Higgs Boson Decays to Second Generation Fermions and other Higgs Boson Rare Decays at the ATLAS experiment

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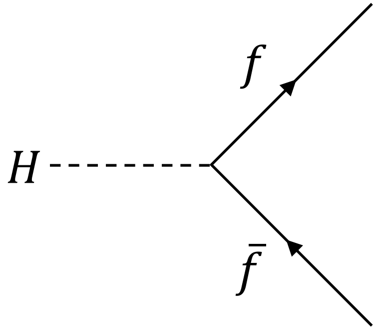
Overview

- The Higgs boson, H, couples to fermions via Yukawa couplings, y_f
  - In the SM these are proportional to fermion mass, m_f:

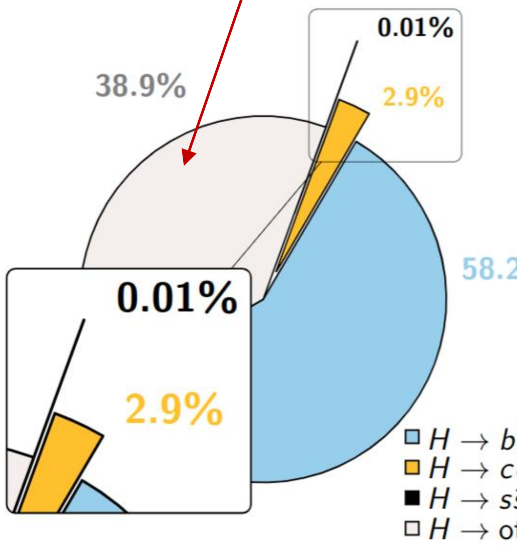
$$y_f^{SM} = \frac{m_f}{v}\sqrt{2}$$

    - Predicts fermion interactions, but doesn't explain the mass hierarchy
    - Deviations of y_f from SM predictions could provide hints to new physics
  - H couplings to 3rd generation fermions have been established experimentally
    - **2nd generation is the next frontier**
- ATLAS has several analyses investigating H decays to 2nd generation fermions, and other rare H decay modes:
  - $H \to \mu^+\mu^-$ and $H \to e^+e^-$
  - $H \to c\bar{c}$ via the VH production mode
  - Exclusive H decays to a meson and a photon, including $H \to J/\psi\,\gamma$
  - $H \to \gamma\gamma^* \to \ell^+\ell^-\gamma$ and $H \to Z\gamma \to \ell^+\ell^-\gamma$

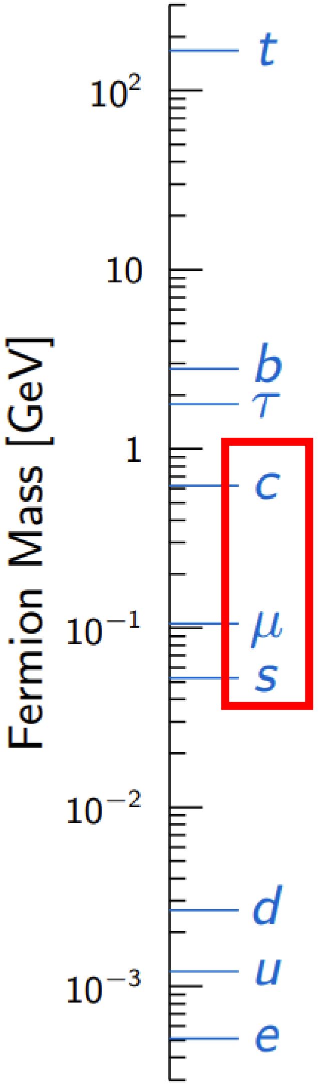
$v \approx 246$ GeV



$BR^{SM}_{H\to\mu^+\mu^-} \approx 10^{-4}$



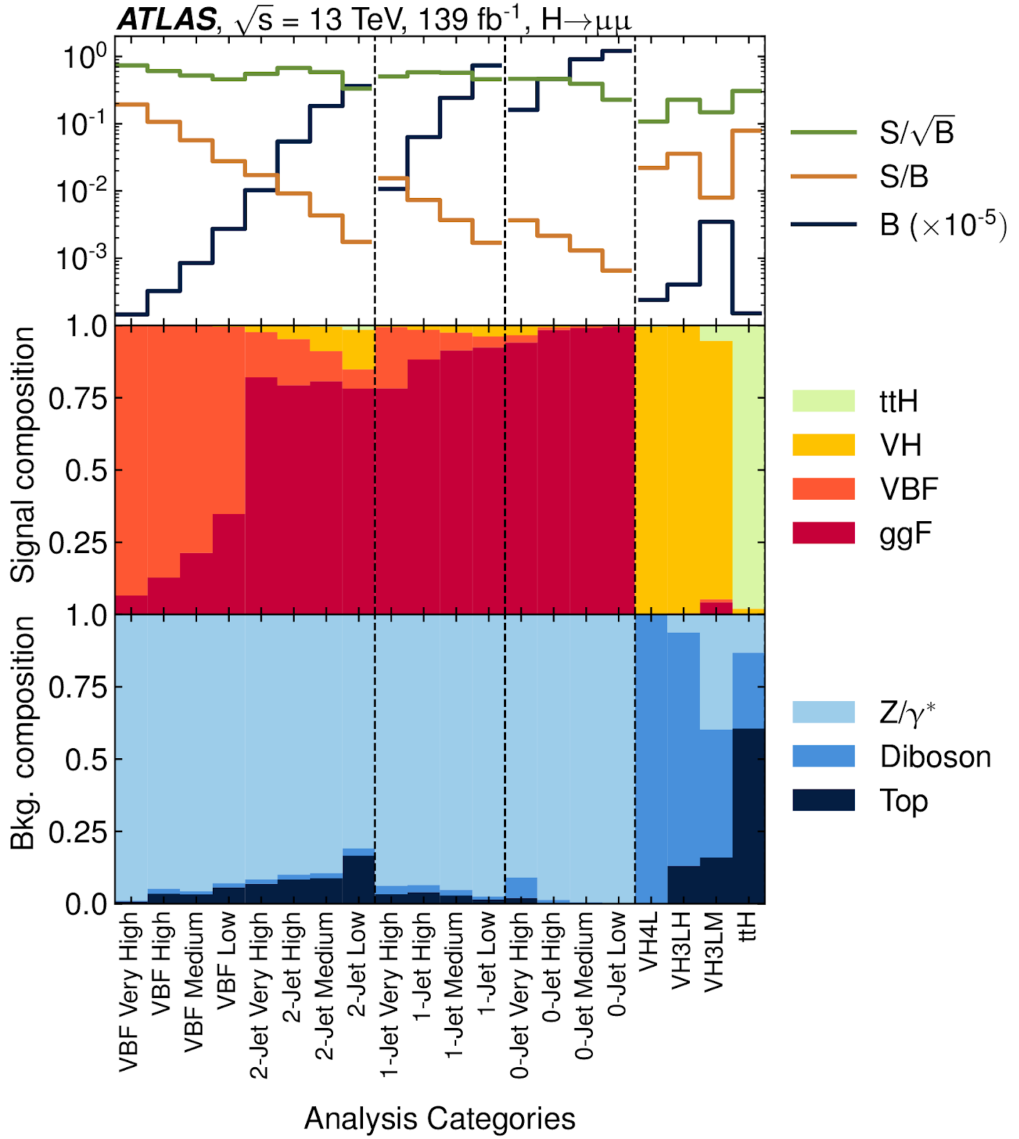
$BR^{SM}_{H\to q\bar{q}}$



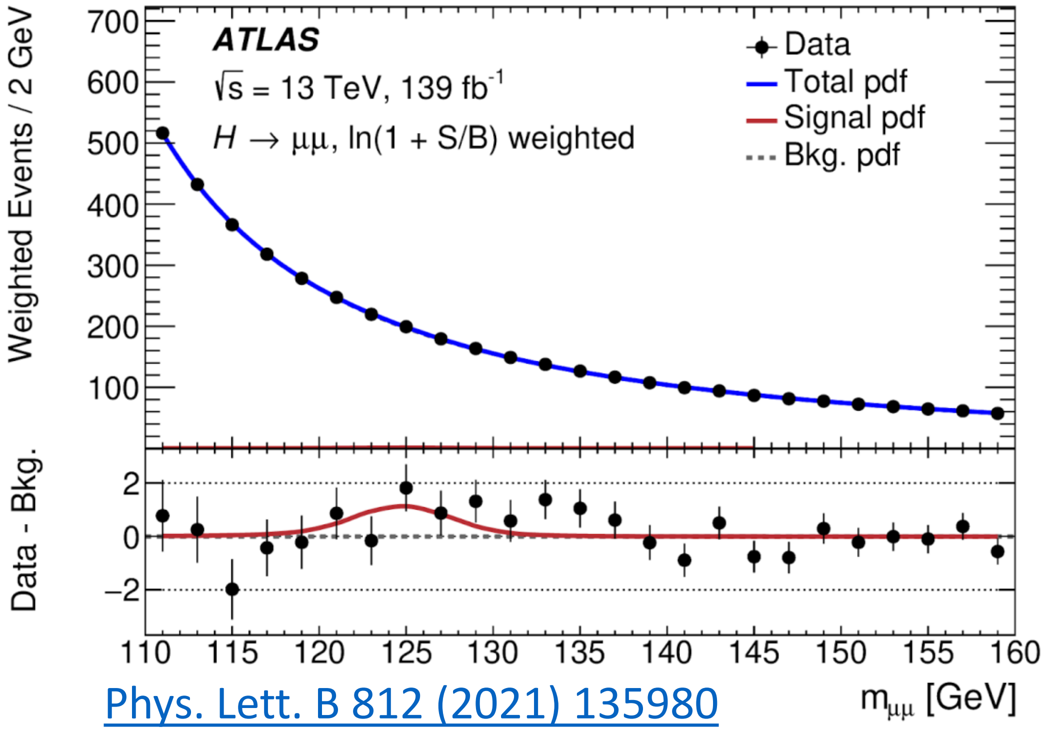
Search for $H \rightarrow \mu^+\mu^-$: 139 fb^{-1} Analysis Strategy

- $H \rightarrow \mu^+\mu^-$ directly probes the magnitude of y_μ
  - $BR^{\text{SM}}_{H\rightarrow\mu^+\mu^-} = (2.17 \pm 0.04) \times 10^{-4}$
  - Most promising 2nd generation decay to observe at the LHC
- Use single muon triggers
- Categorise events according to H production mode ($t\bar{t}H$, VH, VBF, and ggF)
  - Divide production modes into sub-categories using process-specific boosted decision trees
  - S/B between $120 - 130$ GeV ranges from $< 0.1\%$ to 18%
    - 0.2% inclusive
  - Signal resolution $\approx 2\%$ in total
- Model main Drell-Yan background with LO DY line-shape × empirical functions constrained in data

Phys. Lett. B 812 (2021) 135980

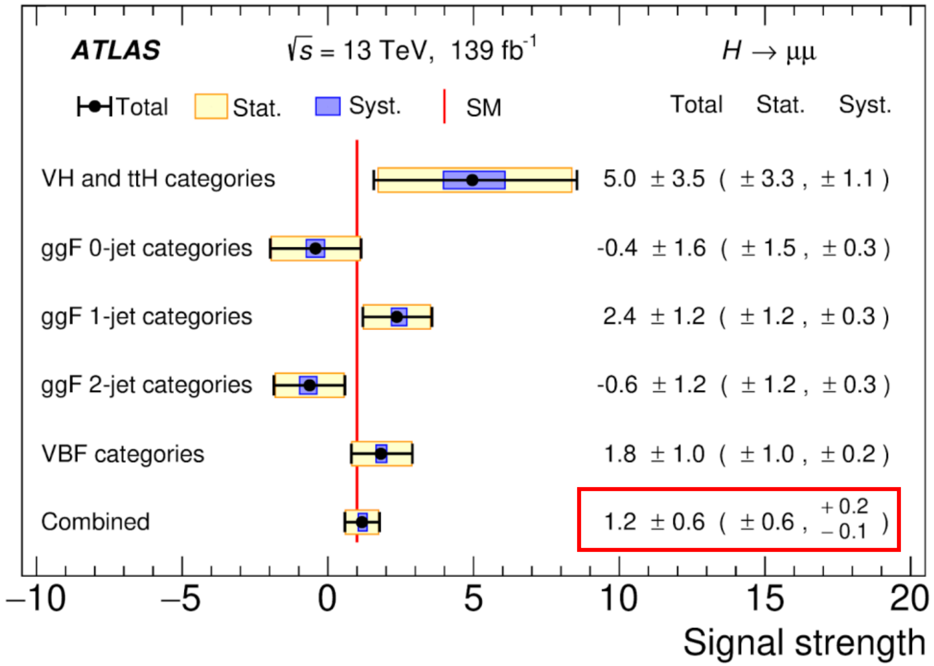


Search for $H \rightarrow \mu^+\mu^-$: 139 fb^{-1} Analysis Results



Phys. Lett. B 812 (2021) 135980

- Binned (0.1 GeV) likelihood fit in $m(\mu^+\mu^-)$ between $110 - 160$ GeV
- Observed (expected) signal:
  - 2.0σ (1.7σ)
- Observed (expected with SM) 95% CL upper limit:
  - $BR(H \rightarrow \mu^+\mu^-) < 4.7\ (2.4) \times 10^{-4} = 2.2\ (2.0) \times \mathrm{SM}$

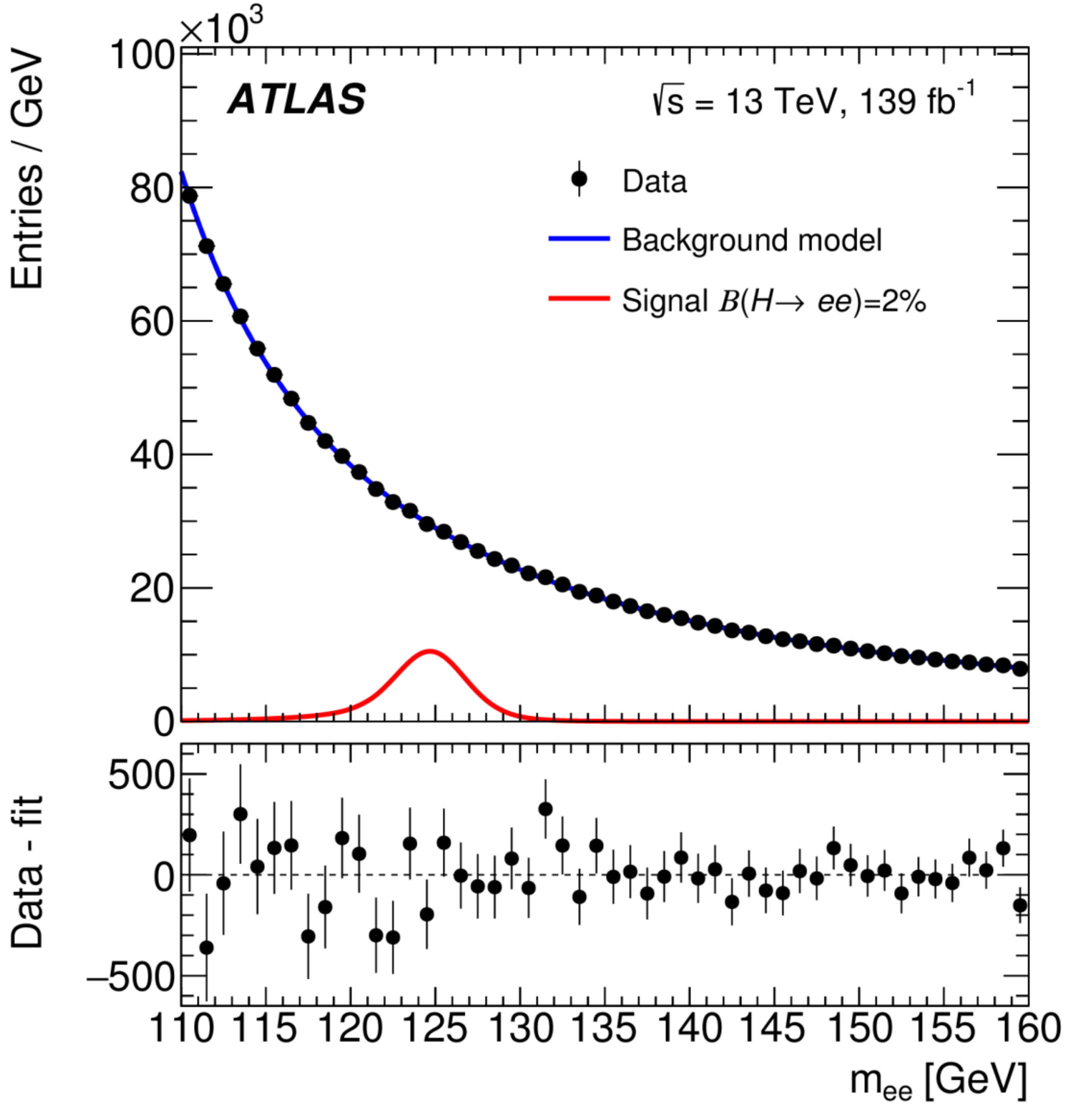


- Uncertainty on signal strength dominated by statistics
  - Main systematics are signal theory uncertainties $(^{+0.13}_{-0.08})$ and spurious-signal uncertainties (± 0.1)
- Improvement of a factor 2.5 compared to 36.1 fb^{-1} ATLAS result
  - Factor of 2 from larger dataset, and an additional 25% from refined event categorisation and improved background modelling

Search for $H \to e^+e^-$: 139 fb^{-1} Analysis Overview

- $H \to e^+e^-$ directly probes the magnitude of y_e
  - $BR^{SM}_{H\to e^+e^-} \approx 10^{-9}$
- Analysis strategy based on 36.1 fb^{-1} $H \to \mu^+\mu^-$ analysis*
  - Main background from DY process
  - Binned likelihood fit to $m(e^+e^-)$ between $110 - 160$ GeV
- Observed (expected) limits @ 95% CL:
  - $BR_{H\to e^+e^-} < 3.6\ (3.5) \times 10^{-4}$
- Include search for lepton flavour violating decay $H \to e\mu$
  - DY background significantly reduced
  - $BR_{H\to e\mu} < 6.2\ (5.9) \times 10^{-5}$

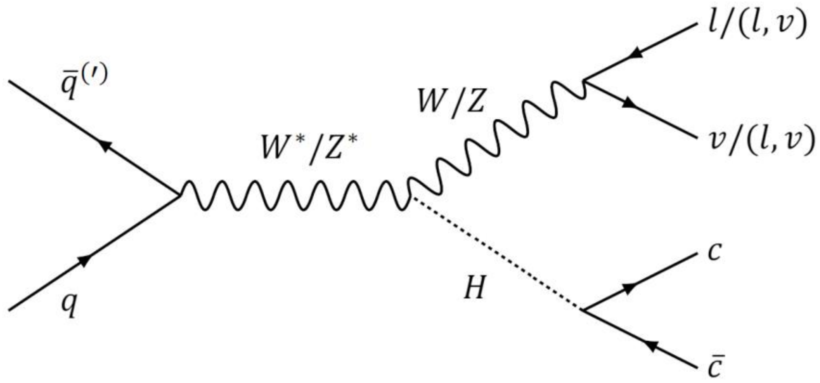
Phys. Lett. B 801 (2020) 135148

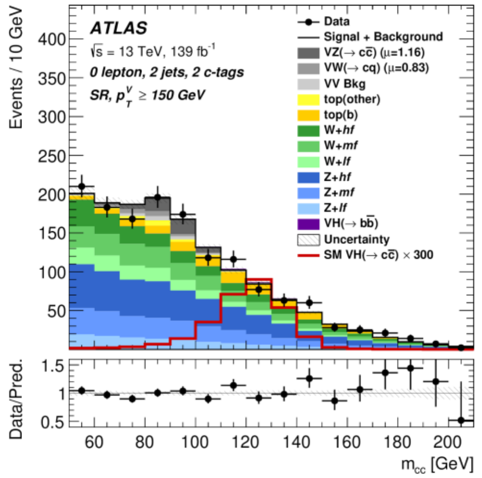


*Phys. Rev. Lett. 119 (2017) 051802

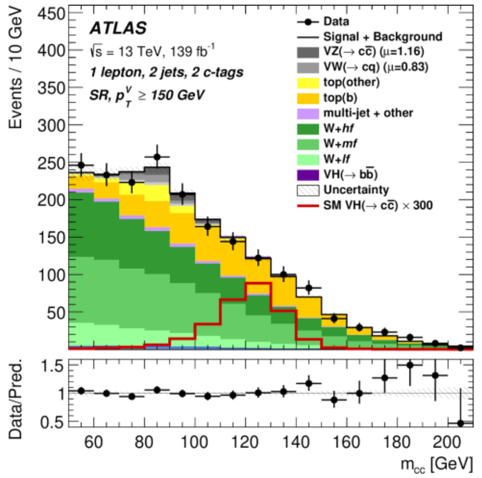
Search for $VH(\rightarrow c\bar{c})$: 139 fb^{-1} Analysis Strategy

- $H \rightarrow c\bar{c}$ directly probes the magnitude of y_c
  - $BR^{\mathrm{SM}}_{H\rightarrow c\bar{c}} = (2.88^{+0.16}_{-0.06})\%$, where $BR^{\mathrm{SM}}_{H\rightarrow b\bar{b}} \approx 20 \times BR^{\mathrm{SM}}_{H\rightarrow c\bar{c}}$
- Target $VH(\rightarrow c\bar{c})$; validate method with $VW(\rightarrow cq)$ and $VZ(\rightarrow c\bar{c})$
  - Better S/B compared to inclusive H production, especially at high p_{T}^{V}
  - Split into three channels:

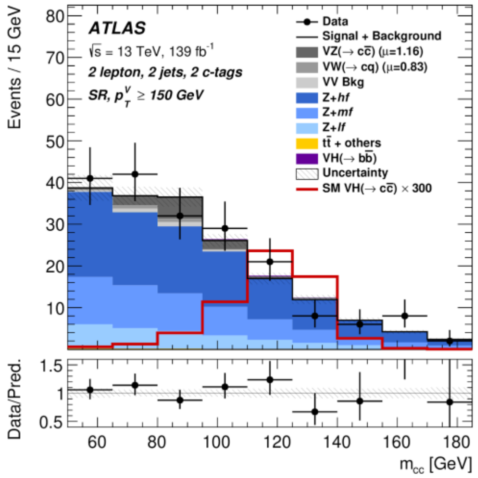




0-lepton: $Z(\rightarrow \nu\nu)H(\rightarrow c\bar{c})$
Missing E_{T} triggers

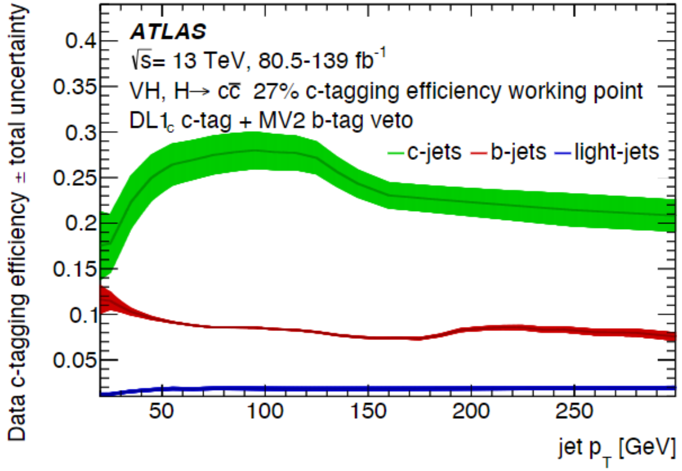


1-lepton: $W(\rightarrow \ell\nu)H(\rightarrow c\bar{c})$
Missing E_{T} and single lepton triggers



2-lepton: $Z(\rightarrow \ell\ell)H(\rightarrow c\bar{c})$
Single lepton triggers

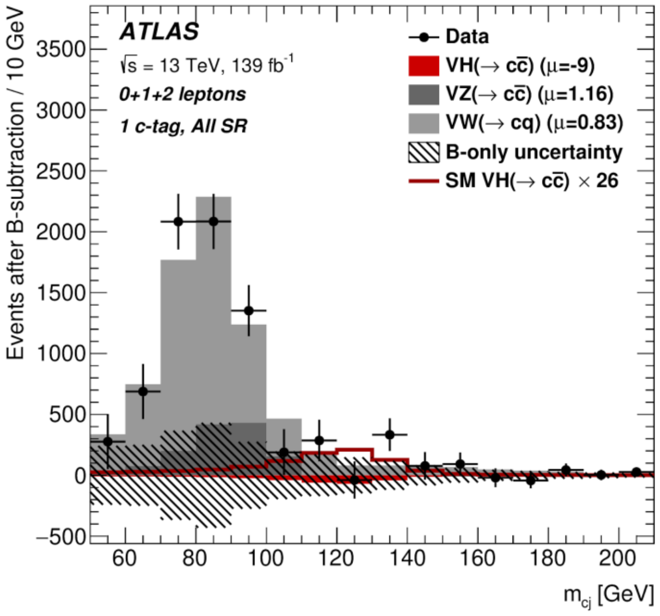
arXiv:2201.11428

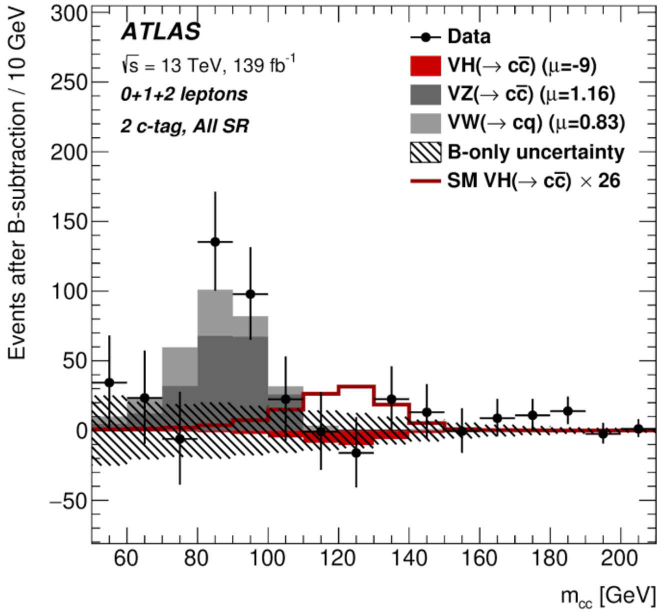


See talk on flavour tagging by A. Chisholm

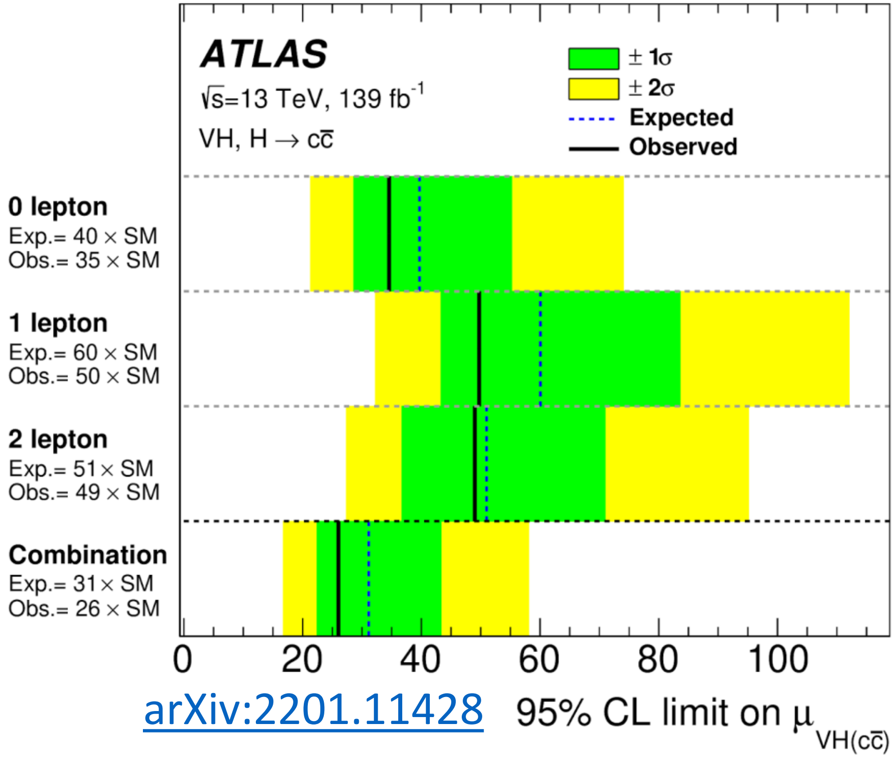
- Use an optimised c-jet tagger in event selection with a b-tag veto
  - Analysis is conceptually similar to $VH(\rightarrow b\bar{b})$ with an **orthogonal selection**

Search for $VH(\rightarrow c\bar{c})$: 139 fb^{-1} Analysis Results





- Observed (expected) significances:
  - $3.8\sigma\ (4.6\sigma)$ for $VW(cq)$
  - $2.6\sigma\ (2.2\sigma)$ for $VZ(c\bar{c})$
- Observed (expected) limit:
  - $BR_{H\rightarrow c\bar{c}} <\ 26\ (31) \times \text{SM}$ @ 95% CL



arXiv:2201.11428

- Statistical and systematic uncertainties similar in magnitude
  - Main systematics from the background modelling, dominated by Z + jets, followed by statistics of simulated samples
- Factor 5 improvement compared to 36.1 fb^{-1} result
  - Better flavour tagging gives 36% improvement (43% improvement with new 2-lepton signal/control regions)
  - Factor 2 improvement with increased dataset of 139 fb^{-1}
  - Further improvement from new 0-lepton and 1-lepton channels

Search for $VH(\to c\bar{c})$: κ_c Interpretation

- Define κ_c coupling modifier as the ratio of y_c over the SM-expectation:

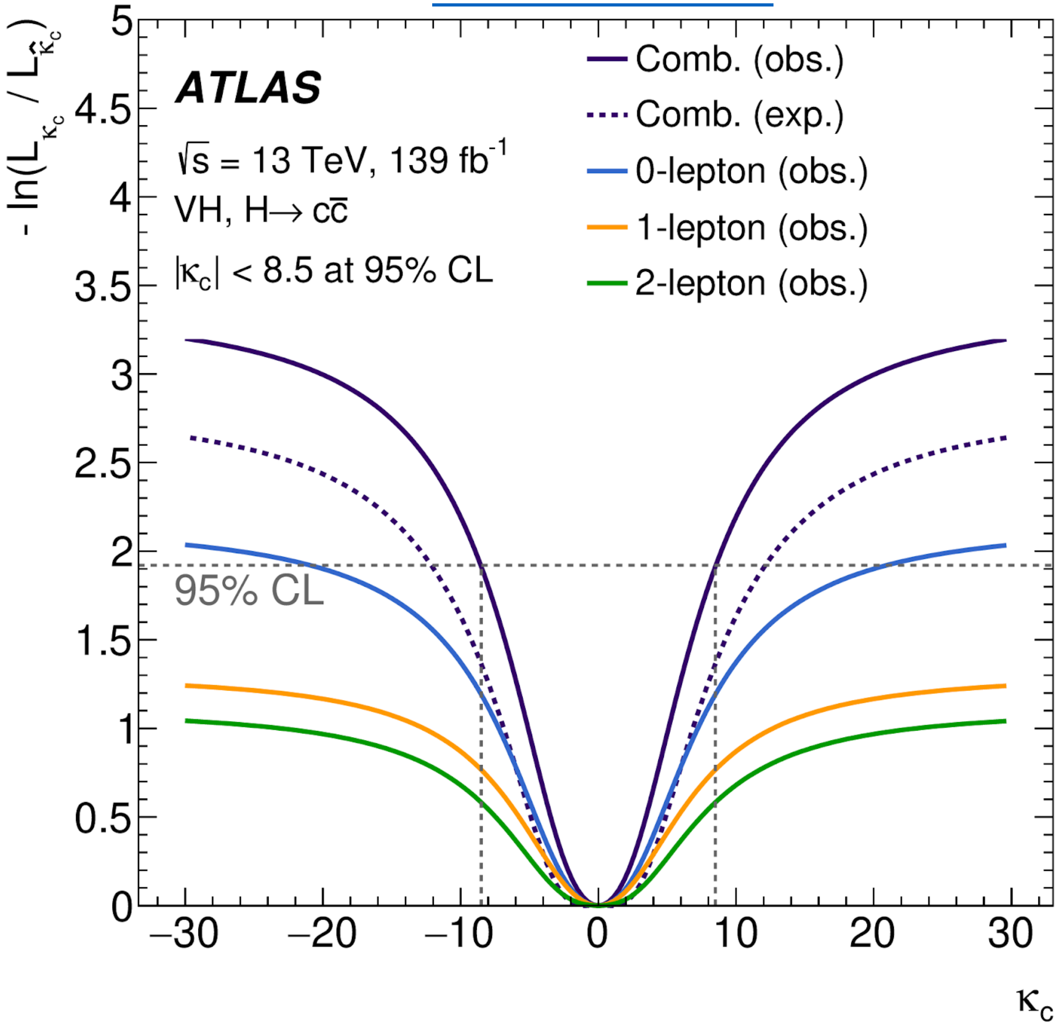
$$\kappa_c = \frac{y_c}{y_c^{\mathrm{SM}}}$$

- Parameterise $\mu_{VH(c\bar{c})}$ in terms of κ_c in maximum-likelihood fit:

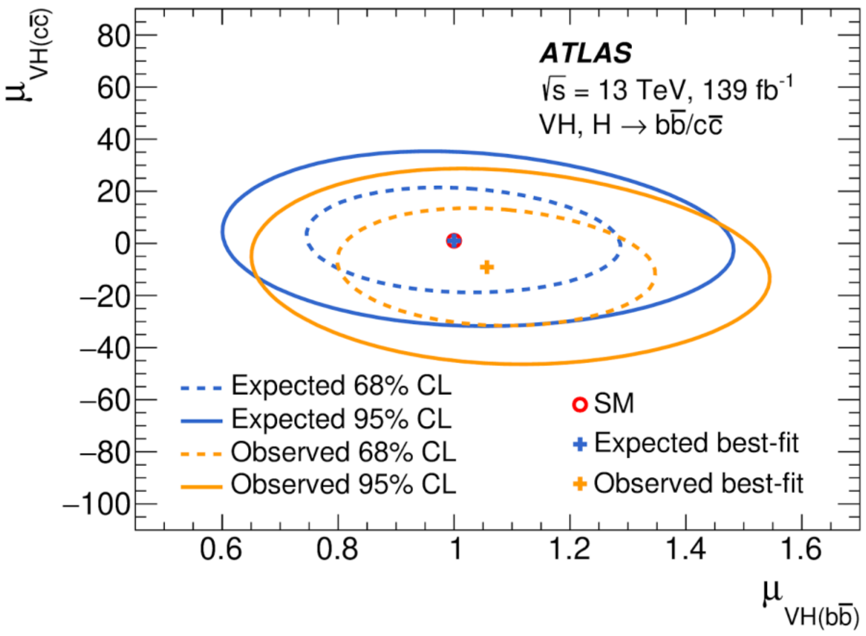
$$\mu_{VH(c\bar{c})}(\kappa_c) = \frac{\kappa_c^2}{1 + (\kappa_c^2 - 1) \times BR^{\mathrm{SM}}_{H\to c\bar{c}}}$$

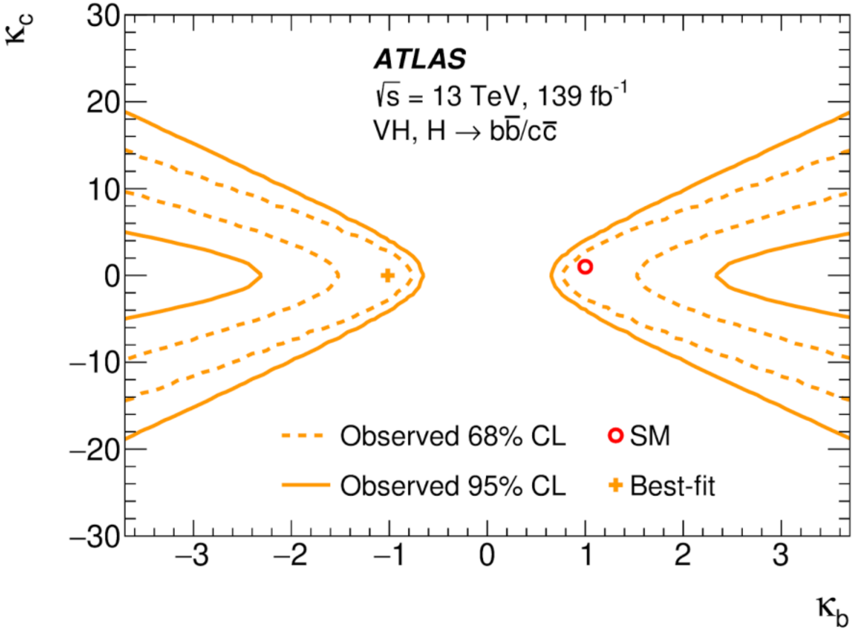
- Observed (expected) constraints:
  - $|\kappa_c| < 8.5\ (12.4)$ @ 95% CL

arXiv:2201.11428



Combination of 139 fb^{-1} $VH(\rightarrow c\bar{c})$ and $VH(\rightarrow b\bar{b})$





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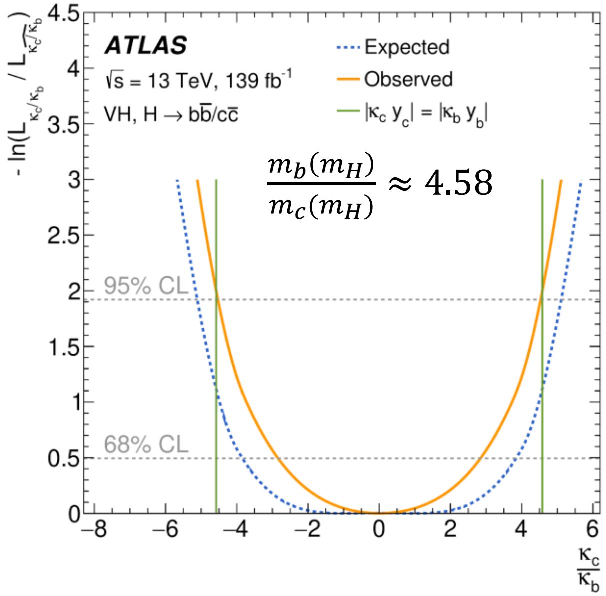
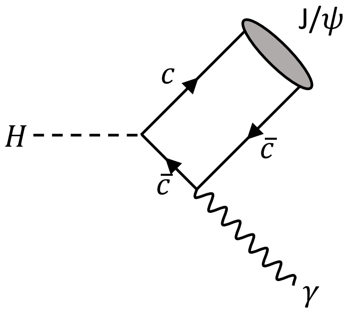


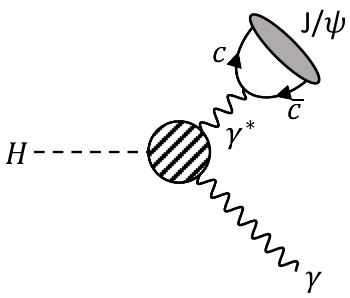
- Best fit value of $(\kappa_b, \kappa_c) = (-1.02, 0)$
  - Small asymmetry for κ_b in likelihood from b-quark loop contributions in $gg \rightarrow ZH$ production
  - Preference to negative κ_b is small: difference in log-likelihood between $(\pm 1.02, 0)$ is 0.02
- Observed (expected) constraints for κ_c/κ_b ratio:
  - $|\kappa_c/\kappa_b| < 4.5\ (5.1)$ @ 95% CL

Search for $H \to Q(\to \mu^+\mu^-)\gamma$: 139 fb^{-1} Analysis Strategy

- $H \to Q\gamma$ decays are sensitive to magnitude **and sign** of $y_{c,b}$
  - $\mathcal{A}_{\text{dir}}$ and $\mathcal{A}_{\text{ind}}$ contributions destructively interfere



Direct ($\mathcal{A}_{dir}$)



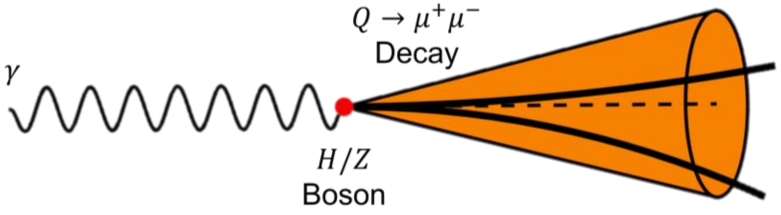
Indirect ($\mathcal{A}_{ind}$)

Charmonium: $Q = \mathrm{J}/\psi, \psi(2S)$

- $BR^{\text{SM}}_{H\to\psi(nS)\gamma} \approx 10^{-6}$ †
- $|\mathcal{A}_{\text{ind}}| \approx 20 \times |\mathcal{A}_{\text{dir}}|$

Bottomonium: $Q = \Upsilon(1S, 2S, 3S)$

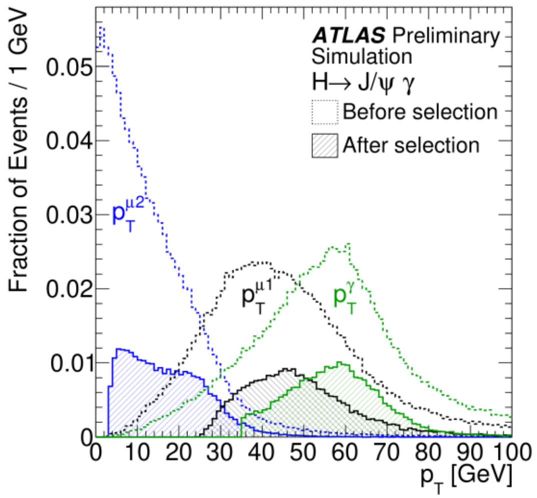
- $BR^{\text{SM}}_{H\to\Upsilon(nS)\gamma} \approx 10^{-9} - 10^{-8}$ †
- $\mathcal{A}_{\text{ind}}, \mathcal{A}_{\text{dir}}$ almost cancel in SM

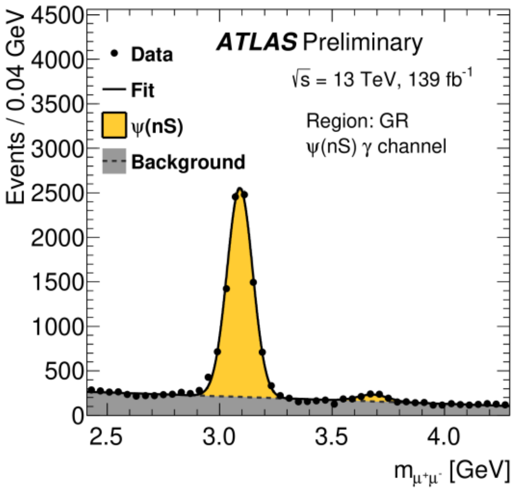


- Include analogous searches for $Z \to Q\gamma$: $BR^{\text{SM}}_{Z\to Q\gamma} \approx 10^{-8} - 10^{-7}$ ‡

- **Dedicated** combined single photon + muon triggers
  - Distinct signature in detector with small QCD backgrounds
- Split background model into two components
  - Inclusive: γ + jet and multi-jet events involving Q or $\mu^+\mu^-$
    - Non-parametric data-driven background model **– see talk by J. Silva**
  - Exclusive: $q\bar{q} \to \mu^+\mu^-\gamma$, modelled using MC

See my poster on this analysis for more details!



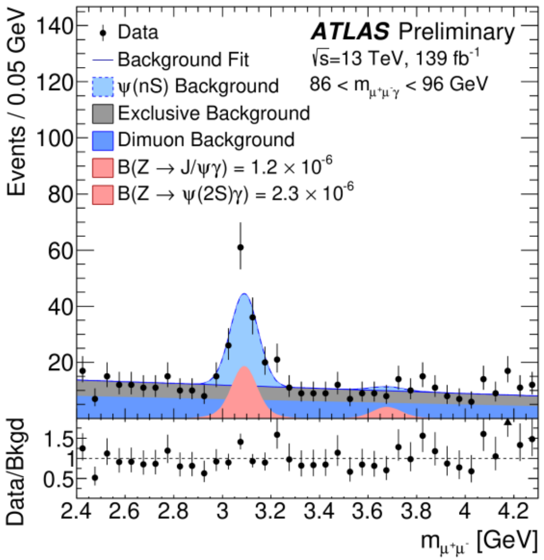


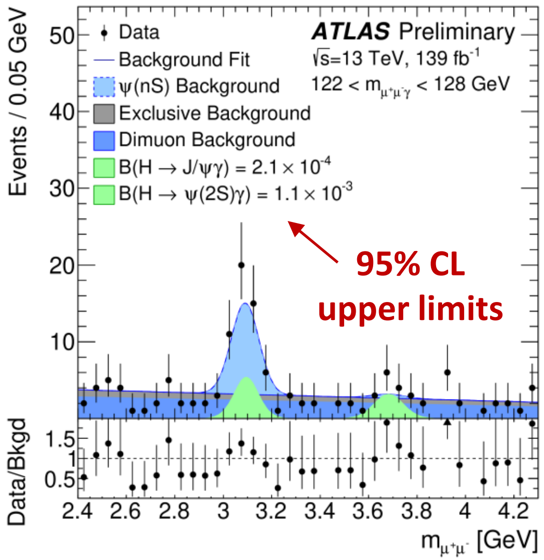
Preliminary Results

†Phys. Rev. D 100 (2019) 054038 ‡Phys. Rev. D 97 (2018) 016009

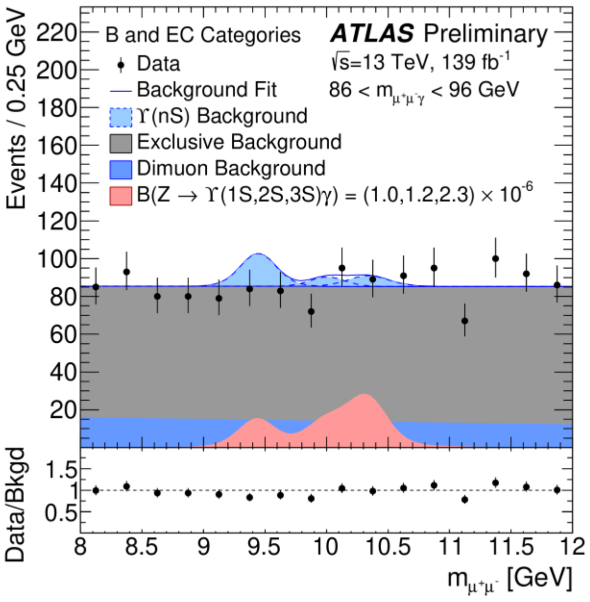
Search for $H \to Q(\to \mu^+\mu^-)\gamma$: 139 fb^{-1} Analysis Results

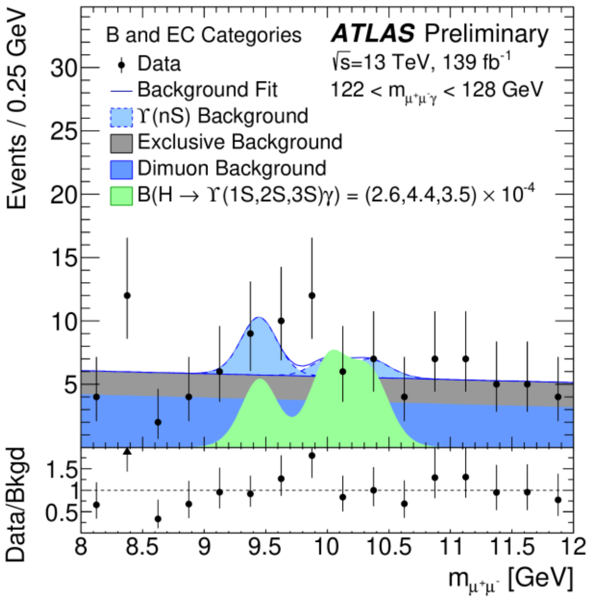
- Signal resolution $\approx$ 1.7% (simulate ggF, VBF, VH, $t\bar{t}H$)
- Use **2D** unbinned likelihood fit in $m(\mu^+\mu^-), m(\mu^+\mu^-\gamma)$
  - Discriminates between **all** signal and background contributions
- Statistical uncertainty dominates
  - Systematics reduce sensitivity to the H (Z) signals by at most 1% (5%)
  - Main systematics are in the inclusive background shape





Preliminary Results





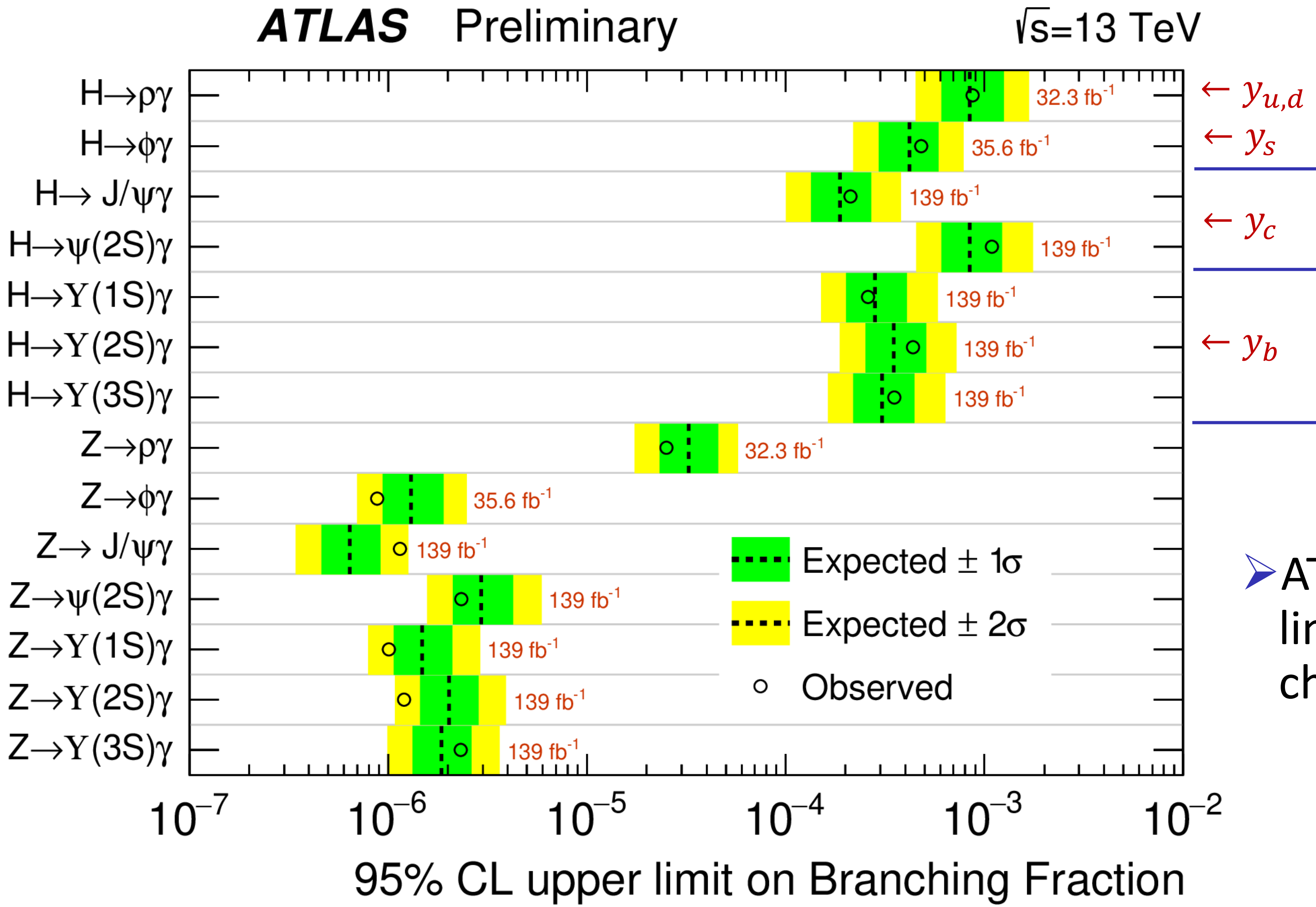
- Combine with $H \to \gamma\gamma$ § to interpret in terms of $\kappa_{c,b}/\kappa_\gamma$:

$$\frac{\mu_{H\to J/\psi\,\gamma}}{\mu_{H\to\gamma\gamma}} \approx \frac{\left|\mathcal{A}_{\text{ind}} + \frac{\kappa_c}{\kappa_\gamma}\mathcal{A}_{\text{dir}}\right|^2}{\Gamma^{\text{SM}}_{H\to J/\psi\,\gamma}}$$

- Observed (expected) bounds @ 95% CL:
  - κ_c/κ_γ: $[-136, 178]$ ($[-123, 164]$) from $H \to J/\psi\,\gamma$
  - κ_b/κ_γ: $[-38, 40]$ ($[-37, 40]$) from combined $H \to \Upsilon(nS)\gamma$

§ATLAS-CONF-2020-026

Summary of Exclusive $H \to M\gamma$ Search Results



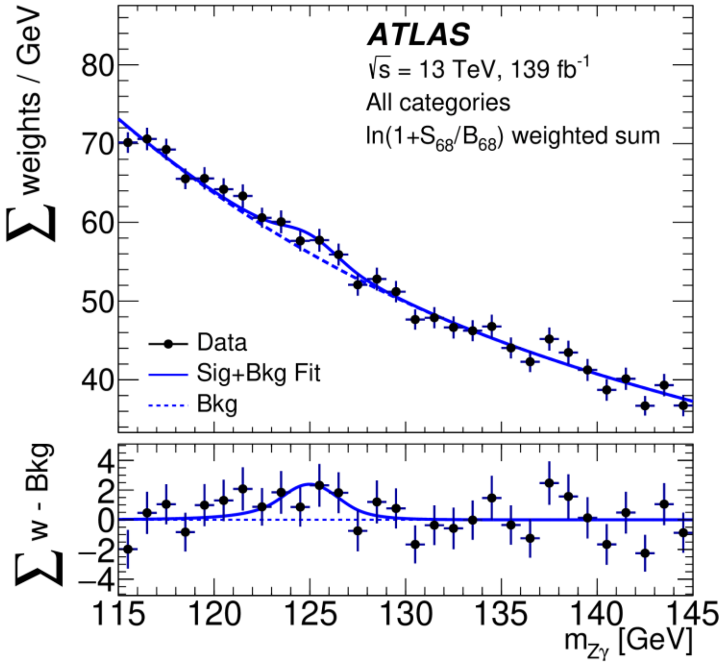
[JHEP 07 (2018) 127]

[Preliminary Results]

- ATLAS has the most stringent limits on each of these decay channels

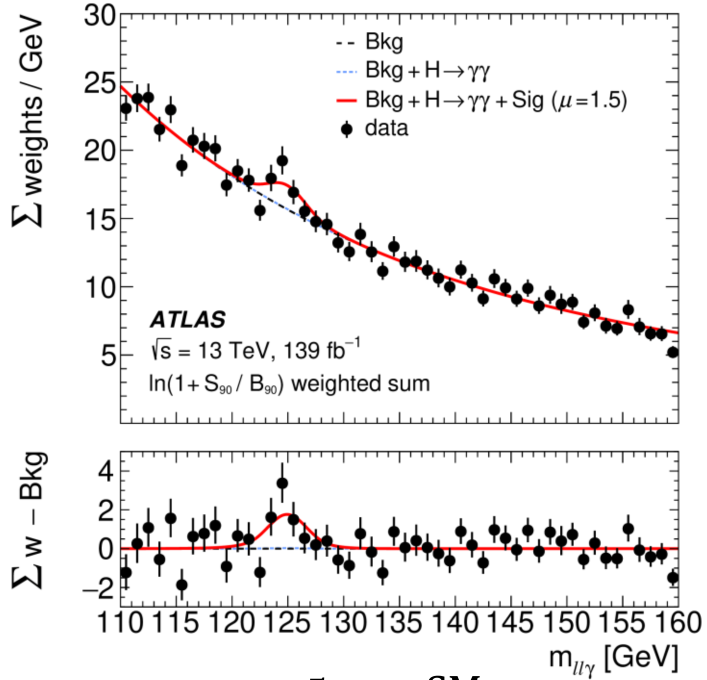
Searches for $H \to (Z/\gamma^*)\gamma \to \ell^+\ell^-\gamma$ $(\ell = e,\mu)$: 139 fb^{-1} Results

$H \to Z\gamma \to \ell^+\ell^-\gamma$: Phys. Lett. B 809 (2020) 135754



- $BR^{\text{SM}}_{H\to Z\gamma} = 0.154\%$
- $81.2 < m_{\ell\ell} < 101.2$ GeV
  - Main background is non-resonant $Z\gamma$ production
- Observed (expected with SM) 95% CL:
  - $BR^{\text{SM}}_{H\to Z\gamma} < 3.6\ (2.6) \times$ SM
  - Factor 2.4 improvement compared to previous analysis

$H \to \gamma^*\gamma \to \ell^+\ell^-\gamma$: Phys. Lett. B 819 (2021) 136412

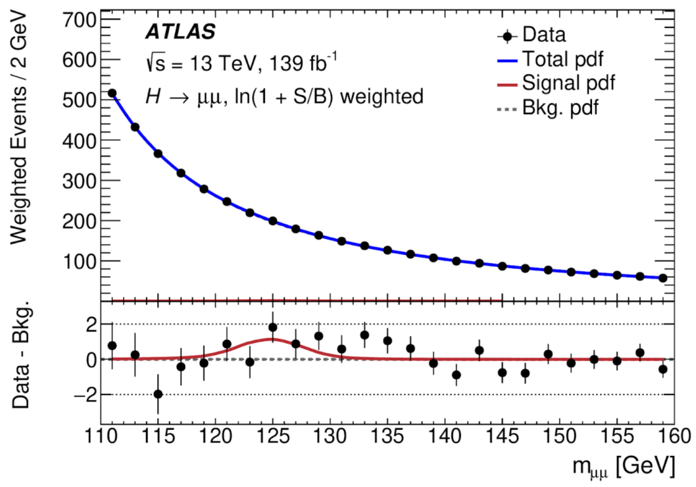


- $BR^{\text{SM}}_{H\to ee\gamma} = 7.20\times 10^{-5}$; $BR^{\text{SM}}_{H\to \mu\mu\gamma} = 3.42\times 10^{-5}$
- $m_{\ell\ell} < 30$ GeV, excluding J/ψ and $\Upsilon(nS)$ resonances
  - Main background is non-resonant $\ell\ell\gamma$ production
- Observed (expected with SM) significance:
  - 3.2σ (2.1σ)
  - **First evidence for $H \to \ell\ell\gamma$**

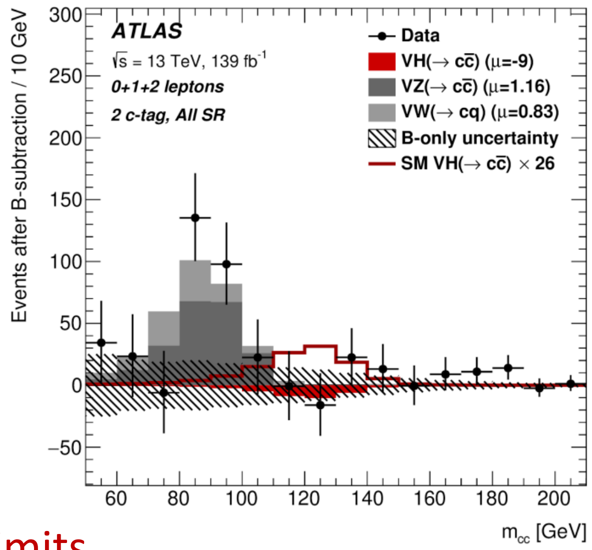
Summary

- ATLAS has many analyses searching for H decays to 2nd generation fermions and other rare decays:
  - $H \to \mu^+\mu^-$ and $H \to e^+e^-$
  - $VH \to c\bar{c}$ – **combine with $\boldsymbol{VH \to b\bar{b}}$**
  - $H \to Q\gamma$ – **new result!**
  - $H \to (\phi/\rho)\gamma$
  - $H \to Z\gamma \ \to \ell^+\ell^-\gamma$
  - $H \to \gamma^*\gamma \ \to \ell^+\ell^-\gamma$ – **evidence for process**
- **Many exciting avenues to test SM predictions and to search for new physics scenarios**

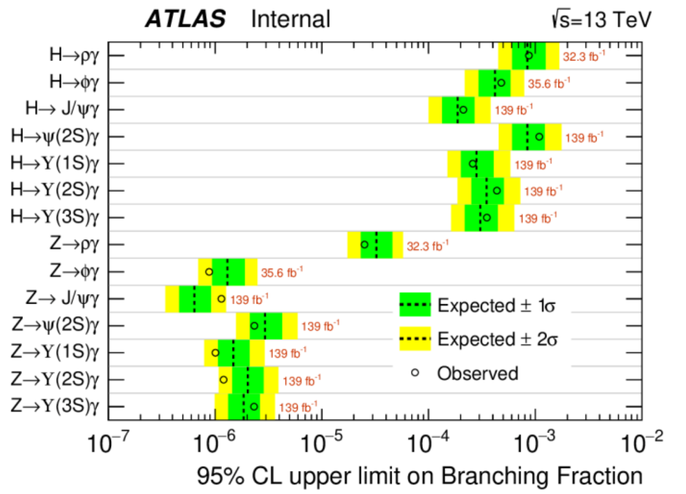
$H \to \mu^+\mu^-$



$VH(\to c\bar{c})$



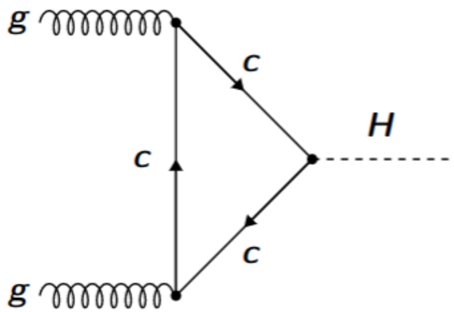
$H \to M\gamma$ Limits



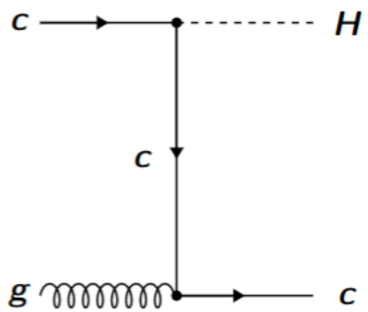
ADDITIONAL SLIDES

Precision measurements of p_{T}^{H}: 139 fb^{-1} Analysis Overview

- H production modes are sensitive to c- and b-quark couplings, for example:



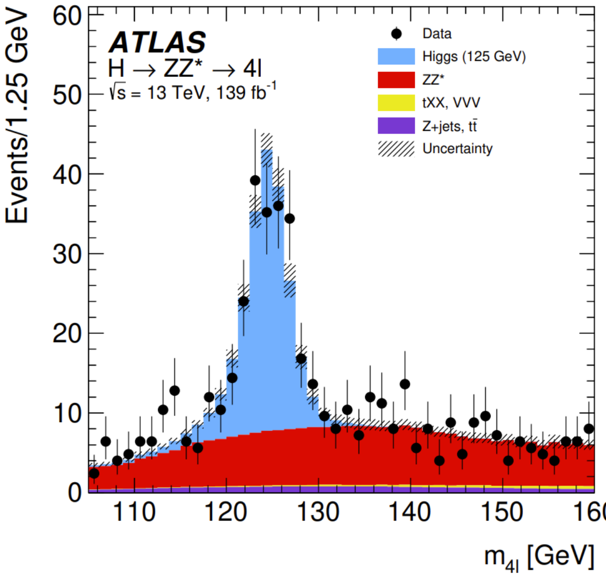
ggF with c-quark loop



c-quark initiated production

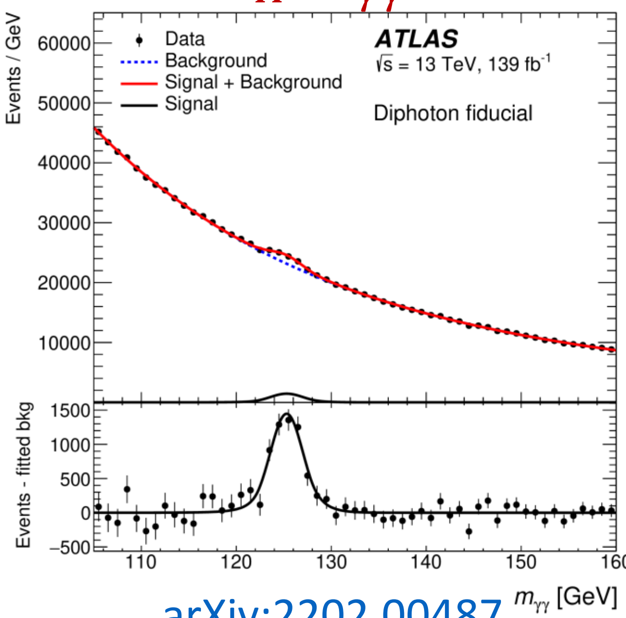
- Variations in y_c and y_b can alter p_{T} distribution of produced Higgs bosons
- Use precision measurements of the differential p_{T}^{H} cross section from $H \rightarrow ZZ^{*} \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ analyses to indirectly constrain κ_c and κ_b
    - Sensitive to the sign of κ_c and κ_b
    - Combine results for increased sensitivity

$H \rightarrow ZZ^{*} \rightarrow 4l$

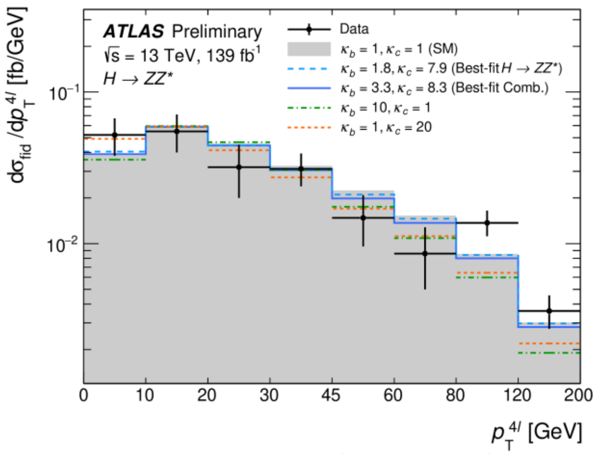


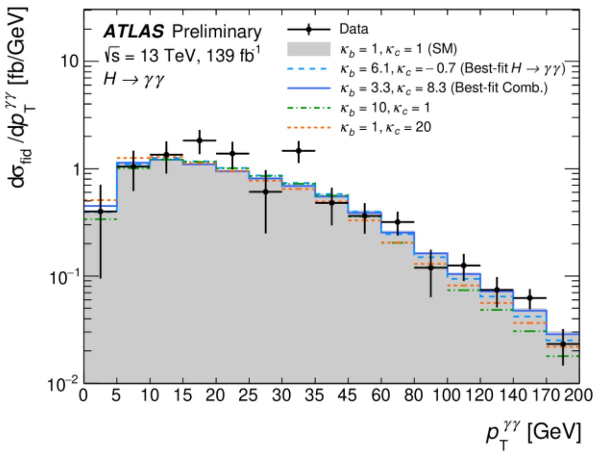
Eur. Phys. J. C 80 (2020) 942

$H \rightarrow \gamma\gamma$



arXiv:2202.00487



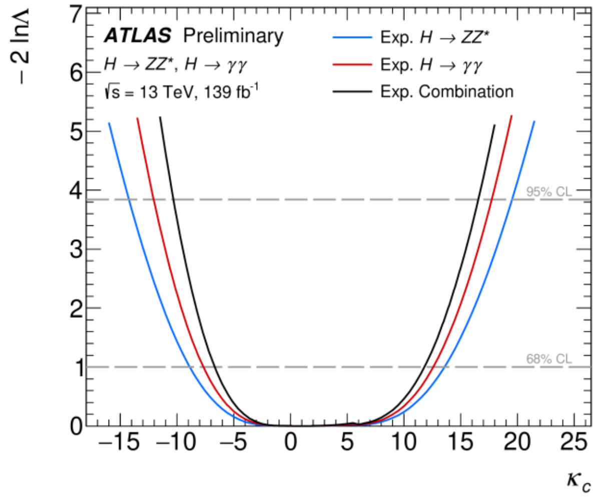


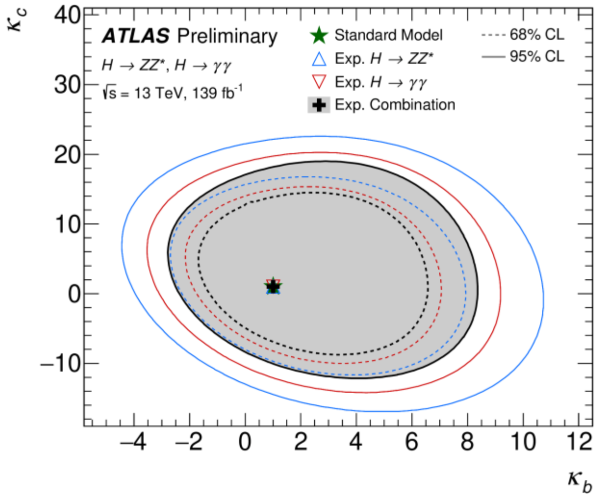
New result - combination: ATLAS-CONF-2022-002

Precision measurements of p_T^H: 139 fb^{-1} Analysis Results

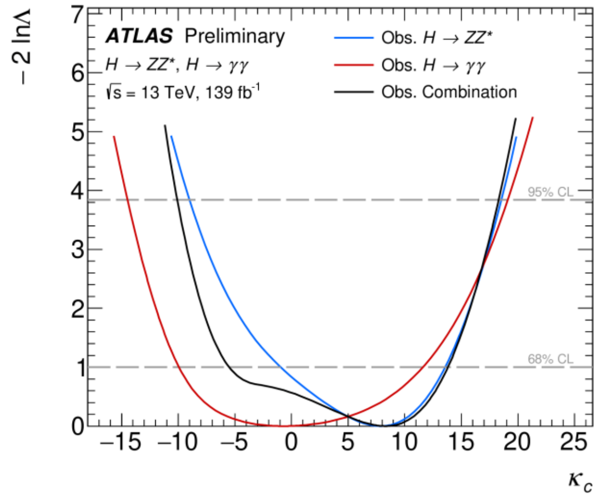
- Combined p_T^H measurement remains dominated by statistical uncertainties
  - Compatibility of result with SM is 20%
- Only consider measured shape in $\kappa_{c,b}$ interpretation
  - Removes assumptions associated with various branching fractions caused by $\kappa_{c,b}$ dependence of Γ_H
- Expected combined constraint more stringent than individual channels
- Observed combined constraint typically less stringent than $H \rightarrow ZZ^* \rightarrow 4l$
  - Partially caused by double minimum in likelihood associated with quadratic dependence of $\frac{d\sigma}{dp_T^H}$ on $\kappa_{c,b}$

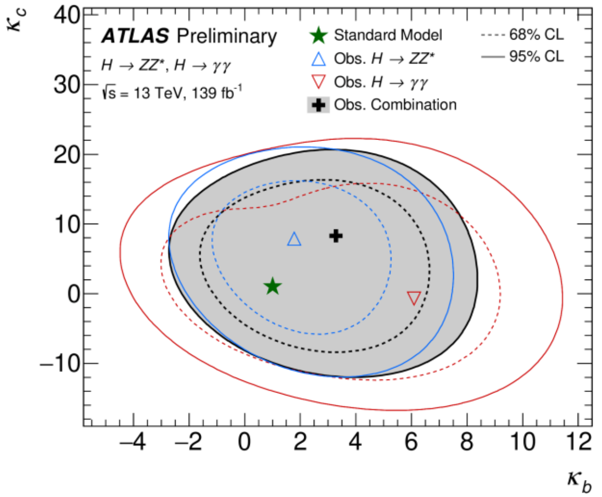
Expected





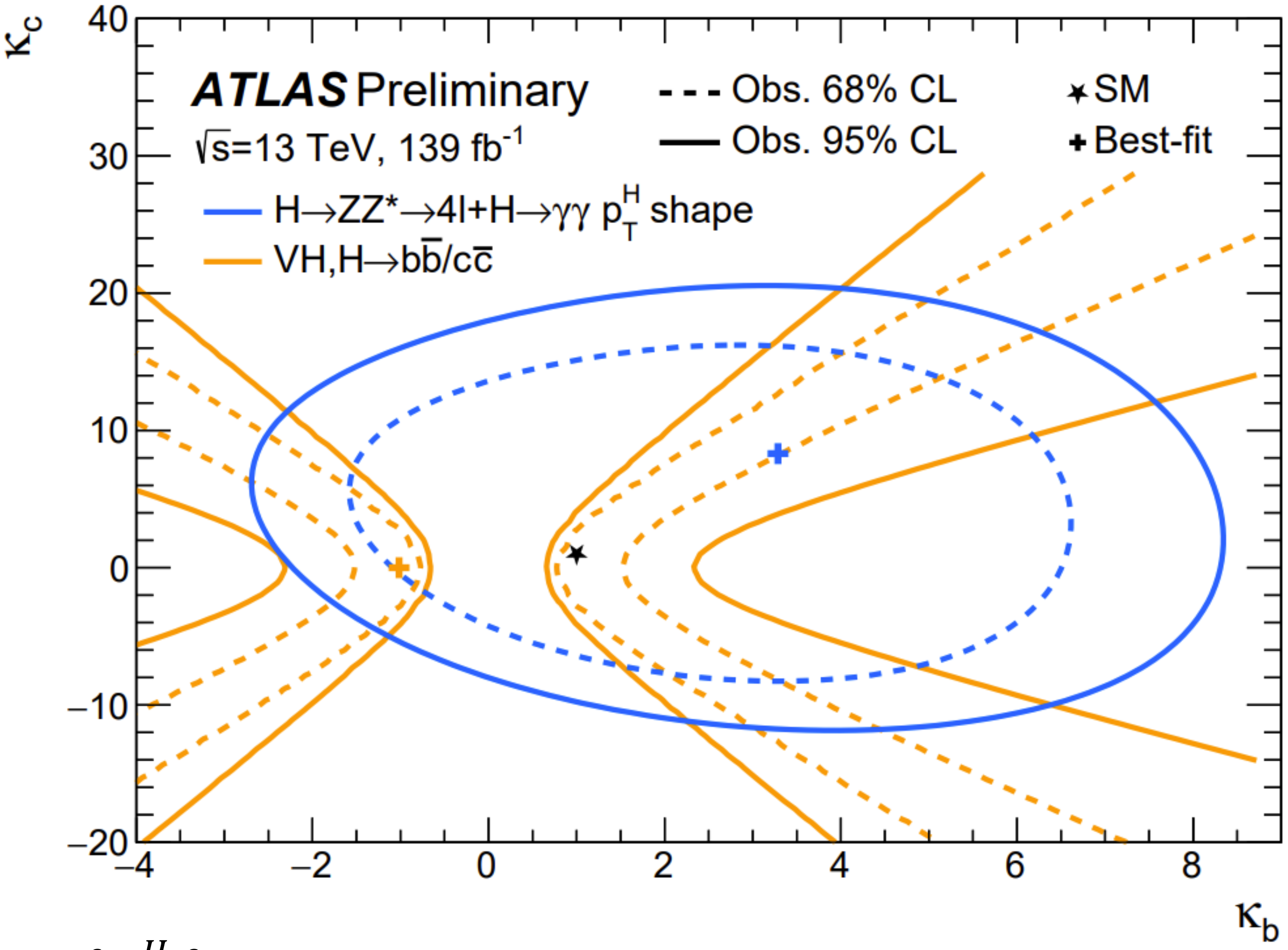
Observed





Combination: ATLAS-CONF-2022-002

Complementarity with $VH(\rightarrow b\bar{b}/c\bar{c})$



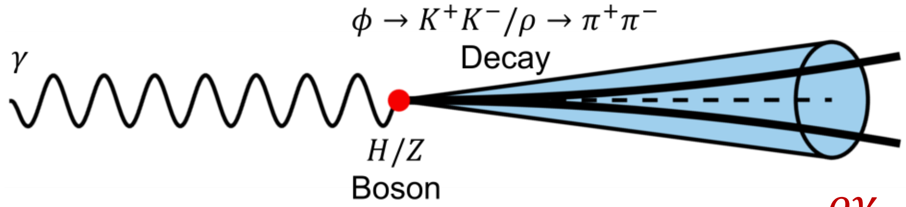
- ➢ Consider measured shape of p_{T}^{H} for $\kappa_{c,b}$ interpretation
- ➢ Complements $VH(\rightarrow c\bar{c}/b\bar{b})$ result

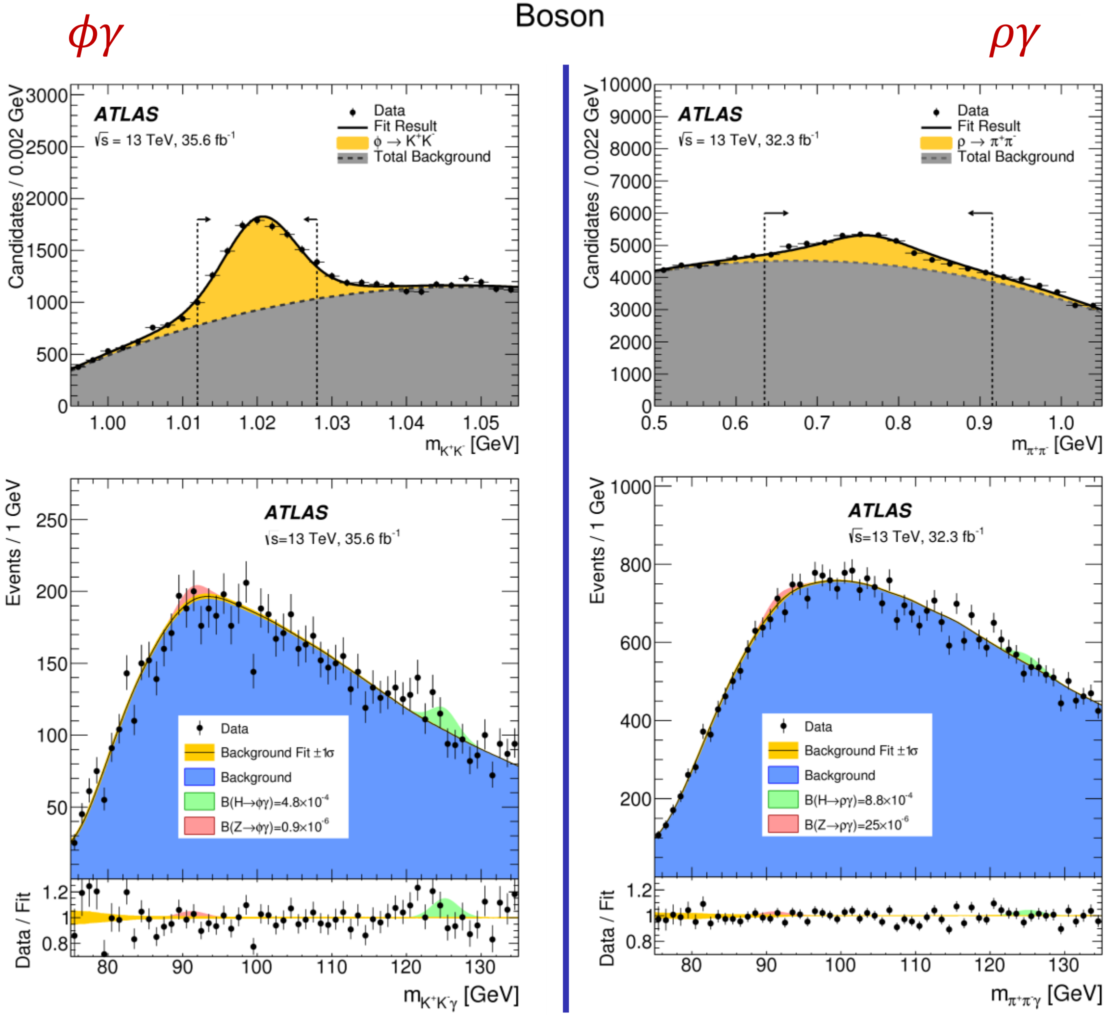
Indirect constraints on $\kappa_{c,b}$ from p_T^H Measurements

Channel	Parameter best-fit	Observed 95% confidence interval	Expected 95% confidence interval
$H \to ZZ^* \to 4\ell$	$\kappa_b = 1.8^{+2.3}_{-2.1}$	$[-1.9,\ 6.3]$	$[-3.6,\ 9.3]$
	$\kappa_c = 7.9^{+5.7}_{-8.8}$	$[-9.0,\ 18.5]$	$[-14.2,\ 19.5]$
$H \to \gamma\gamma$	$\kappa_b = 6.1^{+2.0}_{-8.2}$	$[-3.7,\ 10.2]$	$[-2.8,\ 8.1]$
	$\kappa_c = -0.7^{+12.3}_{-9.2}$	$[-14.5,\ 19.1]$	$[-12.0,\ 17.7]$
Combined	$\kappa_b = 3.3^{+2.4}_{-4.1}$	$[-2.1,\ 7.4]$	$[-2.2,\ 7.4]$
	$\kappa_c = 8.3^{+5.5}_{-13.8}$	$[-10.1,\ 18.3]$	$[-10.3,\ 16.6]$

Search for $H \to (\phi/\rho)\gamma$: Early Run-2 Analysis Results

- $H \to \phi(K^+K^-)\gamma$ sensitive to magnitude and sign of y_s
  - $H \to \rho(\pi^+\pi^-)\gamma$ sensitive to magnitude and sign of $y_{u,d}$
- Direct and indirect decay amplitudes analogous to $H \to Q\gamma$
  - $BR^{\mathrm{SM}}_{H\to\phi\gamma(\rho\gamma)} \approx 10^{-6}(10^{-5})$
- Include analogous searches for $Z \to (\phi/\rho)\gamma$
  - $BR^{\mathrm{SM}}_{Z\to\phi\gamma(\rho\gamma)} \approx 10^{-8}$
- **Dedicated** triggers based on single photon + modified τ-lepton algorithms
  - Signal resolution $\approx 1.8\%$
- Similar signal and background modelling strategy to $H \to Q\gamma$
  - Background model is fully data driven
    - No backgrounds resonant in $m(K^+K^-\gamma)$ or $m(\pi^+\pi^-\gamma)$
    - Validate model in $m(K^+K^-)$ and $m(\pi^+\pi^-)$ sidebands
- Use unbinned likelihood fit to $m(K^+K^-\gamma)$ and $m(\pi^+\pi^-\gamma)$





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Limits for $H \to (Q, \phi, \rho)\gamma$

95% CL$_s$ upper limits						
	Branching fraction				$\sigma \times \mathcal{B}$	
Decay channel	Higgs boson [10^{-4}]		Z boson [10^{-6}]		Higgs boson [fb]	Z boson [fb]
	Expected	Observed	Expected	Observed	Observed	Observed
$J/\psi\,\gamma$	$1.9^{+0.8}_{-0.5}$	2.1	$0.6^{+0.3}_{-0.2}$	1.2	12	71
$\psi\,(2S)\,\gamma$	$8.5^{+3.8}_{-2.4}$	10.9	$2.9^{+1.3}_{-0.8}$	2.3	61	135
$\Upsilon(1S)\,\gamma$	$2.8^{+1.3}_{-0.8}$	2.6	$1.5^{+0.6}_{-0.4}$	1.0	14	59
$\Upsilon(2S)\,\gamma$	$3.5^{+1.6}_{-1.0}$	4.4	$2.0^{+0.8}_{-0.6}$	1.2	24	71
$\Upsilon(3S)\,\gamma$	$3.1^{+1.4}_{-0.9}$	3.5	$1.9^{+0.8}_{-0.5}$	2.3	19	135

Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}\,(H \to \phi\gamma)$ [10^{-4}]	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}\,(Z \to \phi\gamma)$ [10^{-6}]	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}\,(H \to \rho\gamma)$ [10^{-4}]	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}\,(Z \to \rho\gamma)$ [10^{-6}]	33^{+13}_{-9}	25