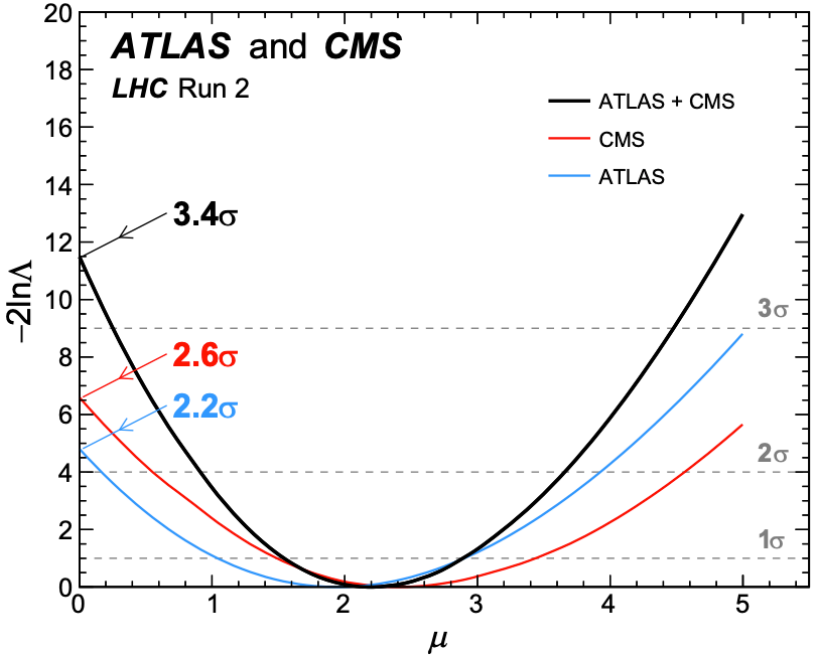
- **Signals and backgrounds modeled with analytic function**
  - Sig: Double-Sided Crystal Ball function
  - Bkg: using exponential, power law functions, Laurent series and Bernstein Polynomial functions

$H \to Z\gamma$ Analysis: Results

PhysRevLett.132.021803

- **Binned-maximum likelihood fit** to all $m_{Z\gamma}$ distributions
  - From **ATLAS+CMS** combination, $\mu = 2.2 \pm 0.6(\text{stat})^{+0.3}_{-0.2}(\text{syst})$
  - **Observed** (expected) significance of 3.4σ (1.6σ) → **First evidence of $H \to Z\gamma$ decay!**

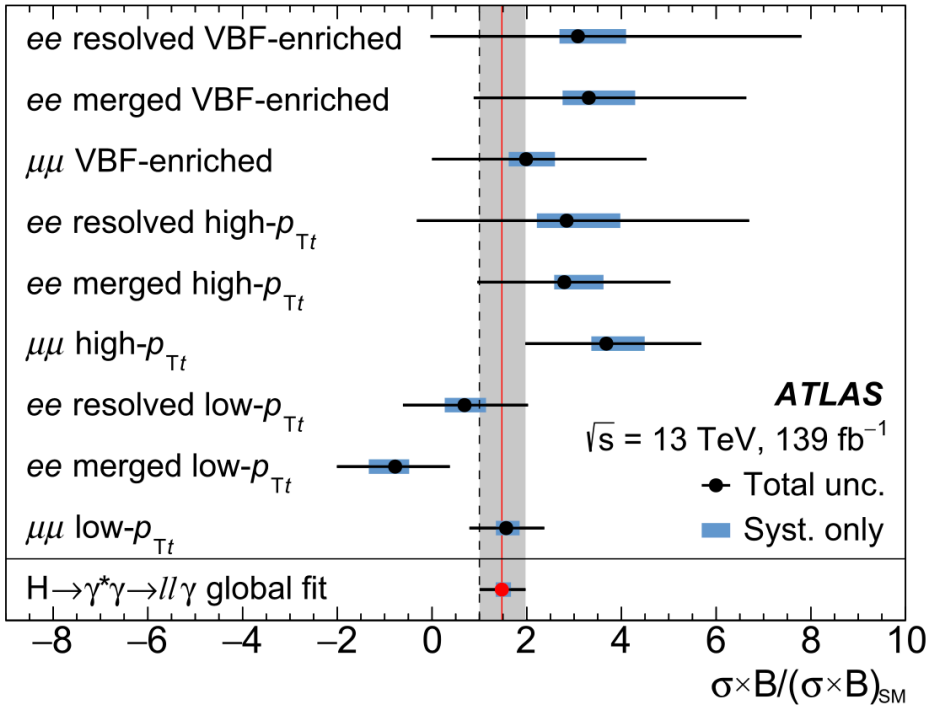




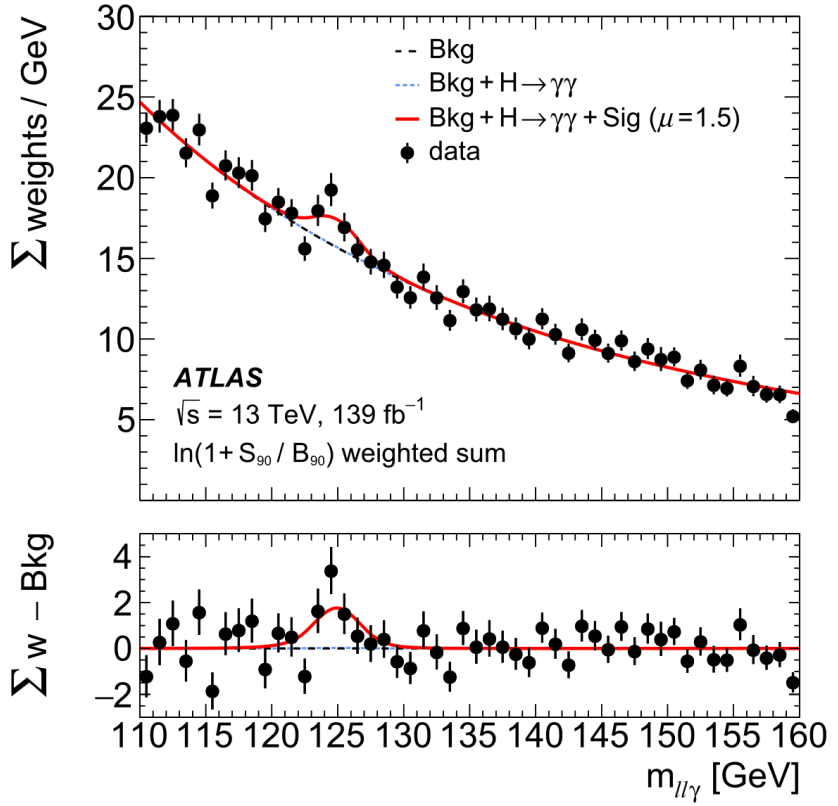
- **Results agree** with the expectations from theoretical predictions within 1.9σ ANA-HIGP-2024-19
- With the ongoing Run3, the precision is expected to improve a lot due to increased statistics.
  - The analysis group launched EB request recently and targets to *Spring/Summer 2025*. ***Stay tuned!***

$H \to \gamma\gamma^*$ Analysis

- **Find Higgs decaying to $ll\gamma$ final state**
- Complementary to $Z\gamma$ search: **fiducial cut $m_{ll} < 30$ GeV**
  - **CP properties** (three body final state) and **BSM couplings**
- Categorization: depending on leptons and kinematics
- **Signal and background** modeled by **analytic functions**
- **Simultaneous unbinned likelihood fit** in all categories.



Phys. Lett. B 819 (2021) 136412



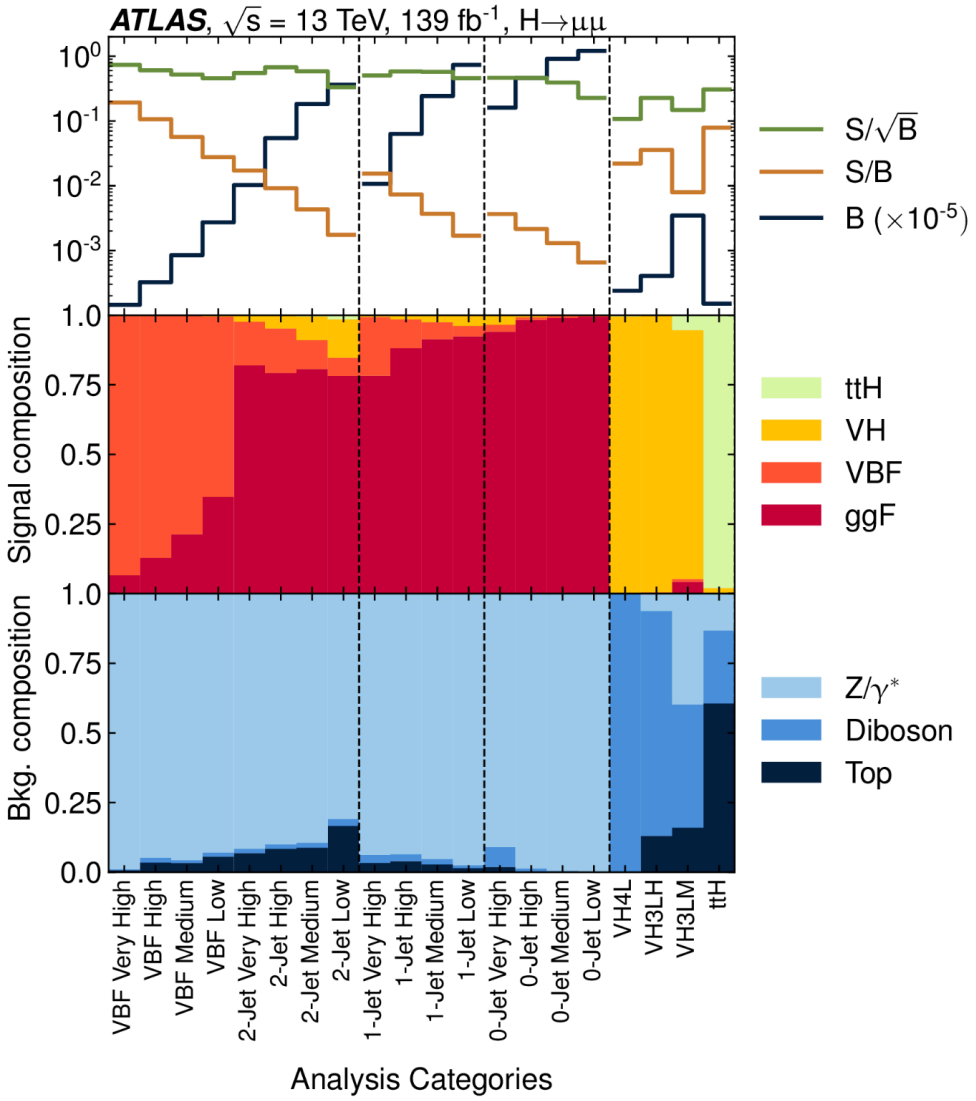
- Observed: $\mu = 1.5 \pm 0.5$
- Significance of $H \to ll\gamma$:
  - **Observed** 3.2σ (expected 2.1σ)
- **First evidence of $H \to \gamma\gamma^* \to ll\gamma$!**

$$H \to f\bar{f}\,(\,\mu^+\mu^-\ \textbf{and}\ c\bar{c}\,)$$

$H \to \mu\mu$ Analysis: Overview

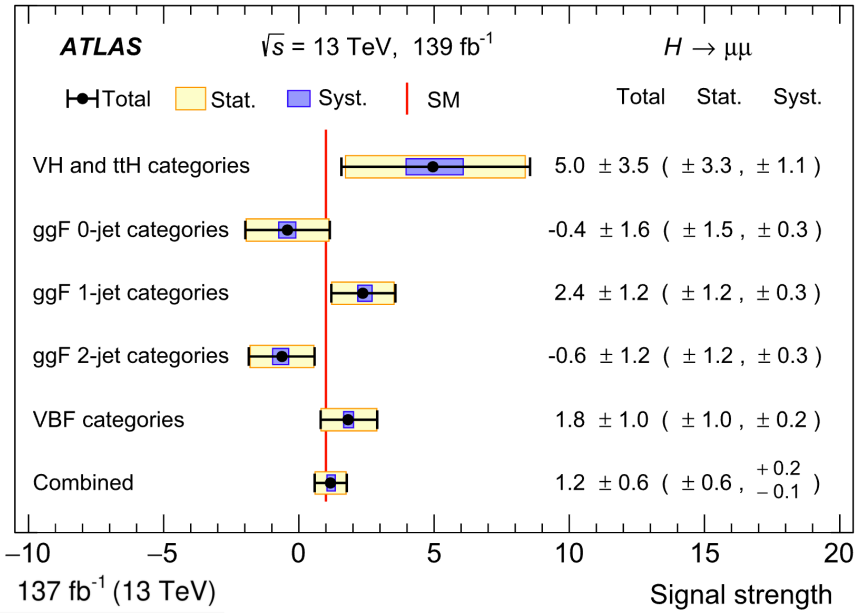
[Phys. Lett. B 812 (2021)]

- Analysis **targets main production modes** ($ggFH$, $VBFH$, VH, $t\bar{t}H$)
  - Final state with **two muons**: **excellent signal resolution**
- Main experimental challenges:
  - **Small branching ratio** ($Br \approx 2.2 \times 10^{-4}$)
    - Physics beyond the SM can modify it
  - **Large irreducible bkg**: **Drell-Yan process** ($Z \to \mu\mu$)
  - S/B ~ 0.2% in the SR (120 GeV $< m_{\mu\mu} <$ 130 GeV)
- **BDTs** used to discriminate signal and background events for each production mode
  - Events categorized in **20 regions**

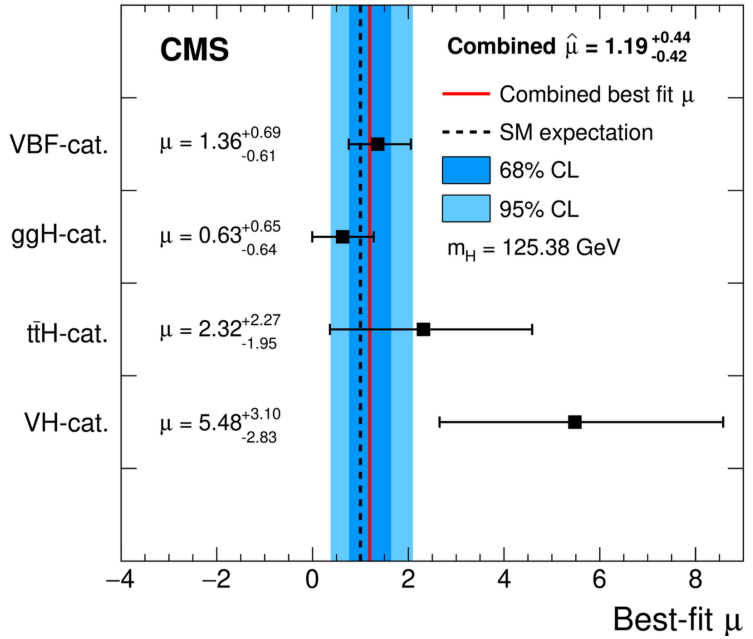


$H \to \mu\mu$ Analysis: Results

- **Fit to $m_{\mu\mu}$** performed between **110-160 GeV**
- Signal modeled using **double-sided crystal ball function**
- Background modeled using **empirical functional forms**
- **Simultaneous binned-likelihood fit:**
  - **Best fit signal strength** $\mu = 1.2 \pm 0.6$
  - Observed significance: 2.0σ(expected 1.7σ)



- Results from **CMS**:
  - $\mu = 1.19^{+0.41}_{-0.40}(\text{ stat })^{+0.17}_{-0.16}(\text{syst})$
- **Observed significance:** 3.0σ
  - **First evidence!**



Phys. Lett. B 812 (2021)

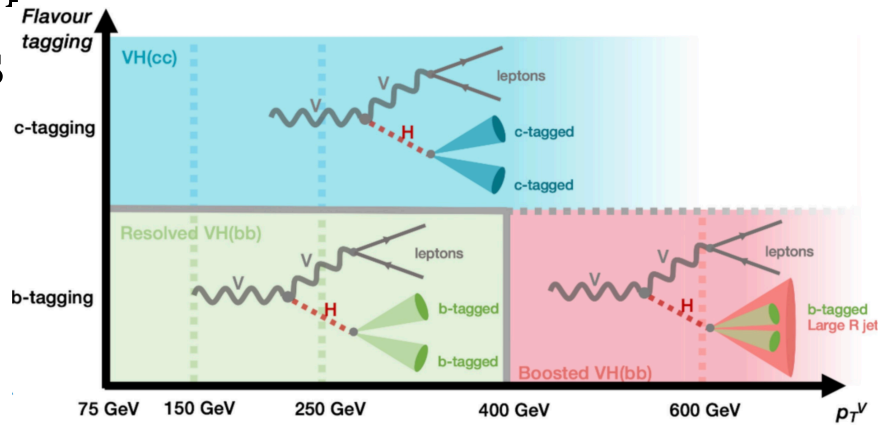
JHEP01(2021)148

- The ongoing Run3 will bring some improvements. ***Stay tuned!***

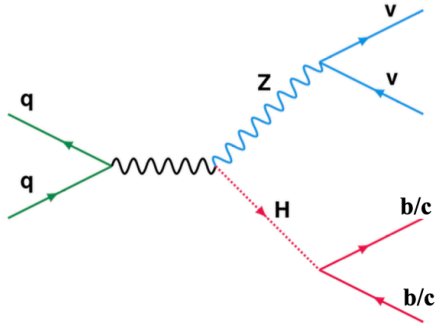
$VH \to c\bar{c}$ Analysis: Overview

arxiv.2410.19611

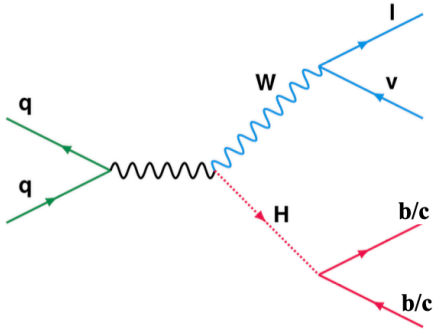
- **Small** $Br(H \to c\bar{c}) \approx 3\,\%$ → analysis targets **the** $V(lep)H$ **production**
- Simultaneous study of the **VH($b\bar{b}$)** and **VH($c\bar{c}$)** final states



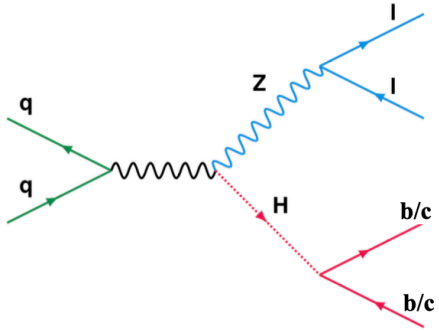
0-lepton channel



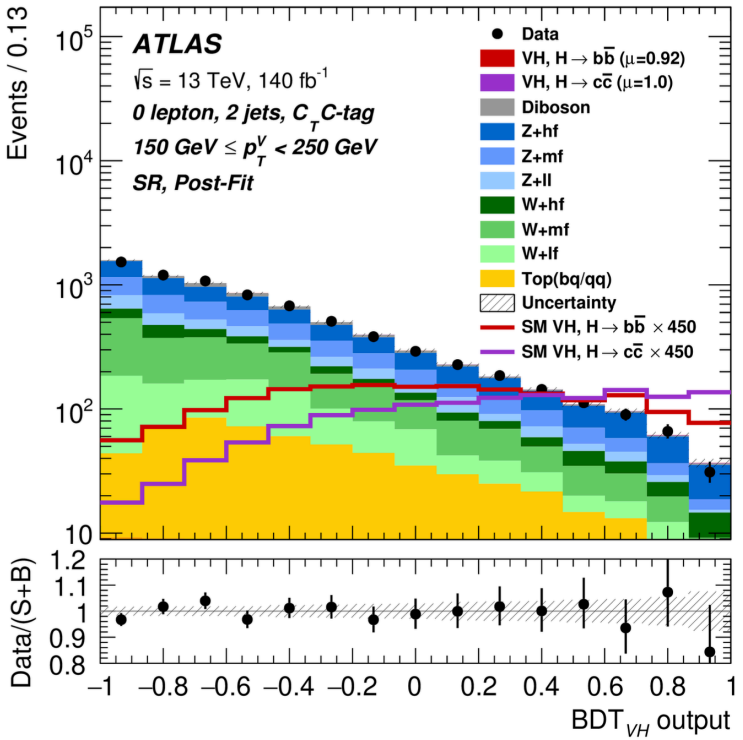
1-lepton channel



2-lepton channel



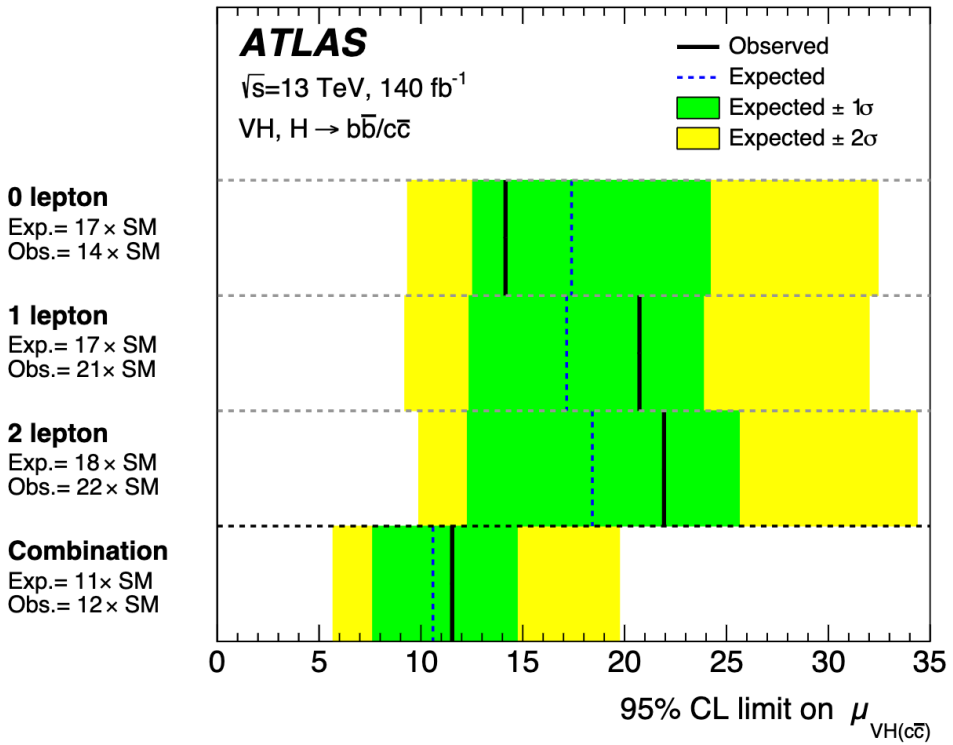
- **Categorization** based on **flavours**, **#leptons**, **#additional jets**, **pT of the vector boson (p_{T}^V)**
- Major backgrounds from **Z+jets**, **W+jets** and **top**
  - Shape from MC, normalization from the CRs.
- **MVA techniques** to discriminate **VH signal** and **backgrounds**

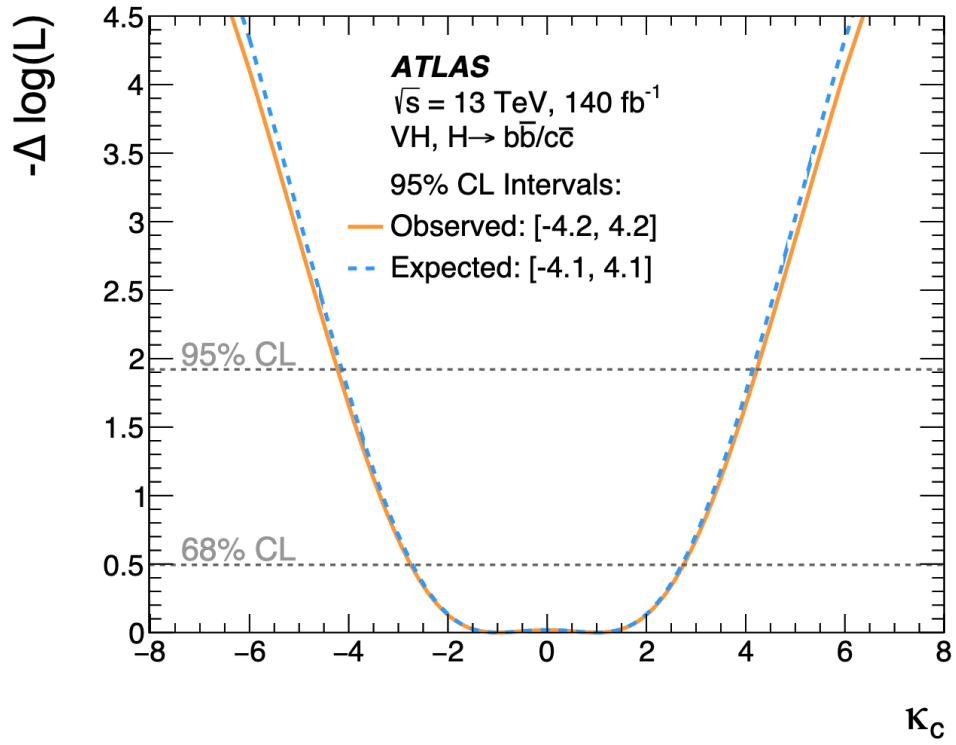


$VH \to c\bar{c}$ Analysis: Results

arxiv.2410.19611

- **Binned maximum likelihood fit** to extract simultaneously $\mu_{VH}^{b\bar{b}}$ and $\mu_{VH}^{c\bar{c}}$
  - $\mu_{VH}^{b\bar{b}} = 0.91^{+0.16}_{-0.14} = 0.91 \pm 0.10\,(\text{stat.})\,^{+0.12}_{-0.11}\,(\text{syst.})$
  - $\mu_{VH}^{c\bar{c}} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}(\text{ stat. })^{+3.6}_{-3.5}(\text{ syst. })$
- **Observed** (expected) **upper limits** on $\mu_{VH}^{c\bar{c}}$ of **11** (10) $\times$ **SM @ 95% CL**
- **1D likelihood scan, fixing** $\kappa_b = 1 : |\kappa_c| < 4.2 @\ 95\,\%\,\text{CL}$

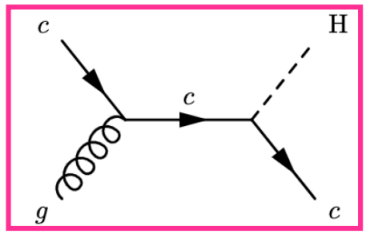


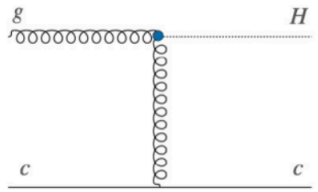


$H(\rightarrow \gamma\gamma) + c$ Analysis

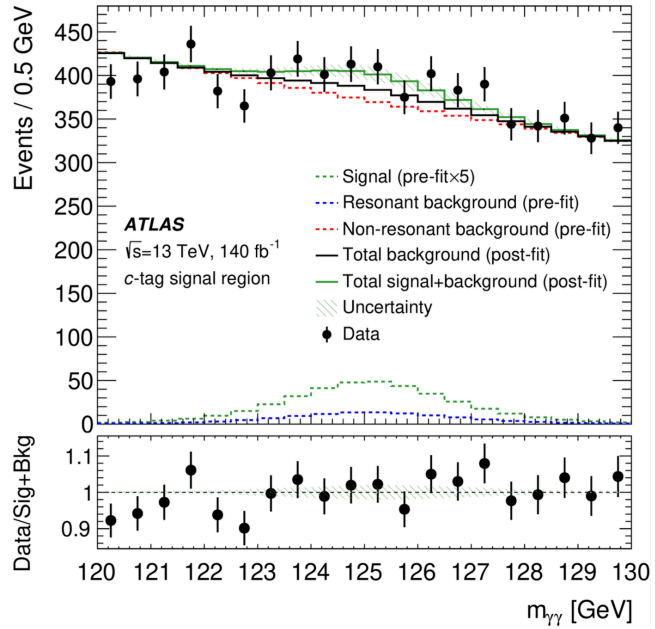
arxiv.2407.15550 CMS-PAS-HIG-23-010

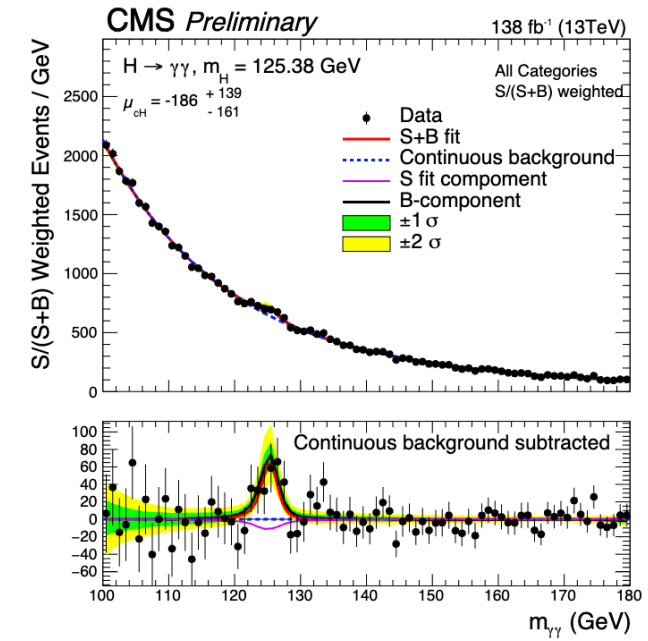
- Search for the $pp \rightarrow H + c$ production
  - Probe the **coupling of the Higgs boson to charm quarks** via the $g + c \rightarrow H + c$ process
  - **Large background contribution** → use clean $H \rightarrow \gamma\gamma$ decay





- **Final state** with **two photons** and **one jet**:
  - ATLAS: the jet can be either a c-tagged jet or non c-tagged jet
  - CMS: only c-tagged jet
- ATLAS: target **inclusive H+c production**
  - $\hat{\sigma}(H + c) = 5.2 \pm 3.0$ pb
  - Observed (expected) limits $\sigma(H + c) < 10.4\ (8.6)$ pb at 95%
- CMS: target the **associated production c+H** to study κ_c
  - Observed (expected) $\mu_{cH} < 243\ (355)$
  - Observed (expected) limits $|\kappa_c| < 38.1\ (72.5)$ at 95%



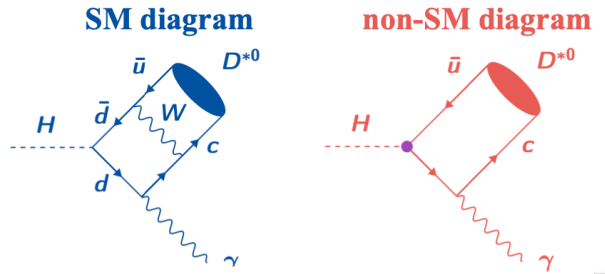


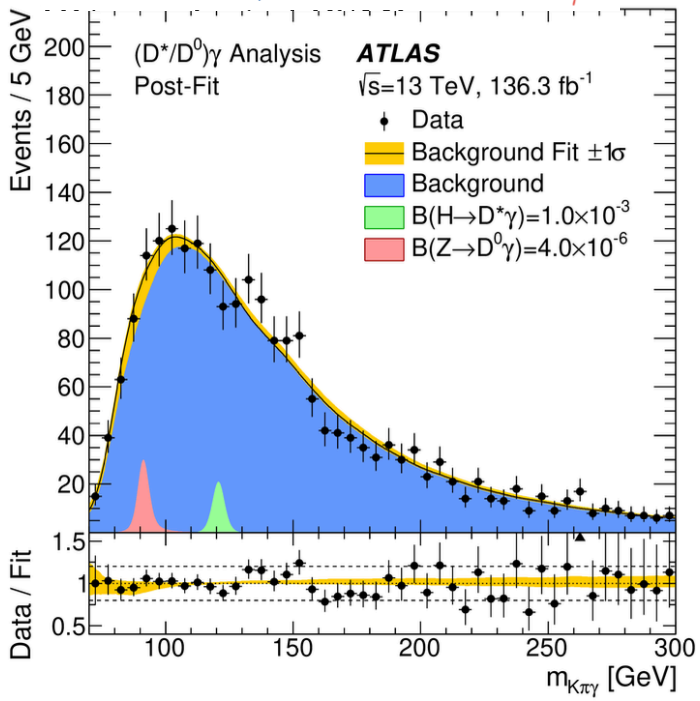
$$H \rightarrow \textbf{mesons(}\ D^{*}, J/\psi/\psi(2S), \rho/\phi/K^{*0}\ \textbf{)} + \textbf{photon}$$

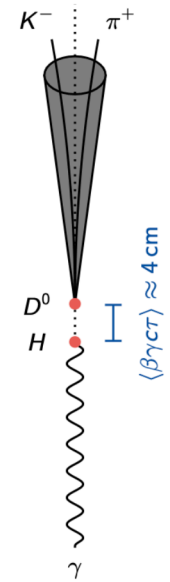
$H \to D^* + \gamma$ Analysis

Phys. Lett. B 855 (2024) 138762

- The **rare decay** allows to
  - Study the **Higgs coupling to light-quarks** (u, d, s)
  - Probe the **flavour changing Yukawa interactions**
- Analysis also exploits $Z \to D^0 + \gamma$ and $Z \to K^0_S + \gamma$
- Almost all D^* decays into $D^0 + \gamma$ or $D^0 + \pi^0$
  - Focus on the $D^0 \to K^-\pi^+$ decay ($Br \approx 4\,\%$)
- Final state characterized by a **distinctive signature**:
  - **Two isolated-tracks** against a photon + **displaced vertex** from a meson decay
- Bkg dominated by γ+**jet and multi-jet processes**
- No significant excess is observed.
  - **First limits on $H \to D^* + \gamma$ and $Z \to K^0_S + \gamma$**
  - **Great improvement (500x)** on the limit of $Z \to D^0 + \gamma$ set by LHCb





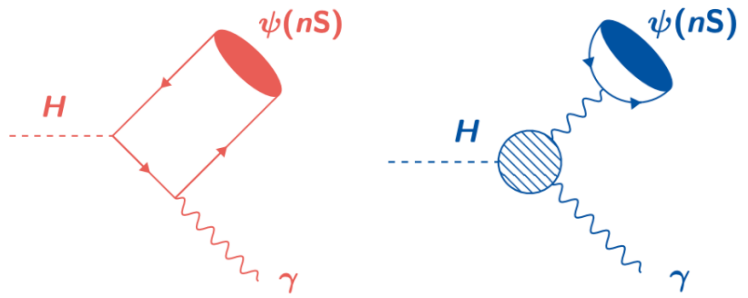


	95% CL upper limit	
	Expected	**Observed**
$\mathcal{B}(H \to D^{*0}\gamma)$	$(1.2^{+0.5}_{-0.3}) \times 10^{-3}$	$\mathbf{1.0 \times 10^{-3}}$
$\mathcal{B}(Z \to D^0\gamma)$	$(3.4^{+1.4}_{-1.0}) \times 10^{-6}$	$\mathbf{4.0 \times 10^{-6}}$
$\mathcal{B}(Z \to K^0_S\gamma)$	$(3.0^{+1.3}_{-0.8}) \times 10^{-6}$	$\mathbf{3.1 \times 10^{-6}}$

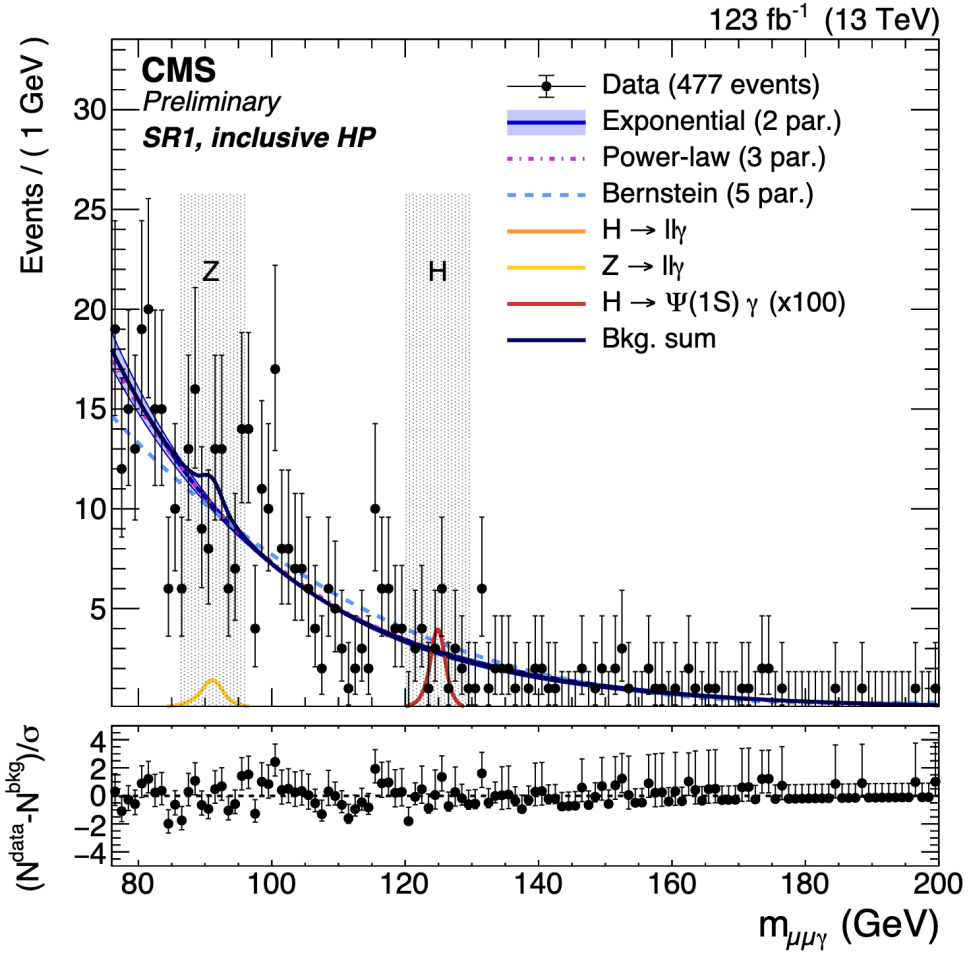
$H \to J/\psi/\psi(2S) + \gamma$ Analysis

CMS-PAS-SMP-22-012

- Allows to access the **c-quark Yukawa coupling**
- **Interference** between **direct** and **indirect** contributions
  - **Direct amplitude** sensitive to **c-quark Yukawa coupling**
  - **Indirect contribution** mimics $H \to \gamma\gamma$ with one photon fragmenting into quark-antiquark pair to form a meson
- $J/\psi/\psi(2S) \to \mu\mu$ considered in the analysis
  - Final state with **two muons** and **one isolated photon**
- Events categorized to target the various H production
- Results extracted from a **fit to $m_{\mu\mu\gamma}$ distribution**
- **No evidence for Br to these rare decays larger** than the SM predictions
  - Obs: $-157 < \kappa_c/\kappa_\gamma < 199$
  - Exp: $-121 < \kappa_c/\kappa_\gamma < 161$



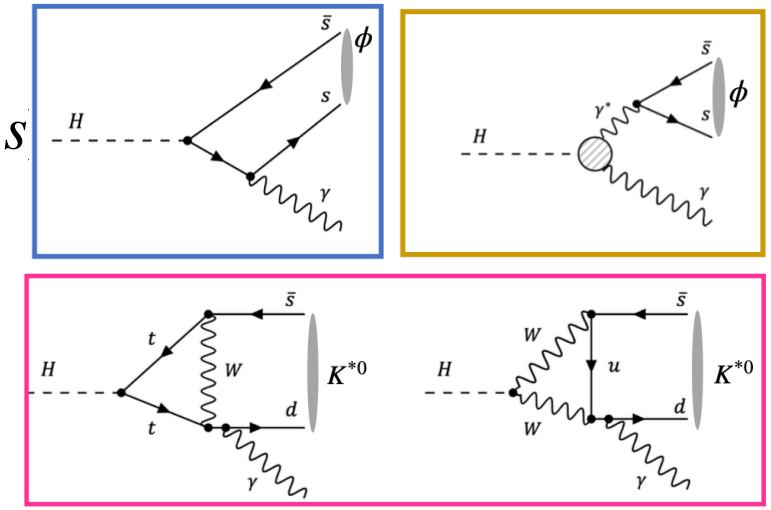
95% CL upper limit (obs.) on branching fraction	
$H \to J/\psi\,\gamma$	2.6×10^{-4}
$H \to \psi(2S)\,\gamma$	9.9×10^{-4}
$Z \to J/\psi\,\gamma$	0.6×10^{-6}
$Z \to \psi(2S)\,\gamma$	1.3×10^{-6}



$H \to \rho/\phi/K^{*0} + \gamma$ Analysis

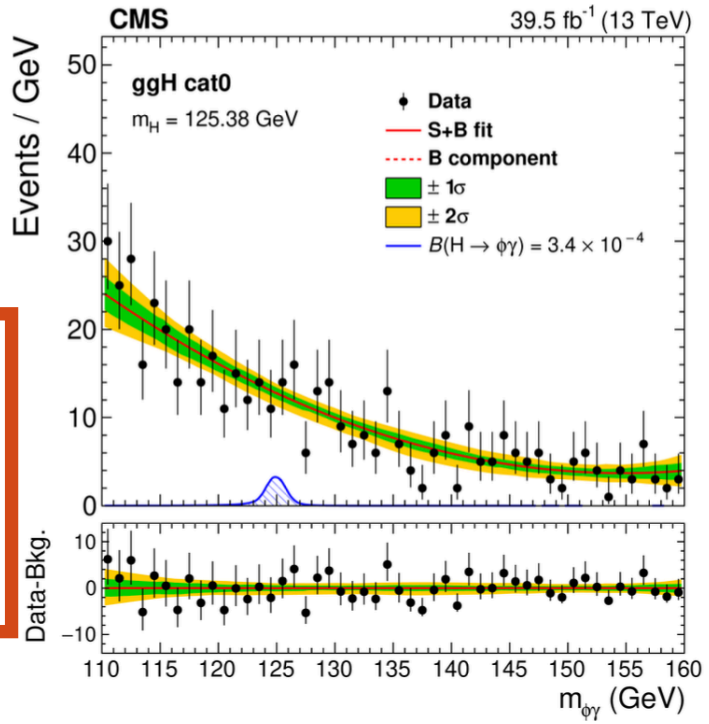
arxiv.2410.18289

- Higgs decays to **light-flavored mesons**.
  - $H \to \rho/\phi + \gamma$ to study the **Higgs coupling to light-quarks** (u, d, s)
    - **Direct contribution** is very small → **main contribution** from **diagram with Higgs to di-photon** , with one off-shell photon
  - $H \to K^{*0} + \gamma$: probe the **flavours changing neutral current**
- Analysis targets **three main production modes** (ggFH, VBFH, VH)
- **Final state** with **one γ+2 tracks** to identify meson decaying to K or π
- Major backgrounds: γ+jet and multi-jets (**Chebychev polynomial**)
- **Unbinned maximum likelihood fit on $m_{M\gamma}$ distributions**
- No excess over the background expectations



	Expected	Observed
$\mathcal{B}(H \to \rho + \gamma)$	5.7×10^{-4}	3.74×10^{-4}
$\mathcal{B}(H \to \phi + \gamma)$	2.9×10^{-4}	2.97×10^{-4}
$\mathcal{B}(H \to K^{*0} + \gamma)$	1.7×10^{-4}	1.71×10^{-4}

Most stringent constraints on these rare decay channels!!

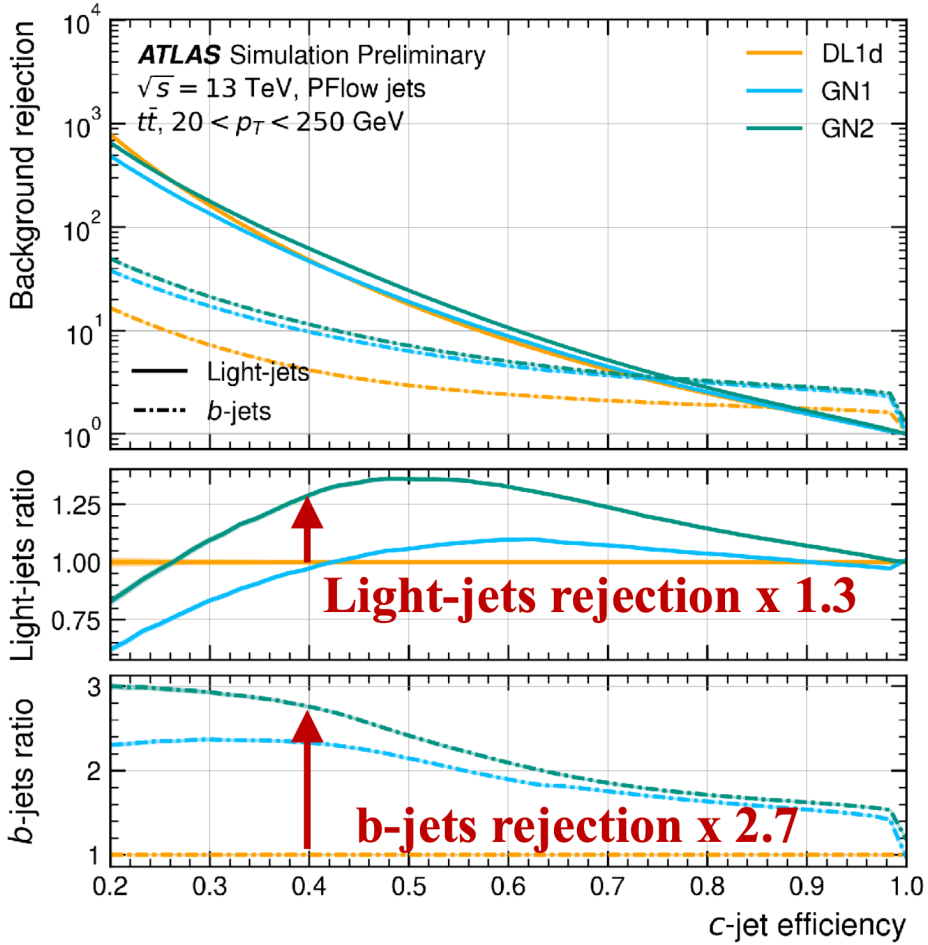


Conclusions

- ATLAS and CMS Collaboration have searched for rare Higgs decays
  - Study Higgs Yukawa coupling to second generation fermions:
    - ★ **Improved constraints on the c-quark Yukawa coupling** from $VH(c\bar{c})$ analysis
    - ★ **First evidence** of the $H \to \mu\mu$ decay
  - ★ **First evidence** of $H \to Z\gamma$ decay
  - ★ **First evidence** of $H \to \gamma\gamma^* \to ll\gamma$ decay
  - Probe Higgs boson coupling to light quarks via Higgs decay to meson + photon

- With improved analysis techniques (i.e. **improved c-tagging algorithm**) and **increased integrated luminosity**, we have great possibilities to observe many rare Higgs decays.

Stay tuned for more exciting results to come!



Thanks for your attention!

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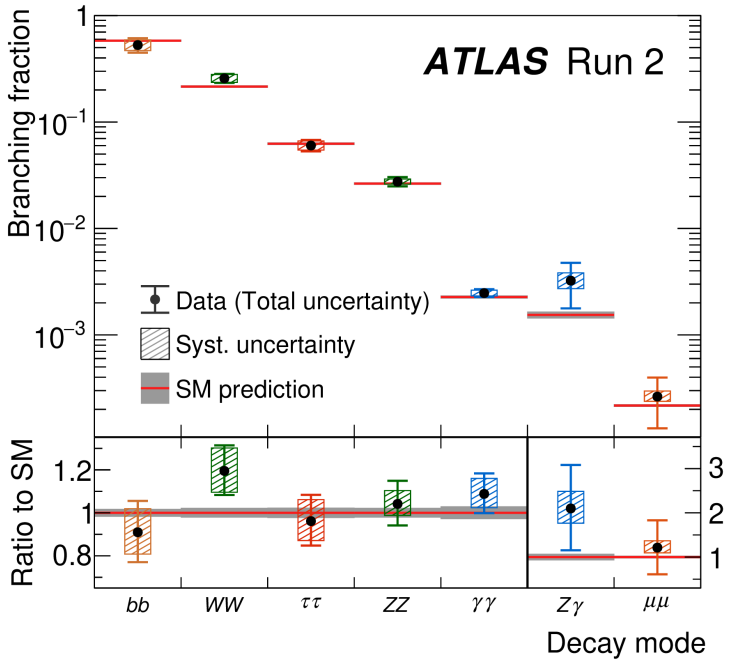
2024-12-20

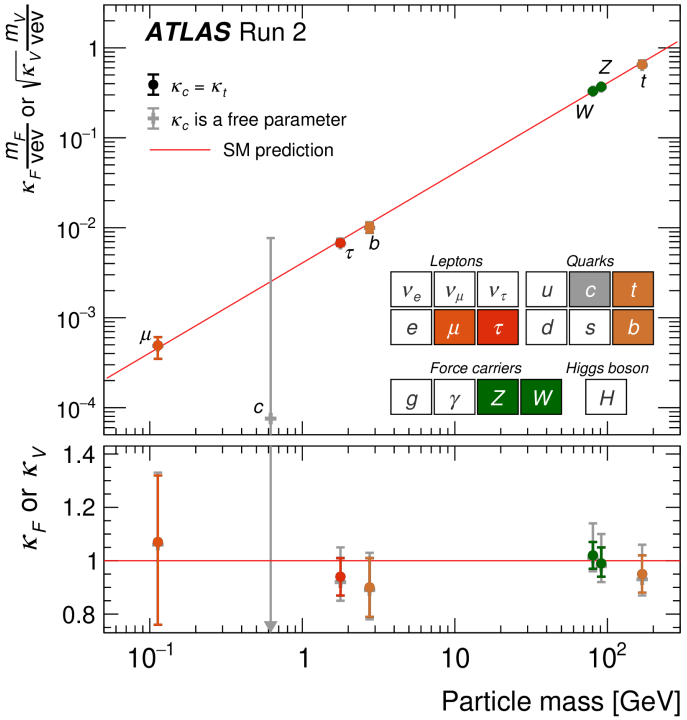
Backup Slides

Overview and Motivation

- Details:
  - $H \to Z\gamma$ (ATLAS + CMS)
  - $H \to \mu^+\mu^-$
  - $H \to \gamma^*\gamma$
  - $VH \to c\bar{c}$ c-quark
  - $cH \to \gamma\gamma$ c-quark
- Quick overview:
  - $H \to D^* + \gamma$ => light-quark (u, d, s)
  - $H \to J/\psi/\psi(2S) + \gamma$ => c-quark
  - $H \to \rho/\phi/K^{*0} + \gamma$ => light-quark (u, d, s)



Nature 607 52 (2022)



$H \to \gamma\gamma^*$ and $H \to Z\gamma$

- Fiducial cut on $m_{ll} < 30$ GeV
- The interference is negligible.