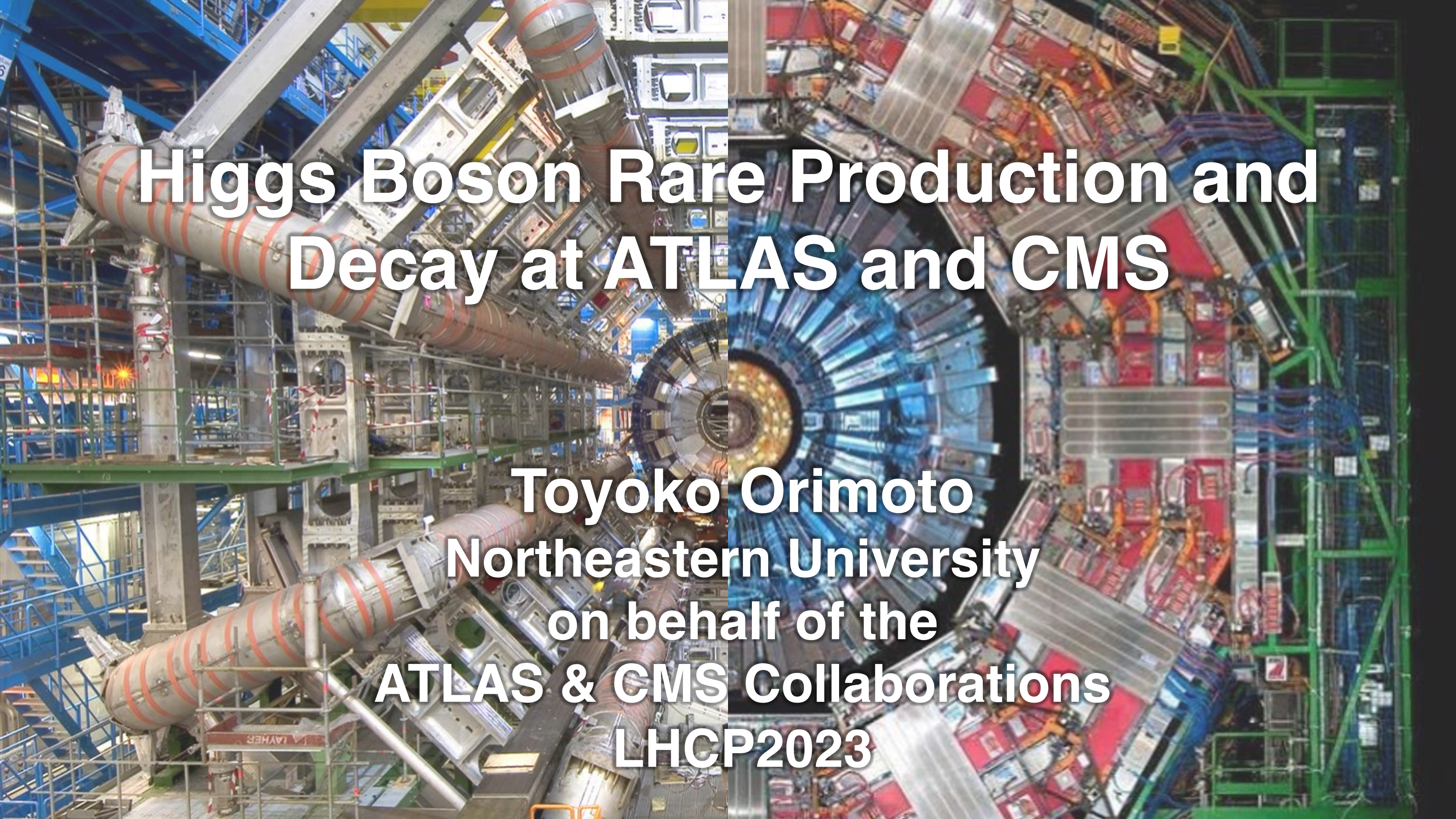


Higgs Boson Rare Production and Decay at ATLAS and CMS

Toyoko Orimoto
Northeastern University
on behalf of the
ATLAS & CMS Collaborations

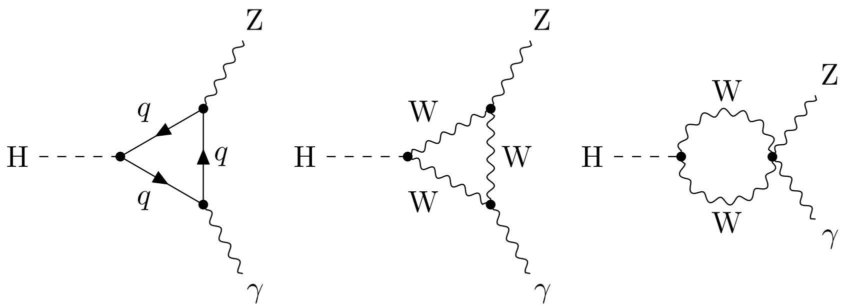
LHCP2023

Rare Higgs Decays & Production

- **Rare Decays**
  - **H → Zγ**: ATLAS + CMS Combination HIG-23-002 NEW
  - **H → cc**: CMS HIG-21-008 + HIG-21-012; ATLAS HIGG-2021-12
  - **H → μμ**: CMS HIG-19-006; ATLAS HIGG-2019-14
  - **H → ee / eμ**: CMS HIG-21-015; ATLAS HIGG-2018-58
  - **H → eτ, μτ**: ATLAS HIGG-2019-11
  - **H → quarkonia**: CMS HIG-20-008; ATLAS ATL-PHYS-PUB-2023-004
- **Rare Production**
  - **γH**: CMS SMP-22-006 NEW

ATLAS + CMS H → Zγ

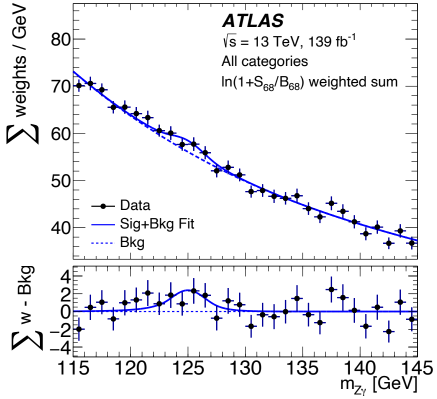
- **Production**: gluon fusion & VBF
- **Expected BR**: ~1.5×10^{-3}
- H → Zγ, like H → γγ, is purely loop induced, and thus sensitive to new physics



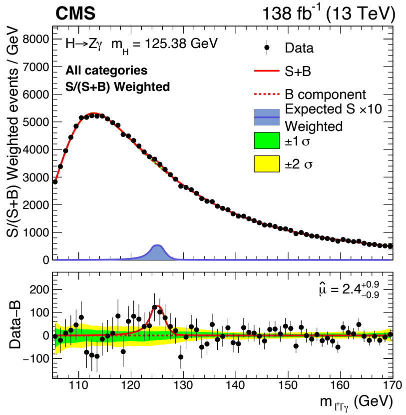
- **Analysis strategy**:
  - Z decays to e or μ pairs with $m_{ll} > 50$ GeV; provides clean signature and good mass resolution
  - Dominant backgrounds from DY + ISR γ and DY + jets
  - Events are categorized & simultaneous S+B fits to $m_{Z\gamma}$ across categories

ATLAS-CONF-2023-025 & CMS HIG-23-002

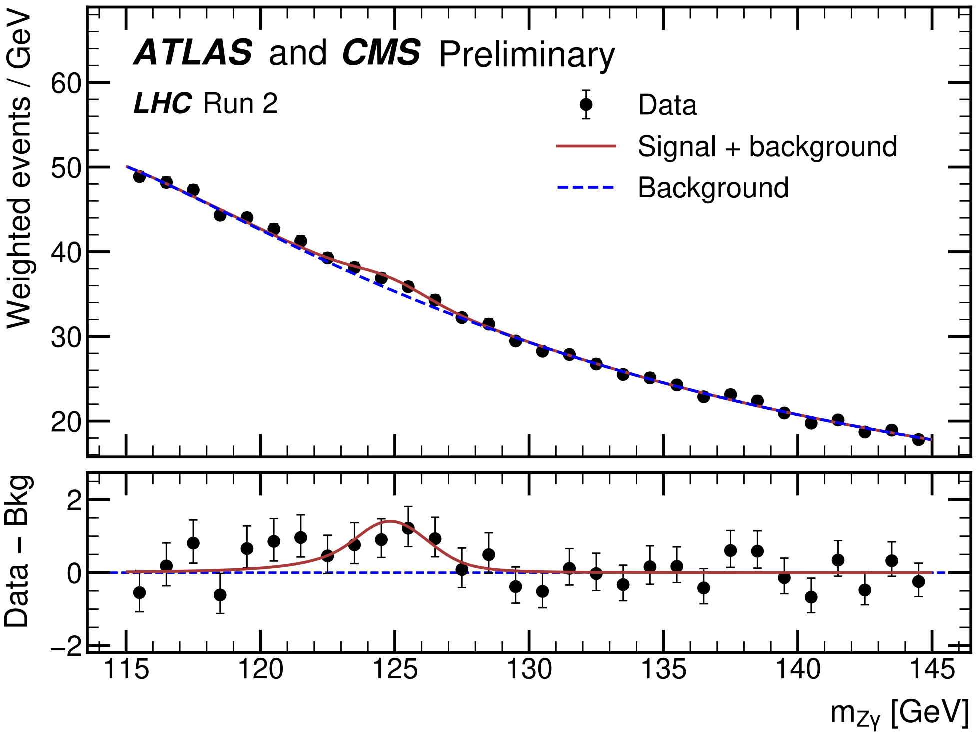
ATLAS + CMS H → Zγ



HIGG-2018-42
(Phys. Lett. B 809 (2020) 135754)



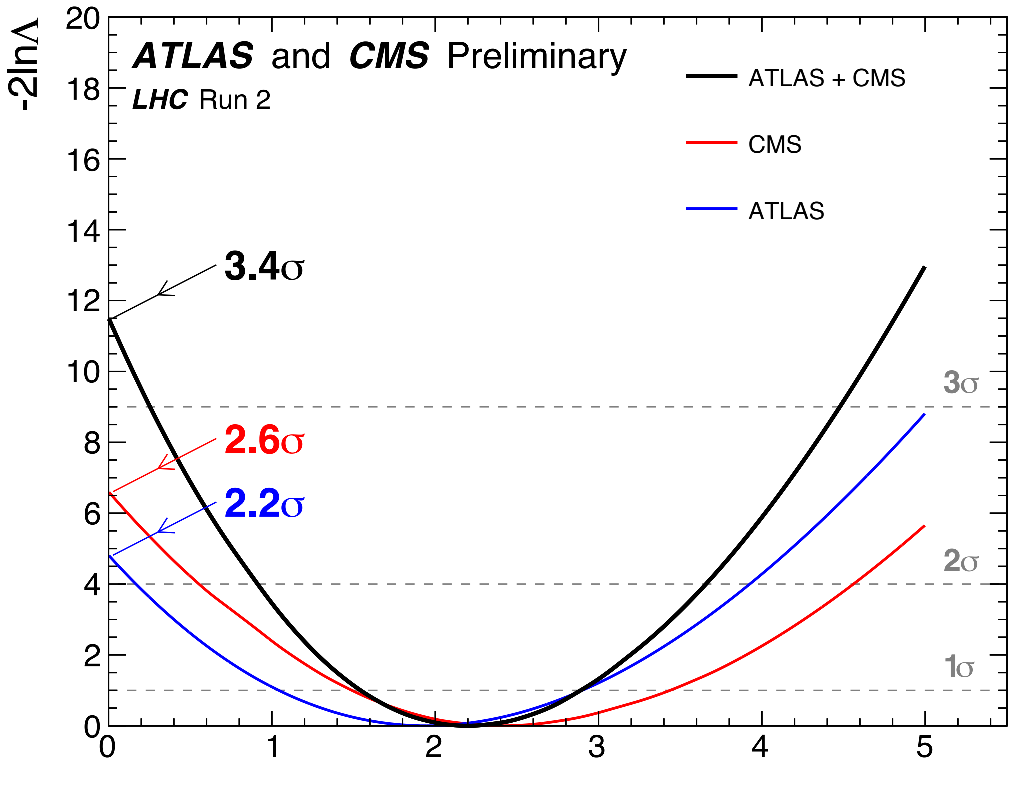
HIG-19-004
(Accepted for JHEP)



ATLAS-CONF-2023-025 & CMS HIG-23-002

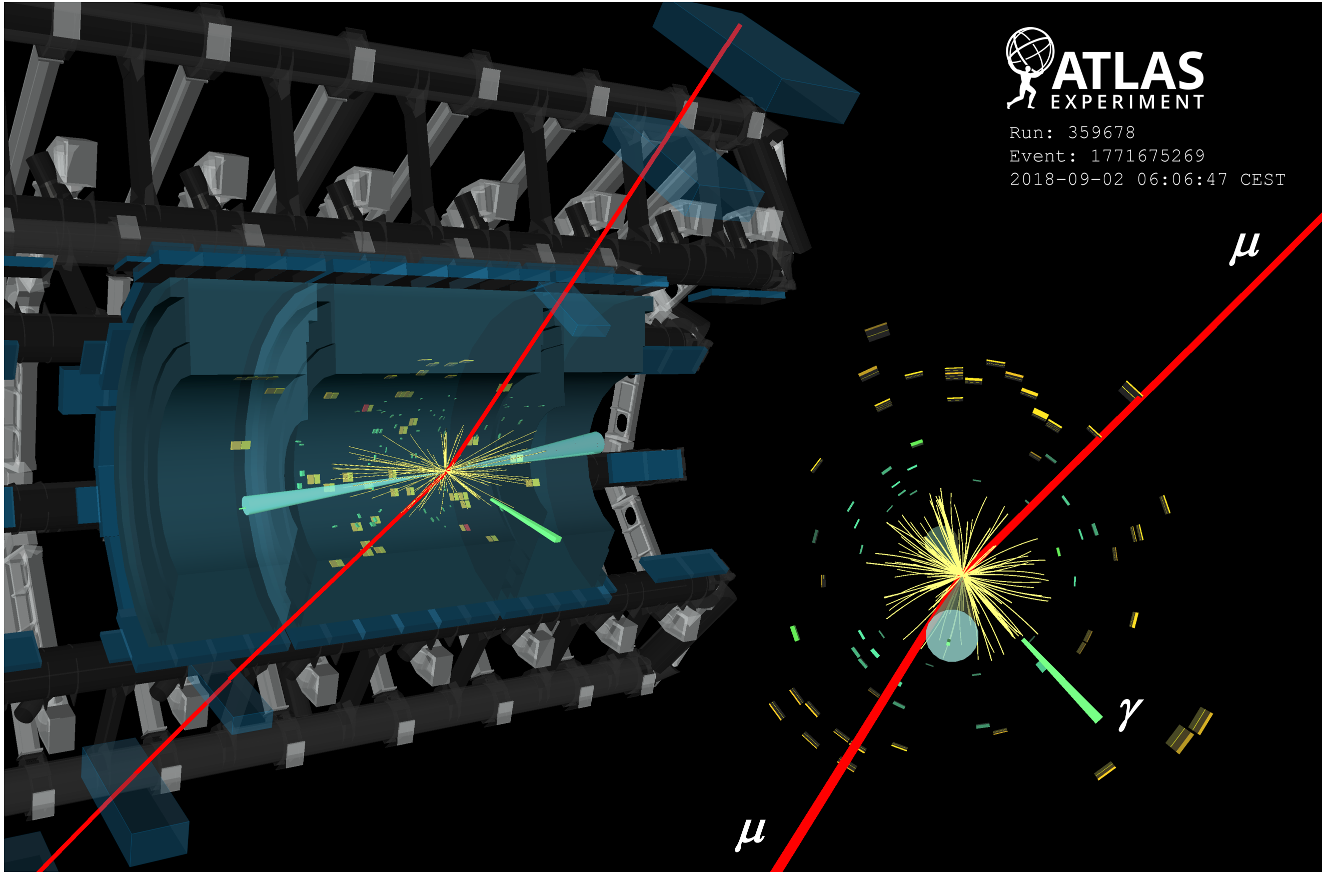
ATLAS + CMS H → Zγ

- Observed (expected) signal yield is 2.2 ± 0.7 (1.0 ± 0.6) x SM
- B(H→Zγ) is measured to be (3.4 ± 1.1) × 10^{-3}, in agreement within 1.9 standard deviations of the SM prediction
- **First evidence for H→Zγ, with statistical significance of 3.4 standard deviations**



ATLAS-CONF-2023-025 & CMS HIG-23-002

ATLAS + CMS H → Zγ

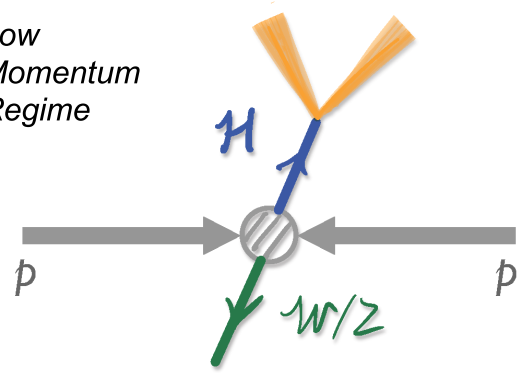


CMS H → cc

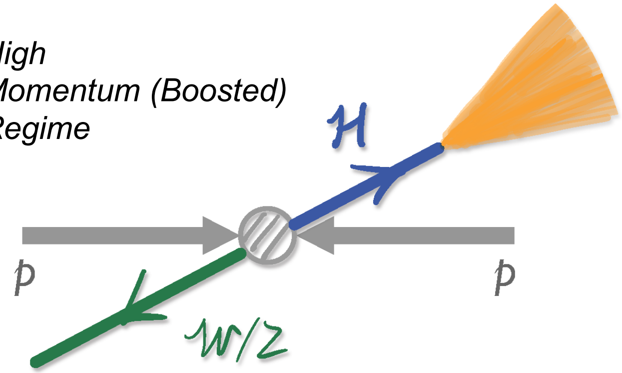
- **Production**: with W/Z decaying leptonically
- **Expected BR**: ~3%
- **Two regimes**:
  - Low momentum: resolved charm quark jets
  - Boosted ($p_T > 300$ GeV): merged, single jet
- Novel charm jet identification and analysis methods using ML (GNN)
- Validated by searching for Z → cc in VZ events

arXiv:2205.05550 (Accepted by PRL)

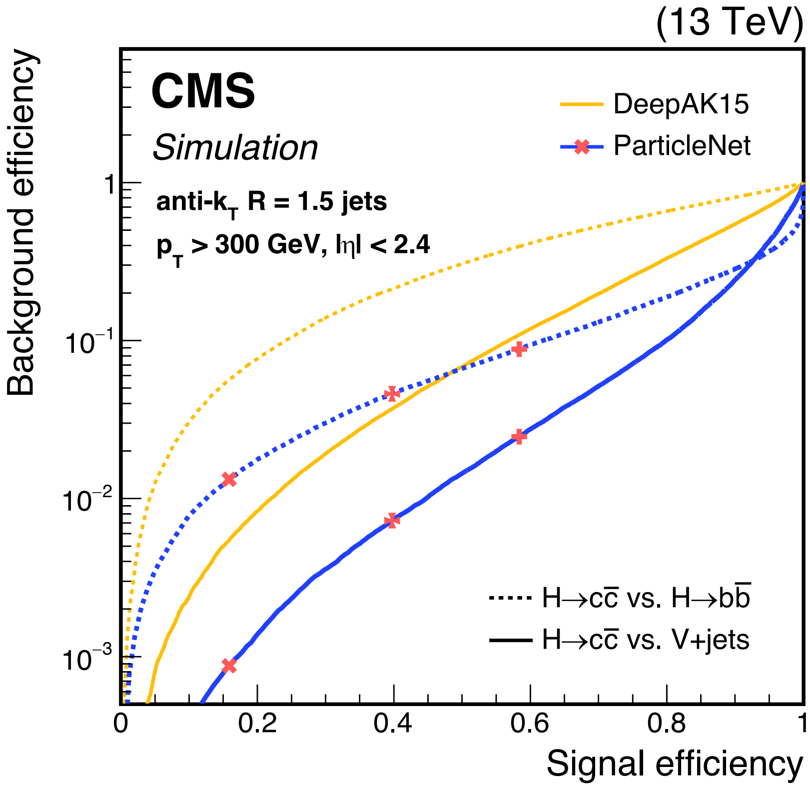
Low Momentum Regime

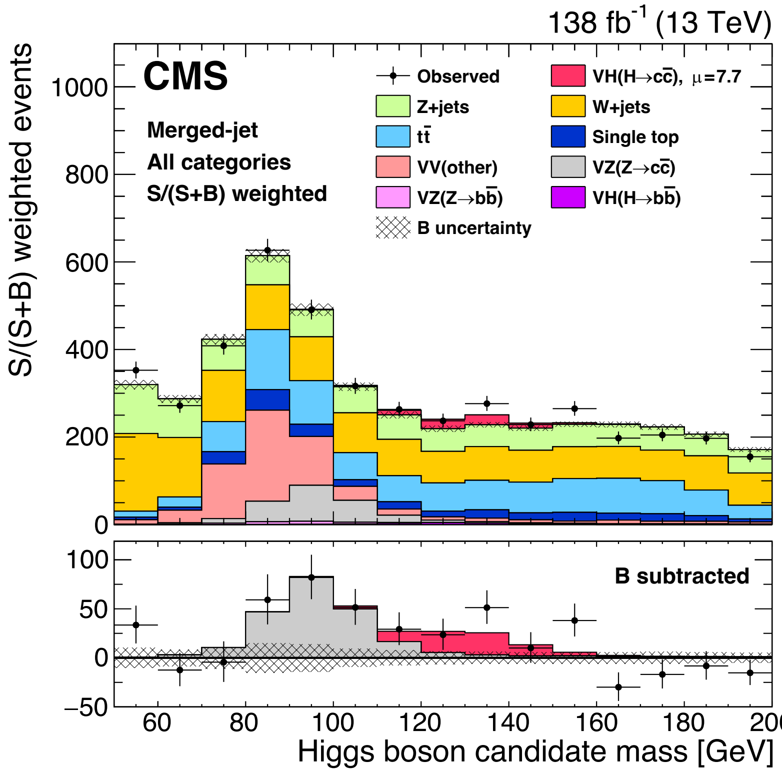


High Momentum (Boosted) Regime



CMS H → cc

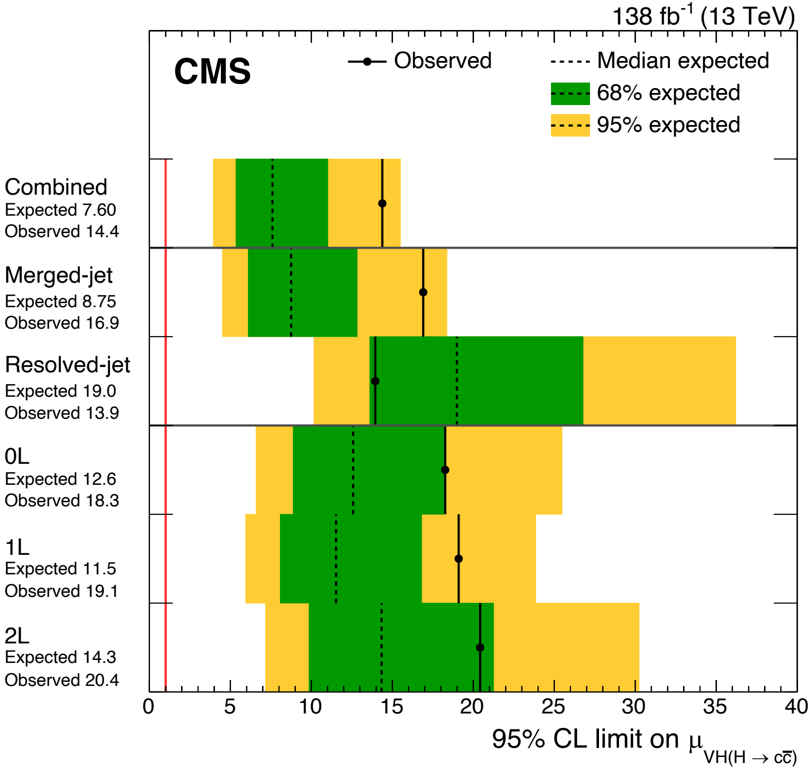




arXiv:2205.05550 (Accepted by PRL)

CMS H → cc

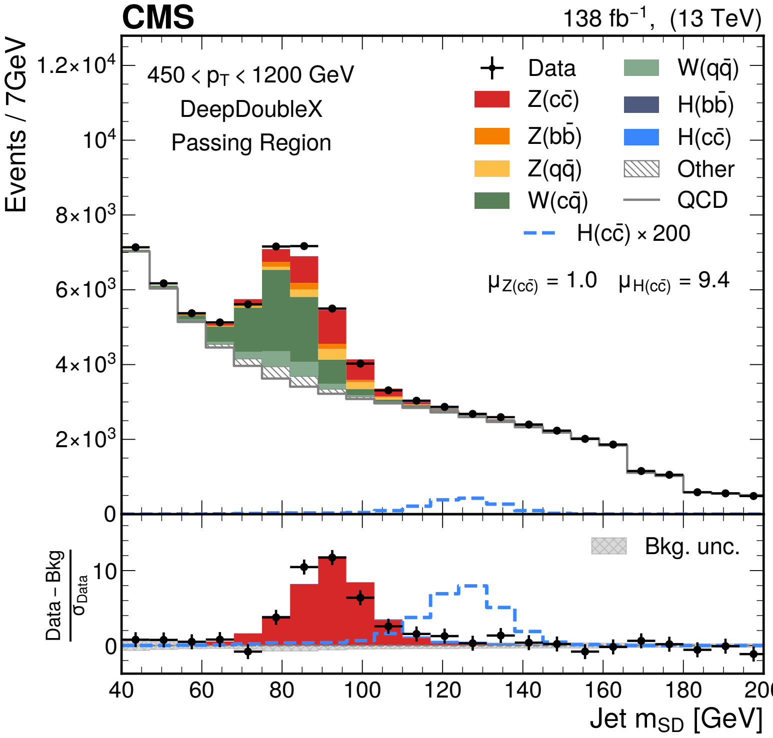
- Observed (expected) upper limit on σ(VH) B(H→cc) is $0.94\ (0.50^{+0.22}_{-0.15})$ pb at 95% CL
- Corresponding to $14\ (7.6^{+3.4}_{-2.3})$ x SM
- For Higgs-charm Yukawa coupling modifier (κ_c), observed (expected) 95% CL interval is $1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$)
- **Most stringent constraint to date**



arXiv:2205.05550 (Accepted by PRL)

CMS (More) Boosted H → cc

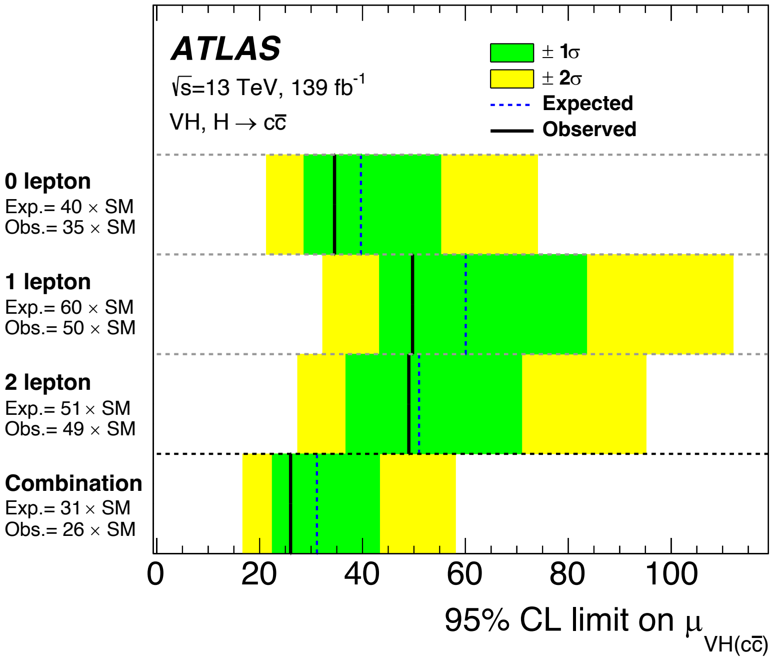
- Boosted H→cc reconstructed as a single large-radius jet
- Identified using a deep neural network charm tagging technique
- Validated by measurement of Z→cc, observed with signal strength of: $1.00^{+0.17}_{-0.14}\,(\text{syst}) \pm 0.08\,(\text{theo}) \pm 0.06\,(\text{stat})$
- Observed (expected) upper limit on σ(H) B(H→cc) is 47 (39) x SM



arXiv:2211.14181 (Accepted by PRL)

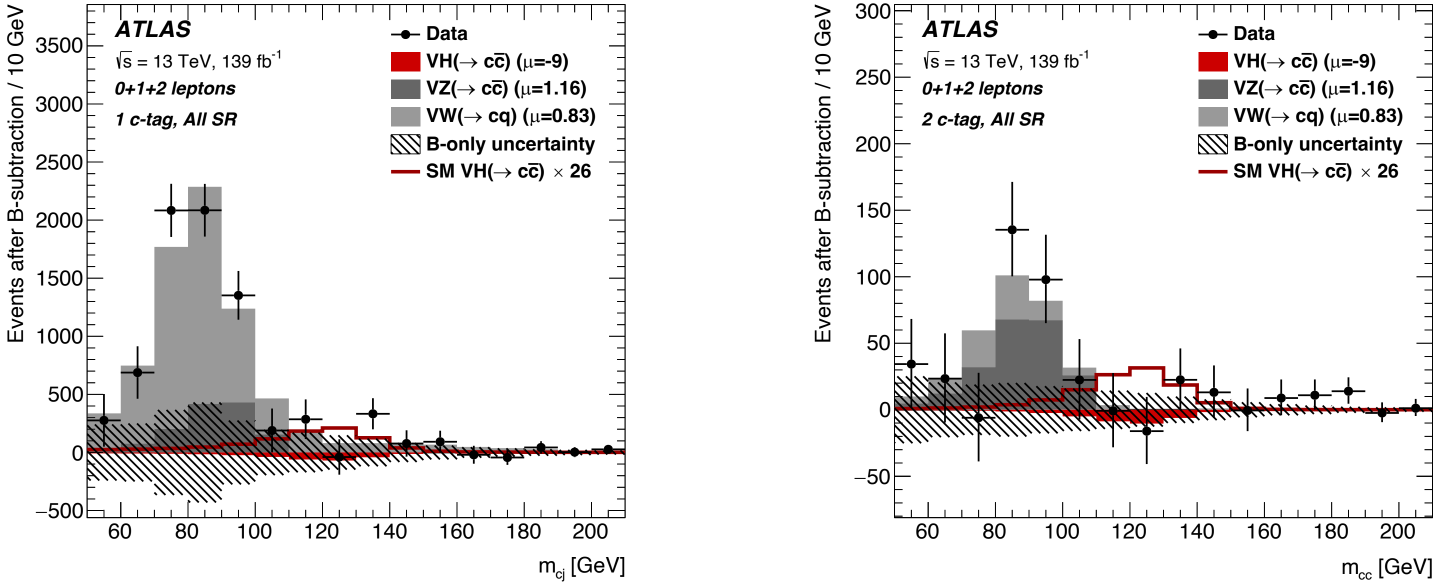
ATLAS H → cc

- Validated with simultaneous measurement of WW, WZ, ZZ production
- Observed (expected) upper limit on (W/Z)Z(→cc) is 2.6 (2.2) standard deviations above background-only prediction and for (W/Z)W(→cq) 3.8 (4.6)
- (W/Z)H(→cc) search yields observed (expected) upper limit of 26 (31) x SM
- For Higgs-charm Yukawa coupling modifier (κ_c), observed (expected) constraint is $|\kappa_c| < 8.5$ (12.4) at 95% CL



Eur. Phys. J. C 82 (2022) 717

ATLAS H → cc

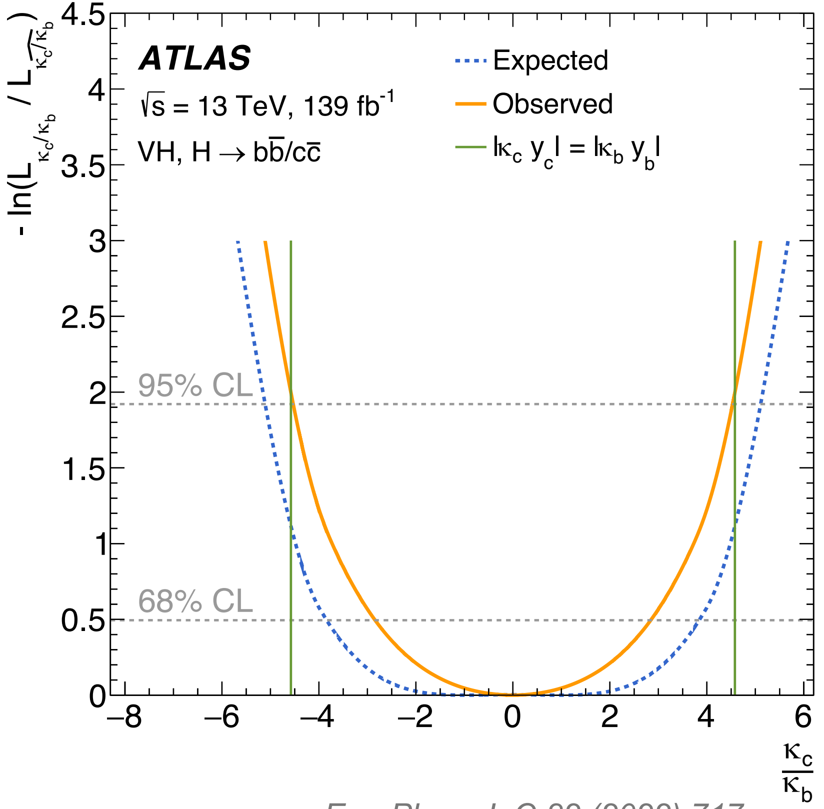


Post-fit m_{cc} distribution summed over all signal regions after subtracting backgrounds, leaving only the $VH(\to c\bar{c})$, $VW(\to cq)$, $VZ(\to c\bar{c})$ processes, for events with (left) one c-tag and (right) two c-tags

Eur. Phys. J. C 82 (2022) 717

ATLAS H → cc

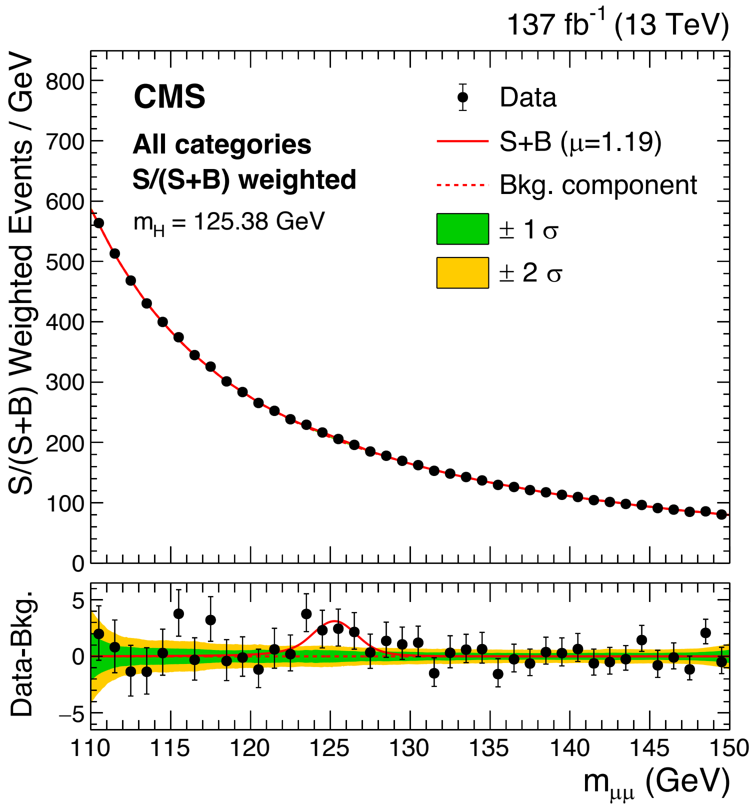
- **Combination with the ATLAS (W/Z)H→bb analysis,** allowing the ratio κ_c/κ_b to be constrained without assumptions about width of the Higgs boson
- $|\kappa_c/\kappa_b| < 4.5$ at 95% CL, smaller than the ratio of the b- and c-quark masses
- Determines the Higgs-charm coupling to be weaker than the Higgs-bottom coupling at 95% CL



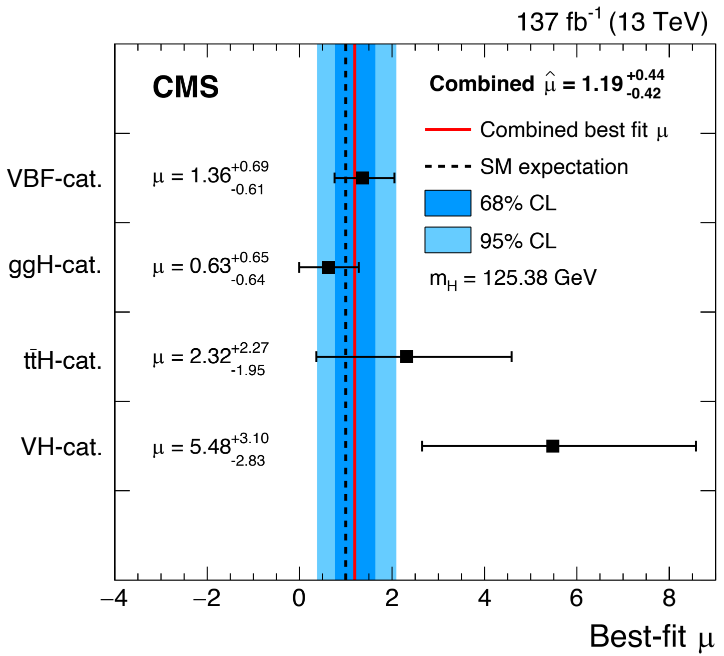
Eur. Phys. J. C 82 (2022) 717

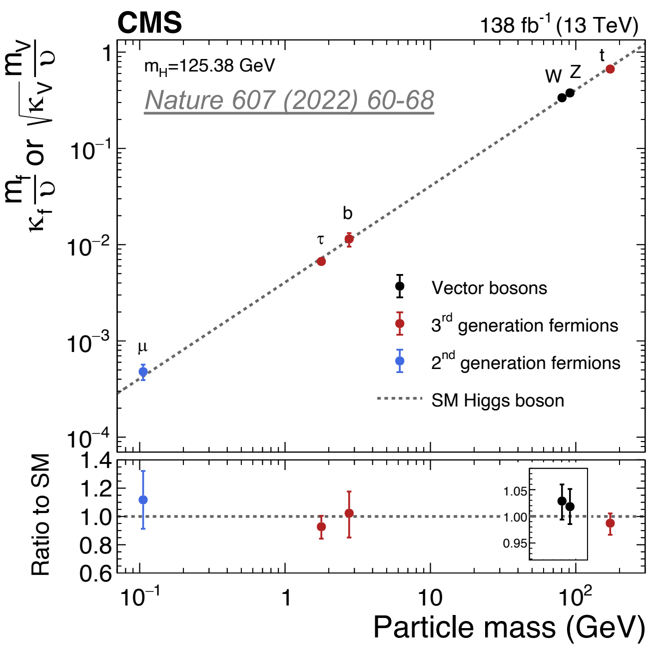
CMS H → μμ

- **Production**: gluon fusion & VBF
- **Expected BR**: 2.17×10^{-4}
- **Analysis strategy:**
  - Indistinguishable DY background with signal to background ≈ 10^{-3}
  - Background modeling essential to search for narrow mass peak
  - Multiple categories based on production processes
  - VBF uses DNN



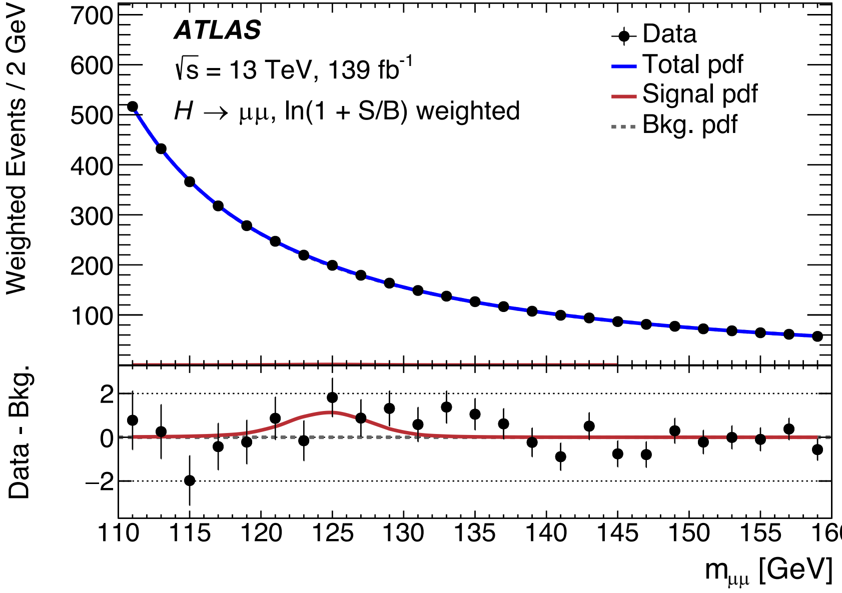
CMS H → μμ

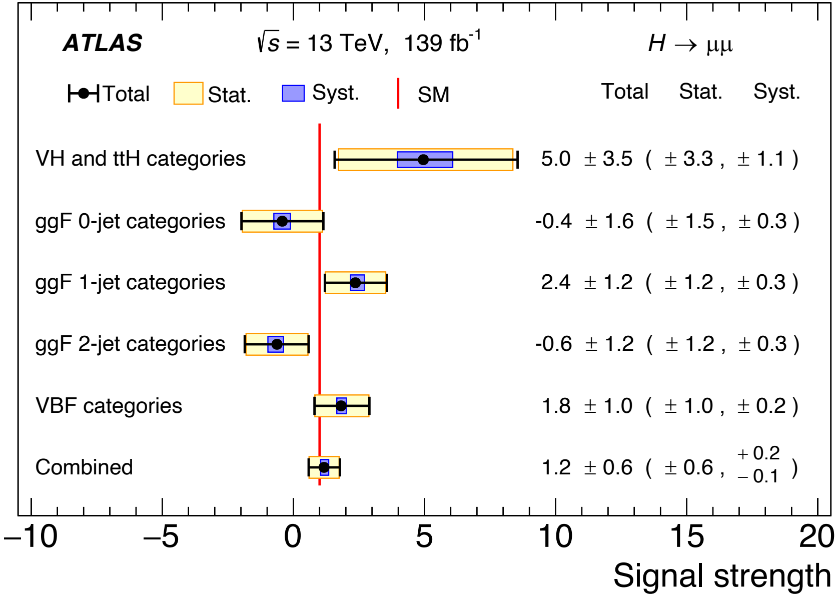




- Measured signal strength, relative to SM: $1.19^{+0.40}_{-0.39}\,(\text{stat})^{+0.15}_{-0.14}(\text{syst})$
- First evidence for H → μμ: 3.0σ (2.5σ) observed (expected)

ATLAS H → μμ



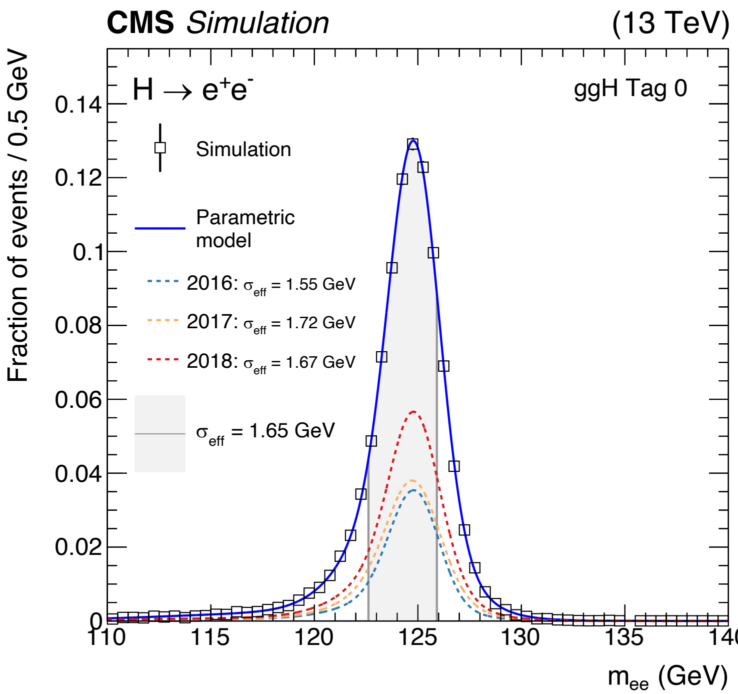


- Observed upper limit on the σ x B for pp → H → μμ: 2.2 x SM at 95% CL
- Best-fit signal strength: $\mu = 1.2 \pm 0.6$
- Observed (expected) significance: 2.0σ (1.7σ)

(Phys. Lett. B 812 (2021) 135980)

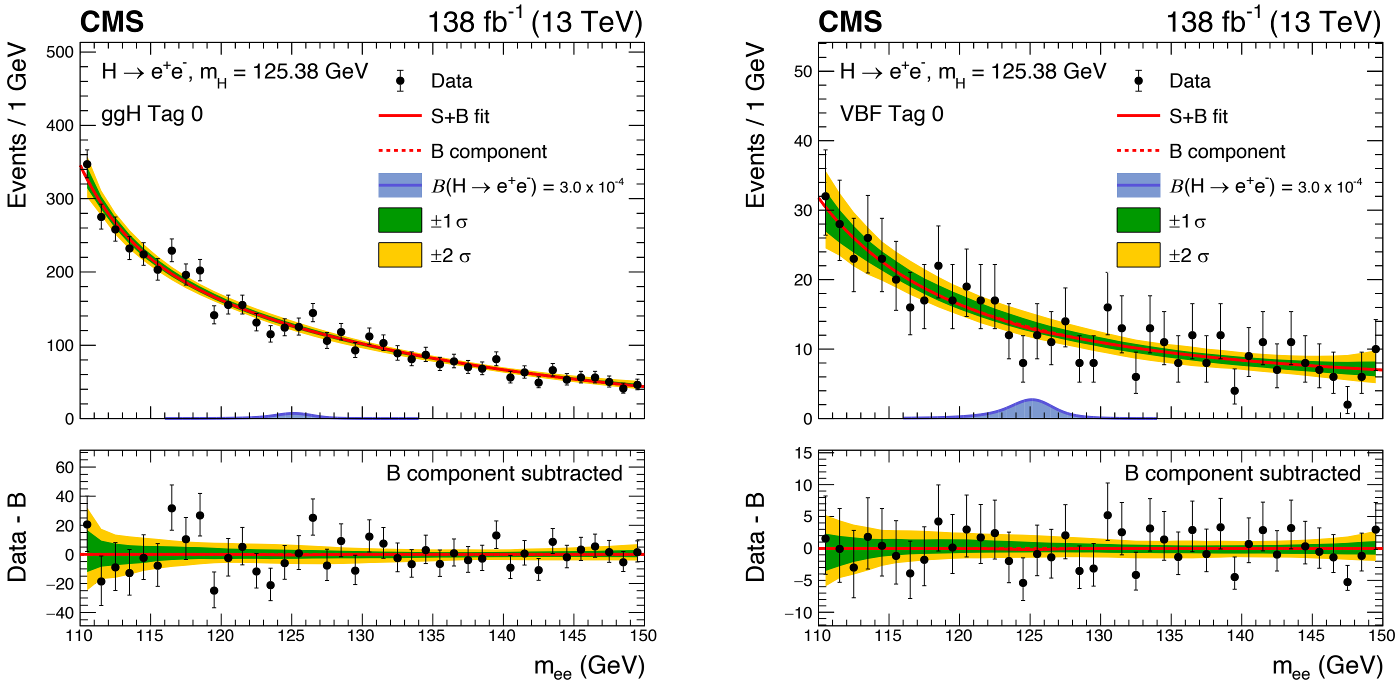
CMS H → ee

- **Production**: gluon fusion & VBF
- **Expected BR**: ~5×10^{-9}
- ATLAS & CMS searches currently provide the only direct probe of Higgs Yukawa coupling to electrons, which is enhanced in several BSM scenarios; indirect probes from EDM, etc.
- **Analysis strategy**: similar to H→γγ
    - MVA-based classifiers to reduce background
    - Classifiers are used to define categories
    - Maximum likelihood fit performed to m_{ee} distribution in each category simultaneously



arXiv:2208.00265 (Accepted by PLB)

CMS H → ee

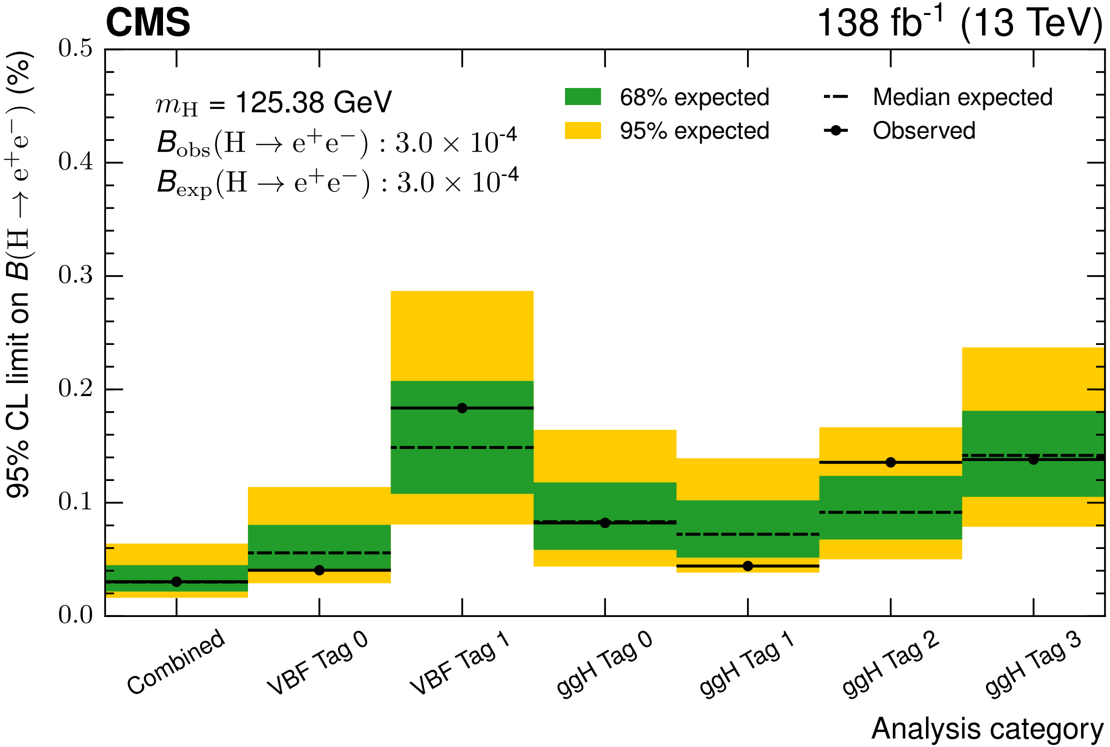


Signal-plus-background model fit to m_{ee} distribution for the highest S/B categories targeting the ggH (left) and VBF (right) processes

arXiv:2208.00265 (Accepted by PLB)

CMS H → ee

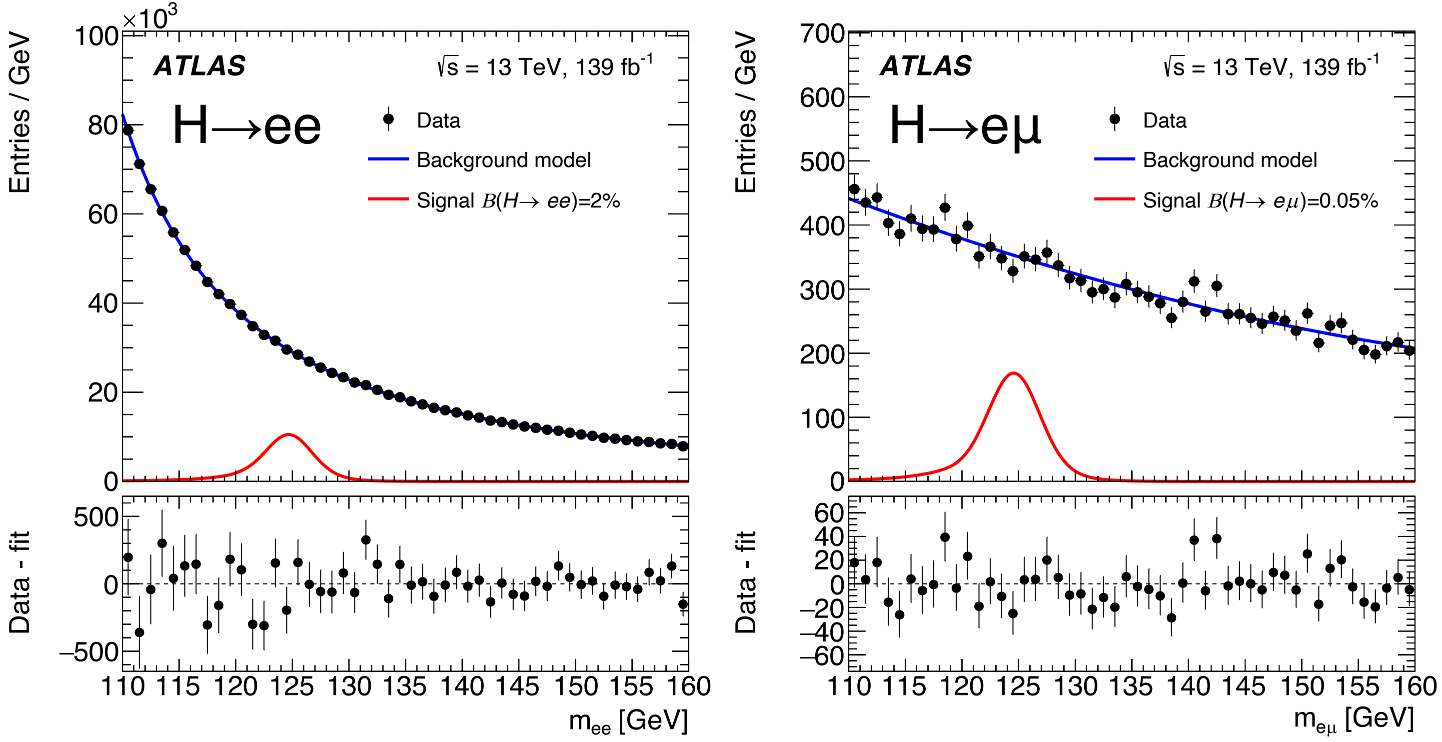
- Observed (expected) upper limit on B(H→ee) is 3.0 × 10^{-4} (3.0 × 10^{-4}) at the 95% CL
- Most stringent limit on this branching fraction to date



arXiv:2208.00265 (Accepted by PLB)

ATLAS H → ee, eμ

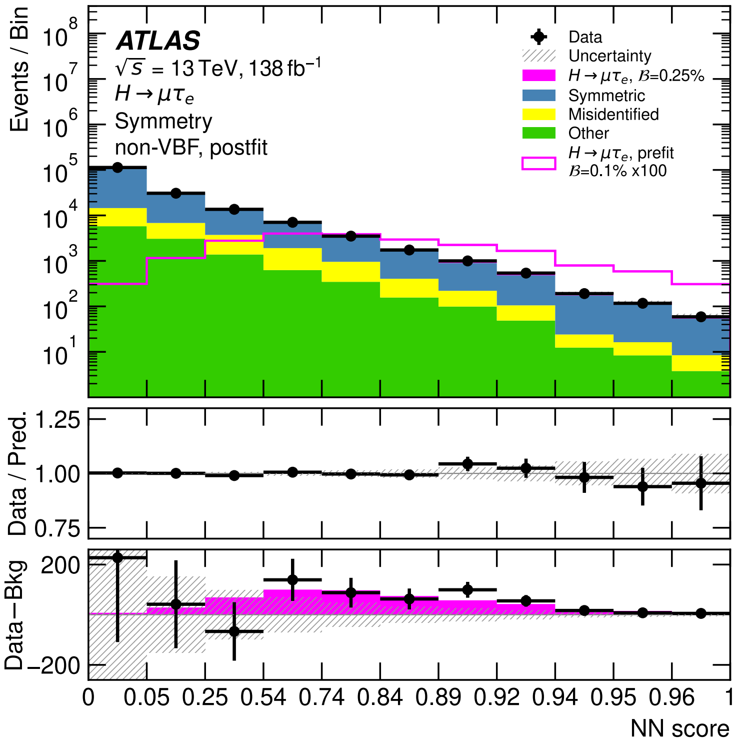
- Observed (expected) upper limits at 95% CL:
  - B(H→ee): 3.6×10^{-4} (3.5×10^{-4})
  - B(H→eμ): 6.2×10^{-5} (5.8×10^{-5})



Phys. Lett. B 801 (2020) 135148

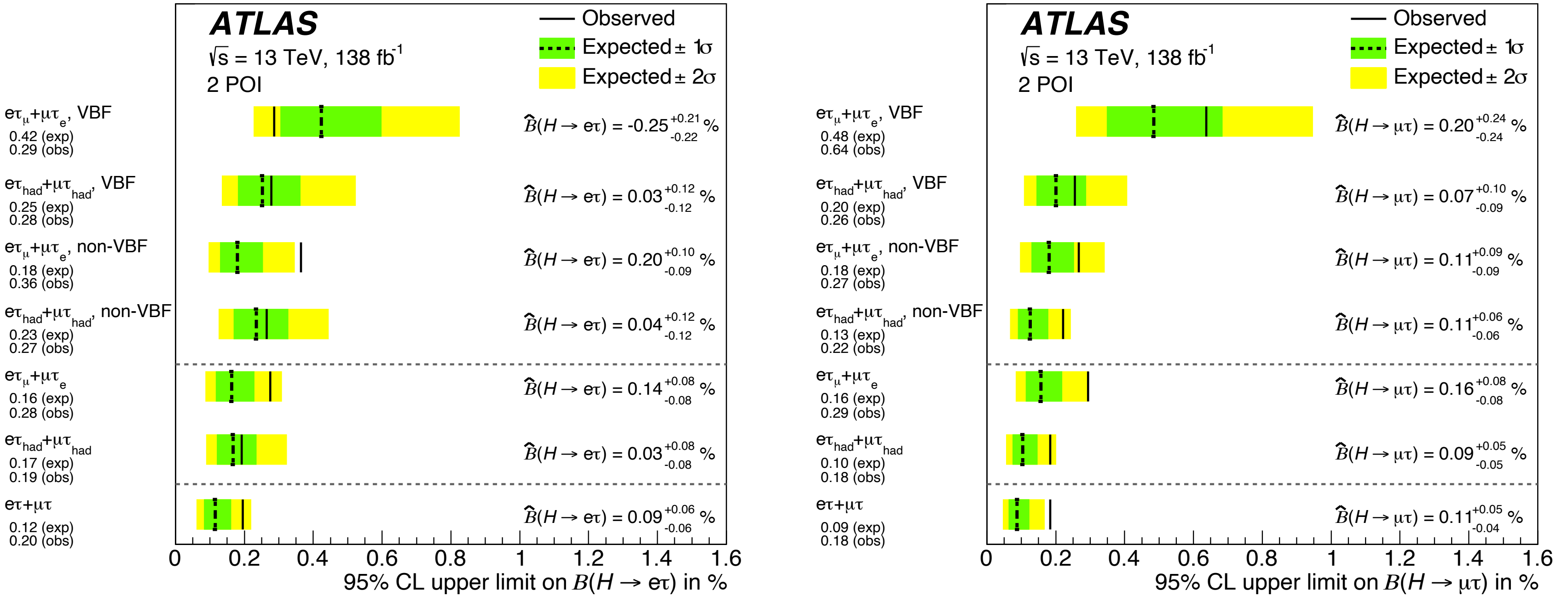
ATLAS H → eτ, μτ

- **Lepton flavor violating decays**
- **Analysis strategy**:
  - MVA-based classifiers to reduce background
  - Two background estimation techniques:
    1) MC-template method, based on data-corrected simulation samples; BDT
    2) Symmetry method, exploiting the symmetry between e & μ in SM backgrounds; NN



arXiv:2302.05225

ATLAS H → eτ, μτ

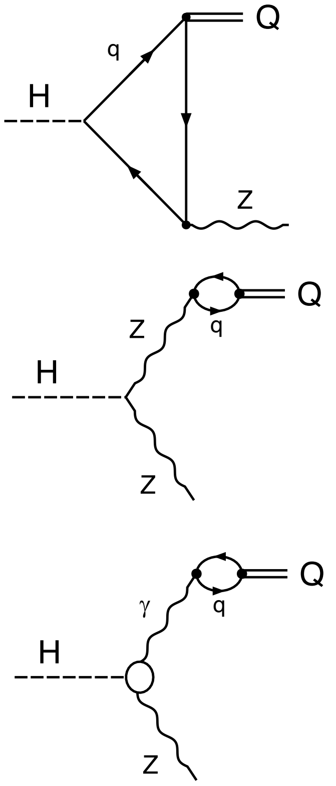


- Obs (exp) limits at 95% CL: B(H→eτ) < 0.20% (0.12%) & B(H→μτ) < 0.18% (0.09%)
- Best-fit B(H→μτ)–B(H→eτ) = (0.25 ± 0.10)%, compatible with zero within 2.5σ

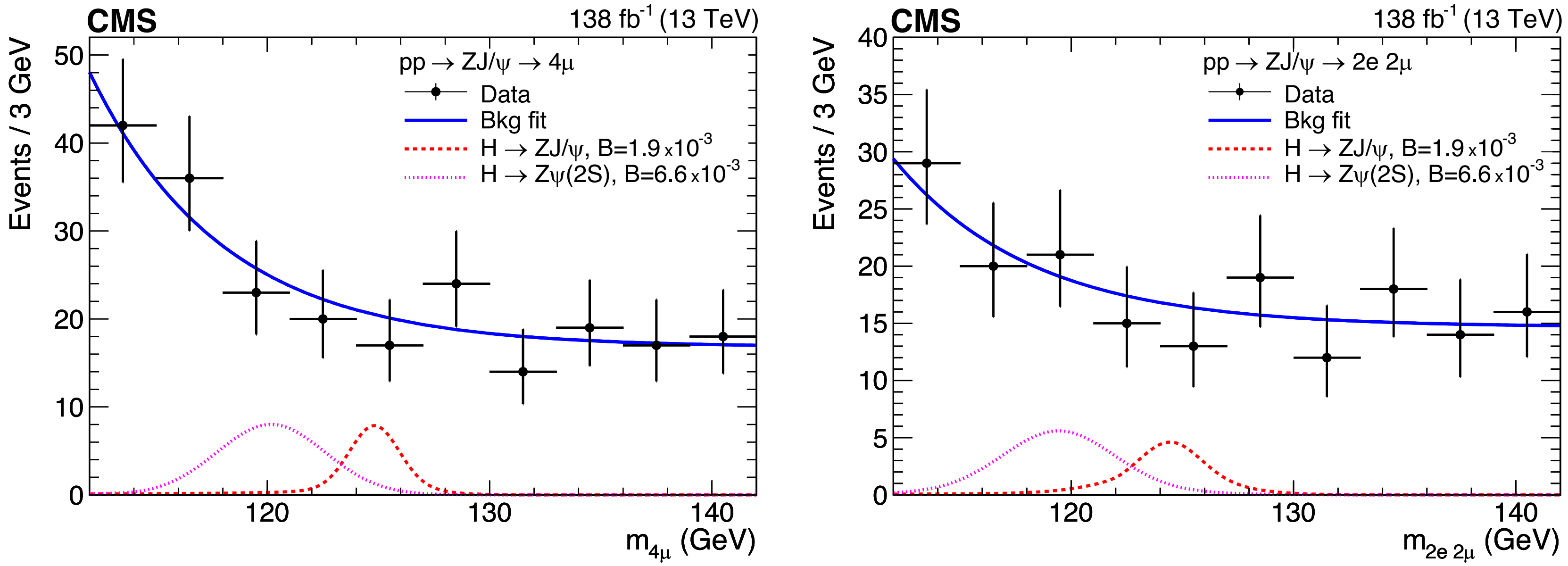
arXiv:2302.05225

CMS H → quarkonia

- **H → Z J/ψ → 4 leptons**
  - B(H → Z J/ψ) = 2.3 × 10^{-6}; B(H → Z ψ(2S)) = 1.7 × 10^{-6}
- **H & Z→ J/ψ J/ψ or $\Upsilon\Upsilon$**
  - B(H → J/ψ J/ψ) = 1.5 × 10^{-10}; B(H → $\Upsilon\Upsilon$) = 2 × 10^{-9}
  - Also search for Higgs or Z decays where, before decaying into muon pairs, one or both J/ψ could be the result of an inclusive ψ(2S) to J/ψ transition
  - Υ(nS)(n=1,2) mesons could be the result of inclusive transitions from Υ(nS)(n=2,3)
- New physics could affect the direct boson couplings or could enter through loops and enhance the BF wrt SM



CMS H → quarkonia



Four-lepton invariant mass distributions for (left) 4μ and (right) 2e2μ channels, with maximum likelihood fit to background superimposed

 arXiv:2206.03525 *(Accepted by PLB)*

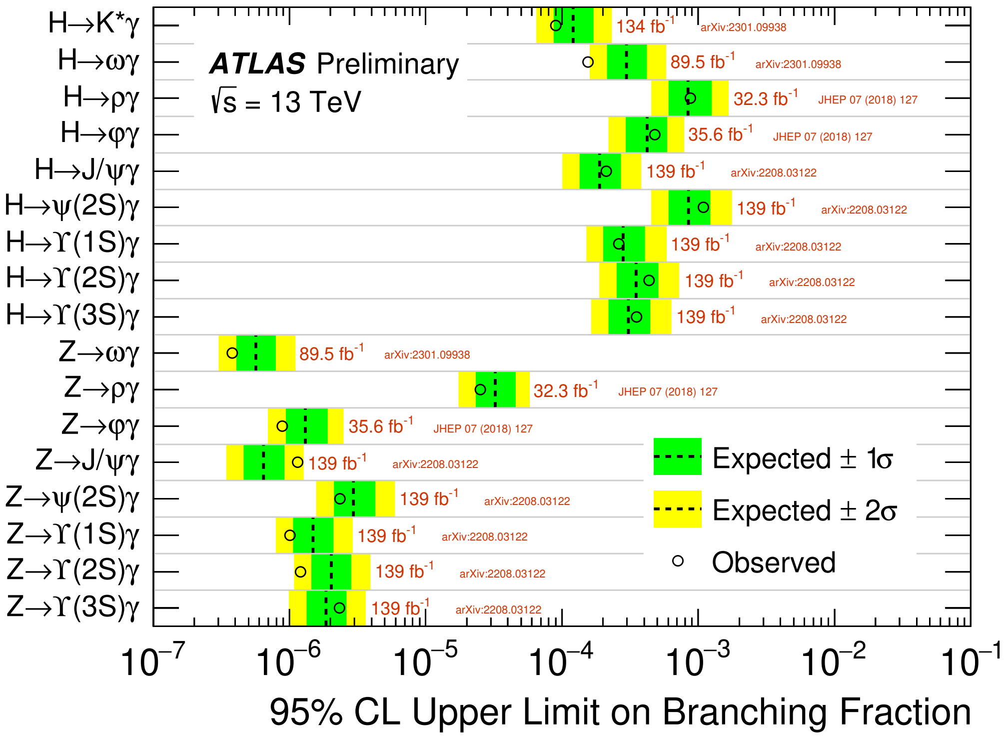
CMS H → quarkonia

Process	Observed	Expected	Observed	
Higgs boson channel	Longitudinal	Longitudinal	Unpolarized	Transverse
$\mathcal{B}(\mathrm{H} \to \mathrm{Z}\mathrm{J}/\psi)$	1.9×10^{-3}	$(2.6^{+1.1}_{-0.7}) \times 10^{-3}$	2.4×10^{-3}	2.8×10^{-3}
$\mathcal{B}(\mathrm{H} \to \mathrm{Z}\psi(2\mathrm{S}))$	6.6×10^{-3}	$(7.1^{+2.8}_{-2.0}) \times 10^{-3}$	8.3×10^{-3}	9.4×10^{-3}
$\mathcal{B}(\mathrm{H} \to \mathrm{J}/\psi\mathrm{J}/\psi)$	3.8×10^{-4}	$(4.6^{+2.0}_{-0.6}) \times 10^{-4}$	4.7×10^{-4}	5.2×10^{-4}
$\mathcal{B}(\mathrm{H} \to \psi(2\mathrm{S})\mathrm{J}/\psi)$	2.1×10^{-3}	$(1.4^{+0.6}_{-0.4}) \times 10^{-3}$	2.6×10^{-3}	2.9×10^{-3}
$\mathcal{B}(\mathrm{H} \to \psi(2\mathrm{S})\psi(2\mathrm{S}))$	3.0×10^{-3}	$(3.3^{+1.5}_{-0.9}) \times 10^{-3}$	3.6×10^{-3}	4.7×10^{-3}
$\mathcal{B}(\mathrm{H} \to \Upsilon(\mathrm{nS})\Upsilon(\mathrm{mS}))$	3.5×10^{-4}	$(3.6^{+0.2}_{-0.3}) \times 10^{-4}$	4.3×10^{-4}	4.6×10^{-4}
$\mathcal{B}(\mathrm{H} \to \Upsilon(1\mathrm{S})\Upsilon(1\mathrm{S}))$	1.7×10^{-3}	$(1.7^{+0.1}_{-0.1}) \times 10^{-3}$	2.0×10^{-3}	2.2×10^{-3}
Z boson channel				
$\mathcal{B}(\mathrm{Z} \to \mathrm{J}/\psi\mathrm{J}/\psi)$	11×10^{-7}	$(9.5^{+3.8}_{-2.6}) \times 10^{-7}$	14×10^{-7}	16×10^{-7}
$\mathcal{B}(\mathrm{Z} \to \Upsilon(\mathrm{nS})\Upsilon(\mathrm{mS}))$	3.9×10^{-7}	$(4.0^{+0.3}_{-0.3}) \times 10^{-7}$	4.9×10^{-7}	5.6×10^{-7}
$\mathcal{B}(\mathrm{Z} \to \Upsilon(1\mathrm{S})\Upsilon(1\mathrm{S}))$	1.8×10^{-6}	$(1.8^{+0.1}_{-0.0}) \times 10^{-6}$	2.2×10^{-6}	2.4×10^{-6}

- Observed upper limit branching fraction for H → Z J/ψ is ~ 800 x SM
- For H → Υ(nS) Υ(mS), upper limit is ~O(10) x earlier SM predictions

ATLAS $H \to \mathcal{M}\gamma$

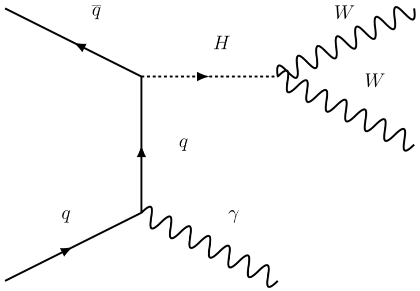
- $H(Z) \to \mathcal{M}\gamma$, $\mathcal{M} = J/\psi, \psi(2S), \Upsilon(1S, 2S, 3S), \phi, \rho, \omega$
- These radiative decays have a distinct experimental signature, which helps suppress the large multi-jet backgrounds that affect direct $H \to q\bar{q}$ searches
- **Summary of 3 results:**
  - $H(Z) \to \omega\gamma$ & $H \to K^*\gamma$: HDBS-2019-33
  - $H(Z) \to Q\gamma$: HDBS-2018-53
  - $H(Z) \to \phi\gamma$ & $\rho\gamma$: HIGG-2016-13



ATL-PHYS-PUB-2023-004

CMS γH Production

- **Production**: **γH, with H→WW**
- WWγ analysis, extended to include γH
- **Sensitive to Higgs coupling to light quarks**
- **Analysis strategy**:
  - Similar to WWγ, but targets Higgs characteristics by requiring $\Delta\phi_{ll} < 2.5$, $\Delta R_{ll} < 2.3$, and $\Delta R_{l\gamma} > 0.8$
  - Profile likelihood ratio test statistic is built in bins of ΔR_{ll} and m_T^{WW}

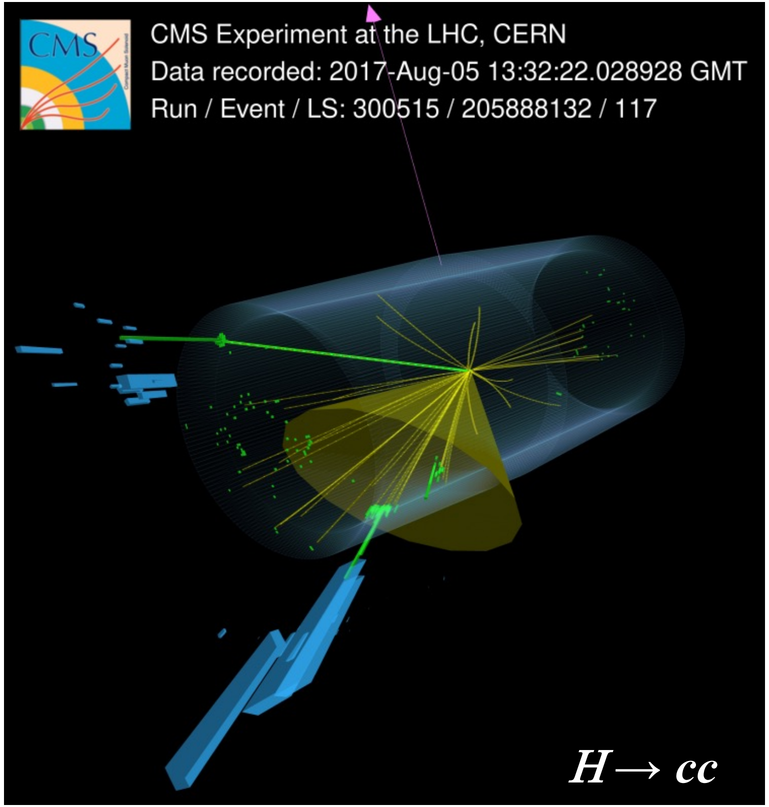


Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.067 (0.085)	$|\kappa_u| \leq$13000 (16000)
$d\bar{d} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.058 (0.072)	$|\kappa_d| \leq$14000 (17000)
$s\bar{s} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.049 (0.068)	$|\kappa_s| \leq$1300 (1700)
$c\bar{c} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.067 (0.087)	$|\kappa_c| \leq$110 (200)

CMS-SMP-22-006

Summary

- **Studies of rare Higgs decays are essential to LHC physics program**
- ATLAS & CMS are making impressive progress in rare Higgs
- Improvements not only come from a larger data set, but also from using innovative analysis techniques
- Run 3 will consolidate the evidence in some decay channels and will bring further improvement in sensitivity



"Searches for BSM scalars" -- ATLAS: Nicholas Kyriacou; CMS: Ram Krishna Sharma
"Exotic production & decays of the 125 GeV Higgs" -- ATLAS: Rocky Bala Garg; CMS: Pallabi Das

Analysis	Experiment	Reference	Obs (Exp) 95% CL
H → Zγ	ATLAS + CMS	ATLAS-CONF-2023-025 & CMS HIG-23-002	• μ = 2.2 ± 0.7 (1.0 ± 0.6) x SM • B(H→Zγ) = (3.4 ± 1.1) × 10^{-3}, within 1.9σ of SM
H → cc	CMS	*Eur. Phys. J. C 82 (2022) 717*	• σ(VH) B(H→cc): $14\ (7.6^{+3.4}_{-2.3})$ x SM • 1.1 < $\lvert\kappa_c\rvert$ < 5.5 ($\lvert\kappa_c\rvert$ < 3.4)
	CMS	arXiv:2211.14181 (Accepted by PRL)	• σ(VH) B(H→cc): 47 (39) x SM
	ATLAS	*Eur. Phys. J. C 82 (2022) 717*	• (W/Z)H(→cc): 26 (31) x SM • $\lvert\kappa_c\rvert$ < 8.5 (12.4)
H → μμ	CMS	*JHEP 01 (2021) 148*	• H → μμ: 3.0σ (2.5σ) • $\mu = 1.19^{+0.40}_{-0.39}\ (\mathrm{stat})^{+0.15}_{-0.14}(\mathrm{syst})$
	ATLAS	*(Phys. Lett. B 812 (2021) 135980)*	• H → μμ: 2.0σ (1.7σ) • μ = 1.2 ± 0.6
H → ee, eμ	CMS	arXiv:2208.00265 (Accepted by PLB)	• B(H→ee) < 3.0 × 10^{-4} (3.0 × 10^{-4})
	ATLAS	*Phys. Lett. B 801 (2020) 135148*	• B(H→ee) < 3.6 × 10^{-4} (3.5 × 10^{-4}) • B(H→eμ) < 6.2 × 10^{-5} (5.8 × 10^{-5})
H → eτ, μτ	ATLAS	arXiv:2302.05225	• B(H→eτ) < 0.20% (0.12%) & B(H→μτ) < 0.18% (0.09%) • B(H→μτ)–B(H→eτ) = (0.25 ± 0.10)%
H → quarkonia	CMS	arXiv:2206.03525 *(Accepted by PLB)*	• H → ZJ/ψ < ~ 800 x SM • H → Υ(nS) Υ(mS) < ~O(10) x SM
	ATLAS	ATL-PHYS-PUB-2023-004	• See table
γH	CMS	CMS-SMP-22-006	• $\lvert\kappa_u\rvert$ ≤ 13000 (16000) • $\lvert\kappa_d\rvert$ ≤ 14000 (17000) • $\lvert\kappa_s\rvert$ ≤ 1300 (1700) • $\lvert\kappa_c\rvert$ ≤ 110 (200)