Rare decays of the Higgs bosons, including second generation fermions (ATLAS + CMS)

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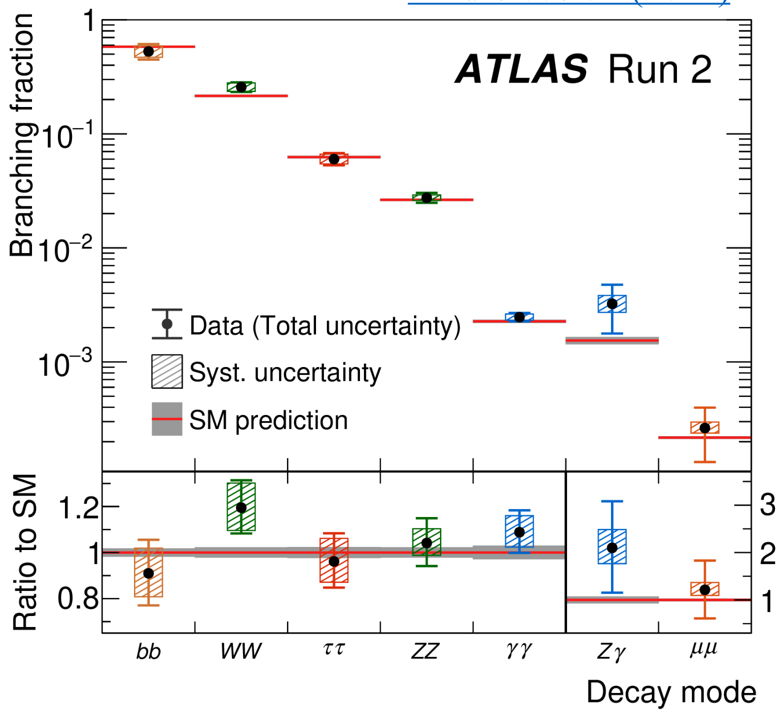
on behalf of ATLAS and CMS Collaborations

07th November 2024

Overview and motivation

- **Over 12M Higgs bosons** produced at LHC
- Higgs decays properties studied by ATLAS and CMS Collaborations
  - **Couplings to 3rd generation fermions** and **boson observed** ($\mathcal{O} \sim 10\%$)
    - consistent with the SM
  - **Rare channels** (i.e. decays to 2nd generation fermions or radiative decays) are possible
    - Experimentally **challenging**
      - Small number of signal events
      - ➡ techniques to reduce relatively large backgrounds with attaining high signal efficiency
    - Discrepancy? Hint to Physics Beyond the SM

Nature 607 52 (2022)

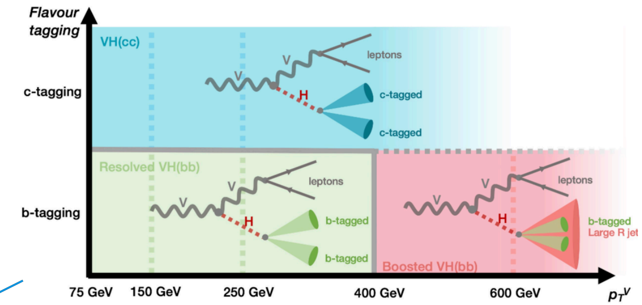


- Overview of the talk:
  - Higgs decay to 2nd generation fermions
  - Rare Higgs decays
  - Higgs decays to meson + γ

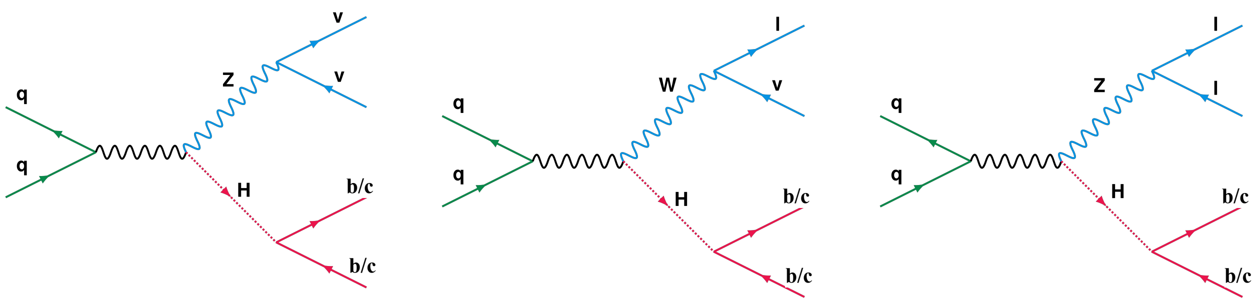
arXiv:2410.19611

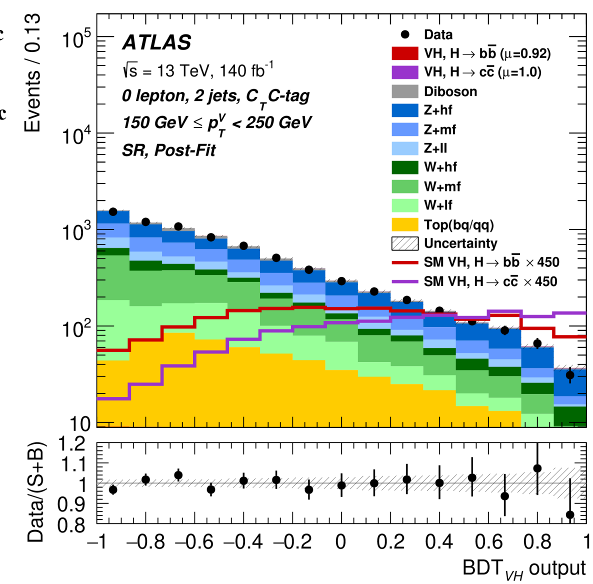
$VH(\rightarrow c\bar{c})$ analysis

- Small $\mathscr{B}(H \rightarrow c\bar{c}) \sim 3\% \rightarrow$ analysis **targeting the *V(lep)H* production**
- Analysis is re-analysis the full Run2 dataset
- Simultaneous study of the **VH($b\bar{b}$)** and **VH($c\bar{c}$)** final states



0-lepton channel **1-lepton channel** **2-lepton channel**





- **Categorisation** based on **flavour categories**, **# leptons, # add. jets,** p_T **of the vector boson** (p_T^V)
- Major backgrounds from **Z+jets**, **W+jets** and **top**
  - Shape from MC, normalisation from the CRs
- **MVA techniques** to discriminate VH signal and bkgs events

More details in Marion's talk

arXiv:2410.19611

ATLAS EXPERIMENT

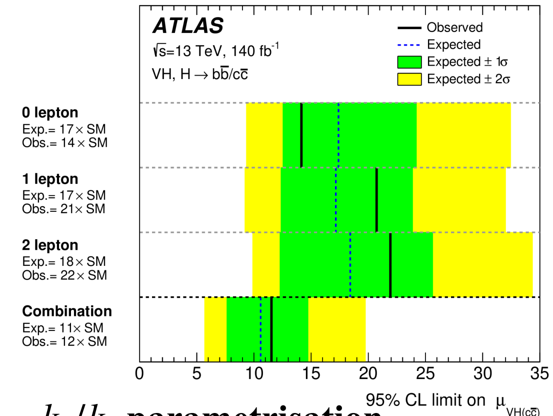
$VH(\to c\bar{c})$ analysis: results

- **Binned maximum likelihood fit** to extract **simultaneously** μ_{VH}^{bb} **and** μ_{VH}^{cc}

$$\mu_{VH}^{bb} = 0.91^{+0.16}_{-0.14} = 0.91 \pm 0.10\,(\text{stat.})\,^{+0.12}_{-0.11}(\text{syst.})$$ **→ +15% improvement on μ_{VH}^{bb} uncertainty!**

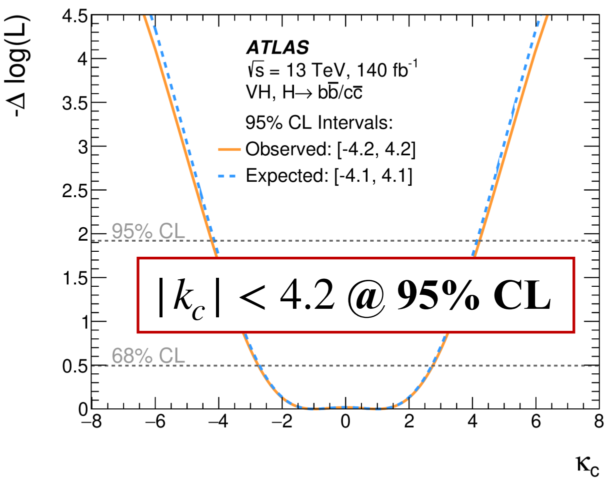
$$\mu_{VH}^{cc} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}(\text{stat.})^{+3.6}_{-3.5}(\text{syst.})$$

- Observed (expected) **upper limits on μ_{VH}^{cc}** of **11 (10) x SM @ 95% CL**
  - **Factor 3 improvement** wrt the previous Run2 publication
- Signal strengths parametrised in terms of k_i **coupling modifiers**



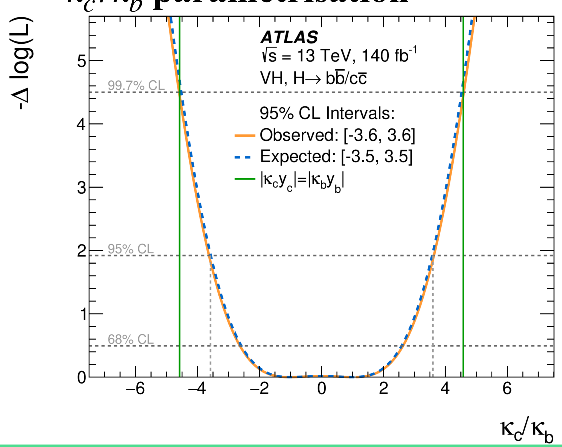
$$\mu_{VH}^{cc} = \frac{k_c^2}{1 + B_{hbb}^{SM}(k_b^2 - 1) + B_{hcc}^{SM}(k_c^2 - 1)}; \quad \mu_{VH}^{bb} = \frac{k_b^2}{1 + B_{hbb}^{SM}(k_b^2 - 1) + B_{hcc}^{SM}(k_c^2 - 1)}$$

1D scan, fixing k_b=1

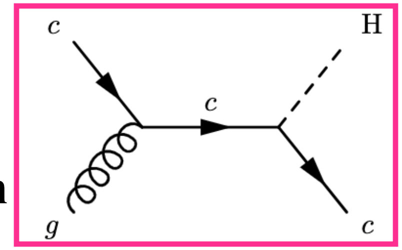


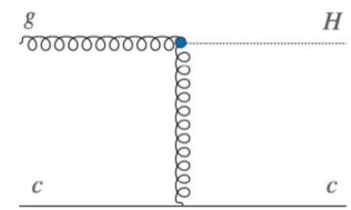
- 1D scan: $|k_c| < 4.2$ **@ 95% CL**
  - Previous extrapolation at HL-LHC estimated $|k_c| < 3$ @ 95% CL
- Alternative k_c/k_b parametrisation: exclude Yukawa coupling universality @ 3σ

k_c/k_b parametrisation

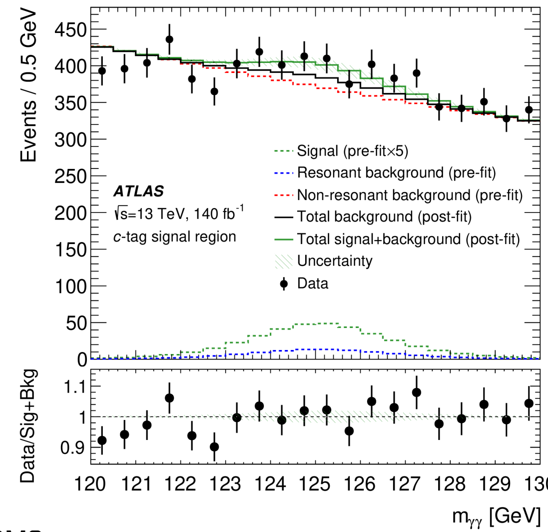


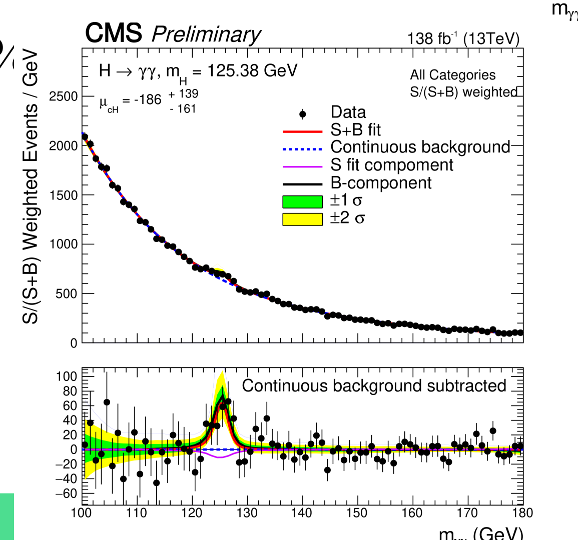
$H(\to \gamma\gamma) + c$ analysis





- Search for the $pp \to H+c$ production
  - Probe of the **coupling of the Higgs boson to charm quarks** via the **$g + c \to H + c$ process**
  - Large bkg contribution → use clean **H→$\gamma\gamma$ 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: jet is a 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 @ 95%
- CMS: **target** the **associated production c+H** to study k_c
  - Observed (expected) $\mu_{cH} < 243$ (355)
  - Observed (expected) limits $|k_c| < 38.1$ (72.5) @ 95%CL





More details in Marion's talk, Tiziano's talk and Sebastian's talk

More details in Anusree's talk

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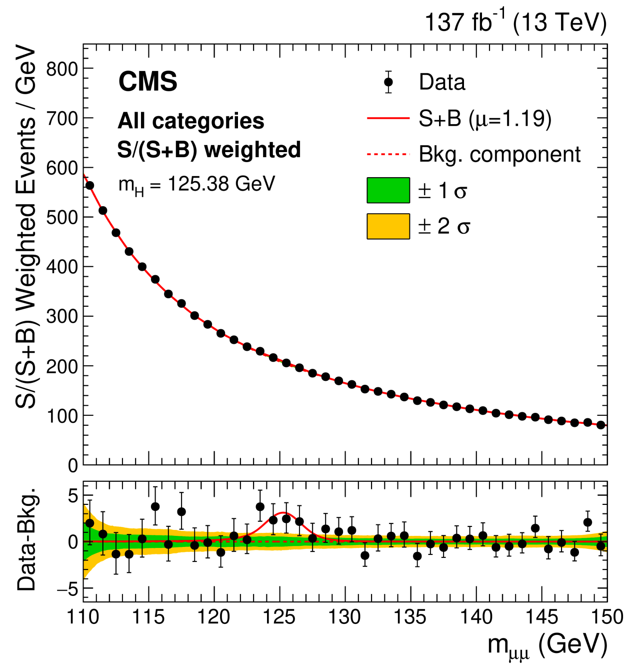
$H \to \mu\mu$ analysis

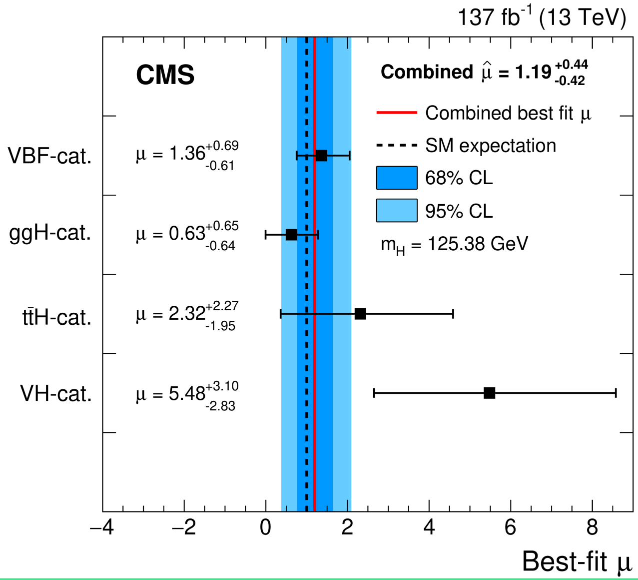
- Analysis **targets main production modes**
- Final state with **two muons** → good signal resolution but small branching ratio (~2.2x10^{-4})
- Trigger: single muon trigger
- Categorisation: based on the Higgs production modes
- **Machine learning techniques** used to **discriminate signal and background events**
  - DNN score used as final discriminant in the VBF category
  - BDT score used to define regions in which $m_{\mu\mu}$ is fit in ggH, VH and ttH categories
- Large **irreducible bkg** from Drell-Yan process ($Z\to\mu\mu$)
- **Simultaneous binned-likelihood fit**

$$\mu = 1.19\,^{+0.41}_{-0.40}(\text{stat})^{+0.17}_{-0.16}(\text{syst})$$

→ Observed (expected) significance 3 (2.5) σ - **Evidence!**

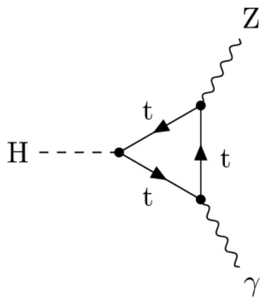
→ upper limits on BR of **1.9×SM** @ 95% CL

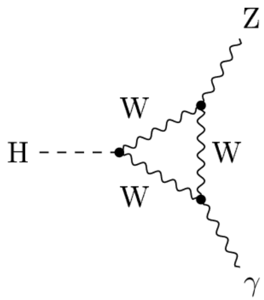


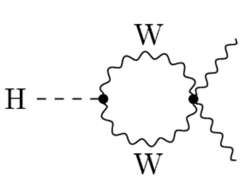


$H \to Z\gamma$ analysis

- **Rare H → $Z\gamma$ decay** via loop diagrams → sensitive to new physics
  - $\mathscr{B}(H \to Z\gamma) = 1.54 \times 10^{-3}$
- Final state with **one photon** and **two same flavor opposite charge leptons** ($\ell = e,\mu$).
  - Additional requirements depending on the target production mode
- Major backgrounds: **Drell-Yan with ISR photon** or **Drell-Yan with jets**
- **Analysis categories** to target the **different H production modes**
  - In some categories, **BDT score** used to define **analysis regions** with different S/B
- **Signal** and **background modelled** with **analytical functions**
  - Signal modelled from Crystal ball and Gaussian function
  - Bkg modelled using exponential, power law functions, Laurent series and Berstein polynomial







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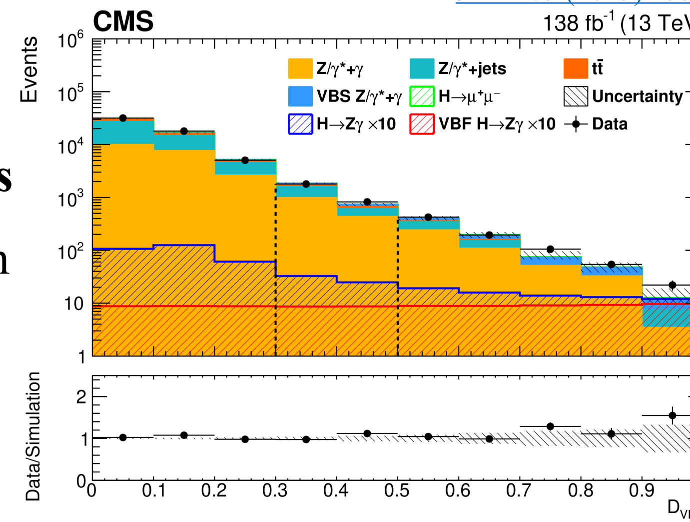


More details in Anusree's talk

Phys. rev. Lett. 132 (2024) 021803

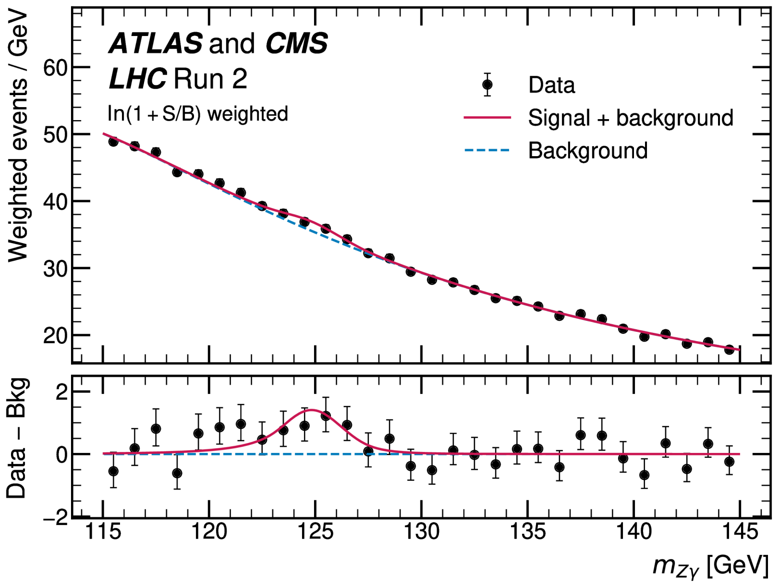
$H \to Z\gamma$ analysis: results

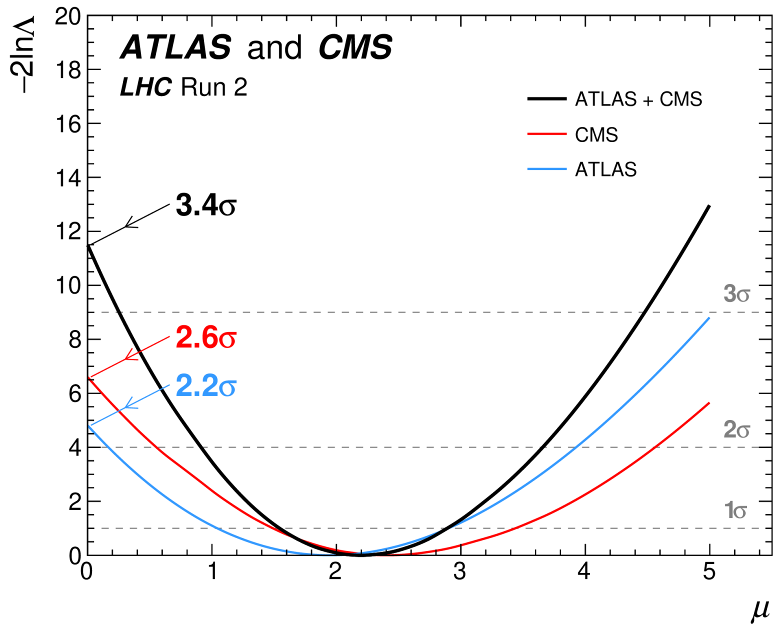
- **Binned-maximum likelihood fit** to all $m_{Z\gamma}$ distributions

  $\mu = 2.2 \pm 0.6\ (\text{stat})^{+0.3}_{-0.2}(\text{syst})$

  Observed (expected) **significance** of **3.4 (1.6)** σ

  → **fist evidence of H → $Z\gamma$ decay!**



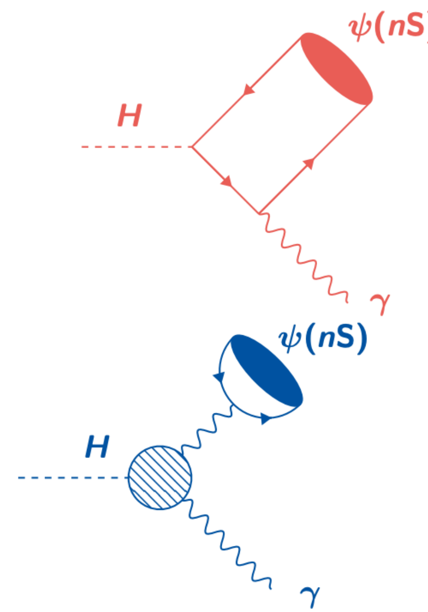


- Measured $\mathscr{B}(H \to Z\gamma) = (3.4 \pm 1.1) \times 10^{-3}$
- **Measurement agrees** with the expectations from SM prediction within 1.9 σ

More details in Anusree's talk

$H \rightarrow J/\psi\,/\,\psi(2S) + \gamma$ analysis

- $H \rightarrow J/\psi\ /\ \psi(2S) + \gamma$ allows to **access the c-quark Yukawa coupling**
  - Radiative decays helps to suppress multi-jet background
- Interference between the **direct** and **indirect** contributions
  - **Direct amplitude** sensitive to c-quark Yukawa coupling
  - **Indirect contribution** mimics $H \rightarrow \gamma\gamma$ with one photon fragmenting into quark-antiquark pair and forming the meson

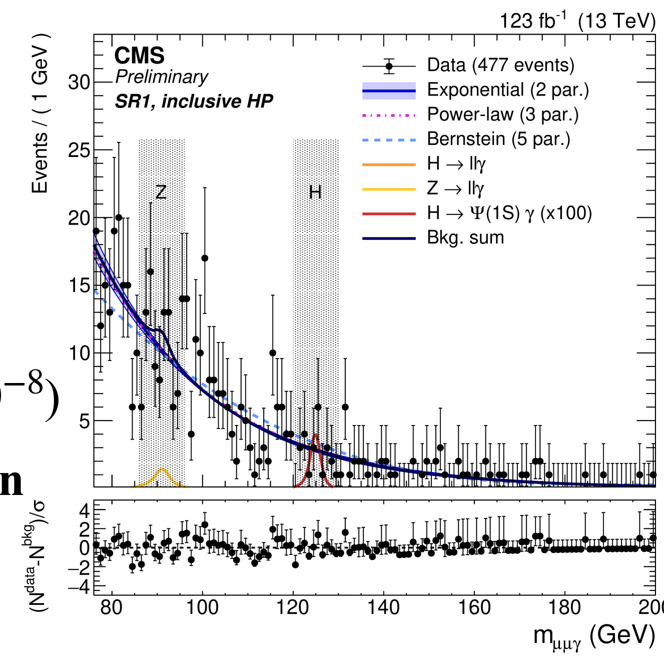


SM branching fraction predictions

$\mathscr{B}(H \rightarrow J/\psi + \gamma) = (2.95 \pm 0.17) \times 10^{-6}$

$\mathscr{B}(H \rightarrow \psi(2S) + \gamma) = (1.03 \pm 0.06) \times 10^{-6}$

- $J/\psi\ /\psi(2S) \rightarrow \mu\mu$ decays considered in the analysis
  - **Final state with two muons** and **one isolated photon**
- Analysis **exploring also the Z boson decays** (expected $\mathscr{B}$~10^{-8})
- Event **categorisation** to **target** the **different Higgs production mechanisms**

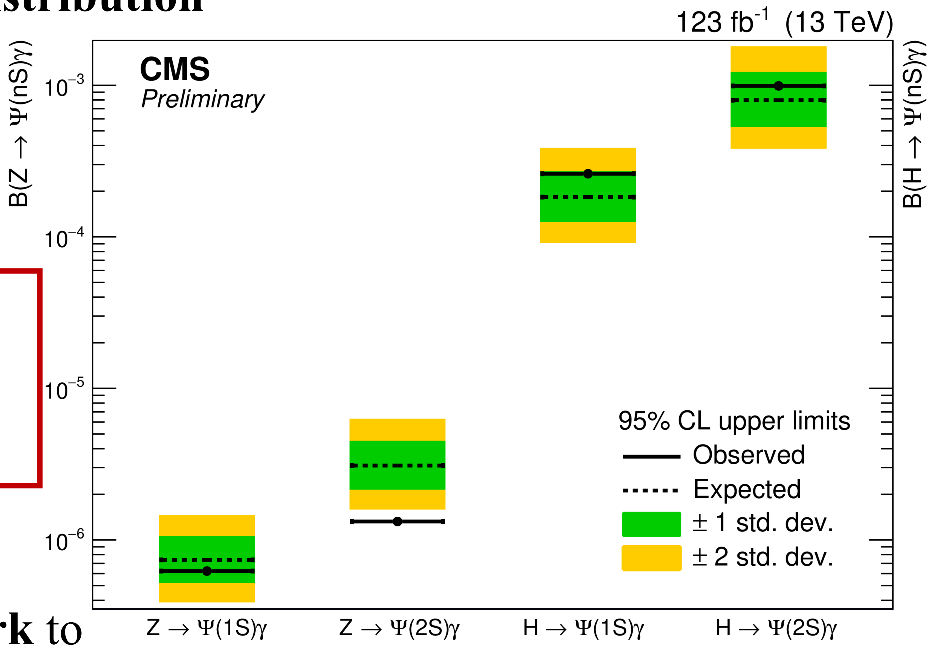


$H \rightarrow J/\psi\, /\, \psi(2S) + \gamma$ analysis: results

- Results extracted performing a **fit to the $m_{\mu\mu\gamma}$ distribution**
- **No evidence for $\mathscr{B}$ to these rare decays** larger than the one predicted by the SM

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

Up to **factor 2x improvement** wrt previous publication

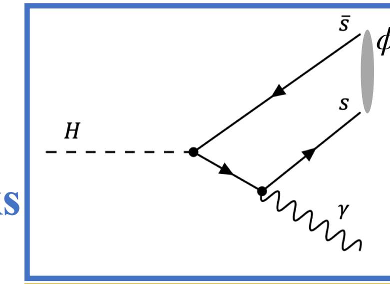


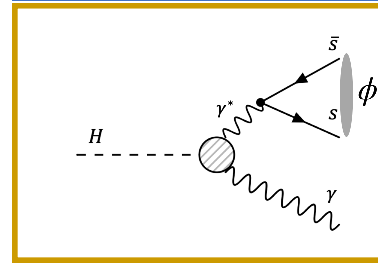
- Signal strength interpreted with the ***k*-framework** to derive **constraints on $H \rightarrow c\bar{c}$ coupling**
  - $\mu(H \rightarrow J/\psi + \gamma)\, /\, \mu(H \rightarrow \gamma\gamma) \sim k_c\, /\, k_\gamma$
  - **Observed** (expected) **constraint @ 95% CL: -157 < k_c / k_γ < 199** (-121 < k_c / k_γ < 161)
- Both branching ratio limits and k_c / k_γ constraints **comparable** to the **one reported by ATLAS** (Eur. Phys. J. C 83 (2023) 781)

arXiv.2410.18289

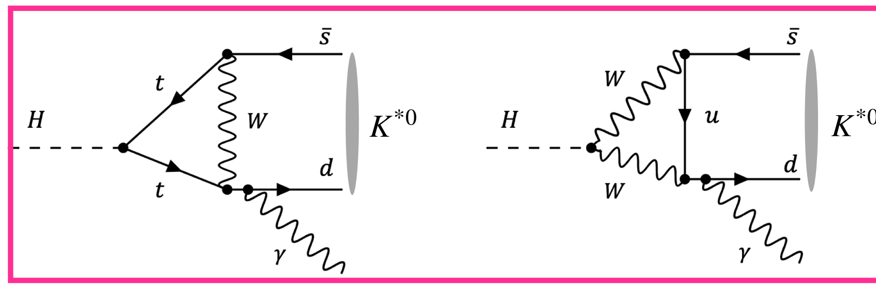
$H \to \rho\,/\,\phi\,/\,K^{*0} + \gamma$ analysis

- H decays to light-flavoured meson
  - $H \to \rho\,/\,\phi + \gamma$: study the **Higgs coupling to light-quarks** (u, d, s)
    - **Diagram with the direct coupling** between **Higgs** and **light-quarks** is very small → main contribution from **diagram** with **Higgs into di-photon decay**, with one off-shell photon.
  - $H \to K^{*0} + \gamma$: probe the **flavour changing neutral current**





- **SM predicted branching ratios**
  - $\mathcal{B}(H \to \rho + \gamma) = (1.68 \pm 0.08) \times 10^{-5}$
  - $\mathcal{B}(H \to \phi + \gamma) = (2.31 \pm 0.11) \times 10^{-6}$
  - $\mathcal{B}(H \to K^{*0} + \gamma) \sim 10^{-19}$
- Subsequent decays of the light mesons:
  - $\rho \to \pi^+\pi^-$ ($\mathcal{B} \sim 100\%$)
  - $\phi \to K^+K^-$ ($\mathcal{B} \sim 49\%$)
  - $K^{*0} \to K^\pm\pi^\mp$ ($\mathcal{B} \sim 100\%$)



- Analysis targeting the **three main Higgs production modes** at LHC (ggF, VBF, VH)
- **Final state** with **one photon** + **2 tracks** to identify the meson decays into K or π
  - Additional requirements depending on the target production mode

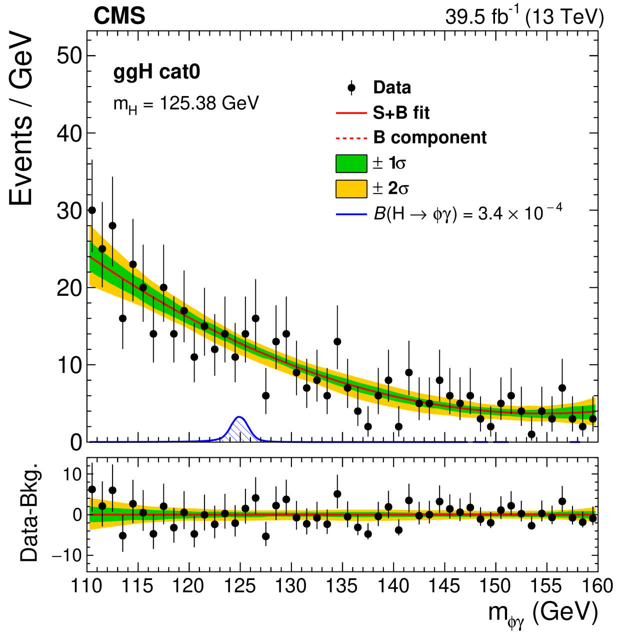
More details in Anusree's talk

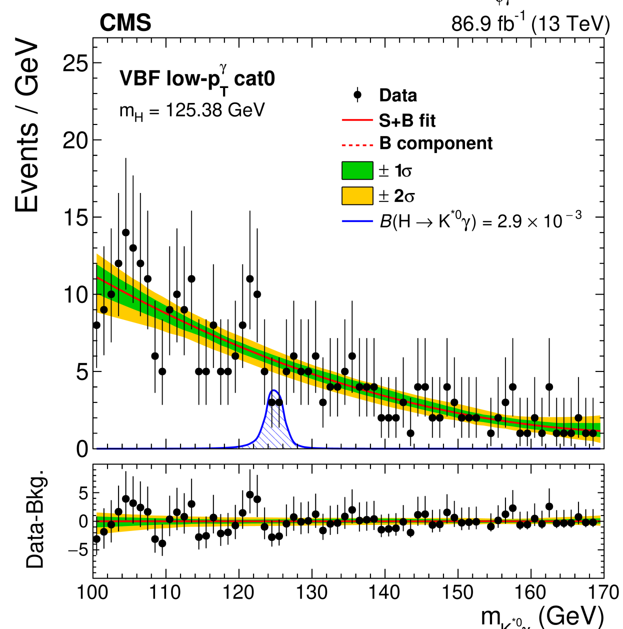
$H \rightarrow \rho \,/\, \phi \,/\, K^{*0} + \gamma$ analysis: results

- Main **background** from **γ+jets and multi-jet processes**
  - Modelled using the **Chebychev polynomial function** using the data sidebands
- **Signal** modelled using **Double-Sided Crystal Ball function**
  - Parameters extracted from MC samples
- **Unbinned maximum likelihood fit** on $m_{M\gamma}$ distributions
- No excess over the bkg expectations
- **Upper limits @ 95% CL on the branching ratios**

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

Most stringent limits to date on $\rho + \gamma$ and $\phi + \gamma$ decays channels!





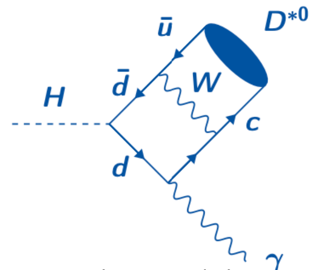
- Compatible results from ATLAS Collaboration (JHEP 07 (2018) 127, Phys. Lett. B 847 (2023) 138292)

More details in Anusree's talk

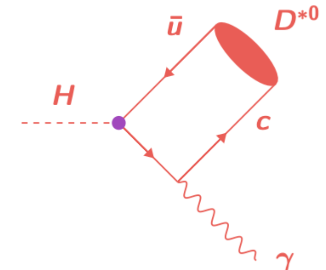
Phys. Lett. B 855 (2024) 138762

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

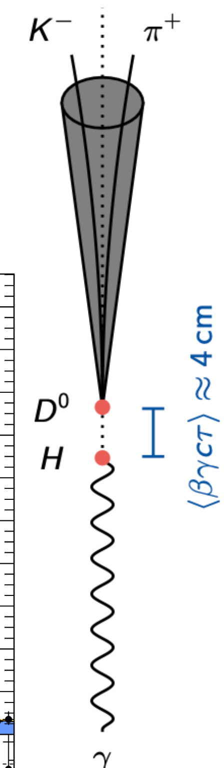
SM diagram

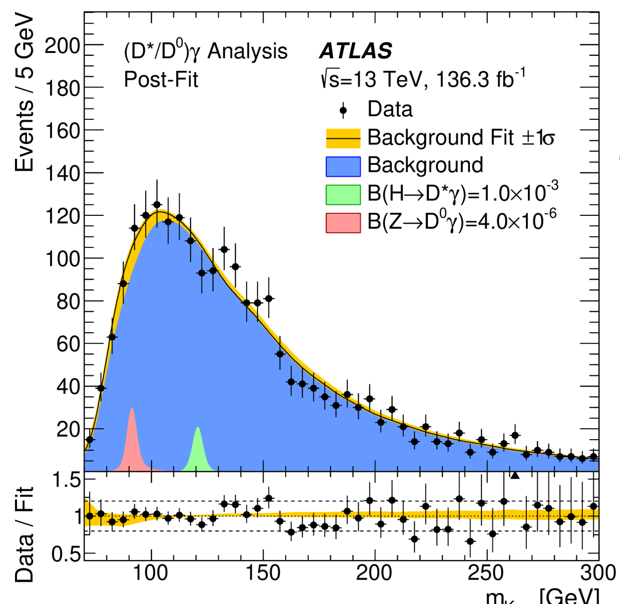


non-SM diagram



- $H \to D^* + \gamma$ allows to
  - study the **Higgs coupling to light-quarks** (u, d, s)
  - probe the **flavour changing Yukawa interactions**
- $\mathscr{B}(H \to D^* + \gamma) \sim 10^{-27} \to$ observation of this decay at LHC is an hint of BSM!
- Analysis exploits also $Z \to D^0 + \gamma$ and $Z \to K_s^0 + \gamma$
- Almost all D^* decays into $D^0 + \gamma$ or $D^0 + \pi^0$
  - Focus on $D^0 \to K^+\pi^-$ decay ($\mathscr{B} \sim 4\%$)
- **Final state** characterised by a distinctive signature:
  - **two isolated tracks against a photon** + **displaced vertex** due to a meson decay*
- Bkg dominated by **γ+jet and multi-jet processes**
  - Modelled with data-driven techniques





*no attempt to reconstruct the soft γ or π^0 from the D^* decay

$H \to D^* + \gamma$ analysis: results

[Phys. Lett. B 855 (2024) 138762]

- **No** significant **signal** is **observed** in any channel

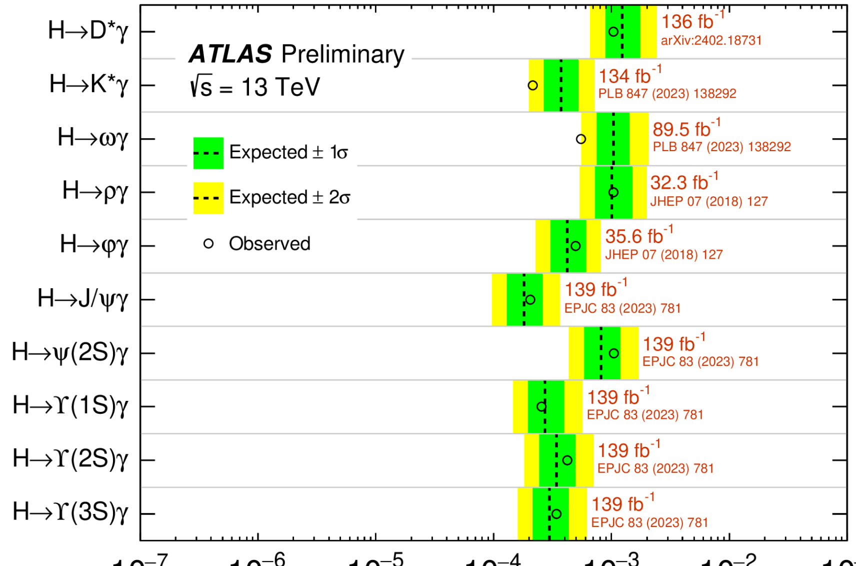
	95% CL upper limit	
	Expected	**Observed**
$\mathcal{B}(H \to D^{*0}\gamma)$	$(1.2^{+0.5}_{-0.3}) \times 10^{-3}$	$\mathbf{1.0 \times 10^{-3}}$
$\mathcal{B}(Z \to D^{0}\gamma)$	$(3.4^{+1.4}_{-1.0}) \times 10^{-6}$	$\mathbf{4.0 \times 10^{-6}}$
$\mathcal{B}(Z \to K^0_S\gamma)$	$(3.0^{+1.3}_{-0.8}) \times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

Fist limits on $H \to D^* + \gamma$ and $Z \to K^0_s + \gamma$ decays!

Enormous improvement (500x) on existing $Z \to D^0 + \gamma$ limit from LHCb

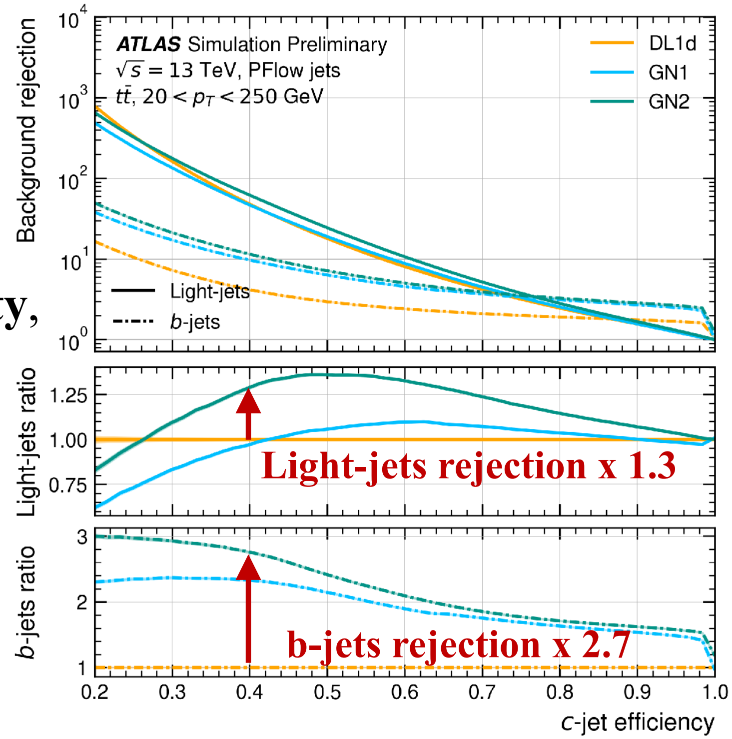
- **These latest limits complement a much broader programme of Higgs decays searches in ATLAS**

[ATL-PHYS-PUB-2023-004]



Conclusions

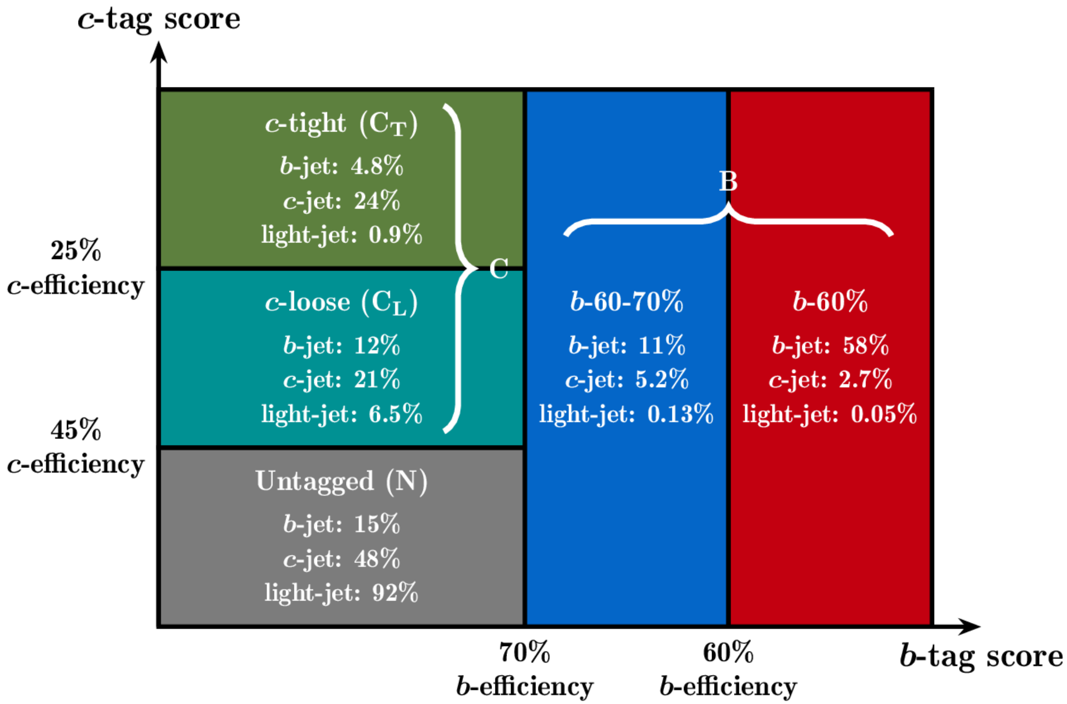
- ATLAS and CMS Collaborations have **searched** for **rare Higgs decays**
  - Study Higgs Yukawa coupling to second generation fermions:
    - ★**Improved constraints on the c-quark Yukawa coupling** from $VH(c\bar{c})$ analysis
    - ★**First evidence** of the $H \rightarrow \mu\mu$ **decay**
  - ★**First evidence** of $H \rightarrow Z + \gamma$ **rare 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 potential to observe many rare Higgs boson decays**.



Stay tuned, more interesting results are coming!

Back-up slides

$VH(\to c\bar{c})$ analysis: flavour tagging

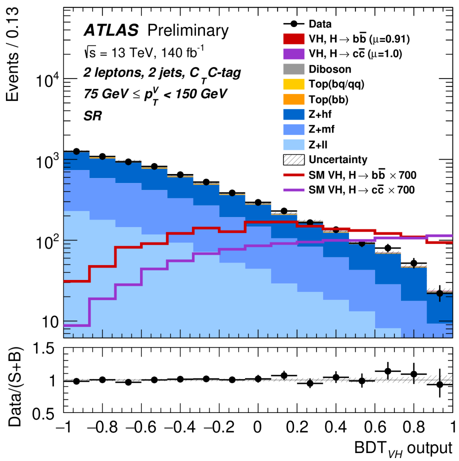


- DL1r tagger: deep neural network tagger that, for each jets, outputs the probabilities of being originated from a b- , c- or light quark
- b- and c-tagging working point definitions obtained orthogonally
- Dedicated calibrations performed for these MPs
    - Calibration precision O(10%) for c-jets and O(3%) for b-jers

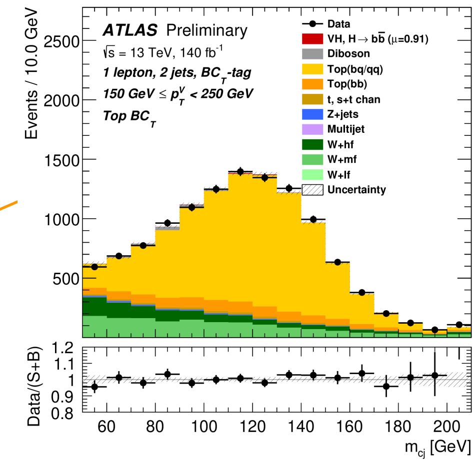
arXiv:2410.19611

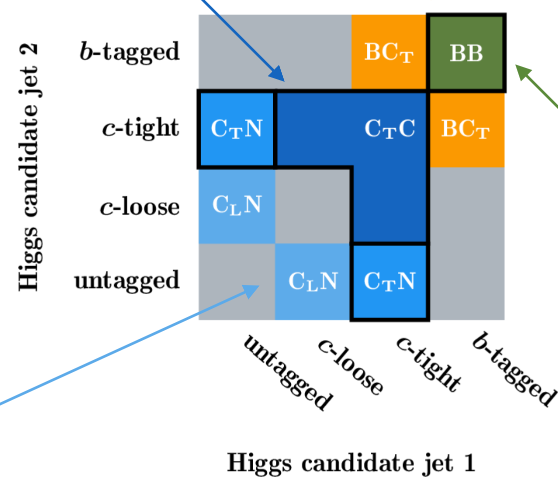
$VH(\to c\bar{c})$ analysis: bb/cc categories

cc SR

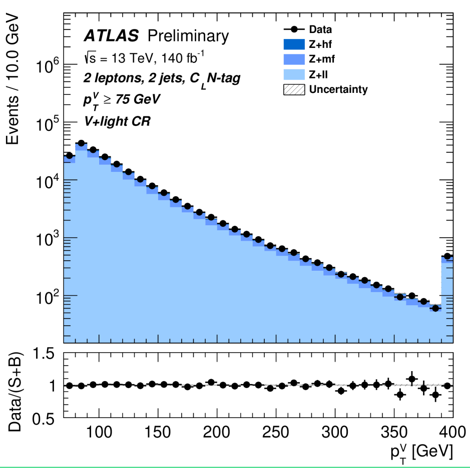


TopCRs

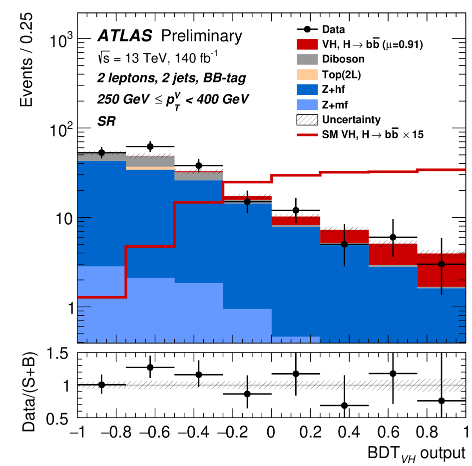




V+light CR

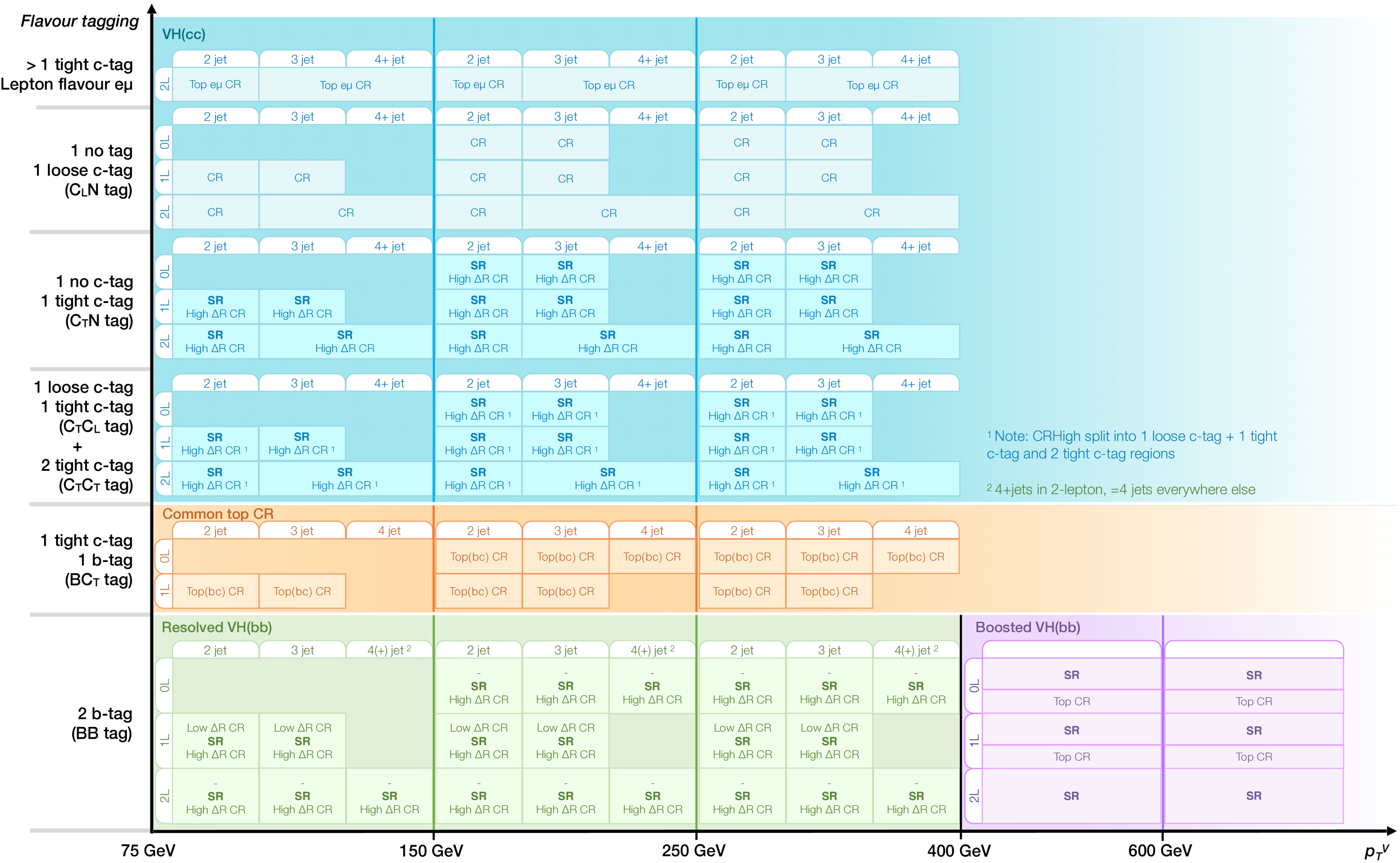


bb SR



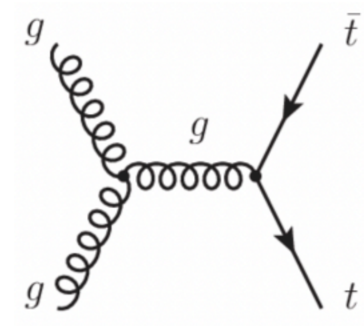
arXiv:2410.19611

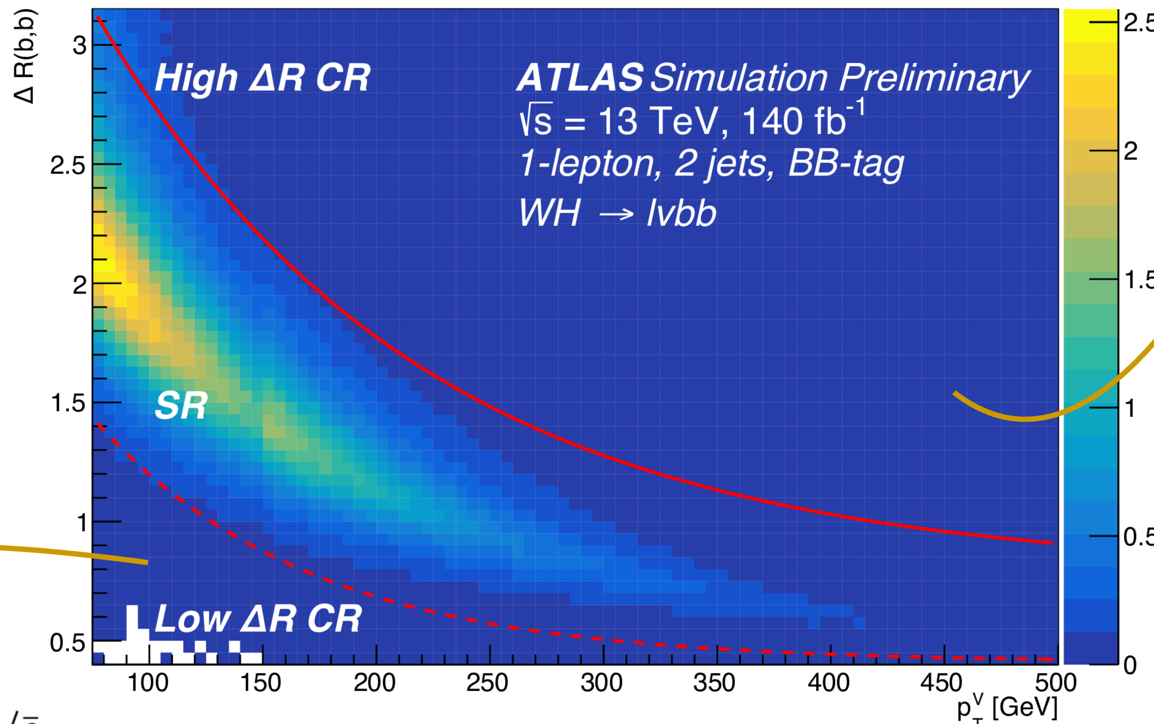
$VH(\rightarrow c\bar{c})$ analysis: SRs/CRs definition

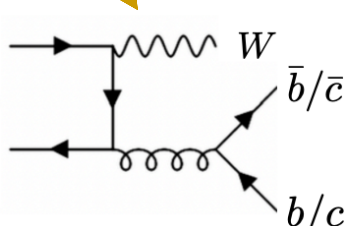


arXiv:2410.19611

$VH(\to c\bar{c})$ analysis: SRs/CRs definition







arXiv:2410.19611

$VH(\rightarrow c\bar{c})$ analysis: NFs

Z+jets

p_T^V region	num. jet	$Z+hf$	$Z+mf$	$Z+lf$
[75,150] GeV	2	1.20 ± 0.04	1.04 ± 0.04	1.12 ± 0.03
	≥3	1.49 ± 0.06	1.11 ± 0.05	1.12 ± 0.05
	3/≥3	0.77 ± 0.03	–	–
[150,250] GeV	2	1.30 ± 0.04	1.08 ± 0.04	1.17 ± 0.02
	≥3	1.59 ± 0.07	1.14± 0.05	1.17 ± 0.04
	3/≥3	0.80 ± 0.04	–	–
[250,400] GeV	2	1.40 ± 0.07	1.31 ± 0.08	1.16 ± 0.03
	≥3	1.78 ± 0.09	1.32 ± 0.07	1.20 ± 0.04
	3/≥3	0.74 ± 0.04	–	–
>400 GeV	-	1.63 ± 0.13		–

W+jets

p_T^V region	num. jet	$W+hf$	$W+mf$	$W+lf$
[75,150] GeV	2	1.09 ± 0.06	1.20 ± 0.03	1.03 ± 0.04
	≥3	1.30 ± 0.07	1.16 ± 0.04	1.07 ± 0.05
[150,250] GeV	2	1.00 ± 0.05	1.31 ± 0.03	1.08 ± 0.03
	≥3	1.28 ± 0.07	1.31 ± 0.04	1.07 ± 0.04
[250,400] GeV	2	0.97 ± 0.08	1.35 ± 0.07	1.05 ± 0.03
	≥3	1.46 ± 0.12	1.32 ± 0.07	1.10 ± 0.04
[400,600] GeV	-	1.49 ± 0.25		–
>600 GeV	-	2.03 ± 0.25		–

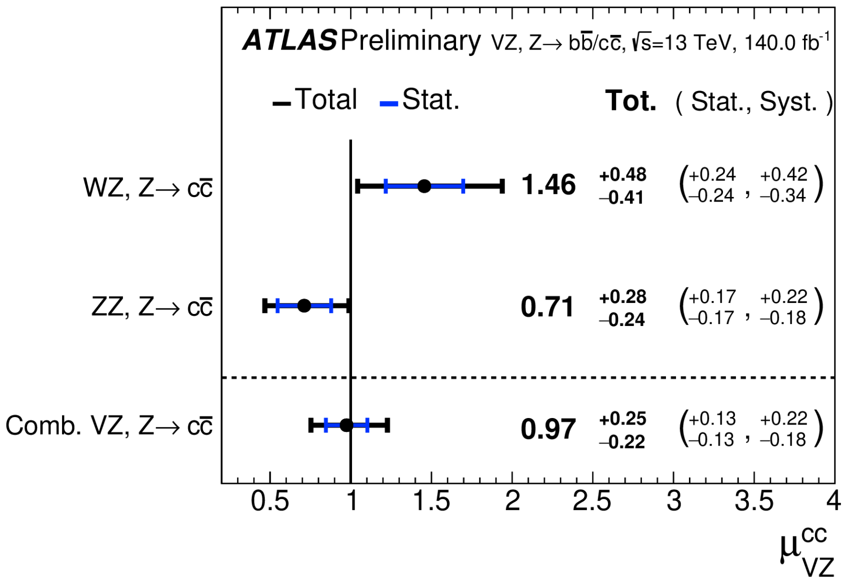
Top NFs

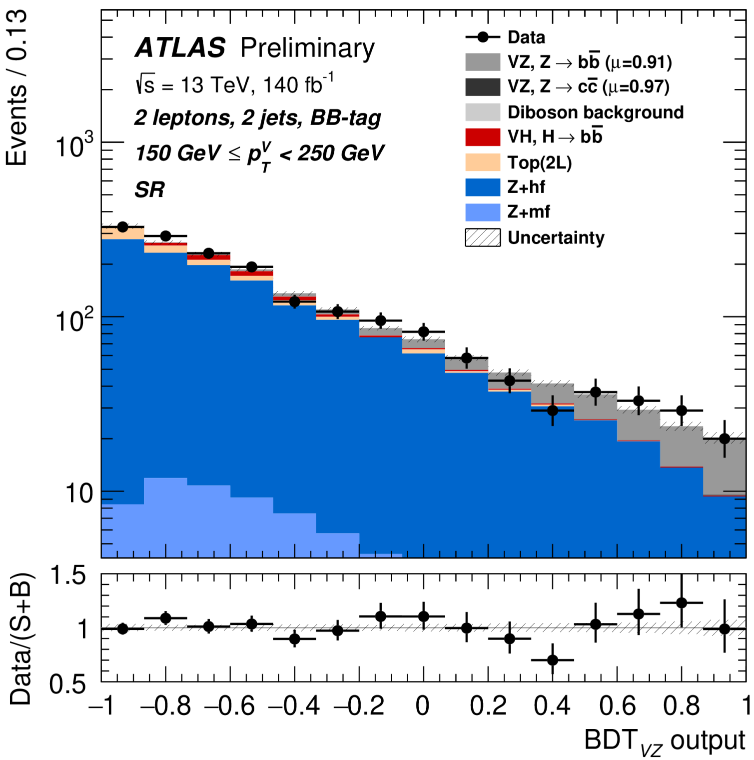
p_T^V region	num. jet	Top(bb)	Top(bq,qq)	Top 2L
[75,150] GeV	2	1.02 ± 0.04	0.98 ± 0.05	1.05 ± 0.05
	3	0.97 ± 0.03	0.98 ± 0.03	0.98 ± 0.05
[150,250] GeV	2	0.89 ± 0.05	0.83 ± 0.04	1.07 ± 0.16
	3	0.91 ± 0.03	0.86 ± 0.03	0.95 ± 0.14
	4	0.97 ± 0.02	0.95 ± 0.03	
[250,400] GeV	2	0.78 ± 0.08	0.82 ± 0.05	1.10 ± 0.50
	3	0.83 ± 0.04	0.80 ± 0.03	
	4	0.93 ± 0.05	0.86 ± 0.04	
[400,600] GeV	-	0.83 ± 0.05		–
>600 GeV	-	0.69 ± 0.07		–

*V+hf = V+bb, V+cc
V+mf = V+bc, V+bl, V+cl

$VH(\to c\bar{c})$ analysis: diboson channel

- BDT trained using VZ as signal
  - Powerful check to test the robustness of the analysis
- Sensitivity
  - WZ(cc) : 3.9 observed (2.7 expected) σ
  - ZZ(cc): 3.1 observed (4.2 expected) σ





First observation of VZ(cc) at 5 σ

$VH(\to c\bar{c})$ analysis: breakdown

Source of uncertainty	σ_μ			
	$VH, H \to b\bar{b}$	$WH, H \to b\bar{b}$	$ZH, H \to b\bar{b}$	$VH, H \to c\bar{c}$
Total	0.153	0.204	0.216	5.31
Statistical	0.097	0.139	0.153	3.94
Systematic	0.118	0.149	0.153	3.57
Statistical uncertainties				
Data statistical	0.090	0.129	0.139	3.67
$t\bar{t}$ $e\mu$ control region	0.009	0.014	0.027	0.08
Background floating normalisations	0.034	0.049	0.042	1.24
Other VH floating normalisation	0.007	0.018	0.014	0.33
Simulation samples size	0.023	0.033	0.030	1.62
Experimental uncertainties				
Jets	0.027	0.035	0.030	1.02
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.010	0.005	0.021	0.23
Leptons	0.003	0.002	0.010	0.25
b-tagging: b-jets	0.020	0.018	0.026	0.29
b-tagging: c-jets	0.013	0.017	0.012	0.73
b-tagging: light-flavour jets	0.005	0.008	0.008	0.66
Pile-up	0.008	0.017	0.002	0.23
Luminosity	0.006	0.007	0.006	0.08
Theoretical and modelling uncertainties				
Signal	0.076	0.074	0.101	0.72
Z + jets	0.042	0.018	0.081	1.77
W + jets	0.054	0.087	0.026	1.42
$t\bar{t}$ and Wt	0.018	0.033	0.018	1.02
Single top-quark (s-, t-ch.)	0.010	0.018	0.002	0.16
Diboson	0.033	0.039	0.049	0.52
Multijet	0.005	0.010	0.005	0.55

WH and ZH signal strength affected by:

- V+jets modelling
- Jet and flavour systs

VH(cc) signal strength affected by:

- V+jets modelling
- Jet and flavour systs
- MC stat unc.

$VH(\rightarrow c\bar{c}/bb)$ analysis: improvements

- Updates wrt previous single analysis:
  - Better object reconstruction/calibration
  - Improved b/c-tagging algorithms
  - Re-optimized MVA, firstly applied to boosted VH(bb) and VH(cc)
  - Updated SRs/CRs, improved bkgs estimation

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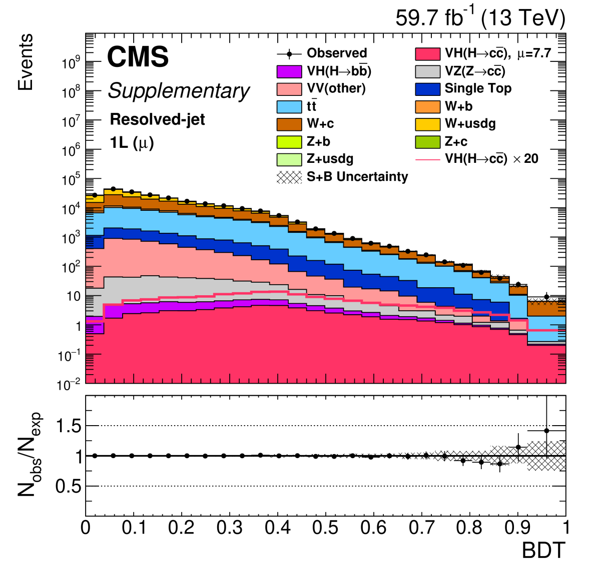
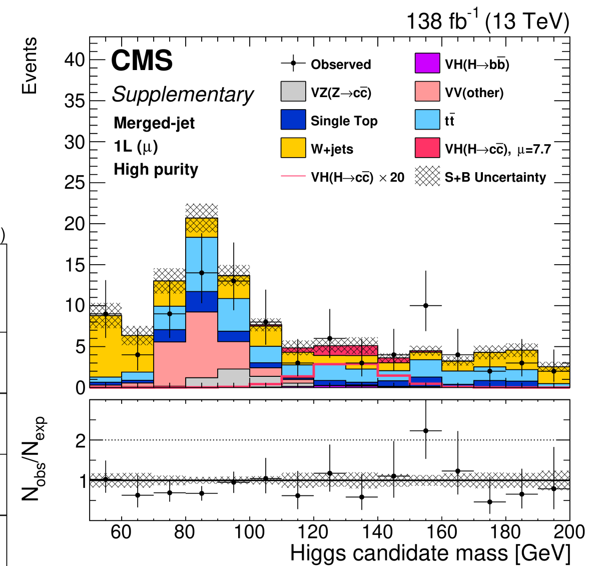
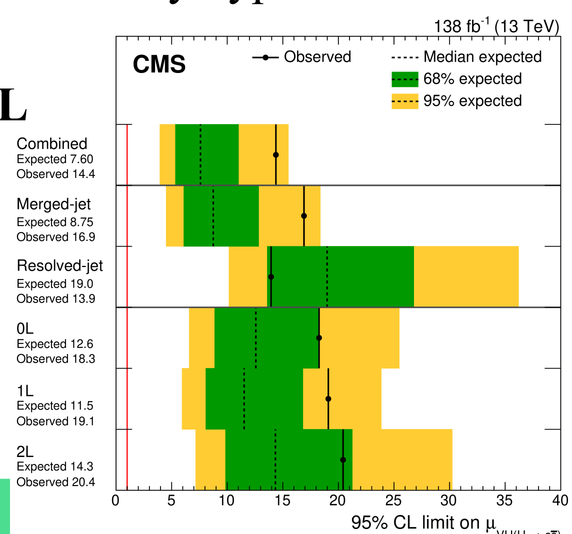
$VH(\rightarrow c\bar{c})$ analysis

- Analysis is studying both resolved and boosted regimes
  - Separation at $p_T(H)$=300 GeV
- Events categorised to target the 3 leptonic VH production mode
- BDT used to discriminate signal vs background
  - +15-20% improvement in sensitivity
- Final discriminant:
  - BDT score distribution in the resolved regime
  - m_H distribution in the boosted regime
- No significant excess over the background only hypothesis
- Observed (expected) **upper limits on μ_{VH}^{cc} of 14.4 (7.8) x SM @ 95% CL**





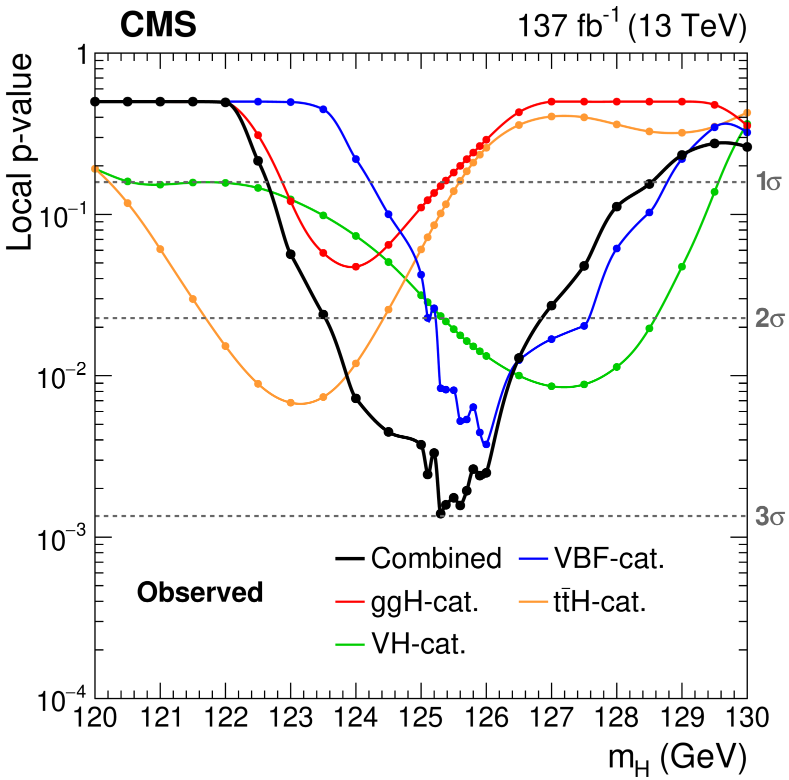


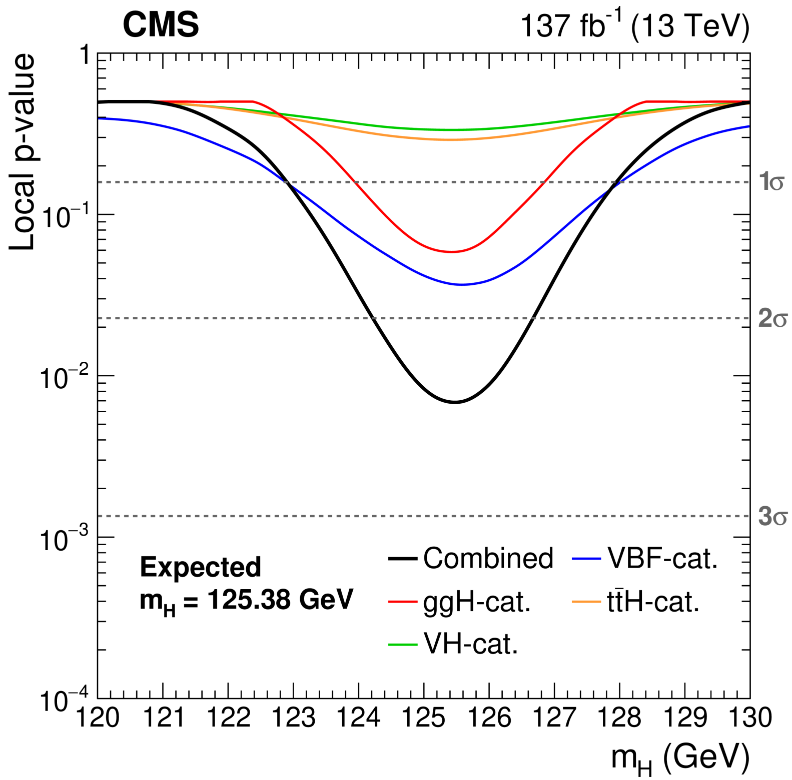
arXiv:2407.15550

$H(\to \gamma\gamma) + c$ analysis: sys breakdown

Uncertainty	$H + c$ uncertainty impact
Statistical (incl. GPR)	79%
GPR posterior	47%
Systematic (excl. GPR)	61%
Theory	40%
Photons	29%
c-tagging	29%
Jets	22%
Spurious signal	12%
Pile-up	5%

$H \to \mu\mu$ analysis: p-values





- **VBF category** has the highest expected sensitivity to H → $\mu\mu$

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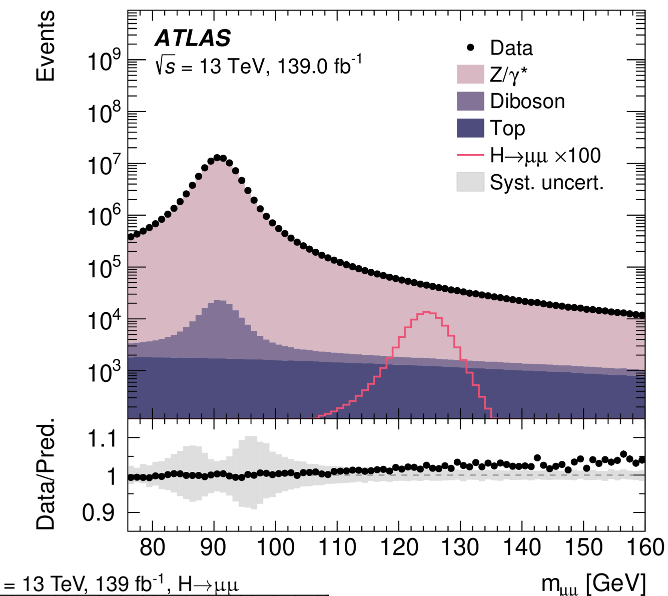
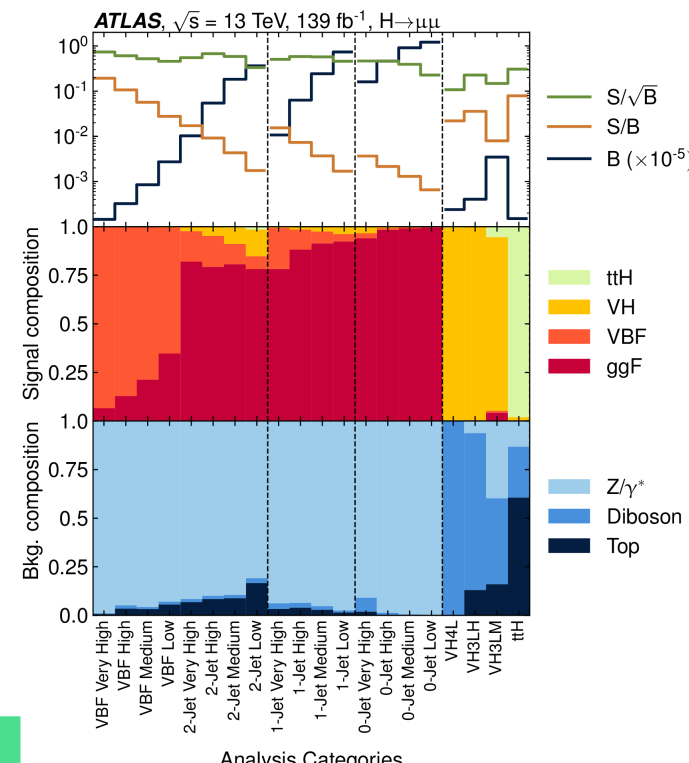
$H \rightarrow \mu\mu$ analysis

- Main experimental challenges
  - Rare process ($\mathscr{B}(H \rightarrow \mu\mu) \sim 10^{-4}$)
  - Large bkg from Drell-Yan production
  - ➡ S/B ~ 0.2% in the SR (120 GeV < $m_{\mu\mu}$ < 130 GeV)
- Analysis target main Higgs production modes @ LHC
- Events categorised in 20 regions, using BDTs for each production modes





More details in Enrique's talk

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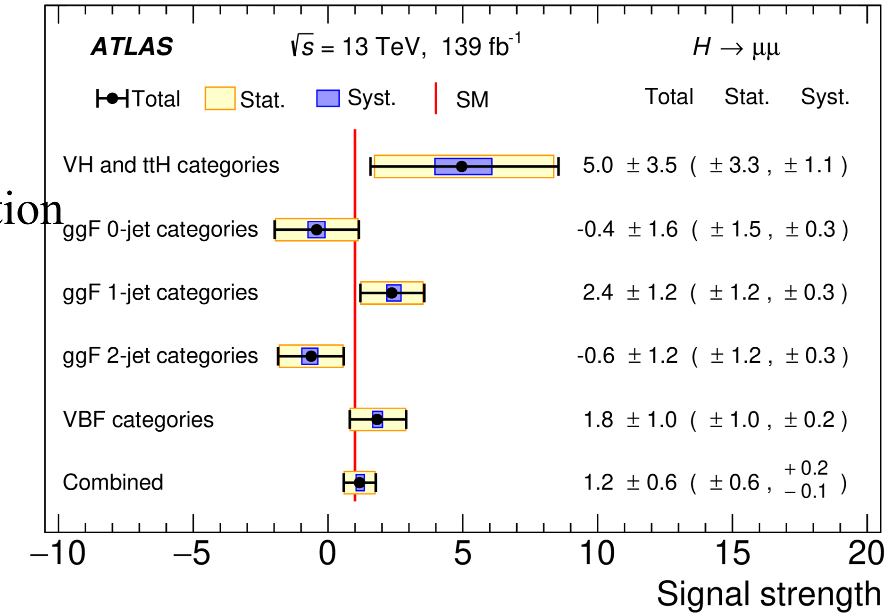
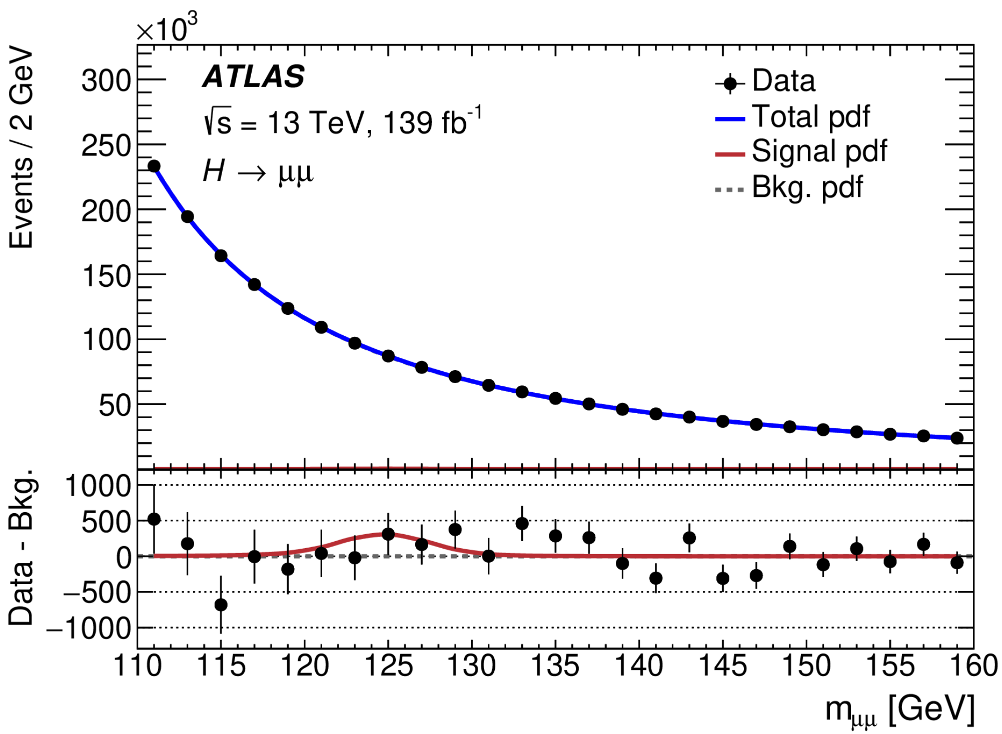
ATLAS EXPERIMENT

$H \to \mu\mu$ analysis: results

- **Fit to** $m_{\mu\mu}$ performed between **110-160 GeV**
- **Signal** modelling: **double-sided crystal ball** function
- **Bkg** modelling using **empirical function**





- Best fit signal strength: 1.2 ± 0.6
- Observed $\mathscr{B}$ limit @ 95% CL: $< \mathbf{4.7} \times 10^{-4}$
- Significance: $2.0\,\sigma$ (1.7σ) observed (expected)

More details in Enrique's talk