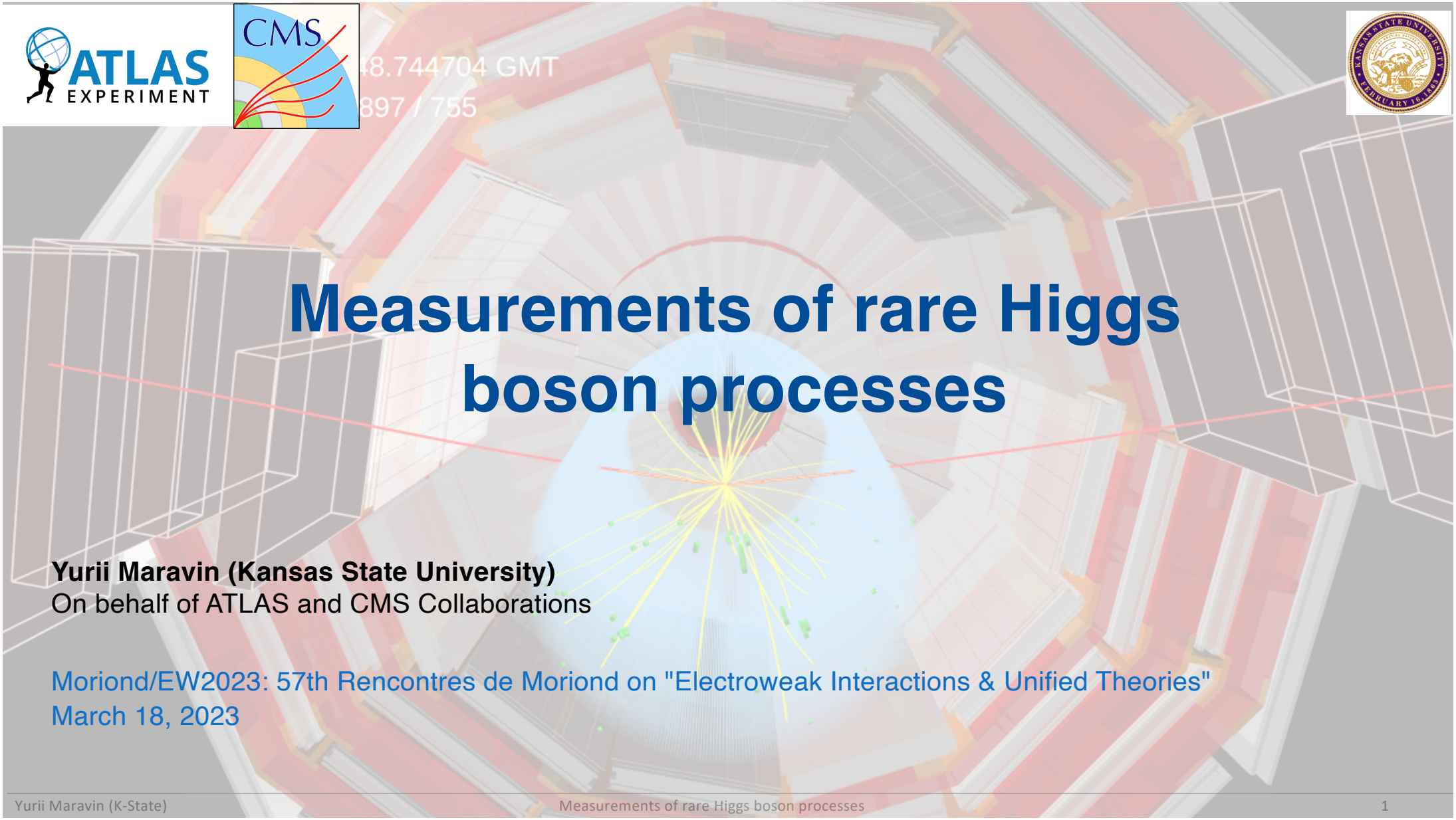


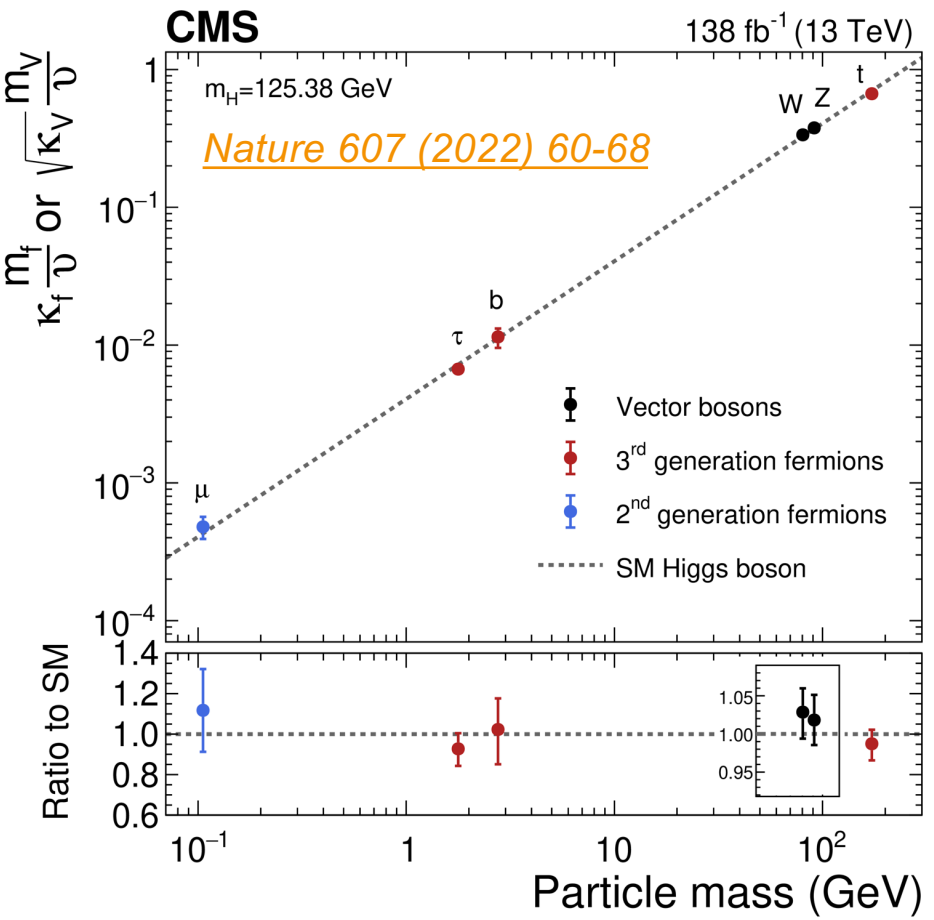
Measurements of rare Higgs boson processes

Yurii Maravin (Kansas State University)
On behalf of ATLAS and CMS Collaborations

Moriond/EW2023: 57th Rencontres de Moriond on "Electroweak Interactions & Unified Theories"
March 18, 2023

A decade since the Higgs discovery

- A triumph of theoretical and experimental physics
- One of few handles to search for new physics
  - Sensitivity to new physics in **rare decays**
    - Experimentally challenging



A decade since the Higgs discovery

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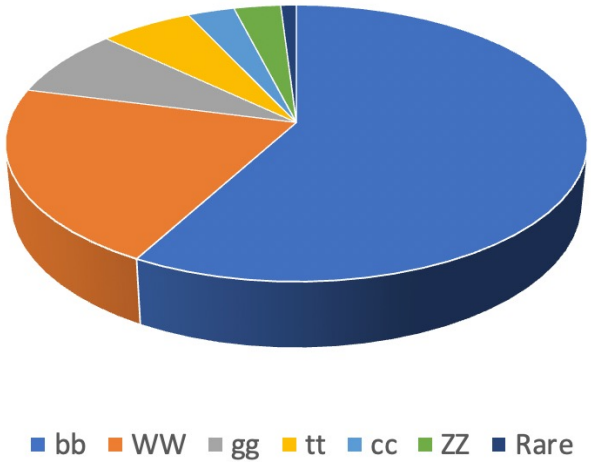
    - Experimentally challenging

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

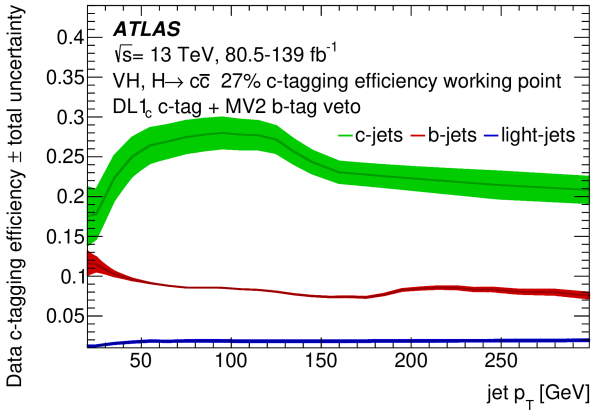


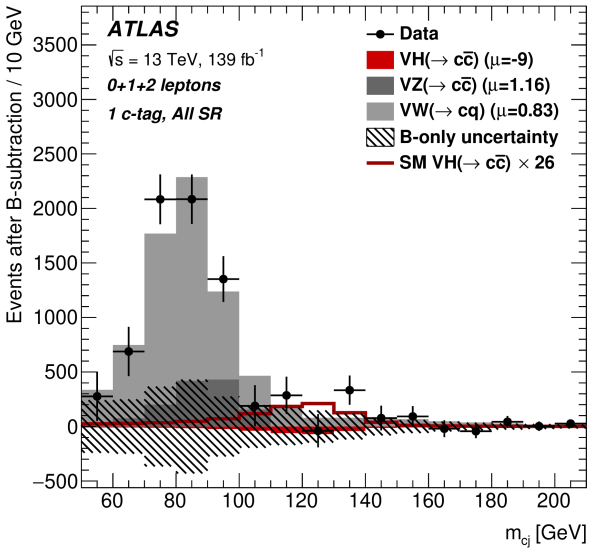
- In this talk:
  - H→cc
  - H→Zγ
  - Decays to quarkonium and vector mesons and a photon

Search for $H \to c\bar{c}$

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

- Very challenging analysis
  - $H \to c\bar{c}$ is difficult to trigger
  - Multijet background is larger by many orders of magnitude
  - Charm-jet tagging is more complex compared to b-tagging
    - **YSF Talk later today on $H \to c\bar{c}$ tagging by Martino Tanasini**
- Search using VH production
  - Categories based on number of leptons
    - Further categorization based on $p_T(V)$ and N_{jets}
  - Validation of methods on $V \to cq$ process
    - Evidence for $VW(\to cq)$: observed (expected) significance is 3.8σ (4.6σ)
    - Observed (expected) significance of $VZ(\to c\bar{c})$ is 2.6σ (2.2σ)





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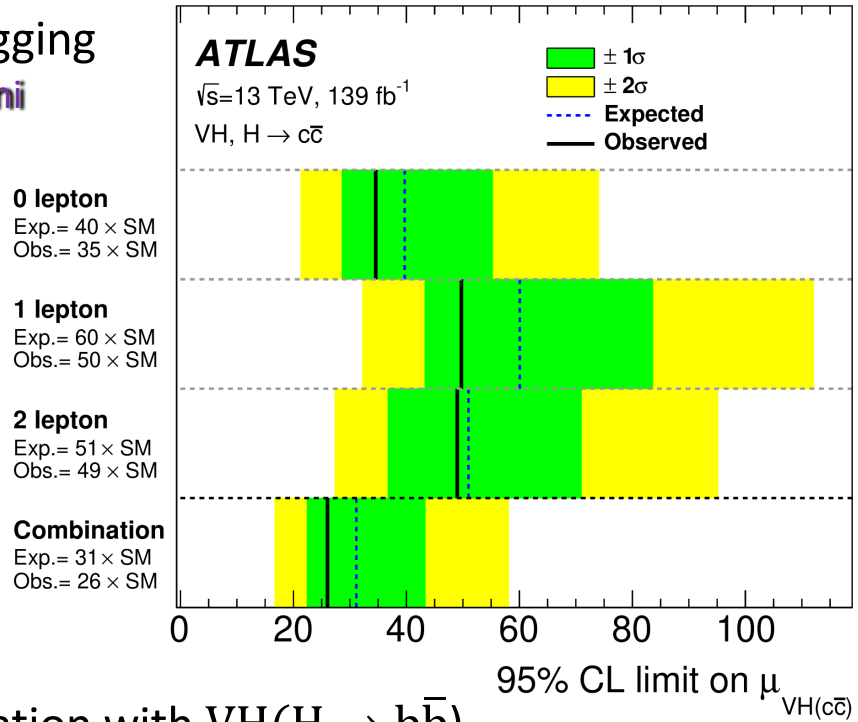
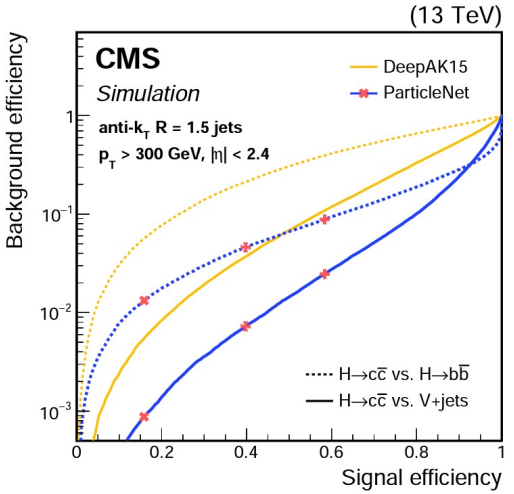
    - Observed (expected) significance of $VZ(\to c\bar{c})$ is 2.6σ (2.2σ)
- Combined observed (expected) limit (95% CL) on $H \to c\bar{c}$ is 26 (31) of the SM signal strength
  - A limit on $|\kappa_c/\kappa_b| < 4.5$ @ 95% CL, from the combination with $VH(H \to b\bar{b})$

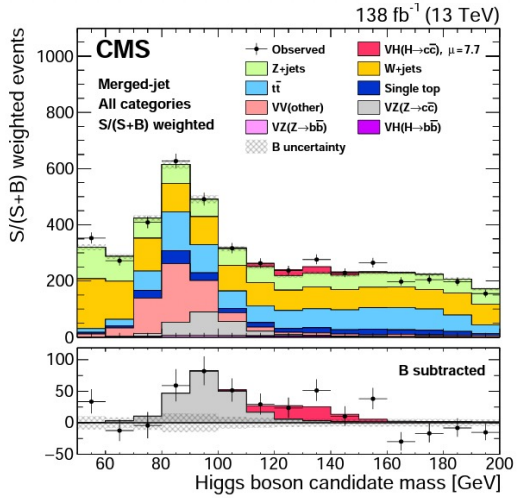


Search for $H \to c\bar{c}$

Accepted in PRL
CMS-DP-2018-046

- Search using VH production
  - Combined resolved and boosted approach
- Significant improvement in c-tagging performance
  - Adopting boosted H production utilizing specialized c-jet tagger based on the ParticleNet algorithm
    - An improvement by a factor of 3 with respect to the CMS previous algorithm (DeepAK15)
- First observation of $VZ(Z \to c\bar{c})$ @ 5.7σ





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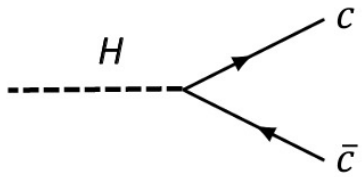
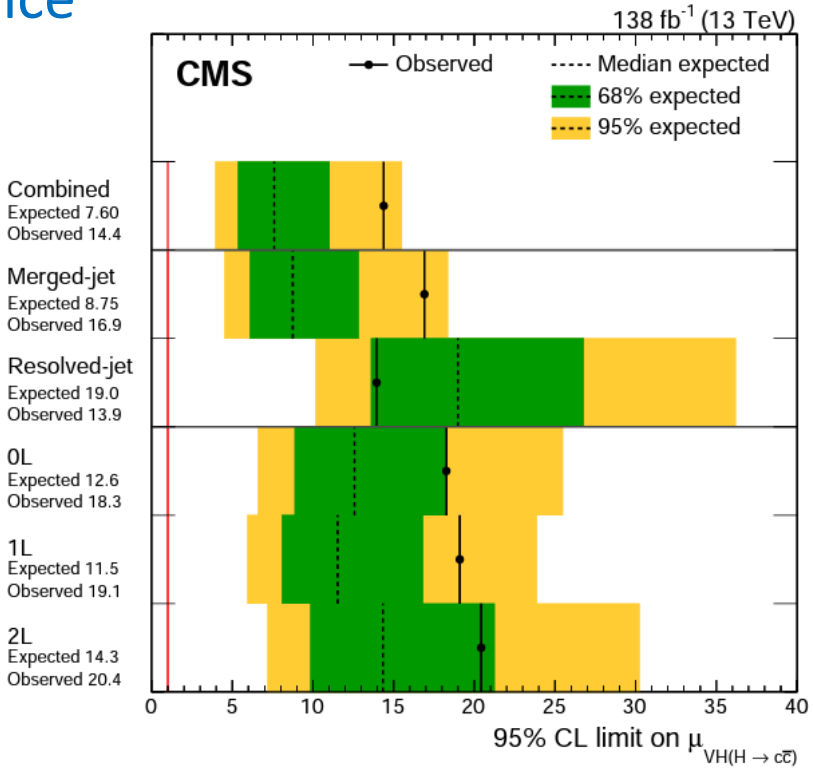
- Combined observed (expected) limit (95% CL) on $H \to c\bar{c}$ is 14 (7.6) of the SM signal strength
  - Most stringent limit: $1.1 < |\kappa_c| < 5.5$ at 95% CL



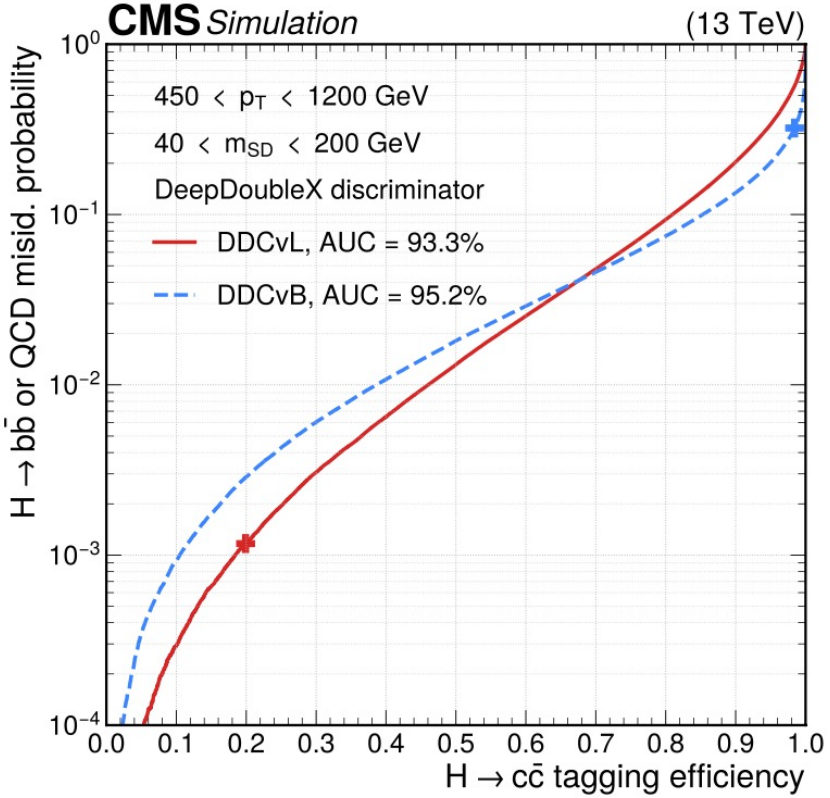


Search for boosted $H \to c\bar{c}$

New!

Submitted to PRL

- Dedicated effort to look for boosted $H \to c\bar{c}$ process enriched with ggH production
  - Target $p_T > 450$ GeV and use decorrelated taggers (DDT)
  - DNN discriminators for signal vs. background (QCD multijet) separation
- Observed $Z \to c\bar{c}$ process with $\mu = 1.00^{+0.19}_{-0.17}$
- Observed (expected) upper limit on the signal is 47 (39) times the SM expectation



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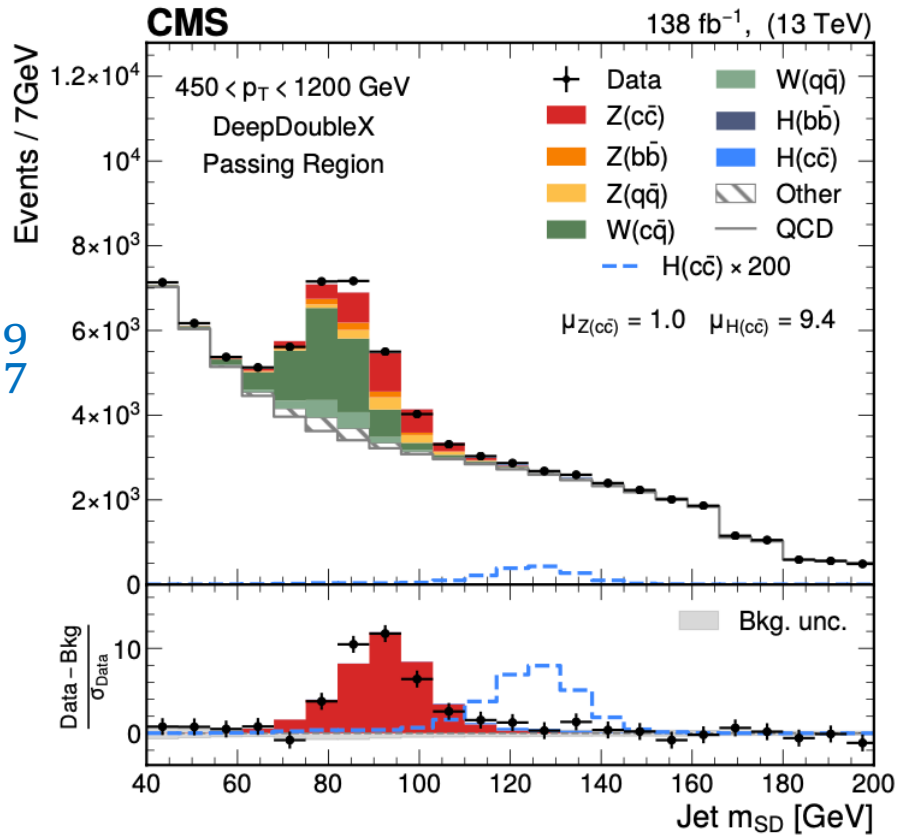
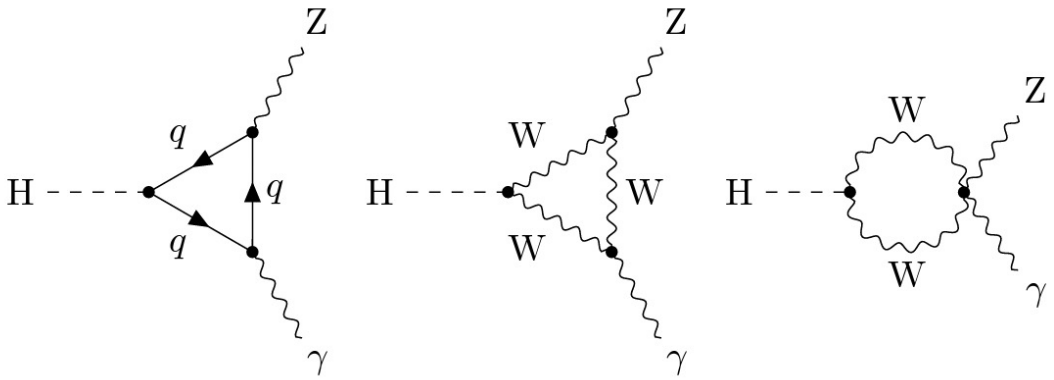


$H \to Z\gamma$

ATLAS: PLB 809 (2020) 135754
CMS: Accepted to JHEP

- Small branching fraction $Br(H \to Z\gamma) \sim O(1.6 \times 10^{-3})$

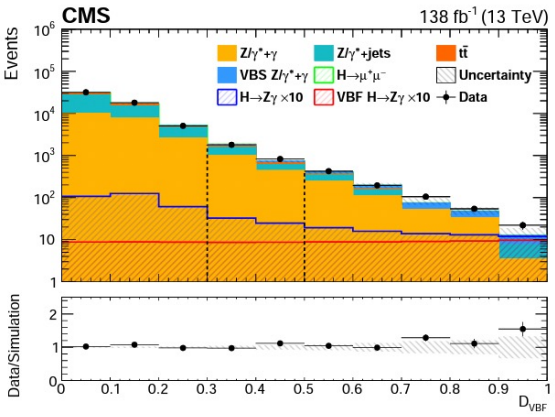


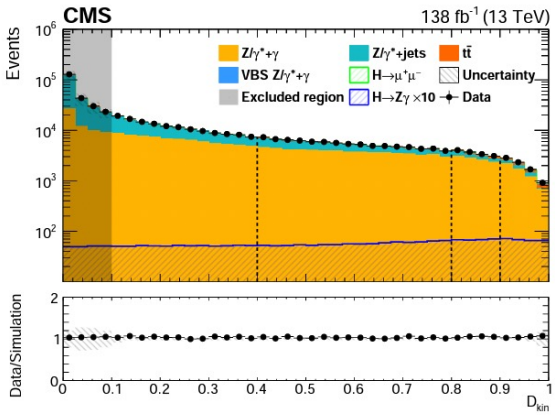
- A ratio of $Br(H \to Z\gamma)/Br(H \to \gamma\gamma)$ is sensitive to BSM effects
  - Some systematics cancels, BSM change two branching fractions differently enhancing the sensitivity
- Pursue $ee\gamma$ and $\mu\mu\gamma$ final states
- Final state radiation recovery to improve the mass resolution

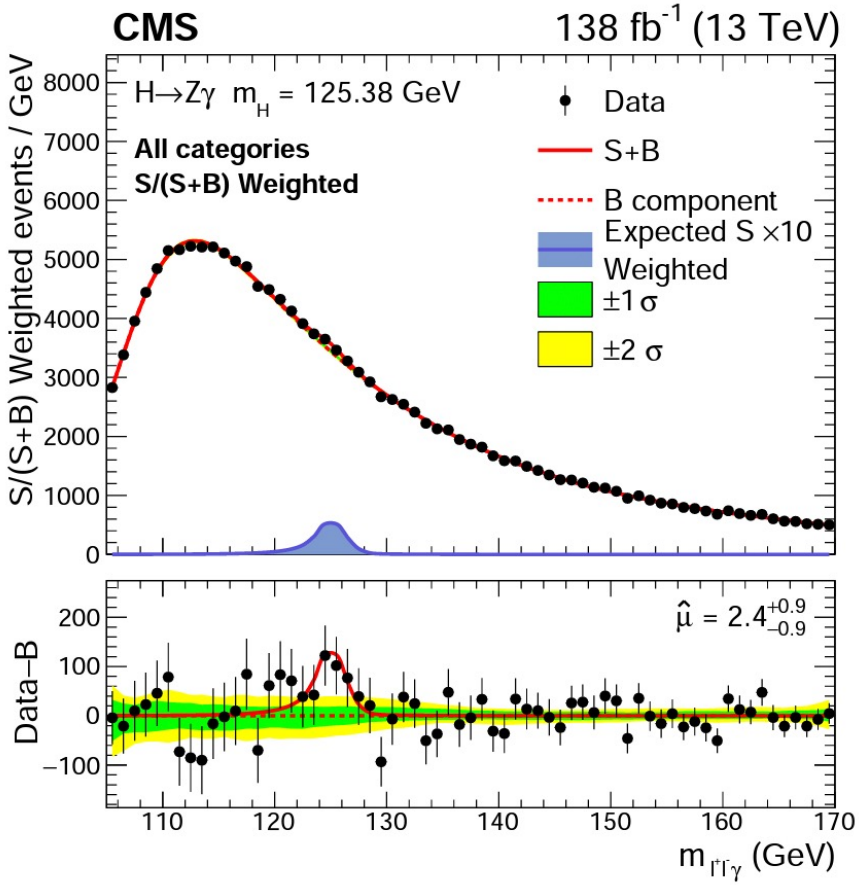
H→Zγ

Accepted to JHEP

- Utilize 8 categories
  - VH and ttH production (lepton-tagged)
  - VBF (dijet-tagged): BDT VBF classifier (D_{VBF})
  - ggH (untagged)
- BDT discriminator (D_{kin}) to improve S/B

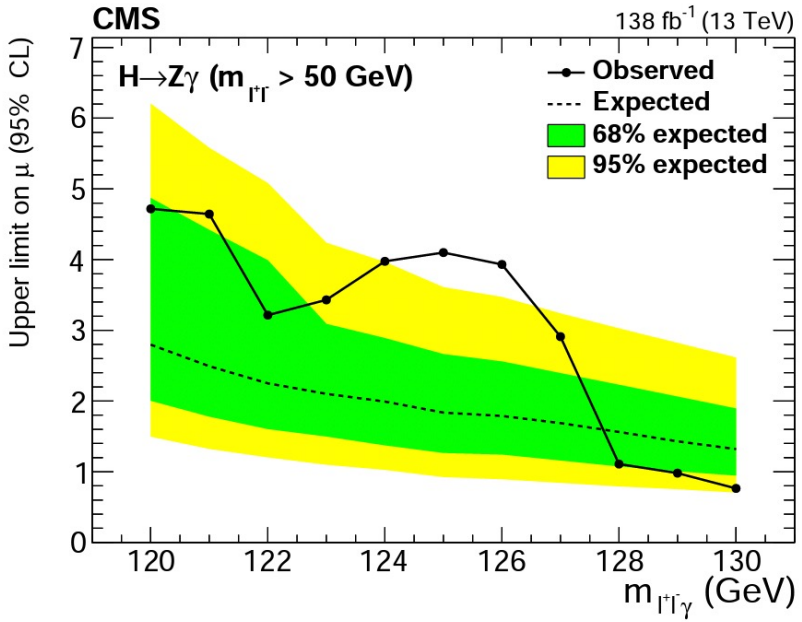


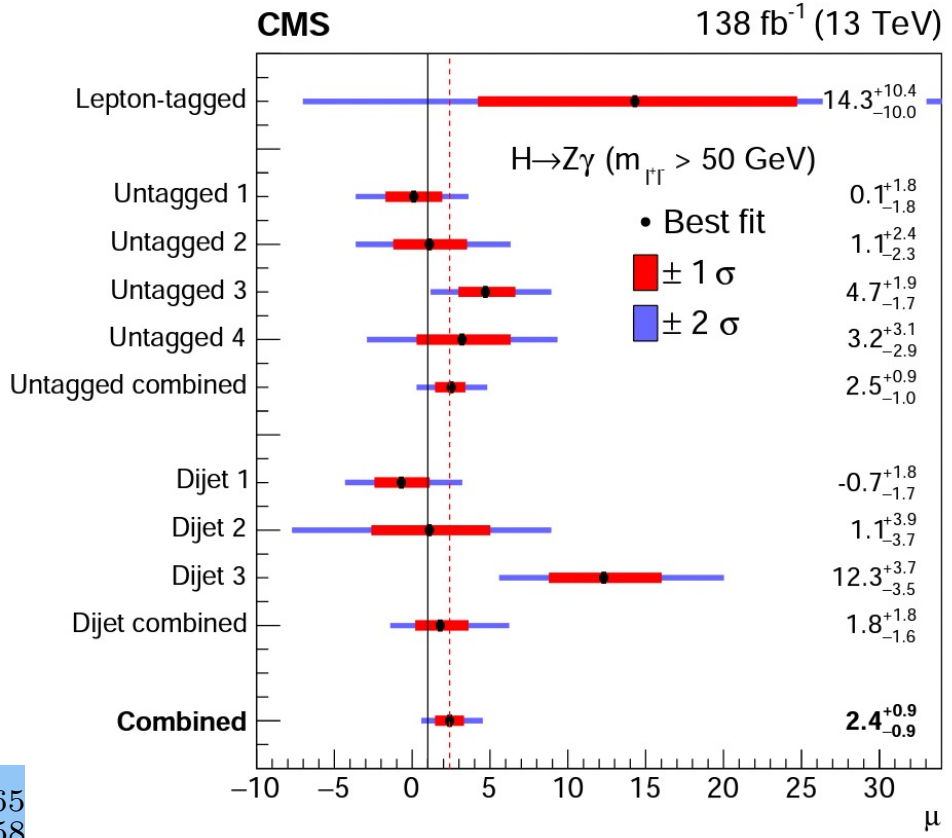




H→Zγ

Accepted to JHEP





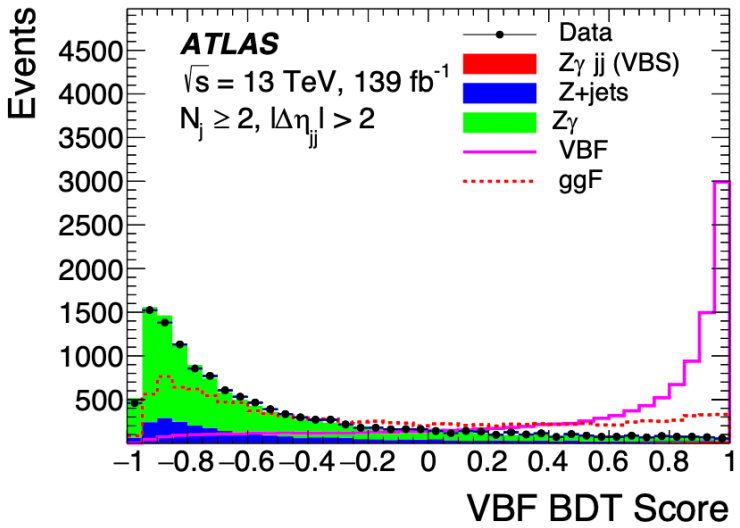
- Observed (expected) signal: 2.7σ (1.2σ)
  - Signal strength: $\hat{\mu} = 2.4 \pm 0.9$
  - Ratio of branching fractions is consistent with the SM @ 1.5σ

$$\frac{Br(H \to Z\gamma)}{Br(H \to \gamma\gamma)} = 1.54^{+0.65}_{-0.58}$$

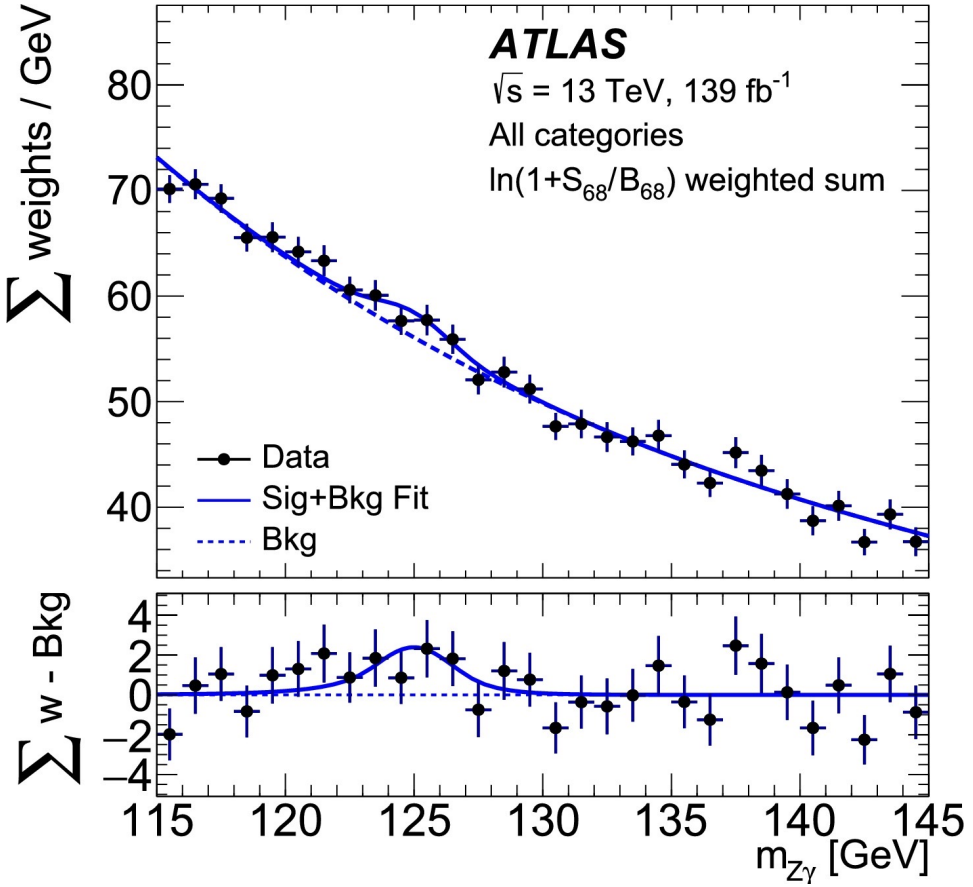
$H \to Z\gamma$

PLB 809 (2020) 135754

- Use 6 categories with different signal-to-background ratio and mass resolution to enhance the sensitivity
  - MVA enriched VBF
  - Using photon and dilepton kinematics to select other signal events



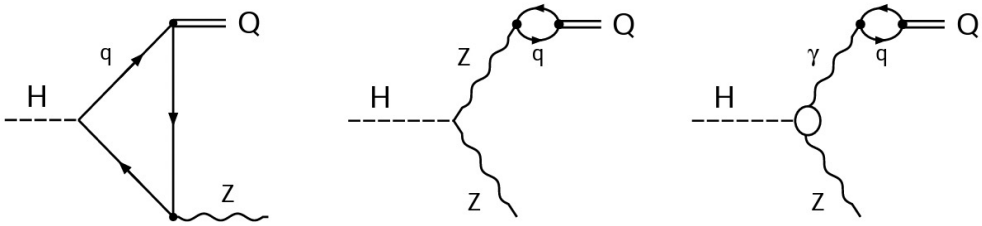
- Observed (expected) significance: 2.2σ (1.2)σ
  - Best fit signal strength value: $\hat{\mu} = 2.4^{+1.0}_{-0.9}$



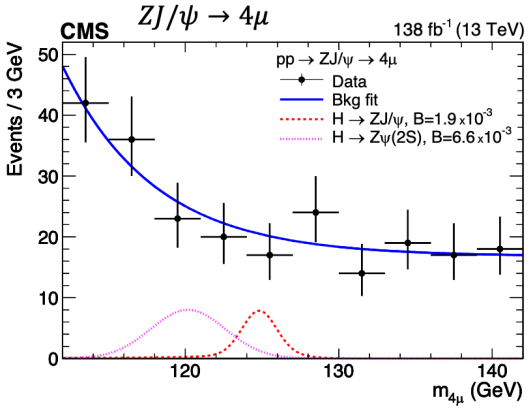
Search for H to quarkonia

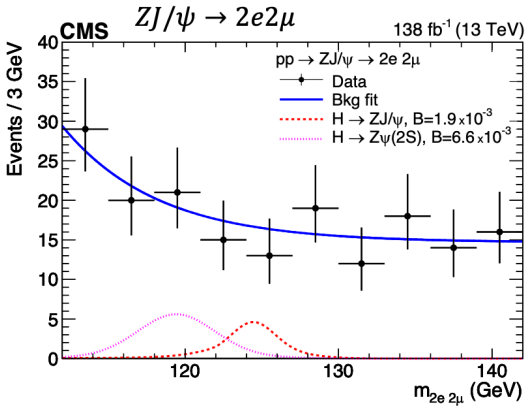
Submitted to PLB

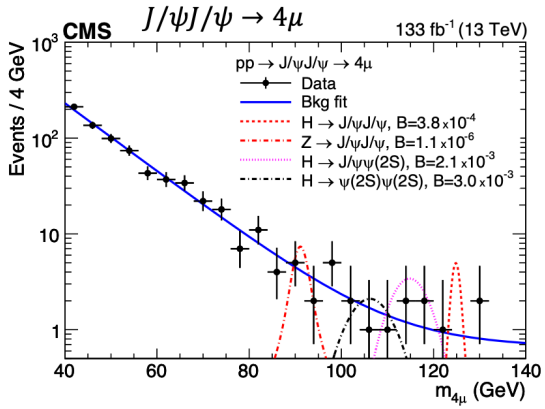
- Small branching fractions
  but clean experimental signature
  - $Br(H \to Z\,J/\Psi) \sim 2\times10^{-6}$,
  - $Br(H \to J/\Psi\,J/\Psi) \sim 2\times10^{-10}$



- Analysis strategy
  - Search for ee, μμ final states from Z and μμ final state from J/Ψ
  - Search for double Υ decays







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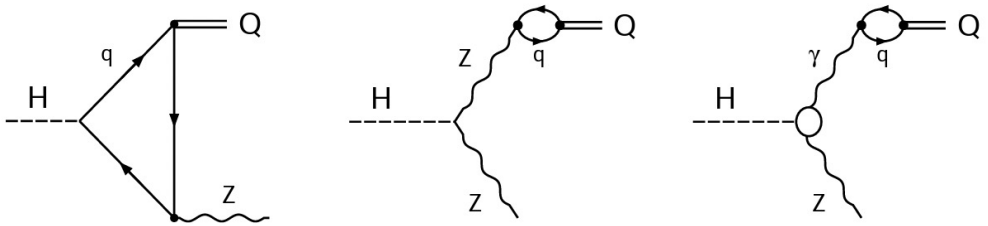
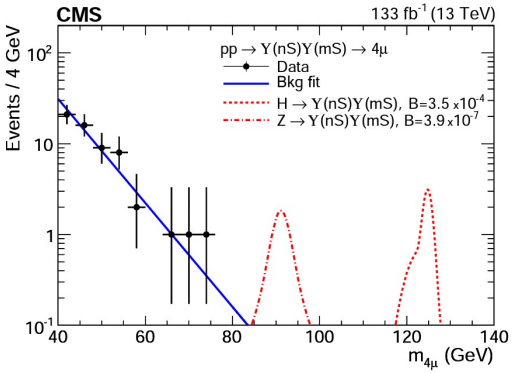
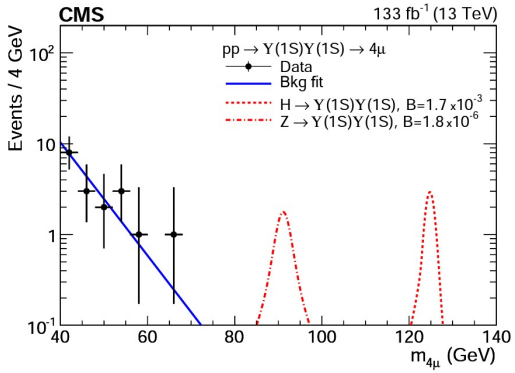




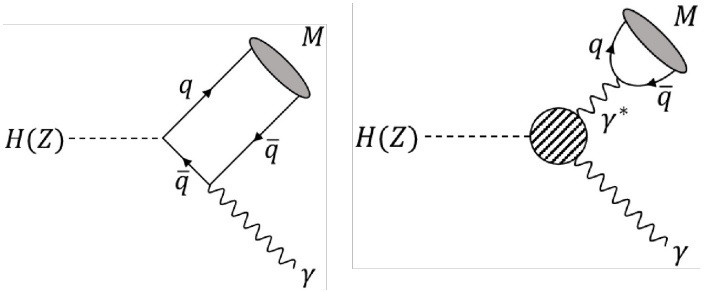


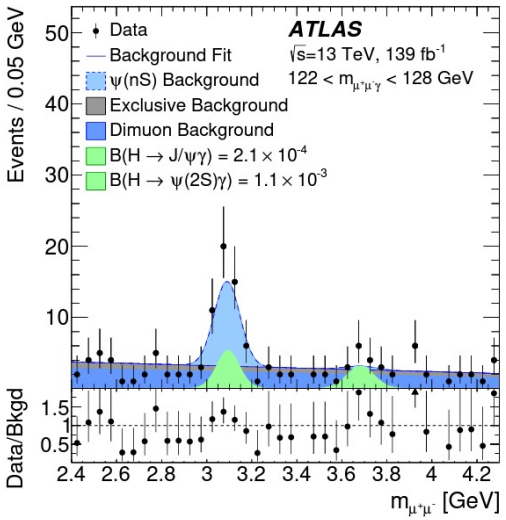
Process	Observed	Expected	Observed	
Higgs boson channel	Longitudinal	Longitudinal	Unpolarized	Transverse
$\mathcal{B}(\mathrm{H} \to \mathrm{ZJ}/\psi)$	1.9×10^{-3}	$(2.6^{+1.1}_{-0.7}) \times 10^{-3}$	2.4×10^{-3}	2.8×10^{-3}
$\mathcal{B}(\mathrm{H} \to \mathrm{Z}\psi(2\mathrm{S}))$	6.6×10^{-3}	$(7.1^{+2.8}_{-2.0}) \times 10^{-3}$	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}

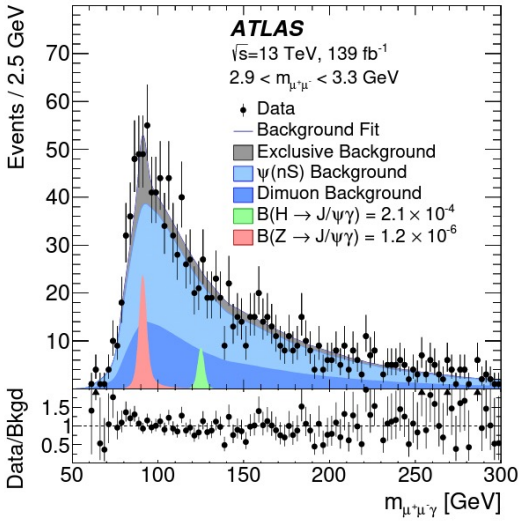
Search for H to quarkonia

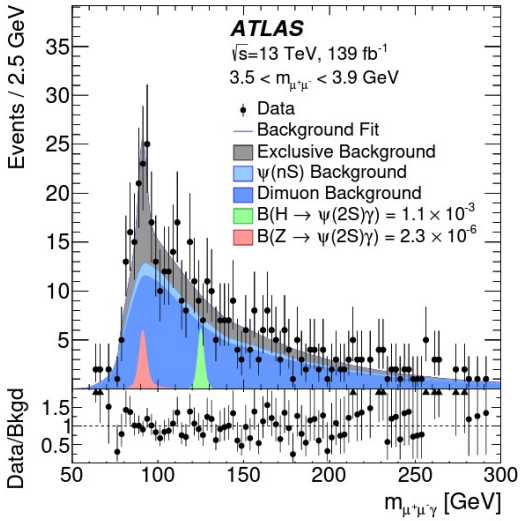
Accepted to EPJC

- Small branching fractions
  - $Br(H \to J/\Psi\,\gamma) \sim 3{\times}10^{-6}$, $Br(H \to \Upsilon\,\gamma) \sim 10^{-9}$
- Focus on $\mu\mu\gamma$ final state
  - Major background is FSR $\mu\mu\gamma$ and γ+jet processes
    - Estimated from data (shape of exclusive background is from MC)
  - 2D simultaneous unbinned fit to $m_{\mu\mu}$ and $m_{\mu\mu\gamma}$





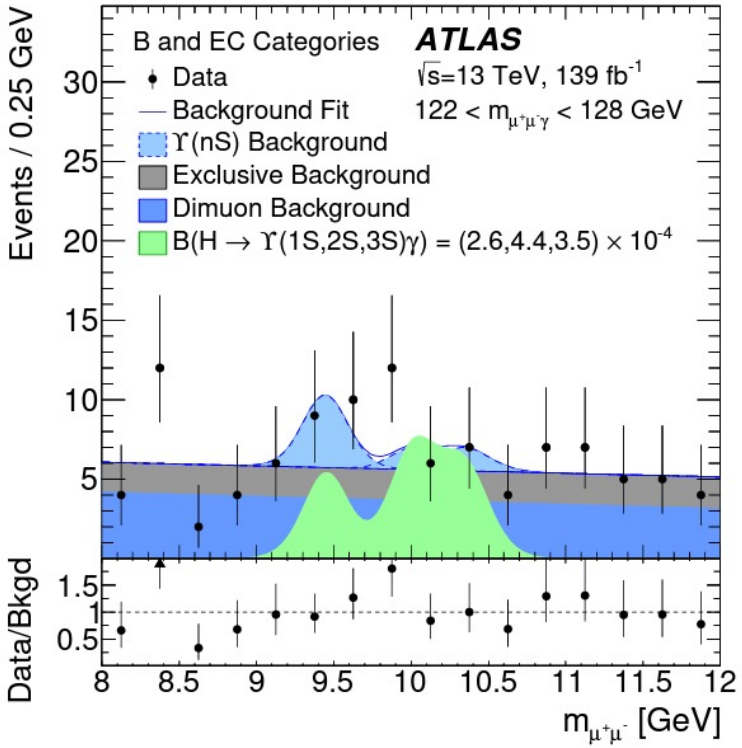


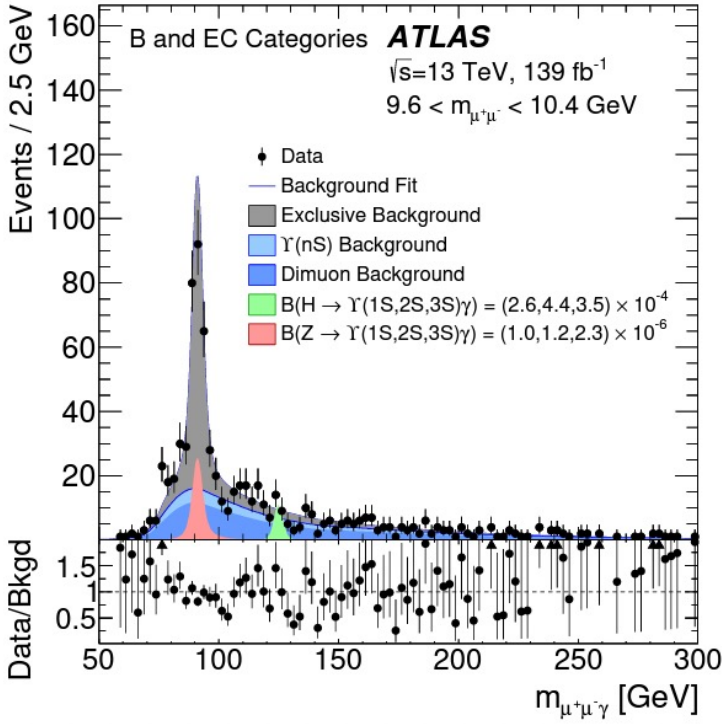


Search for H to quarkonia

Accepted to EPJC

- Similar distributions for $\Upsilon(nS)$

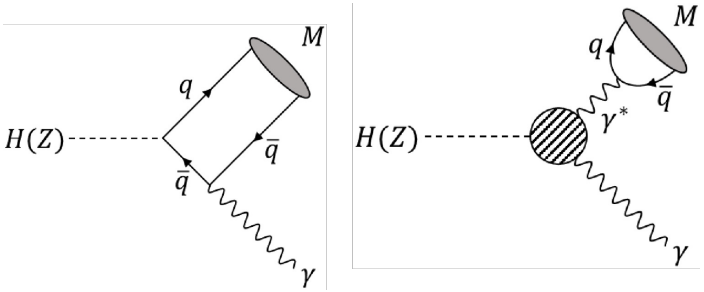




Search for H to quarkonia

Accepted to EPJC

- Similar distributions for $\Upsilon(nS)$
- Observations are consistent with background-only hypotheses
  - $Br(H \to Q\gamma) < O(10^{-4})$



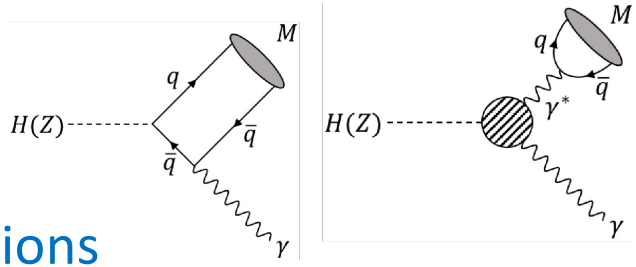
	95% CL_s upper limits					
	Branching fraction				$\sigma \times \mathcal{B}$	
Decay channel	Higgs boson [10^{-4}]		Z boson [10^{-6}]		Higgs boson [fb]	Z boson [fb]
	Expected	Observed	Expected	Observed	Observed	Observed
$J/\psi\,\gamma$	$1.9^{+0.8}_{-0.5}$	2.1	$0.6^{+0.3}_{-0.2}$	1.2	12	71
$\psi(2S)\,\gamma$	$8.5^{+3.8}_{-2.4}$	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

$H \to K^*/\omega + \gamma$

Submitted to PLB

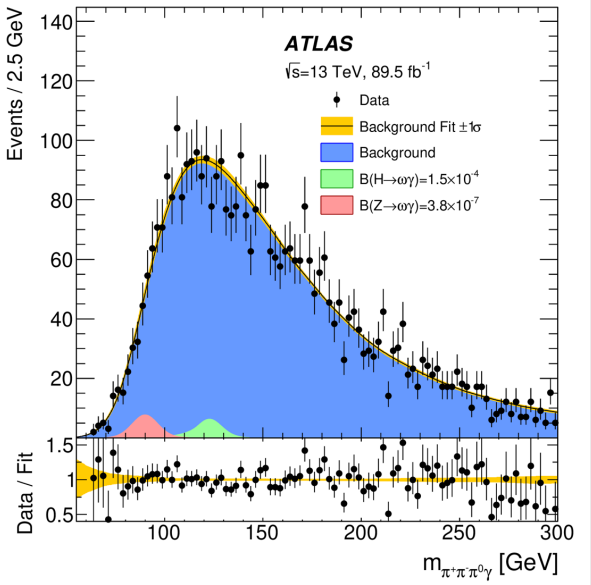
New!

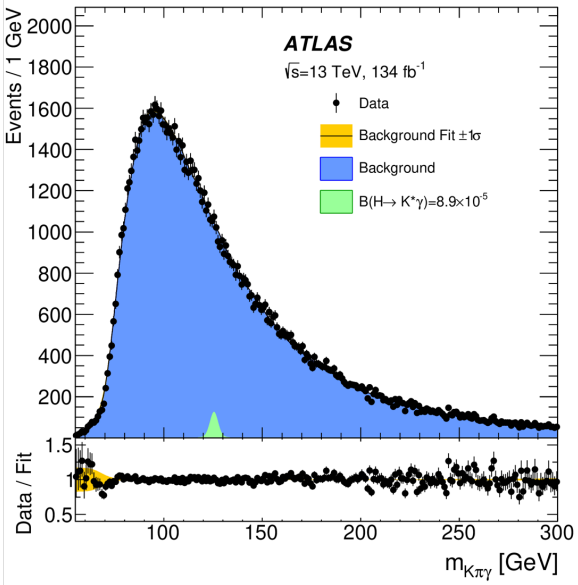
- Flavor conserving/violating decays
  - $H(Z) \to \omega\gamma \to \pi^+\pi^-\pi^0\gamma$
  - $H \to K^* \to K^+ \pi^-\gamma$
- Dedicated trigger and tau lepton particle flow to identify pions
- Backgrounds are determined from data



Channel	95% CL upper limit	
	Expected	Observed
$H \to \omega\gamma$ $[10^{-4}]$	$3.0^{+1.2}_{-0.8}$	1.5
$Z \to \omega\gamma$ $[10^{-7}]$	$5.7^{+2.3}_{-1.6}$	3.8
$H \to K^*\gamma$ $[10^{-5}]$	$12.2^{+4.9}_{-3.4}$	8.9

- Limits for $H \to \omega\gamma$ are ~100 times the SM expected values

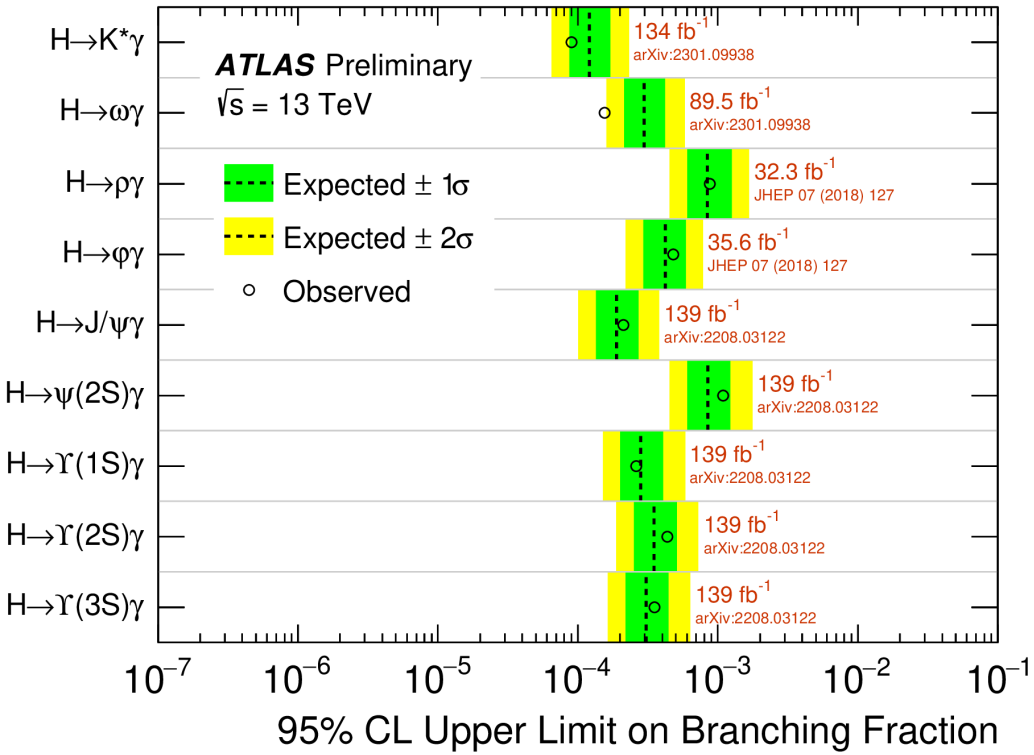




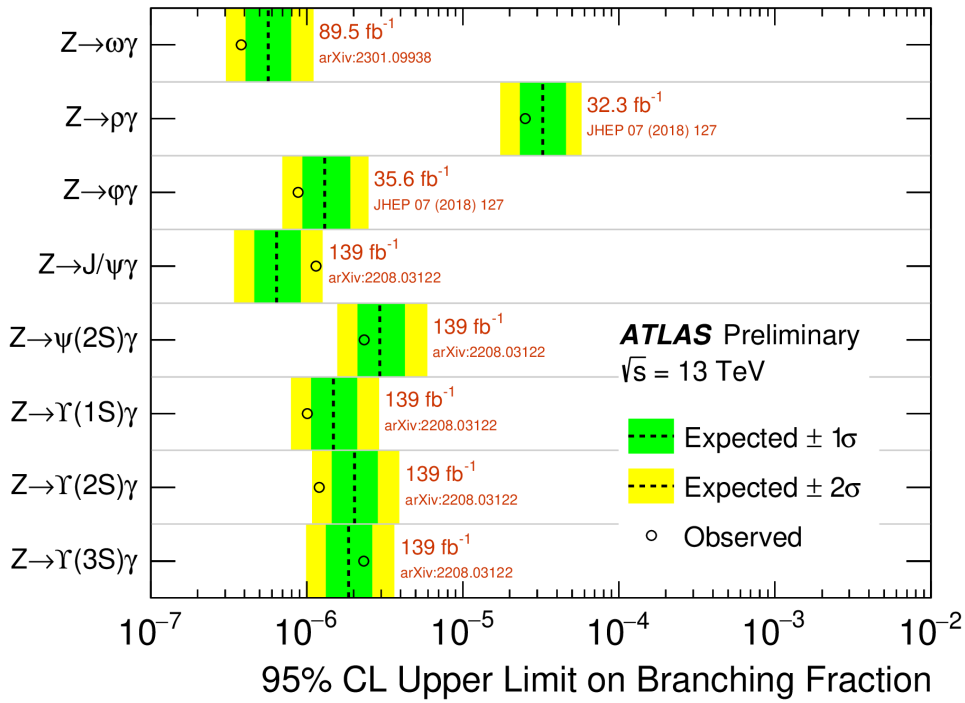
Search for H to meson and gamma

ATLAS: *ATL-PHYS-PUB-2023-004*

- These results together with the other ATLAS results on mesons + photon searches are illustrated below

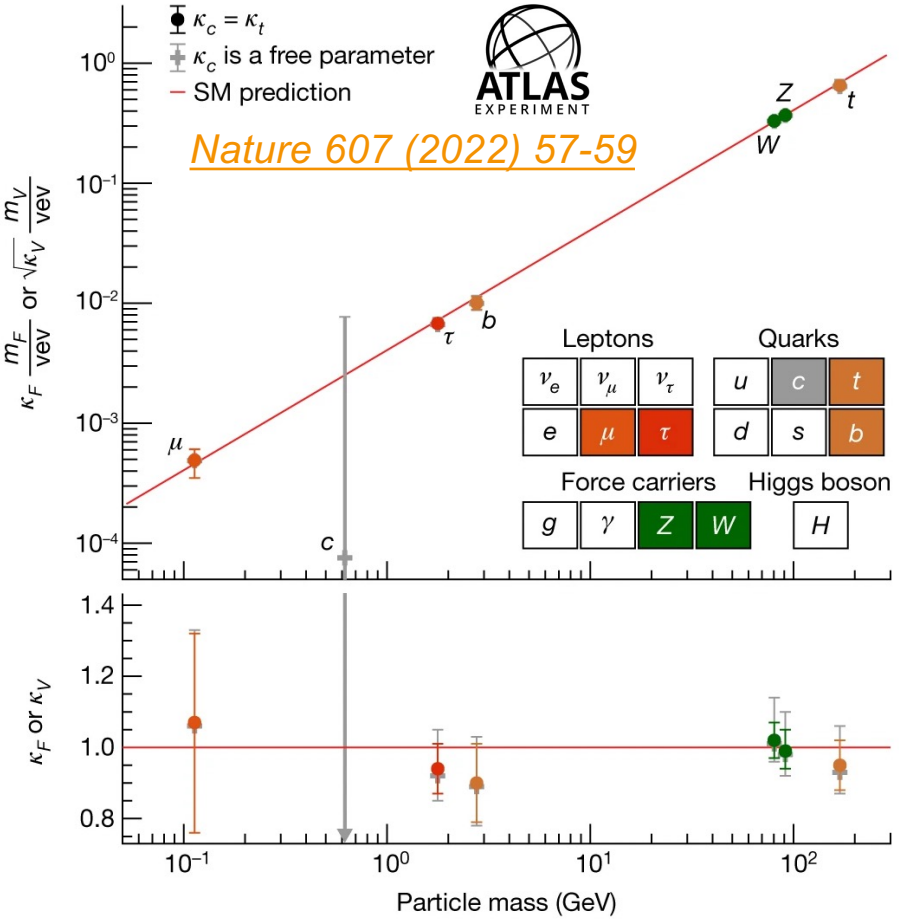


Z to meson and gamma



Summary

- Studies of rare Higgs boson decays are essential in the LHC physics program
- Both experiments are making impressive progress in studying Higgs boson
  - First evidence of Higgs boson couplings to muons at CMS
  - First evidence of Higgs decay to low-mass $\ell\ell\gamma$ in ATLAS
- Improvement not only comes from a larger data set, but also from using innovative MVA techniques
- Run 3 will consolidate the evidence in some decay channels and will bring further improvement in sensitivity

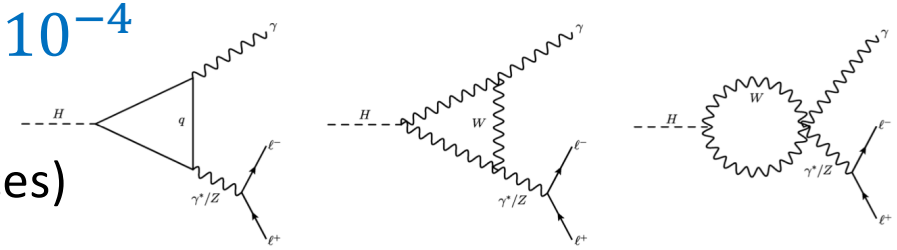


Backup

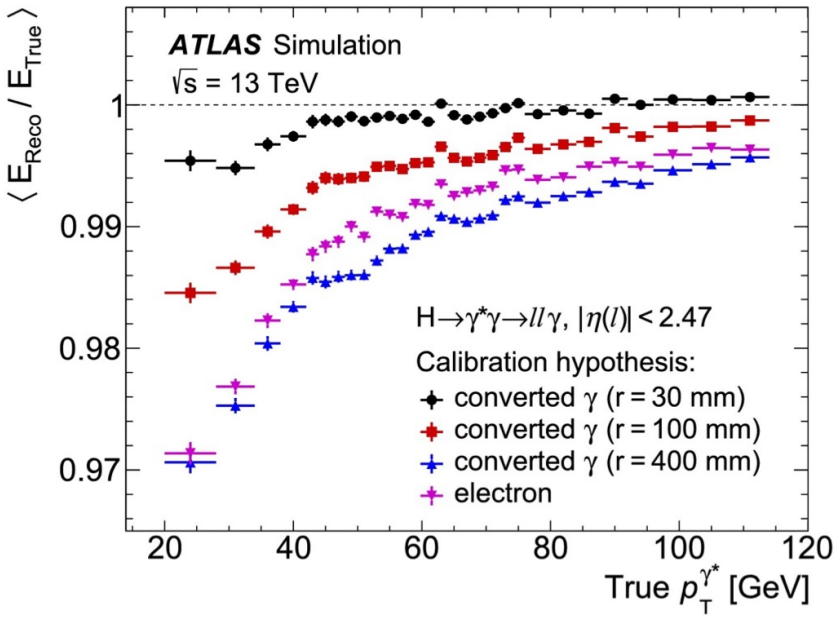
$H \to \gamma^* \gamma$

ATLAS: PLB 819 (2021) 136412

- Small branching fractions $Br(H \to \ell\ell\gamma) \sim 10^{-4}$
  - Use di-electron and di-muon plus photon
  - $m_{\ell\ell} < 30$ GeV (excluding J/Ψ and Υ resonances)



- Three types of categories
  - VBF enriched, high- and low-pTt categories
    - pTt is strongly correlated with the transverse momentum of the $\ell\ell\gamma$ system
- Use both resolved and merged ee signatures
  - Dedicated ID and calibration for merged electrons



$H \to \gamma^* \gamma$

ATLAS: PLB 819 (2021) 136412

- Small branching fractions $Br(H \to \ell\ell\gamma) \sim 10^{-4}$
  - Use di-electron and di-muon plus photon
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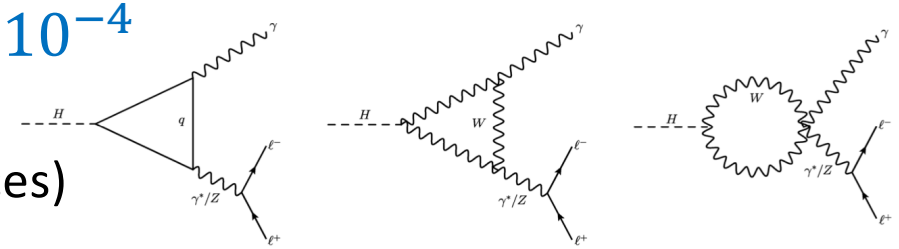
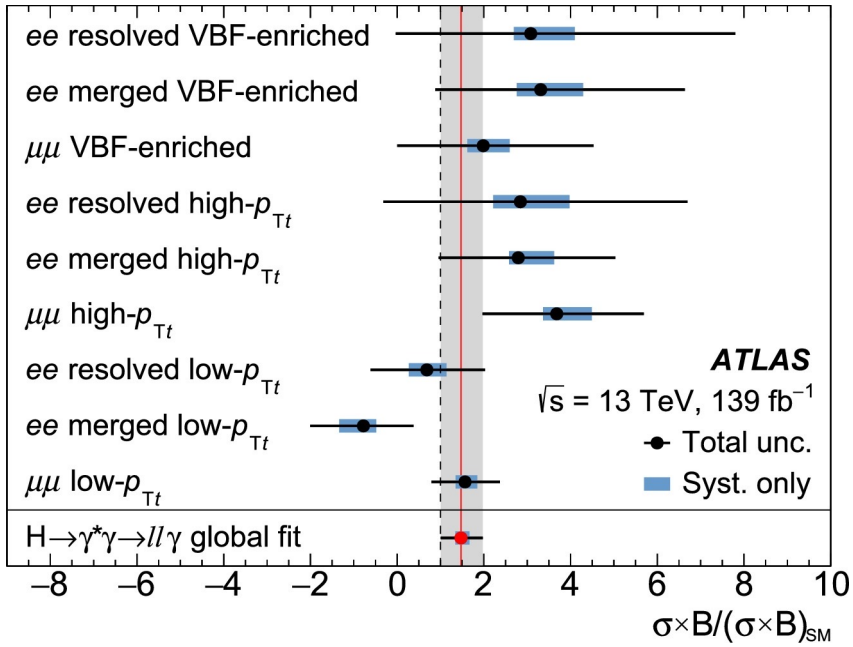


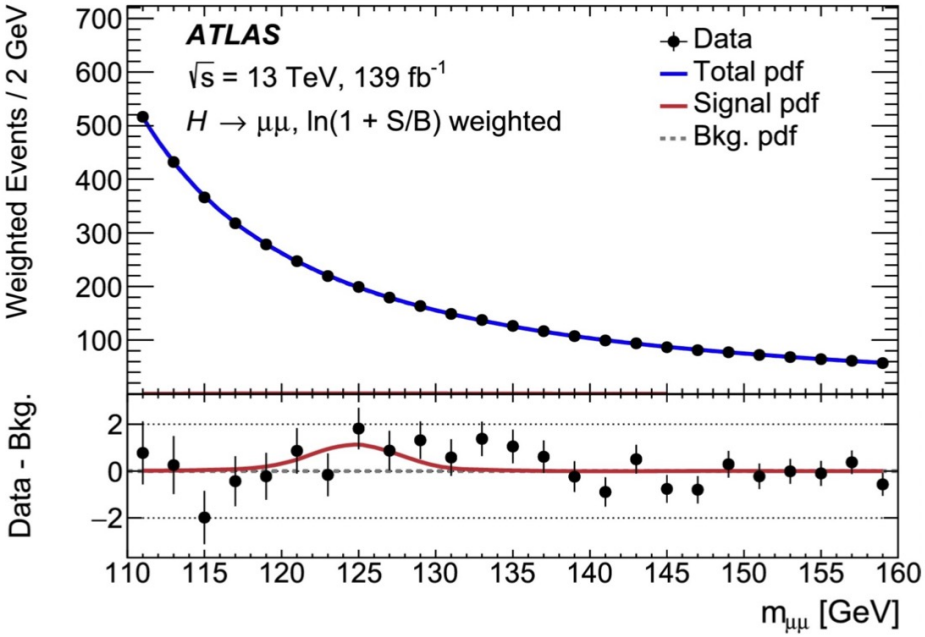
- Three types of categories
  - VBF enriched, high- and low-pTt categories
    - pTt is strongly correlated with the transverse momentum of the $\ell\ell\gamma$ system
- Use both resolved and merged ee signatures
  - Dedicated ID and calibration for merged electrons
- Observed (expected) signal: 3.2σ (2.1σ)
  - Signal strength: $\hat{\mu} = 1.5 \pm 0.5$

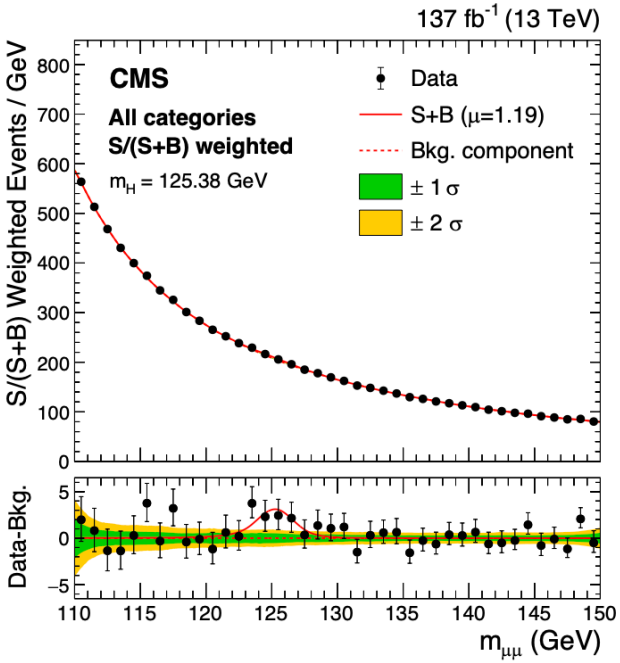


$H \to \mu\mu$

ATLAS: *PLB 812 (2021) 135980*
CMS: *JHEP 01 (2021) 148*

- Very small branching fraction $Br(H \to \mu\mu) = 2.17 \times 10^{-4}$
- Indistinguishable Drell-Yan background with signal to background $\approx 10^{-3}$
- Background modeling is essential to search for the narrow mass peak

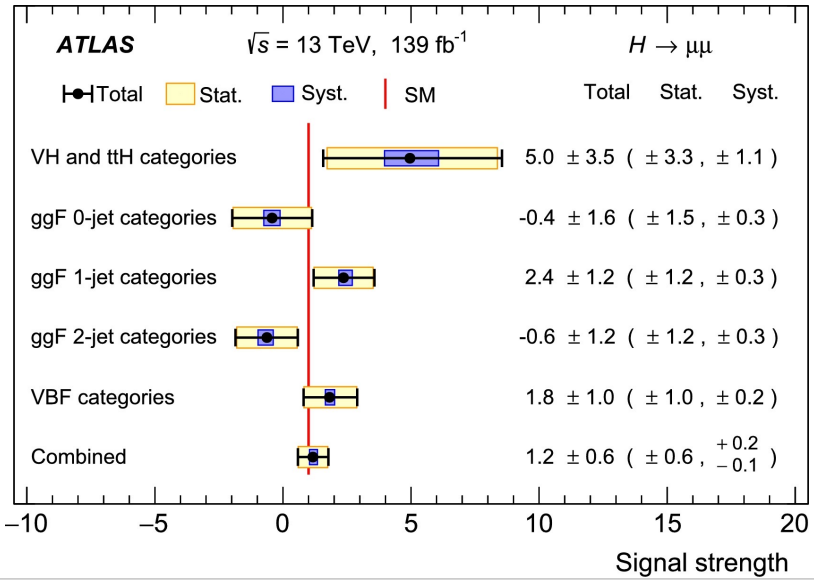


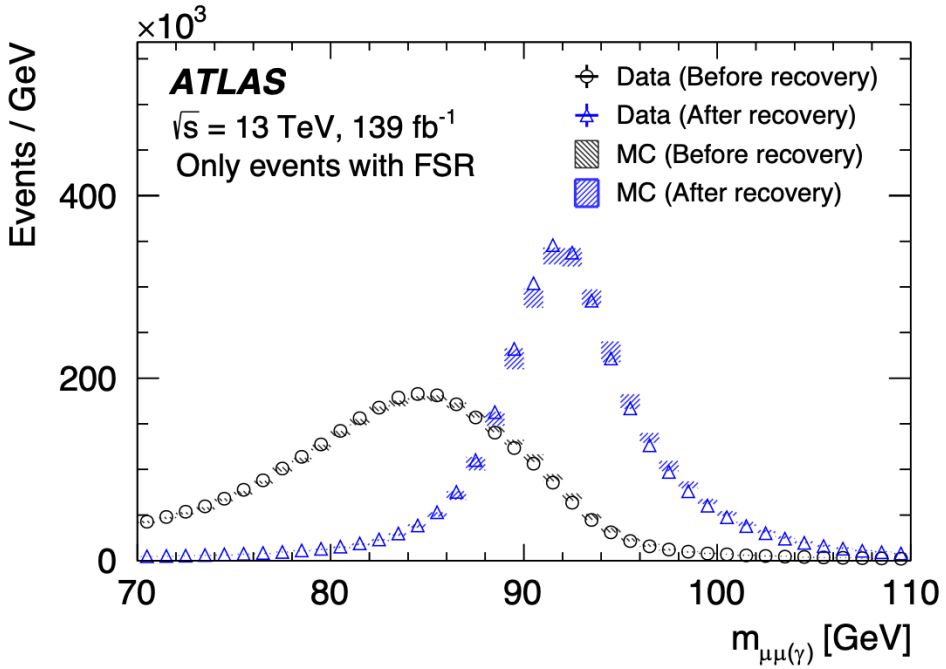


H→μμ (ATLAS)

ATLAS: PLB 812 (2021) 135980

- Final state radiation recovery
- Utilize 20 mutually exclusive categories
  - Exploiting the topological and kinematic differences between production modes
  - Dedicated MVA



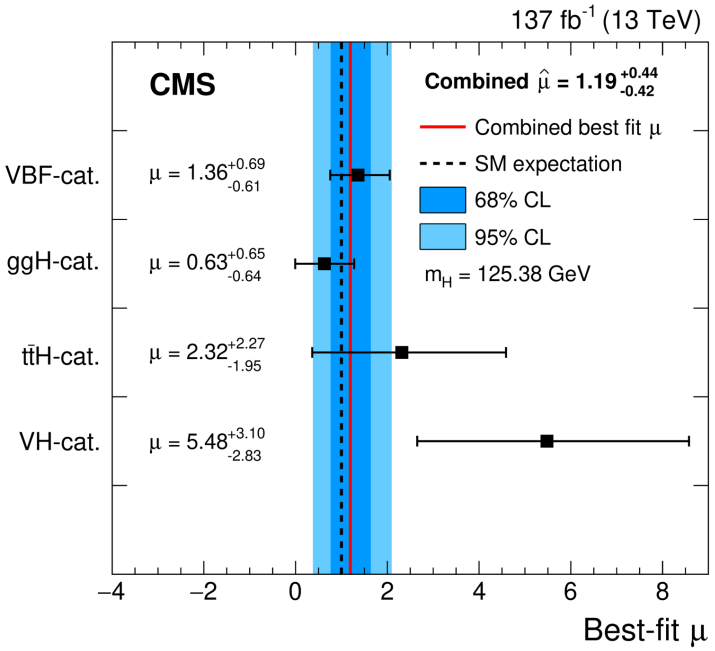


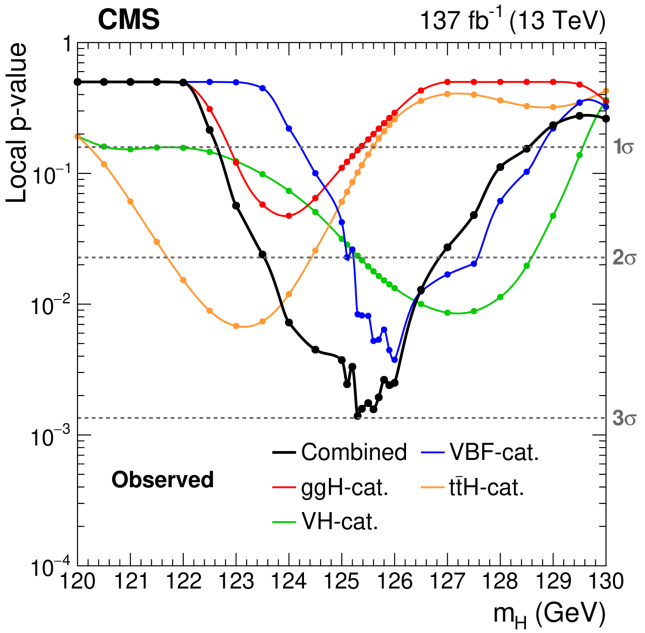
- Limits:
  - Observed (expected) limit: 2.0σ (1.7σ)
  - $Br(H \to \mu\mu) < 4.7\ (2.4) \times 10^{-4}$ obs (exp)
  - About x2 of that of the SM prediction

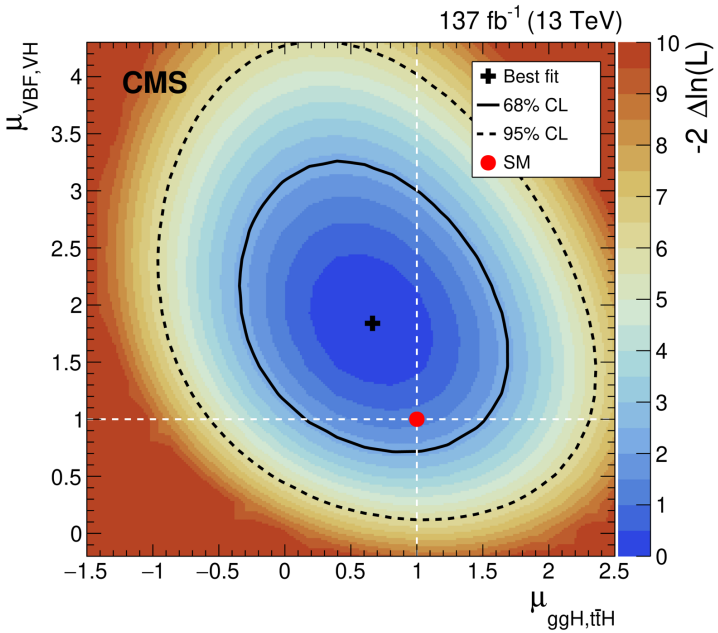
H→μμ (CMS)

CMS: *JHEP 01 (2021) 148*

- Multiple categories based on production processes
  - VBF uses DNN discriminator
- First evidence: 3.0σ (2.5σ) observed (expected)



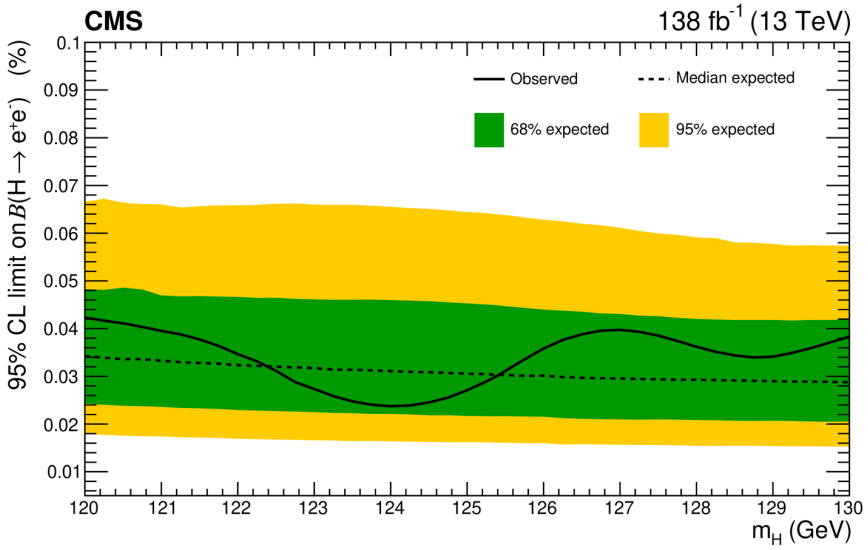


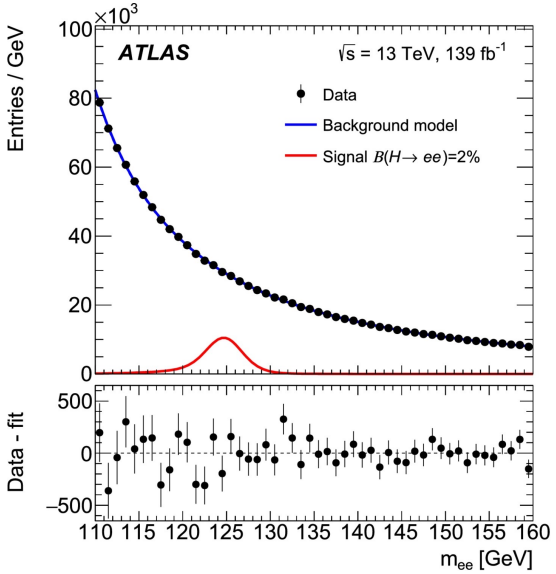


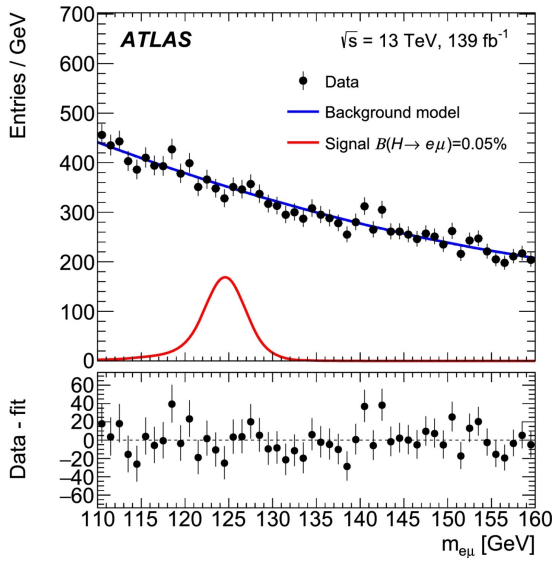
H→ee (eμ)

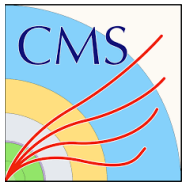
ATLAS: *PLB 801 (2020) 135148*
CMS: *Accepted to PLB*

- **Really** small branching fraction $Br(H \to ee) = 5 \times 10^{-9}$
  - Expected enhancement from BSM sources
- No evidence for the decay, 95% CL limits are set
  - ATLAS: $Br(H \to ee) < 3.6\ (3.5) \times 10^{-5}$ obs (exp)
  - CMS: $Br(H \to ee) < 3.0\ (3.0) \times 10^{-5}$ obs (exp)









LFV $H \to \ell\tau$ ($\ell = e/\mu$)

Submitted to JHEP