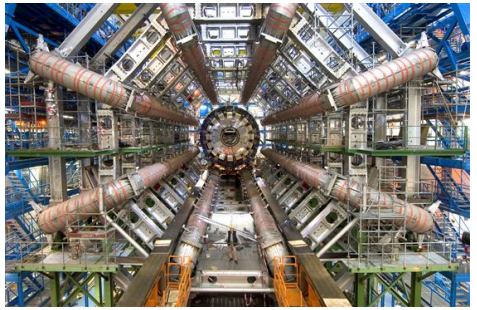
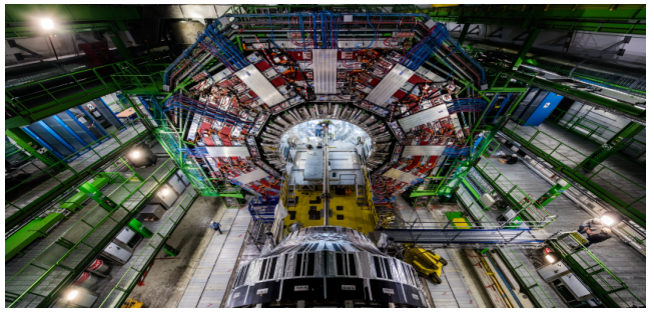
The 10th Annual
Large Hadron Collider Physics Conference
May 16-20, 2022

2022 LHCP TAIPEI Online

ATLAS EXPERIMENT





CMS
Compact Muon Solenoid

Higgs rare decays at ATLAS and CMS

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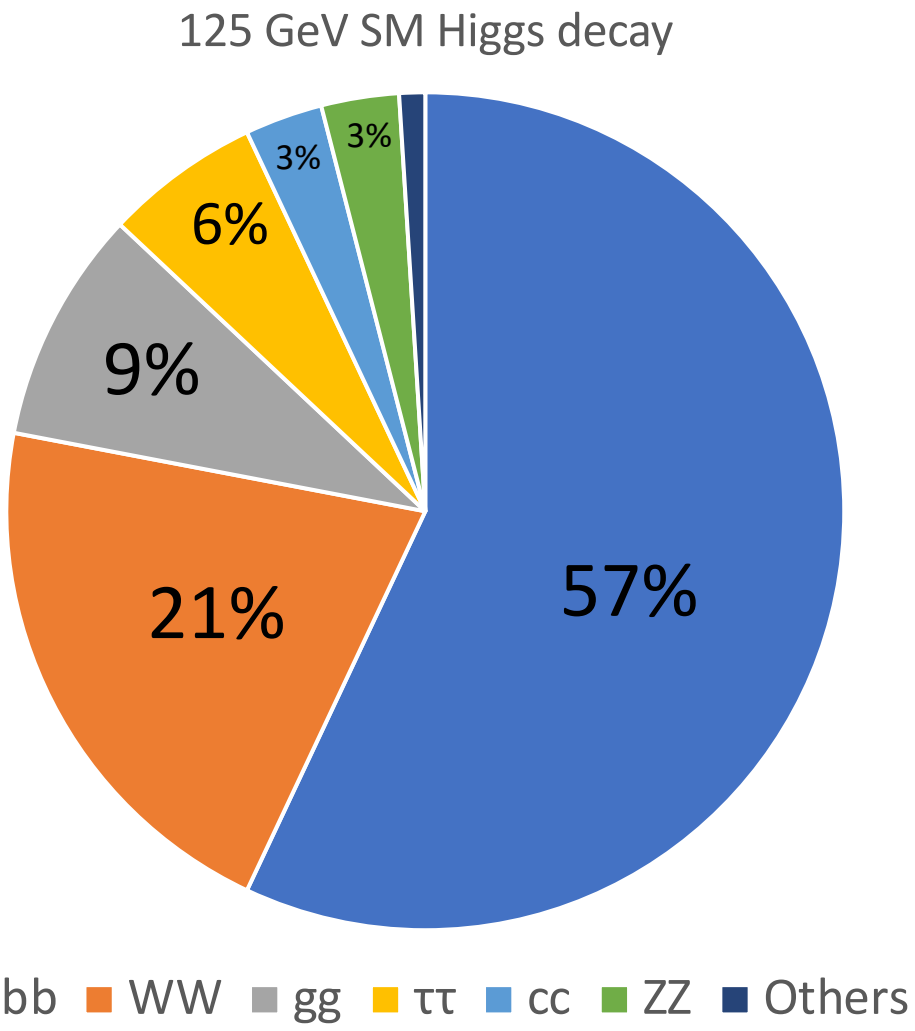
On behalf of the ATLAS and CMS collaborations

16-20 May 2022, Taipei (online)

Motivation for Higgs rare decay searches in SM

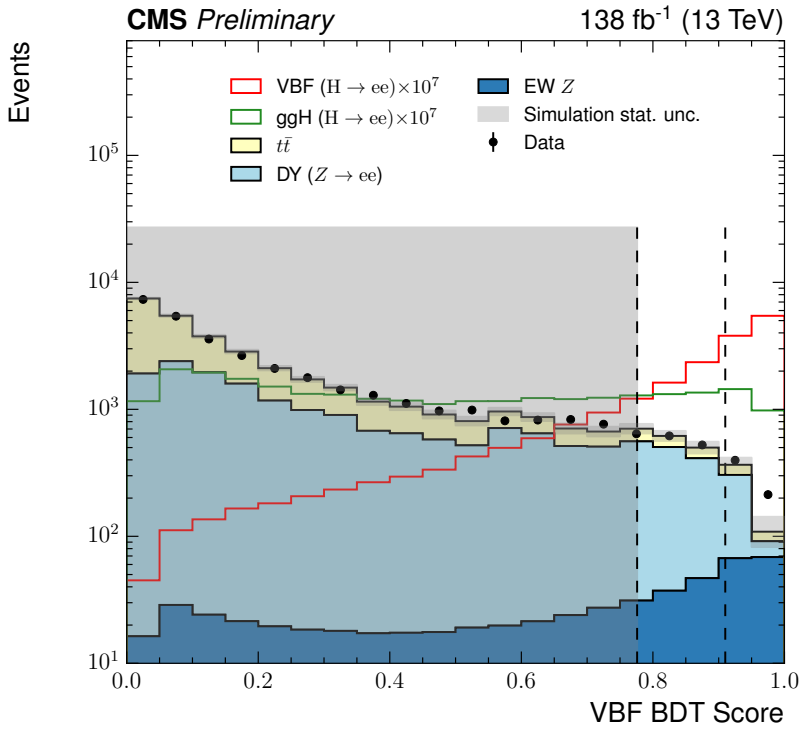
- Decade since the start of the LHC and Higgs discovery observed Higgs decay modes cover ~90% of total width
- Rare decays potentially affected by NP beyond the SM
- Crucial to look for yet unseen and experimentally challenging rare decay modes to have a complete characterization of the Higgs boson physics sector
- LHC Run 2 data: increase in Higgs prod. rate & lumi
- ATLAS and CMS have advanced analysis techniques

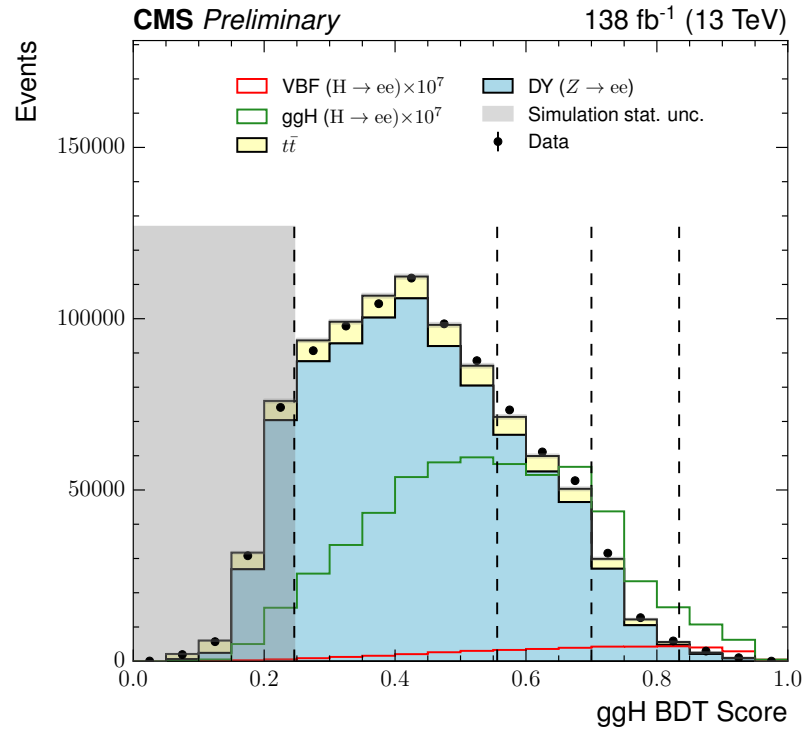


Higgs boson decay to pair of electrons: Overview

ATLAS: Phys. Lett. B 801 (2020) 135148 , CMS: HIG-21-015

- Probe of Higgs boson couplings to first generation fermions: experimentally very challenging
- Small BR(H->ee): 5 x 10^{-9}, enhanced in BSM scenarios (two Higgs doublets, dim 10 operators)
- At CMS: analysis of ggH & VBF
- Main bkg: DY events (& ttbar)
- p_T >(35)25 GeV lead(sublead) and 110 GeV < m_{ee} < 150 GeV
- BDT classifier-> ev. categories:
  - 2 VBF & 4 ggH categories





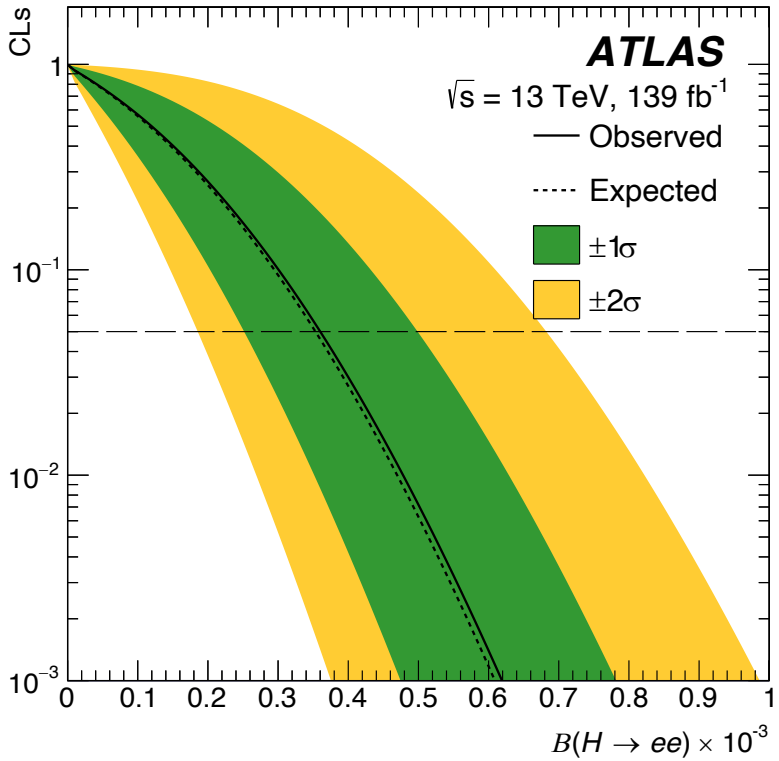
Higgs decay to pair of electrons: Analysis & Results

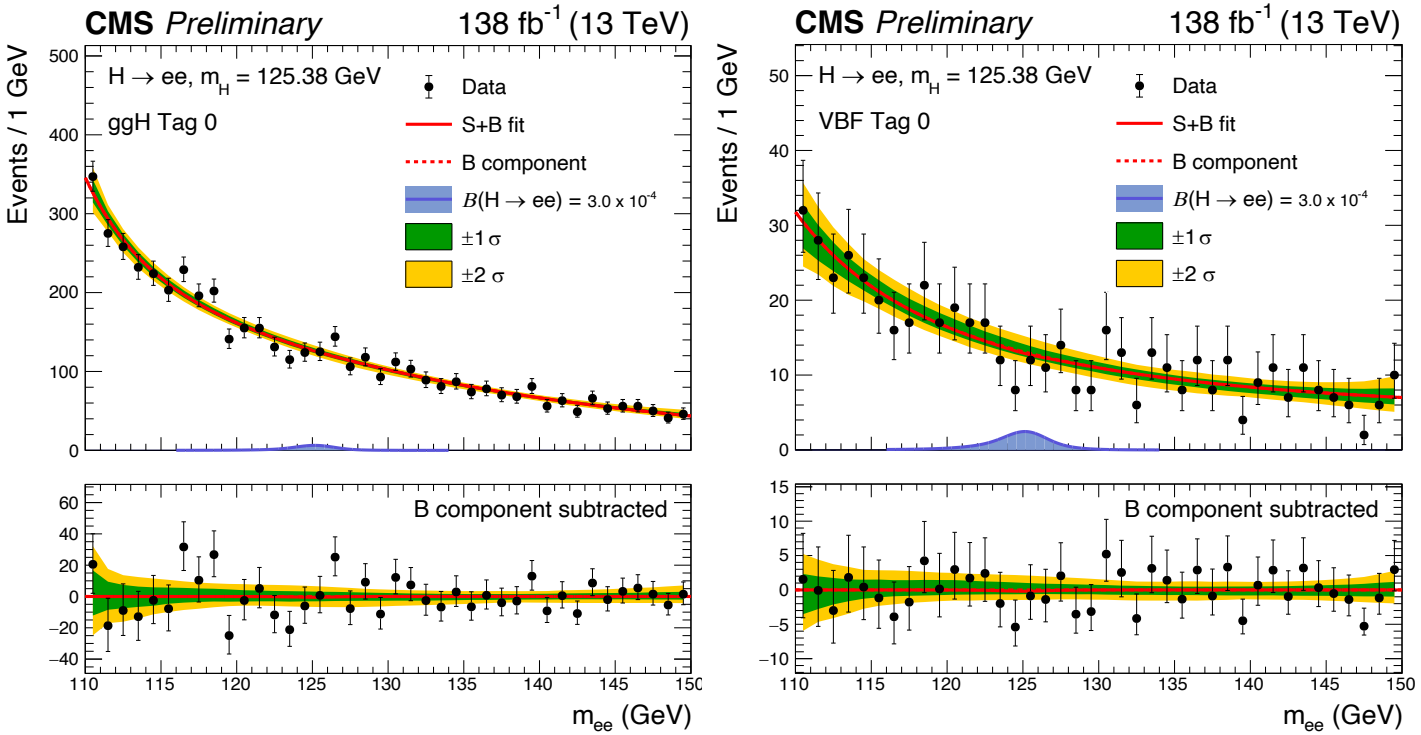
ATLAS: Phys. Lett. B 801 (2020) 135148 , CMS: HIG-21-015

- Observed (expected) limits from fit to m_{ee}:

  B(H->ee) < 3.0 x 10^{-4} (3.0 x 10^{-4}) at 95% CL

- UL on Higgs coupling modifier: $|\kappa_e| < 240$





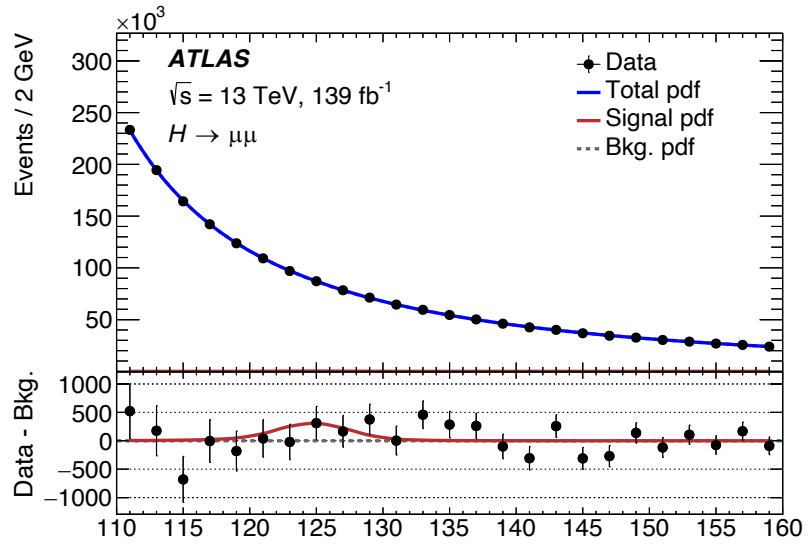
- ATLAS searched for H->ee (also for H->eμ), obs(exp) limits:

  BR(H->ee) < 3.6×10^{-4} (3.5×10^{-4}), BR(H->eμ) < 6.1×10^{-5} (5.8×10^{-5})

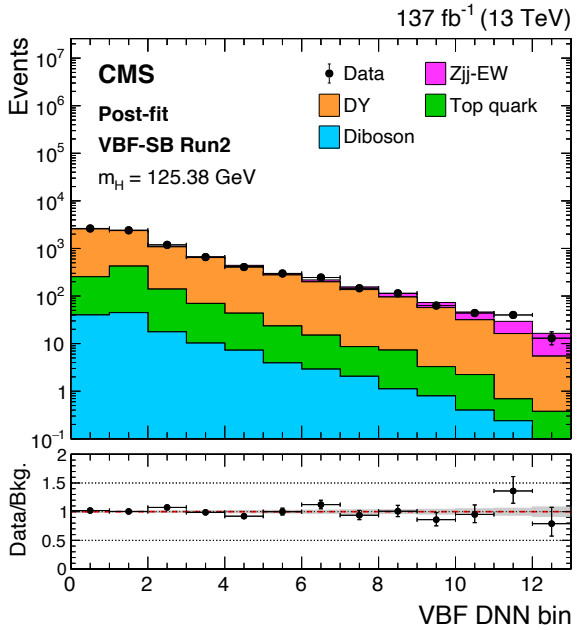
Higgs boson decay to pair of muons: Overview

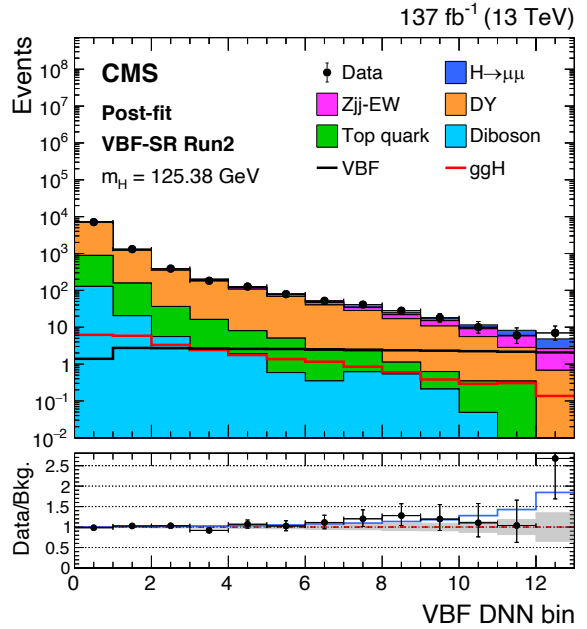
ATLAS: PLB 812 (2021) 135980, CMS: JHEP 01 (2021) 14

- The most experimentally sensitive probe of Higgs boson interactions with the 2nd generation fermions at the LHC
- BR (H->μμ) = 2.18 x 10^{-4} for Higgs boson mass of 125 GeV
- Signal is a narrow resonance in the dimuon invariant mass spectrum on top of falling background: Drell-Yan, ttbar, etc.
- Multivariate analysis techniques applied, targeting main Higgs production modes



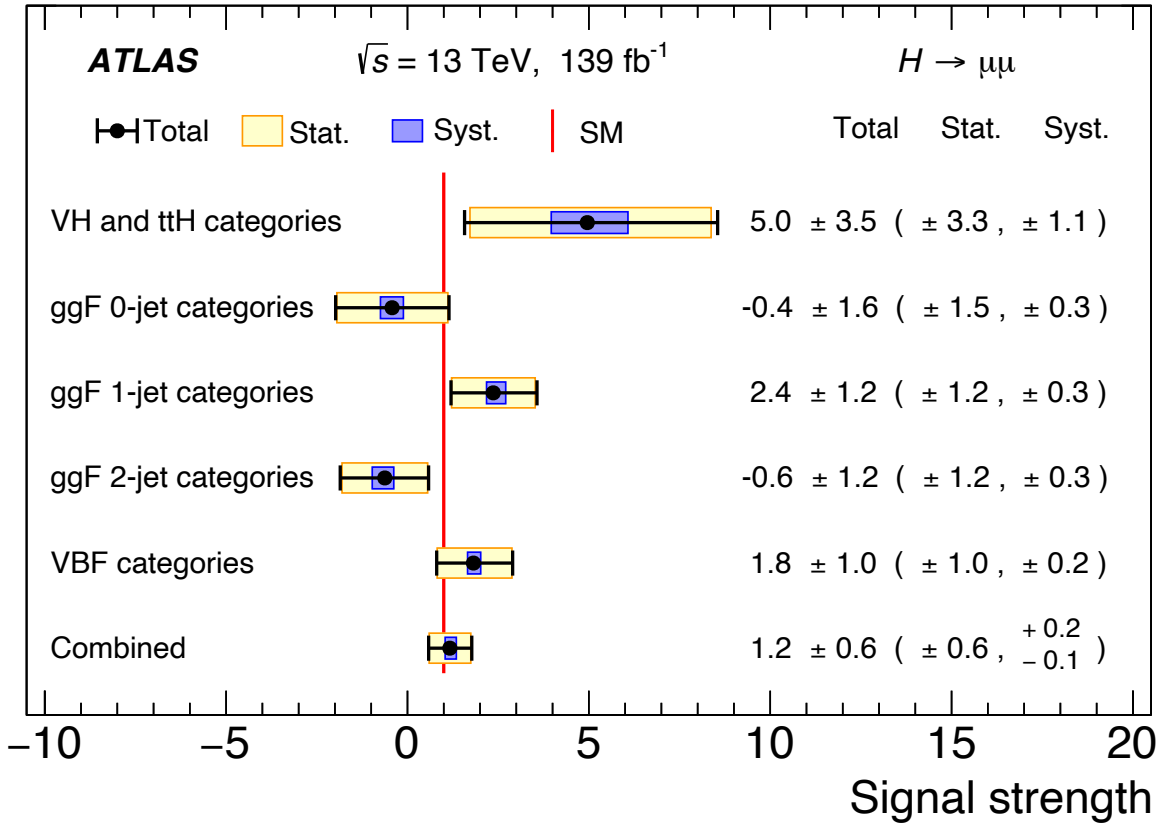
Number of categories	ggH	VBF	VH	ttH
ATLAS	12	4	3	1
CMS	5	DNN	5	5

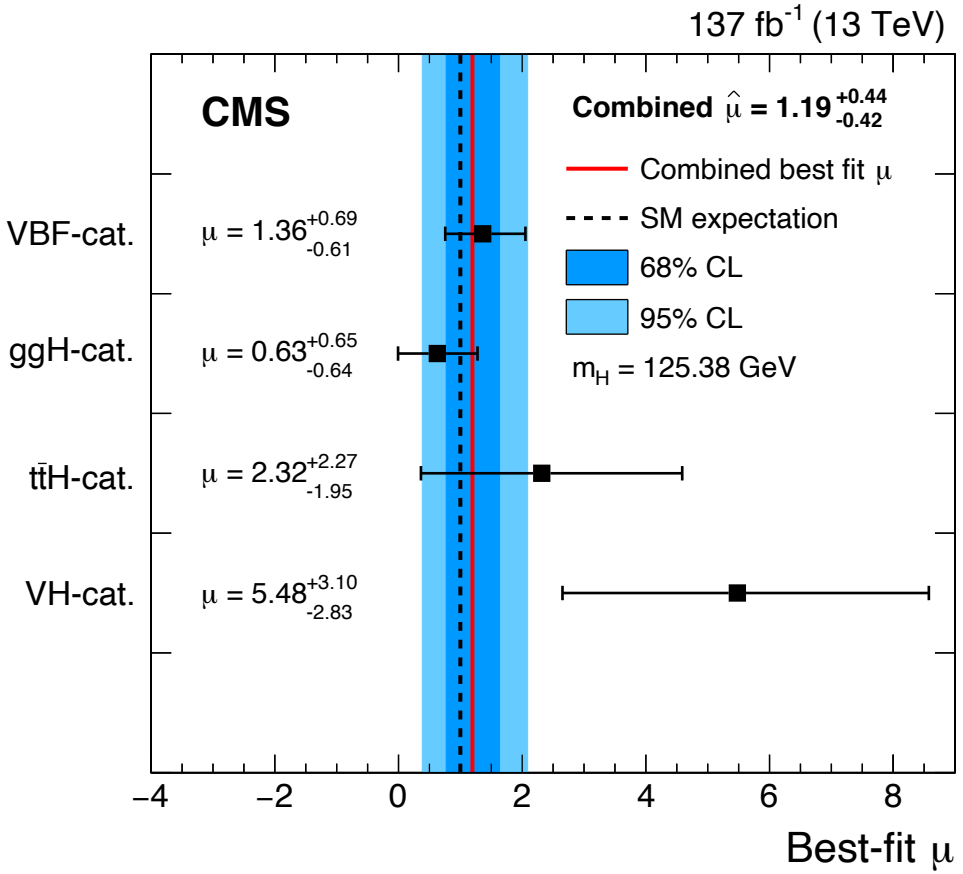




Higgs boson decay to pair of muons: Results

ATLAS: PLB 812 (2021) 135980, CMS: JHEP 01 (2021) 14





ATLAS: Signal significance: 2.0(1.7)σ obs(exp)

$\mu = 1.2 \pm 0.6(\text{stat})^{+0.2}_{-0.1}(\text{syst})$

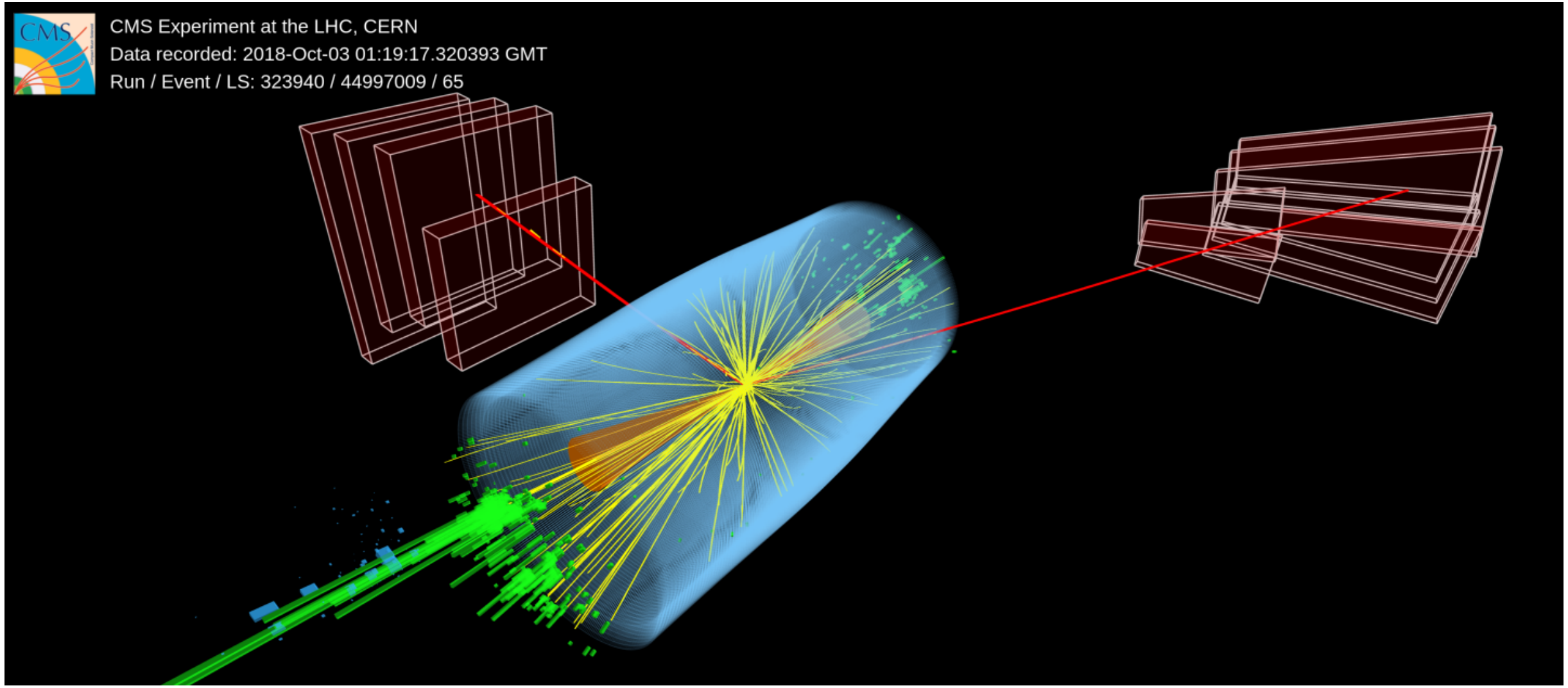
CMS: Signal significance: 3.0(2.5)σ obs(exp)

$\mu = 1.19^{+0.40}_{-0.39}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$

First evidence of Higgs couplings to muons

H boson decay to a pair of muons: Event Display

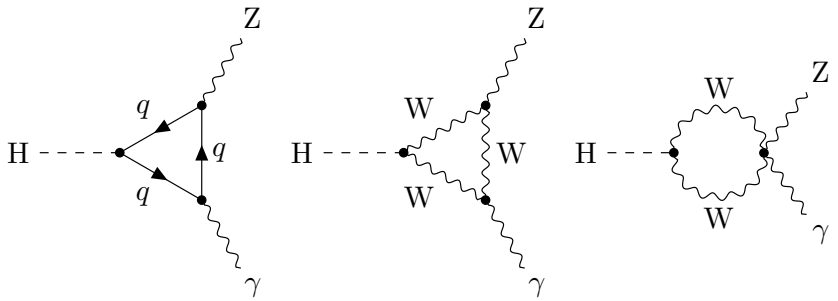
ATLAS: PLB 812 (2021) 135980, CMS: JHEP 01 (2021) 14



Higgs boson decay to Z boson and photon: CMS

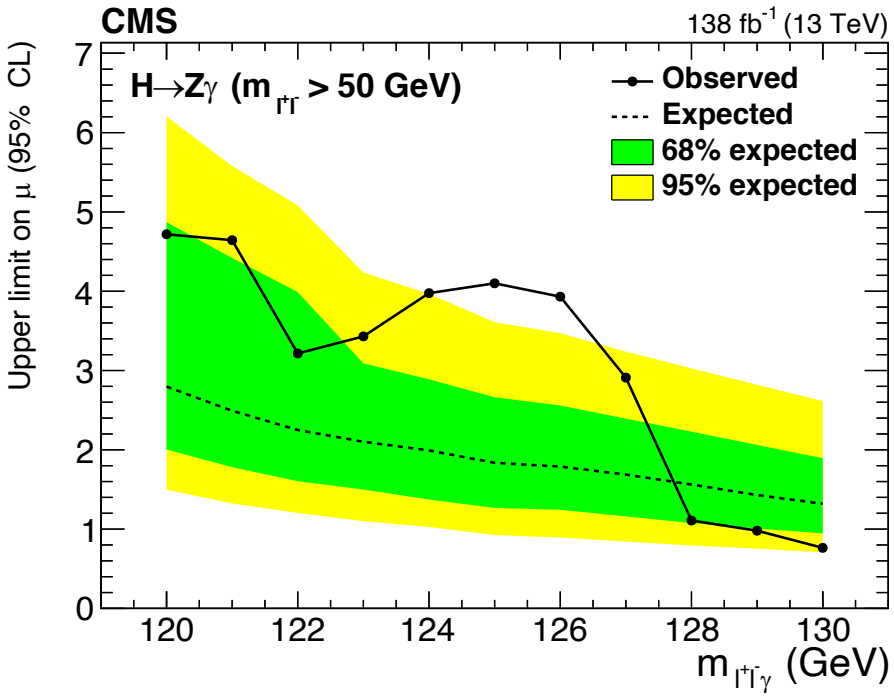
ATLAS: Phys. Lett. B 809 (2020) 135754, CMS: arXiv:2204.12945, Submitted to JHEP

- CMS: H -> Z(ee,μμ)γ search with dilepton mass > 50 GeV

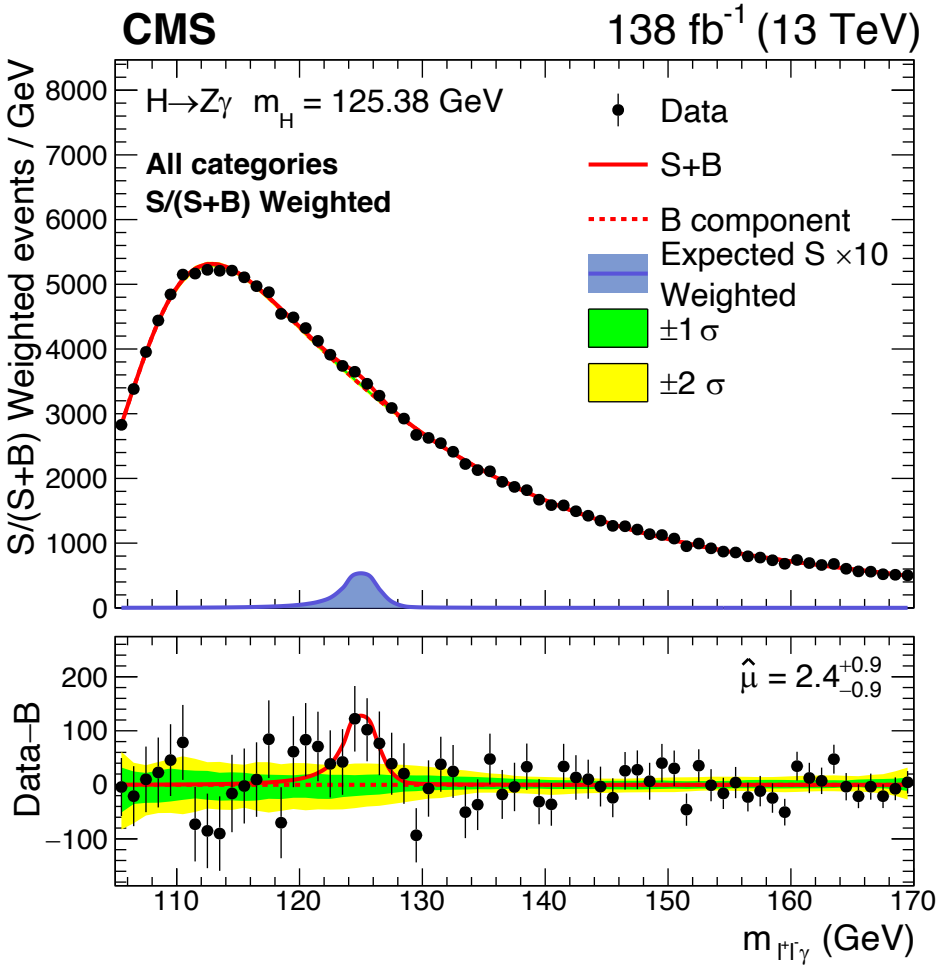


Dilepton+photon inv. mass:

105 GeV < $m_{l^+l^-\gamma}$ < 170 GeV



- All Higgs production modes & 8 mutually exclusive categories



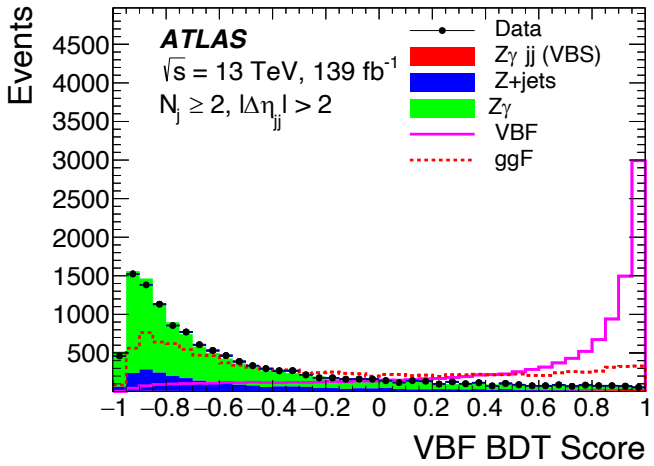
- Obs(exp) limits on σ x BR is 4.1(1.9), an excess of 2.7σ

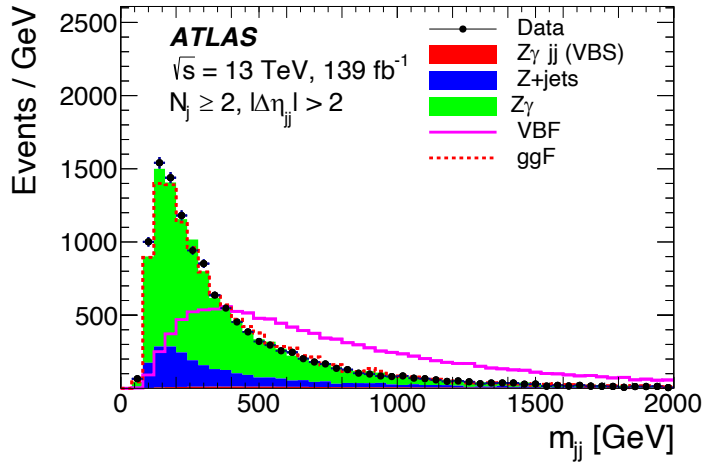
Higgs boson decay to Z boson and photon: ATLAS

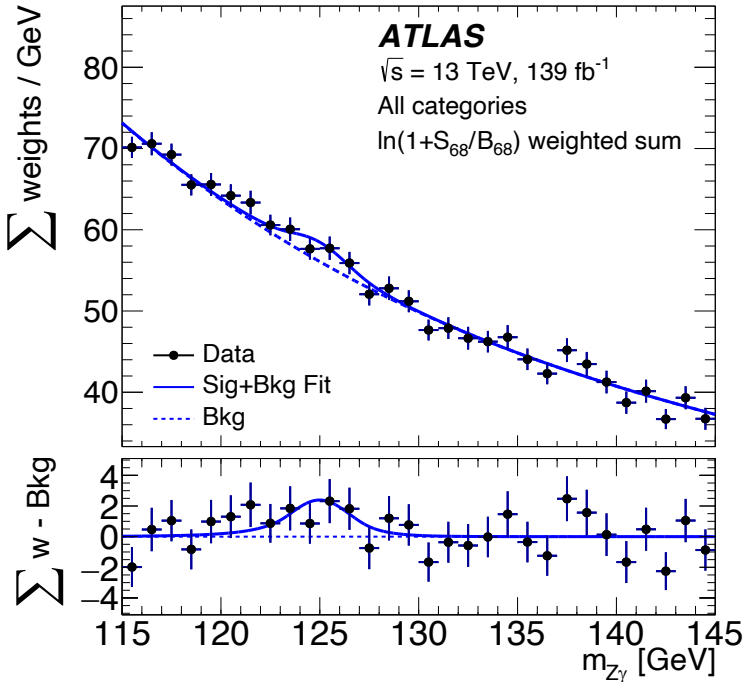
ATLAS: Phys. Lett. B 809 (2020) 135754, CMS: arXiv:2204.12945, Submitted to JHEP

- ATLAS: Z boson invariant mass required to be in [50, 101] GeV and after the FSR and Z boson kinematic fit: 81 GeV < m_Z < 101 GeV
- The invariant mass of final state particle:

  105 < $m_{Z\gamma}$ < 160 GeV



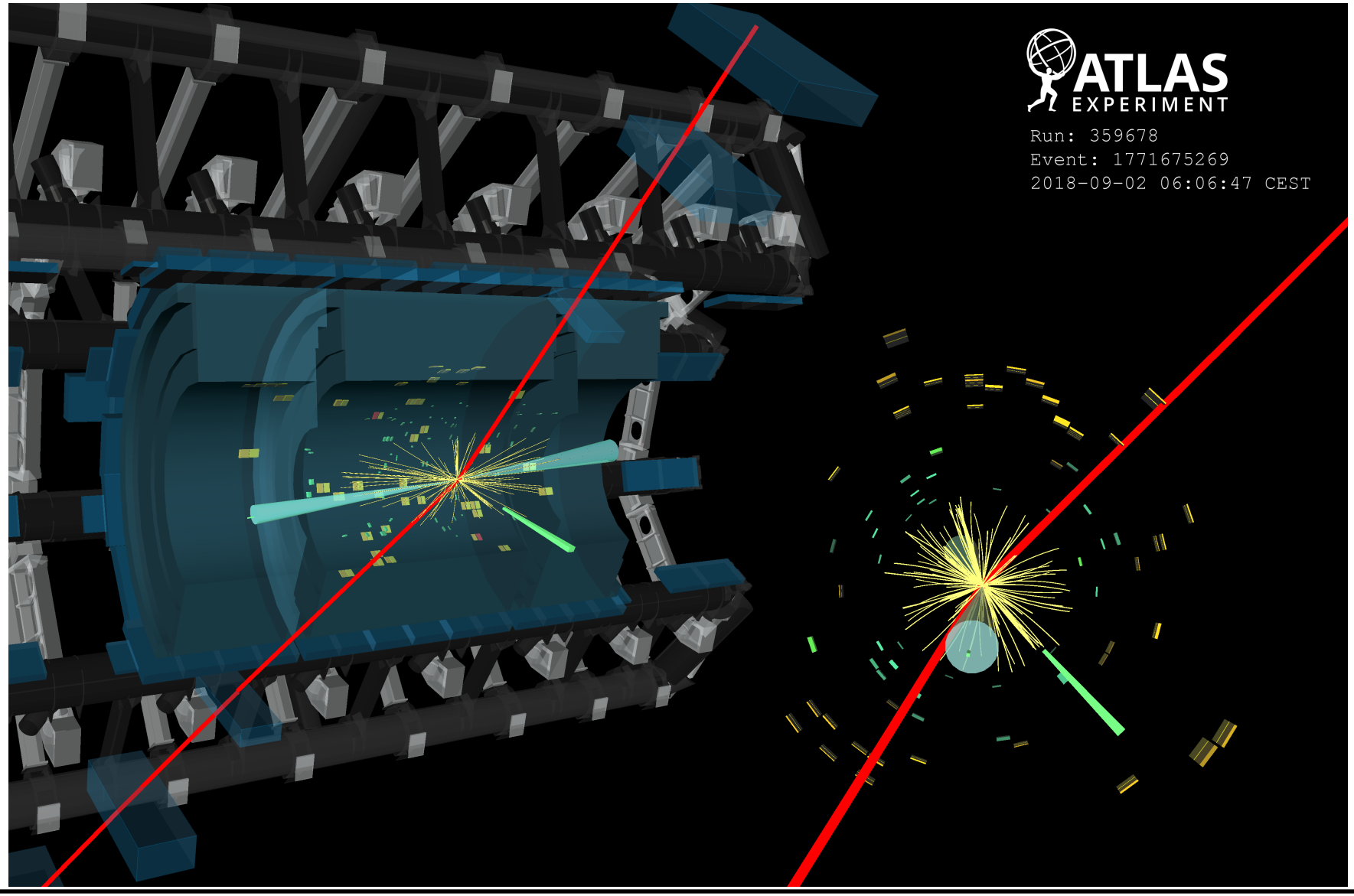




- 6 event categories, based on the lepton flavour and event kinematics
- BDT trained to separate the VBF from other Higgs production modes used to define VBF-enriched category of events with at least two jets
- Significance: 2.2(1.2)σ obs(exp); UL on (σ x B)@95% CL: 3.6 x SM
- Best fit: $\mu = 2.0\ ^{+1.0}_{-0.9}$ (tot.), expected: 1.0 ± 0.8(stat.) ± 0.3(syst.)

H -> Zγ: Event Display

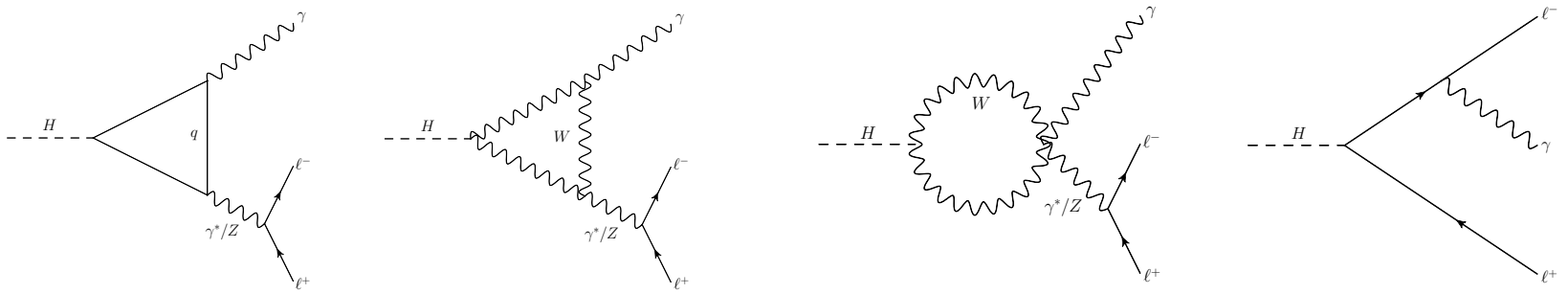
ATLAS: Phys. Lett. B 809 (2020) 135754, CMS: arXiv:2204.12945, Submitted to JHEP

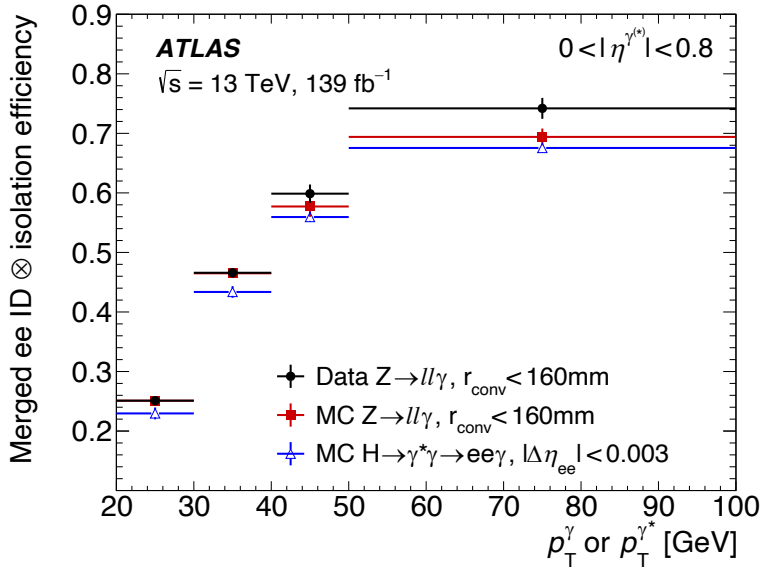


Higgs boson decay to low mass dilepton and photon

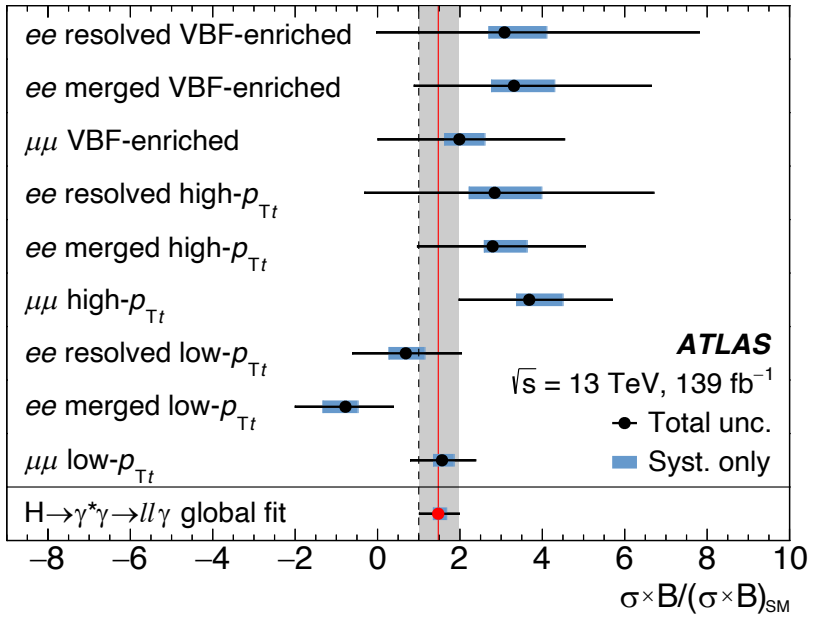
ATLAS: Phys. Lett. B 819 (2021) 136412

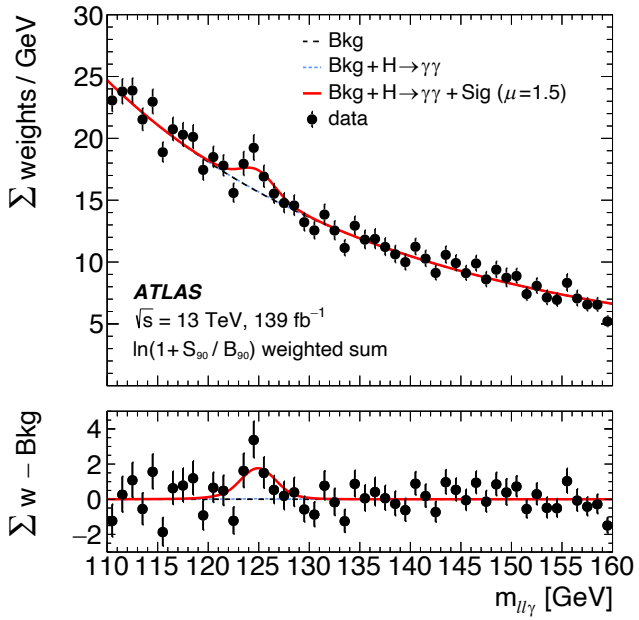
- ATLAS: H->ee,μμ+γ search with dilepton mass < 30 GeV: Dalitz decay and FSR





- Boosted e^+e^- pairs produce overlapping (merged) showers in ECAL -> recovery is crucial, hence dedicated reconstruction info used from various subsystems





- Signal st. best fit: μ = 1.5 ± 0.5(stat.) $^{+0.2}_{-0.1}$ (syst.)
  expected SM val: μ = 1.0 ± 0.5(stat.) $^{+0.2}_{-0.1}$ (syst.)
- Observed (expected) sig. significance: 3.2 (2.1)σ
  First evidence for decay to low mass ll +photon
- Higgs boson production CS x BR measured to be

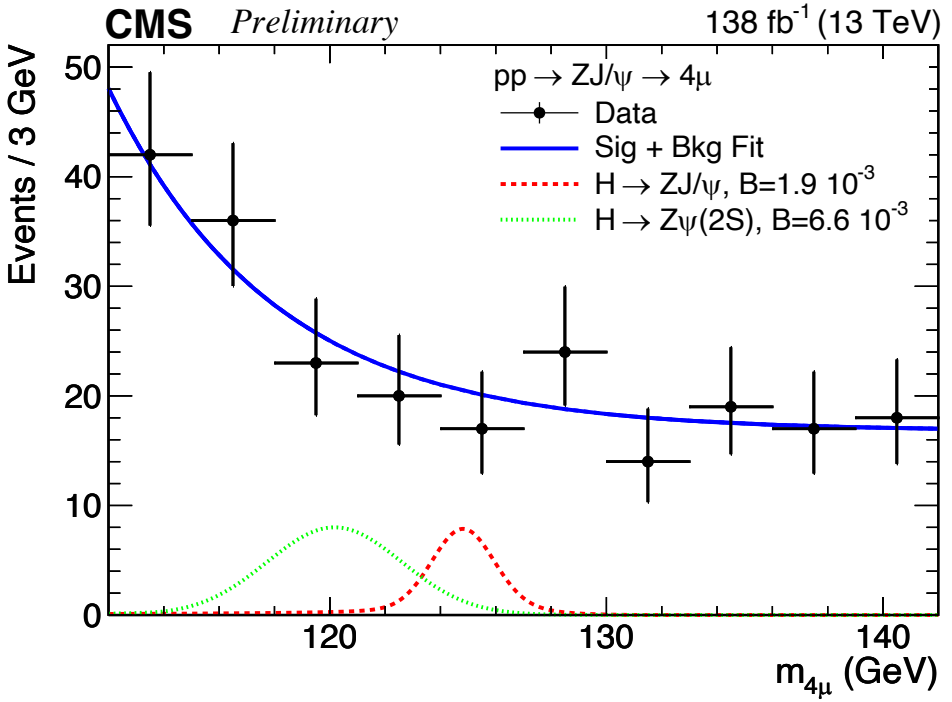
$8.7^{+2.8}_{-2.7}$ fb = 8.7 ± 2.7 (stat.) $^{+0.7}_{-0.6}$ (syst.) fb

H -> Z + J/ψ (and H/Z -> J/ψ J/ψ or YY)

CMS: HIG-20-008

- Higgs decay into Z boson and J/ψ or ψ(2S) in four lepton final state
  - Z -> e^+e^- or $\mu^+\mu^-$, J/ψ -> $\mu^+\mu^-$ and ψ(2S) -> J/ψ π π
- Also Higgs decays to pairs of J/ψ or Υ(1s) or Υ(nS) (n=1,2,3) in 4 μ
- And studies of a Z boson decay to J/ψ pair and Υ(1S) or Υ(nS) pairs

Process	Observed	Expected		
	Longitudinal	Longitudinal	Unpolarized	Transversal
$\mathcal{B}(H \to ZJ/\psi)$	1.9×10^{-3}	$(2.6^{+1.1}_{-0.7}) \times 10^{-3}$	2.4×10^{-3}	2.8×10^{-3}
$\mathcal{B}(H \to Z\psi(2S))$	6.6×10^{-3}	$(7.1^{+2.8}_{-2.0}) \times 10^{-3}$	8.3×10^{-3}	9.4×10^{-3}
$\mathcal{B}(H \to J/\psi J/\psi)$	3.8×10^{-4}	$(4.6^{+2.0}_{-0.6}) \times 10^{-4}$	4.7×10^{-4}	5.2×10^{-4}
$\mathcal{B}(H \to \psi(2S)J/\psi)$	2.1×10^{-3}	$(1.4^{+0.6}_{-0.4}) \times 10^{-3}$	2.6×10^{-3}	2.9×10^{-3}
$\mathcal{B}(H \to \psi(2S)\psi(2S))$	3.0×10^{-3}	$(3.3^{+1.5}_{-0.9}) \times 10^{-3}$	3.6×10^{-3}	4.7×10^{-3}
$\mathcal{B}(H \to \Upsilon(nS)\Upsilon(mS))$	3.5×10^{-4}	$(3.6^{+0.2}_{-0.3}) \times 10^{-4}$	4.3×10^{-4}	4.6×10^{-4}
$\mathcal{B}(H \to \Upsilon(1S)\Upsilon(1S))$	1.7×10^{-3}	$(1.7^{+0.1}_{-0.1}) \times 10^{-3}$	2.0×10^{-3}	2.2×10^{-3}
Zboson channels				
$\mathcal{B}(Z \to J/\psi J/\psi)$	10.8×10^{-7}	$(9.5^{+3.8}_{-2.6}) \times 10^{-7}$	13.9×10^{-7}	16.0×10^{-7}
$\mathcal{B}(Z \to \Upsilon(nS)\Upsilon(mS))$	3.9×10^{-7}	$(4.0^{+0.3}_{-0.3}) \times 10^{-7}$	4.9×10^{-7}	5.6×10^{-7}
$\mathcal{B}(Z \to \Upsilon(1S)\Upsilon(1S))$	1.8×10^{-6}	$(1.8^{+0.1}_{-0.0}) \times 10^{-6}$	2.2×10^{-6}	2.4×10^{-6}

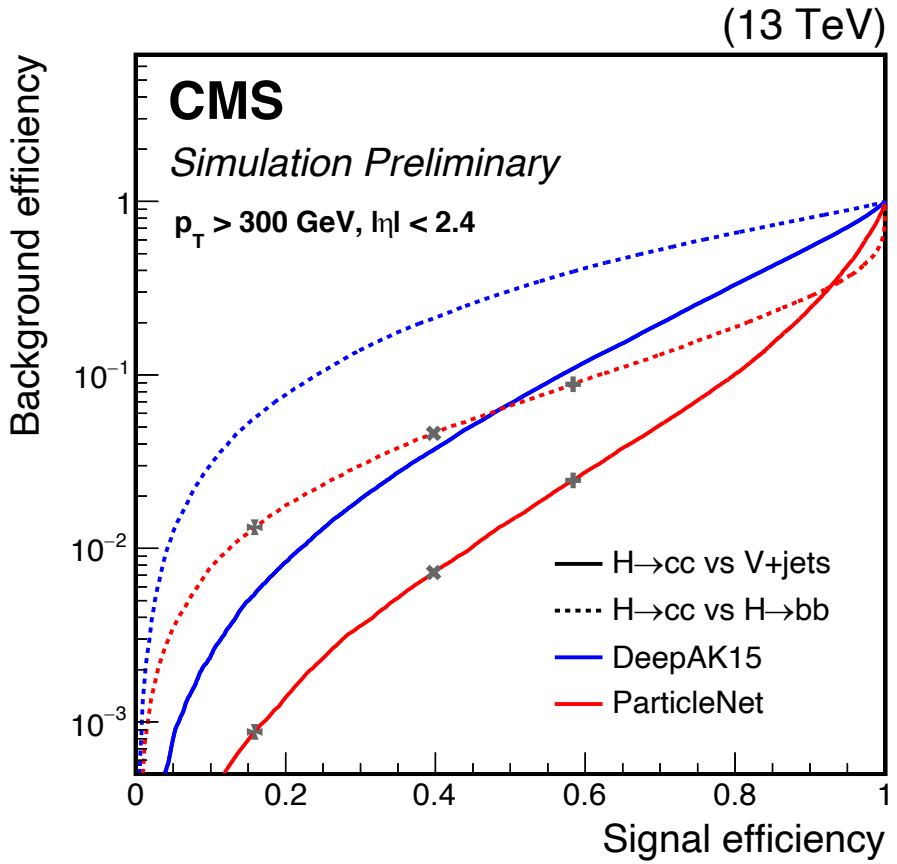


- Main bkg: a Z boson plus a genuine or misID meson
- No excess of Higgs (Z) boson in any of the channels
- Obs(exp) upper limits set for the Higgs and Z decays

Higgs boson decay to pair of charm quarks: Overview

ATLAS: arXiv:2201.11428 Submitted to EPJC, CMS: CMS-PAS-HIG-21-008

- Small BR: 2.89%, large QCD bkg., c-tag, challenge to measure at LHC
- Two ev. topologies: “merged-jet” (p_T(H) > 300 GeV) & “resolved-jet”
- CMS: c - jet tagger w/ DNN ParticleNet -> x3 improval of bkg rejection
- For both ATLAS and CMS, the event categories with 0, 1 or 2 leptons

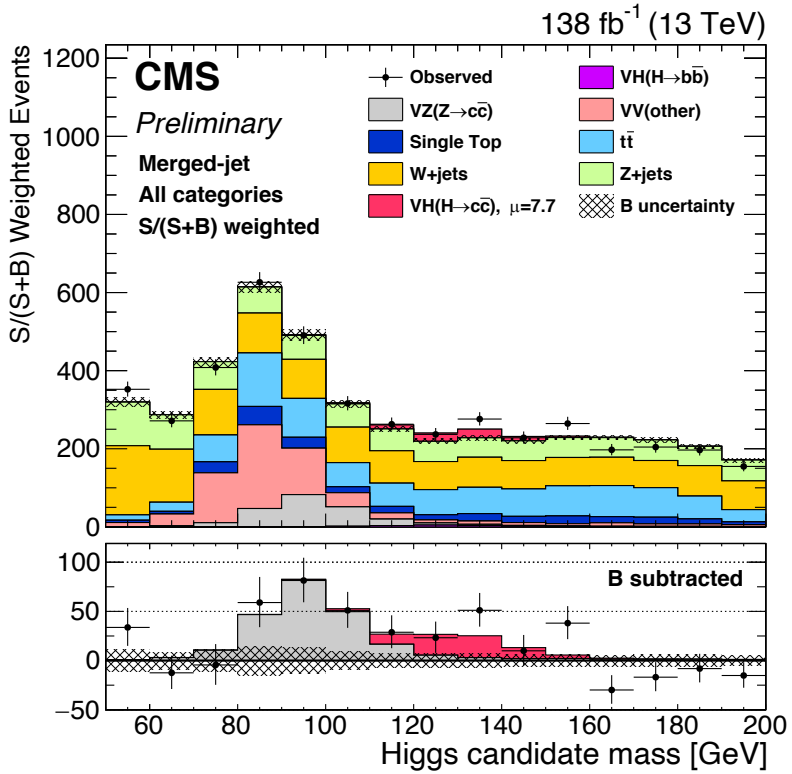


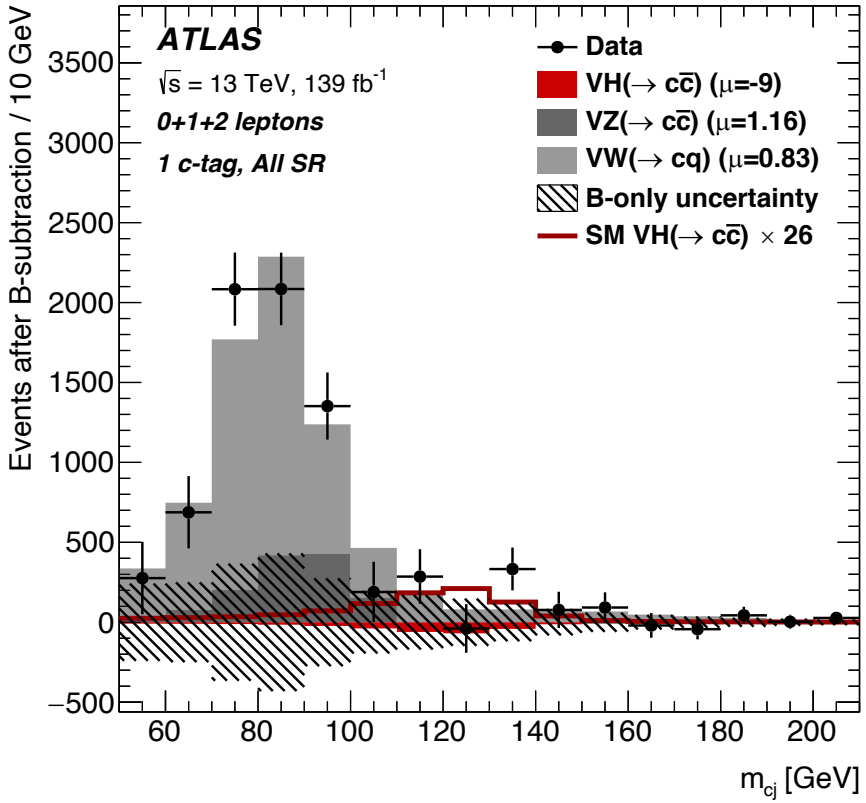
- ATLAS uses two discriminants from multivariate algorithms to tag either b- or c-hadrons
- Eff. to tag c-jets in ttbar MC events is 27% and b- and light jet mis-ID rate is 8% and 16%

Higgs boson decay to pair of charm quarks: Analysis

ATLAS: arXiv:2201.11428 Submitted to EPJC, CMS: CMS-PAS-HIG-21-008

- ATLAS: categorized by V p_T, number of (c-tag) jets
- The m_{cc} used in a likelihood fit to extract the signal
- Analysis strategy validated w/ dibosons: 2.6(2.2)σ for VZ (-> cc) and the 3.8(4.6)σ for the VW (-> cq)





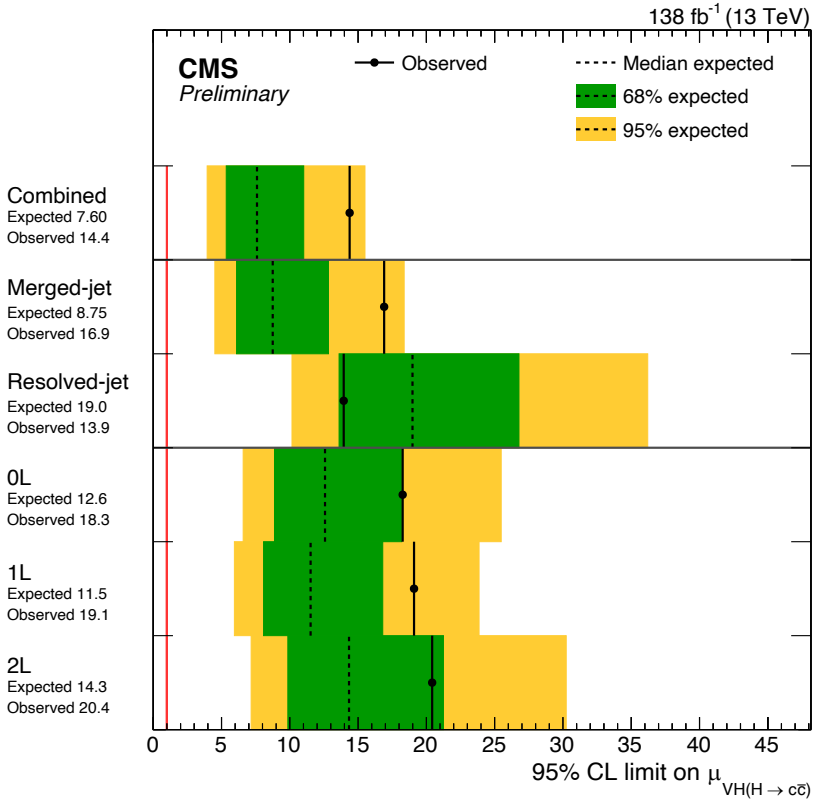
- **Represents an evidence for the VW -> cq decay**

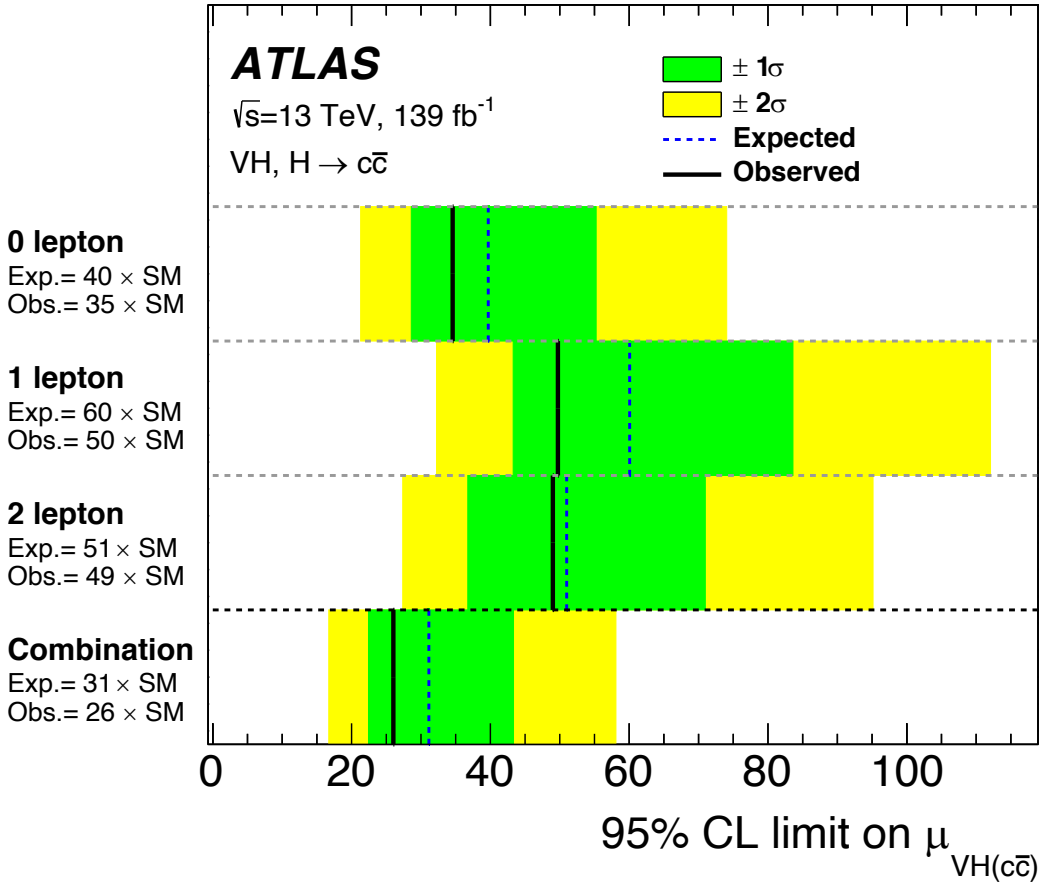
- CMS: the $m(H_{cand})$ variable fitted in the merged-jet analysis and a BDT discriminant in the resolved-jet analysis category
- VZ (Z->cc): 4.4(4.7)σ obs(exp) (@merged), 3.1(3.3)σ (@resolved), 5.7(5.9)σ (comb.): **First observation of Z->cc at hadron collider!**

Higgs boson decay to a pair of charm quarks: Results

ATLAS: arXiv:2201.11428 Submitted to EPJC, CMS: CMS-PAS-HIG-21-008

- ATLAS best limit measured at 26 x SM --> this is 5x improvement over the previous ATLAS result
- Combined VH -> cc with the VH -> bb analysis -> |kc/kb| to be < 4.5(HIGG-2021-12)

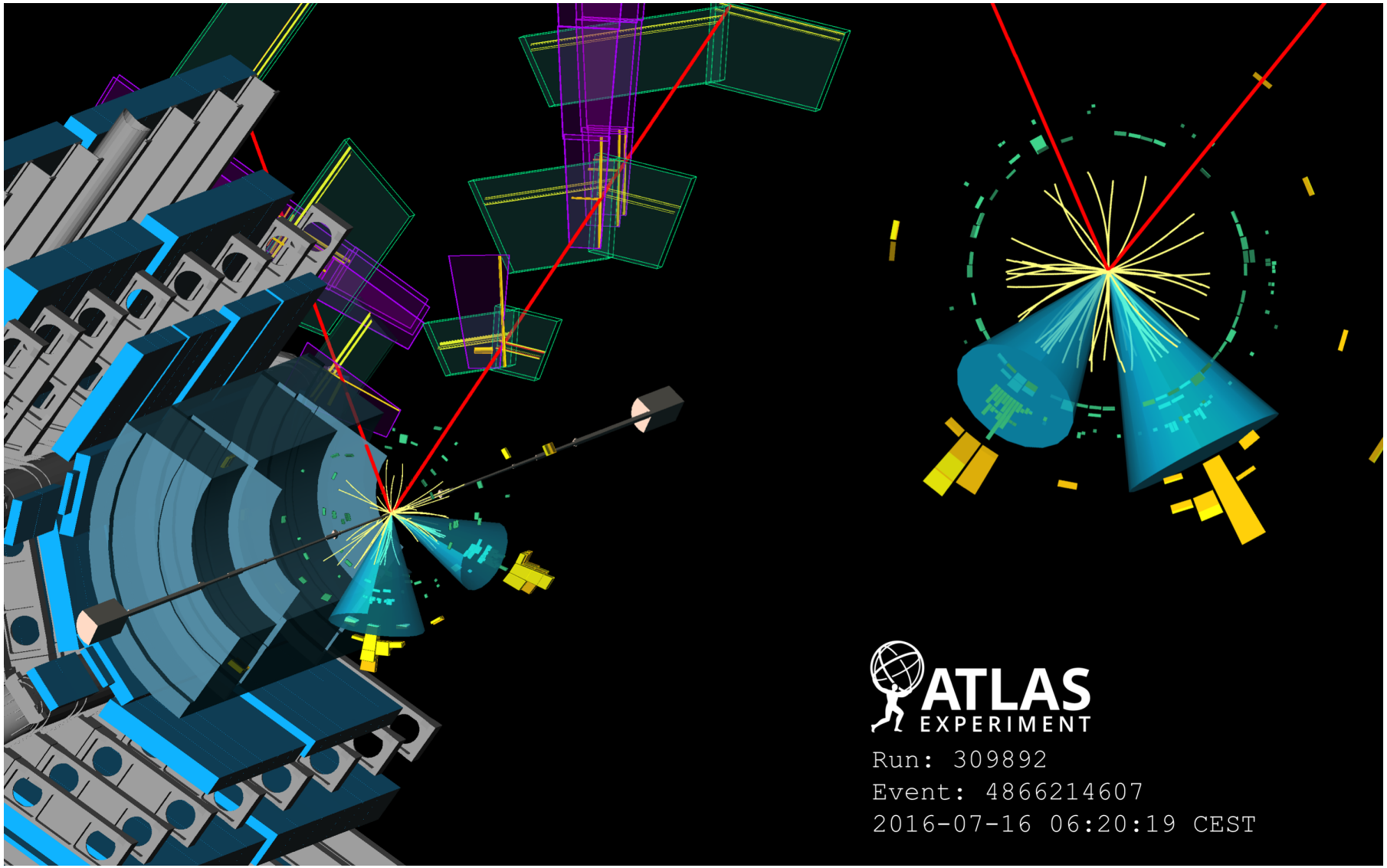




- CMS best limit is 7.7 x SM; and most stringent limit set on $1.1 < |\kappa_c| < 5.5$ the expected upper limit: $|\kappa c| < 3.4$

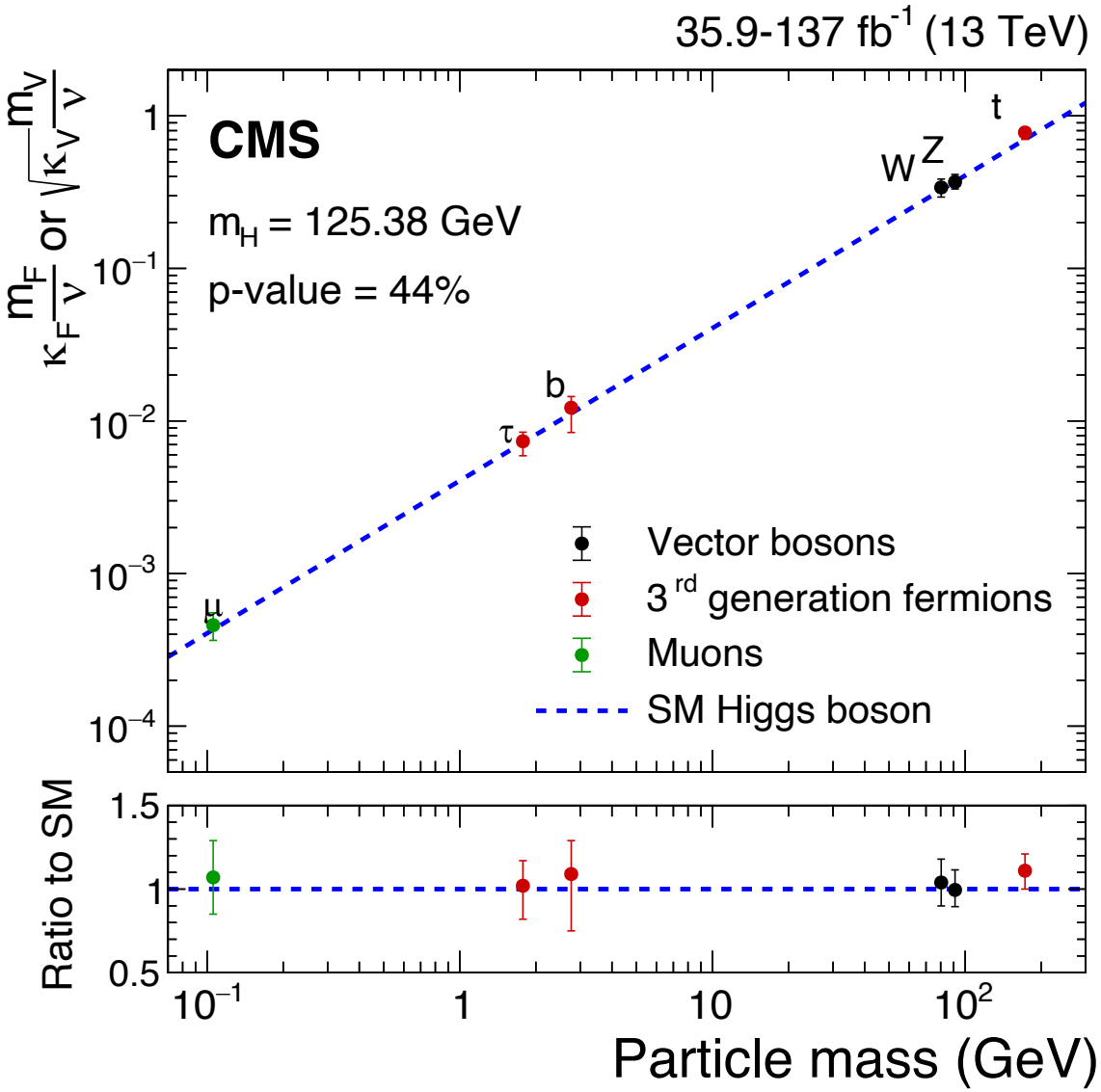
Candidate event for the process ZH -> μμcc̄

ATLAS: arXiv:2201.11428 Submitted to EPJC, CMS: CMS-PAS-HIG-21-008



Summary and Outlook

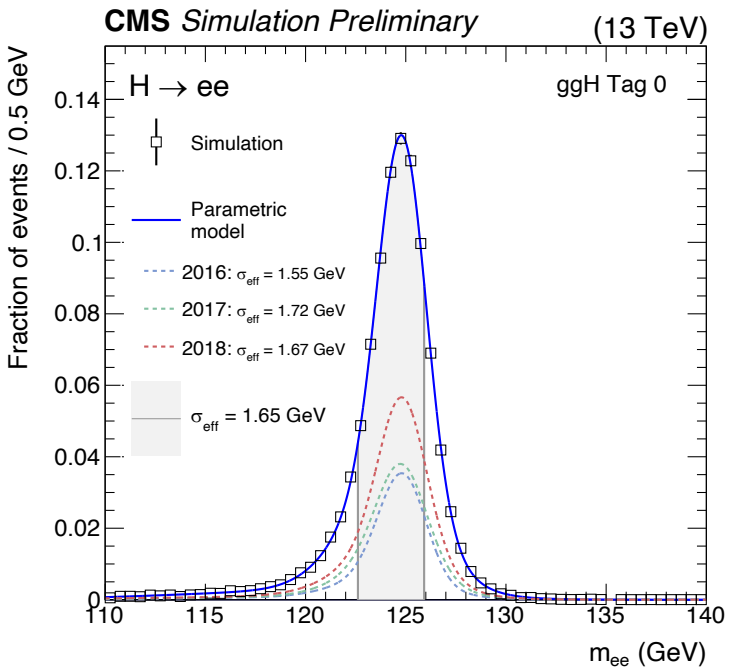
- Studies of rare Higgs boson decays are essential to probe the Higgs sector and search for indirect NP, beyond SM
- Some rare decay modes showing evidence/observation:
  - first evidence of Higgs couplings to muons (at CMS)
  - first evidence of Higgs decay to low mass llγ (ATLAS)
- The outlined evidences & observations are fully in line with the predictions of SM, i.e. no deviations reported
- Most stringent limits on many rare Higgs decay modes, following large improvements wrt the previous analyses
- Further improvements will be obtained with the Run 3 data that is just around the corner and finally with the HL-LHC data, and maybe existence of more rare decays

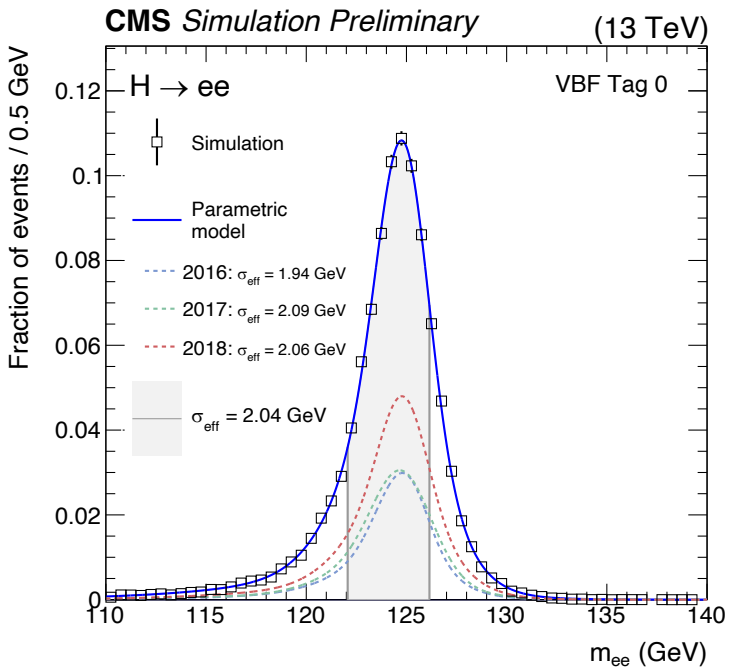


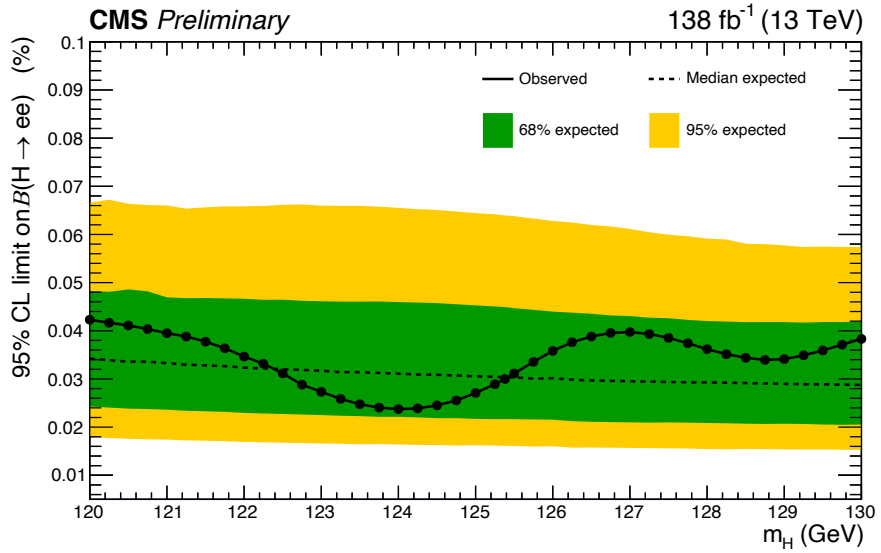
BACKUP SLIDES

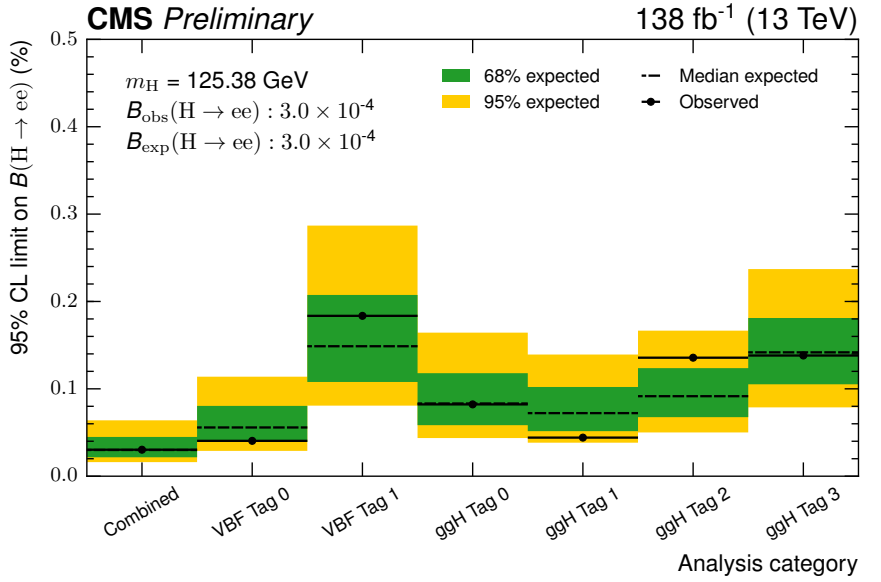
Higgs decay to pair of electrons

CMS: HIG-21-015



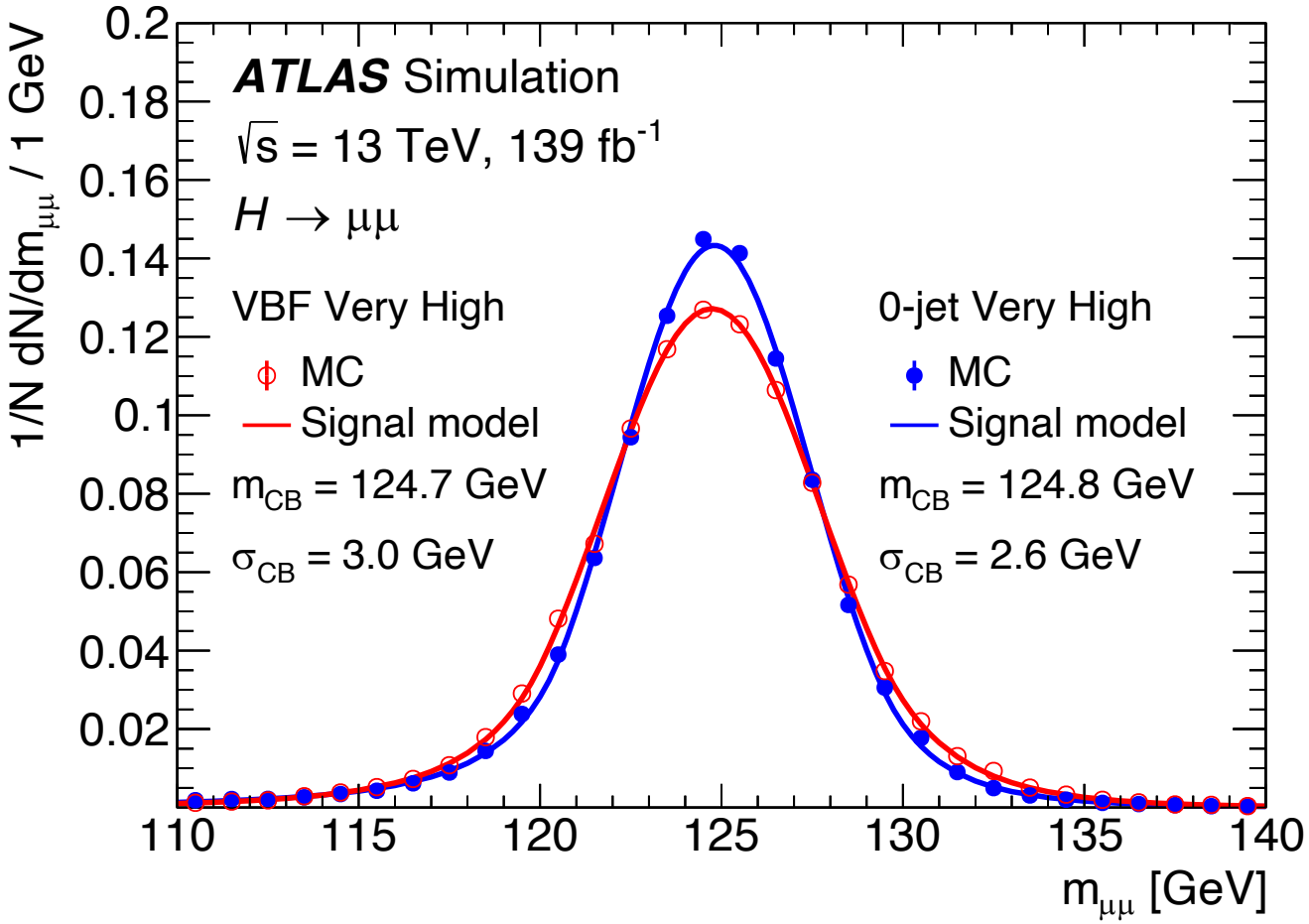


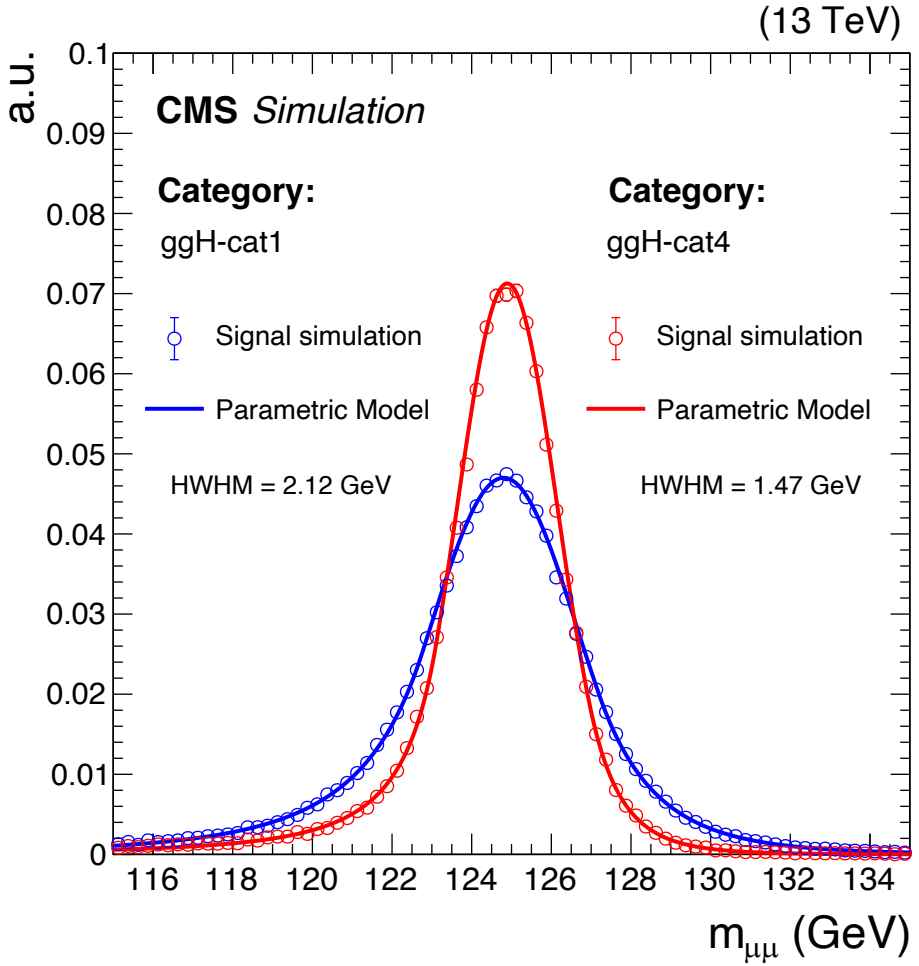




Higgs boson decay to pair of muons

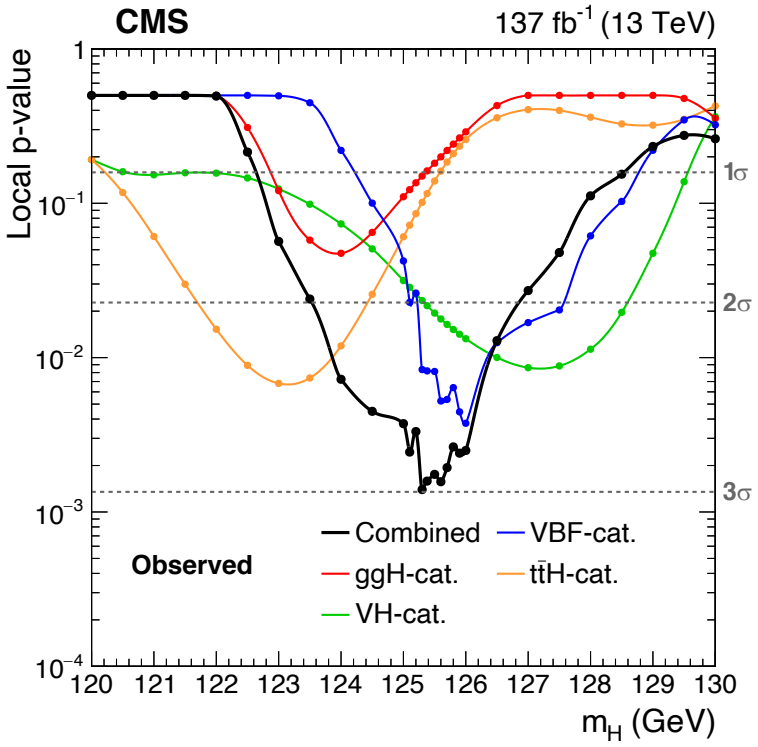
ATLAS: PLB 812 (2021) 135980, CMS: JHEP 01 (2021) 14

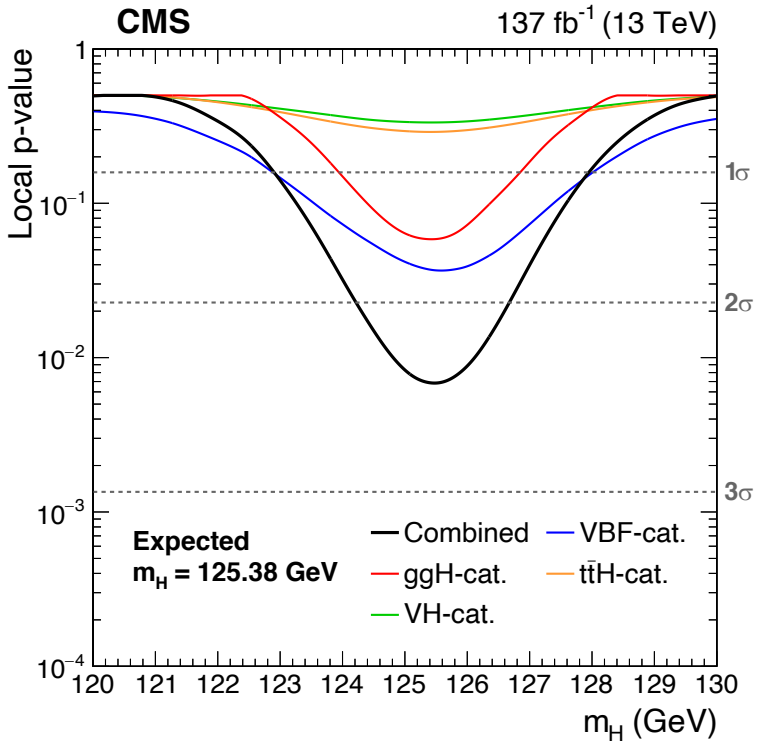


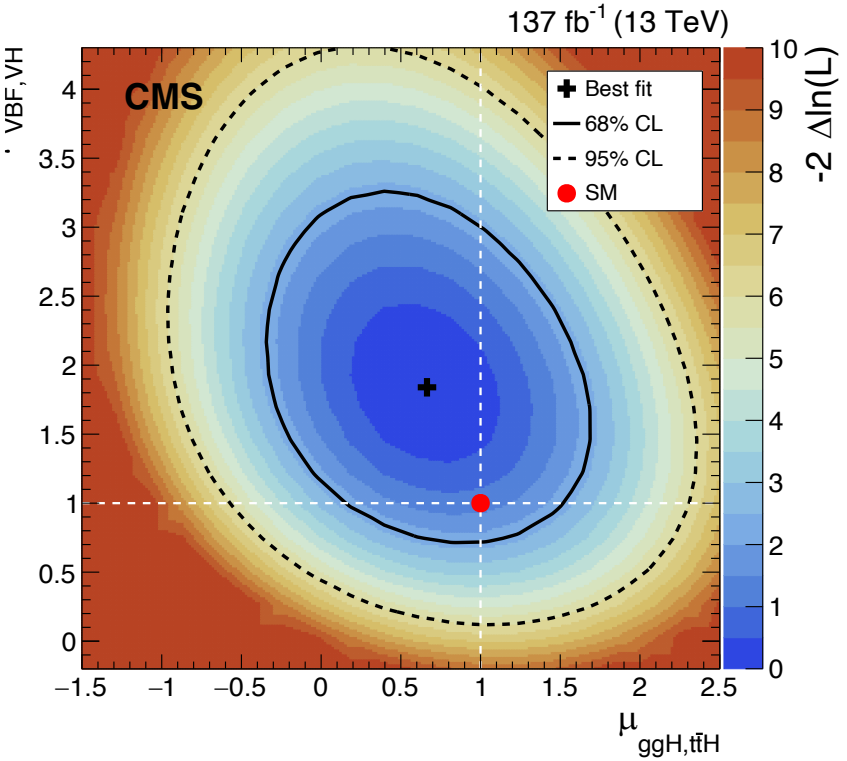


Higgs boson decay to pair of muons

ATLAS: PLB 812 (2021) 135980, CMS: JHEP 01 (2021) 14

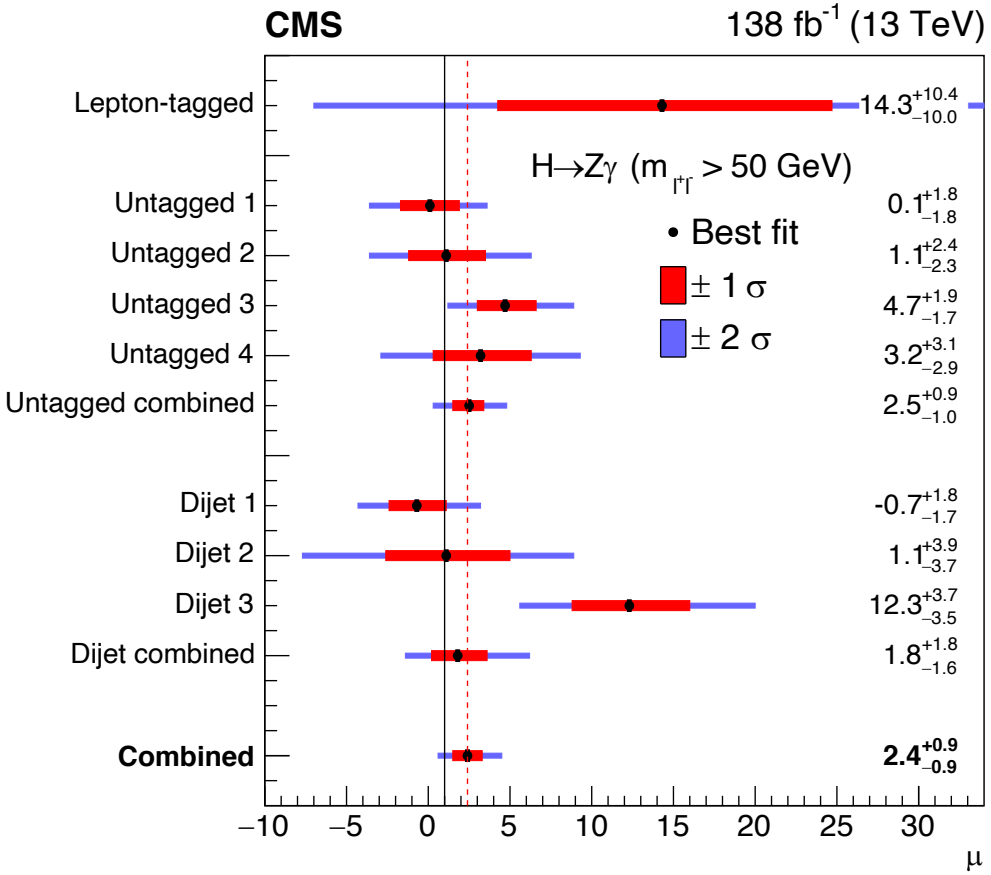






Higgs boson decay to a Z boson and photon

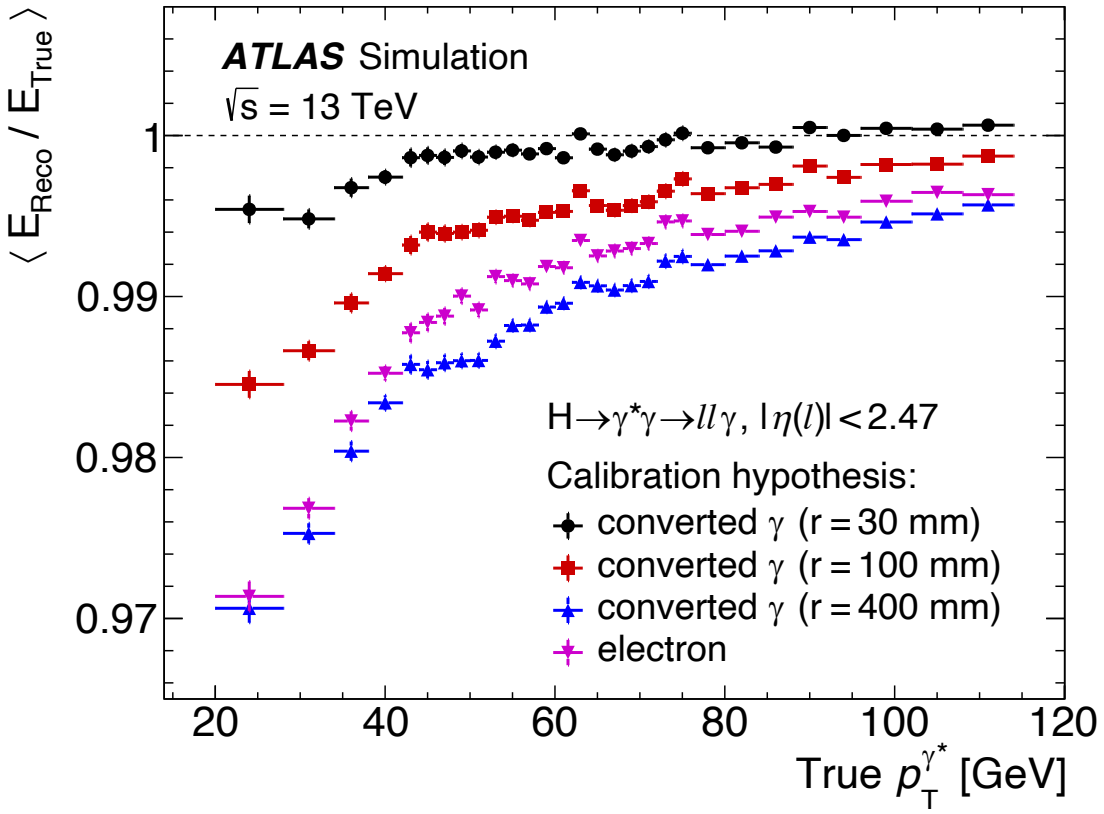
ATLAS: Phys. Lett. B 809 (2020) 135754, CMS: arXiv:2204.12945, Submitted to JHEP



138 fb^{-1}	Lepton		Dijet 1	Dijet 2	Dijet 3	Untagged 1	Untagged 2	Untagged 3	Untagged 4
SM signal yield									
ggH	0.51	e^+e^-	1.10	1.62	9.44	6.89	7.35	29.8	22.5
		$\mu^+\mu^-$	1.41	2.05	12.1	8.52	9.17	38.0	29.0
VBF	0.09	e^+e^-	1.94	0.76	1.13	0.71	0.35	0.92	0.51
		$\mu^+\mu^-$	2.40	0.97	1.43	0.89	0.43	1.18	0.65
VH + $t\bar{t}$H	1.84	e^+e^-	0.04	0.13	1.89	0.31	0.17	0.45	0.27
		$\mu^+\mu^-$	0.05	0.16	2.36	0.39	0.21	0.57	0.33
SM resonant background									
$H \to \mu^+\mu^-$	0.14	$\mu^+\mu^-$	0.27	0.27	0.43	0.62	0.49	2.02	1.78
Mass resolution (GeV)	2.12	e^+e^-	1.91	2.06	2.15	1.80	1.97	2.12	2.33
		$\mu^+\mu^-$	1.52	1.61	1.72	1.37	1.42	1.62	1.83
Data yield	1485		168	589	11596	1485	1541	2559	17608
$S/\sqrt{B}$	0.06		0.54	0.24	0.26	0.45	0.35	0.53	0.30

Higgs boson decay to low mass dilepton and photon

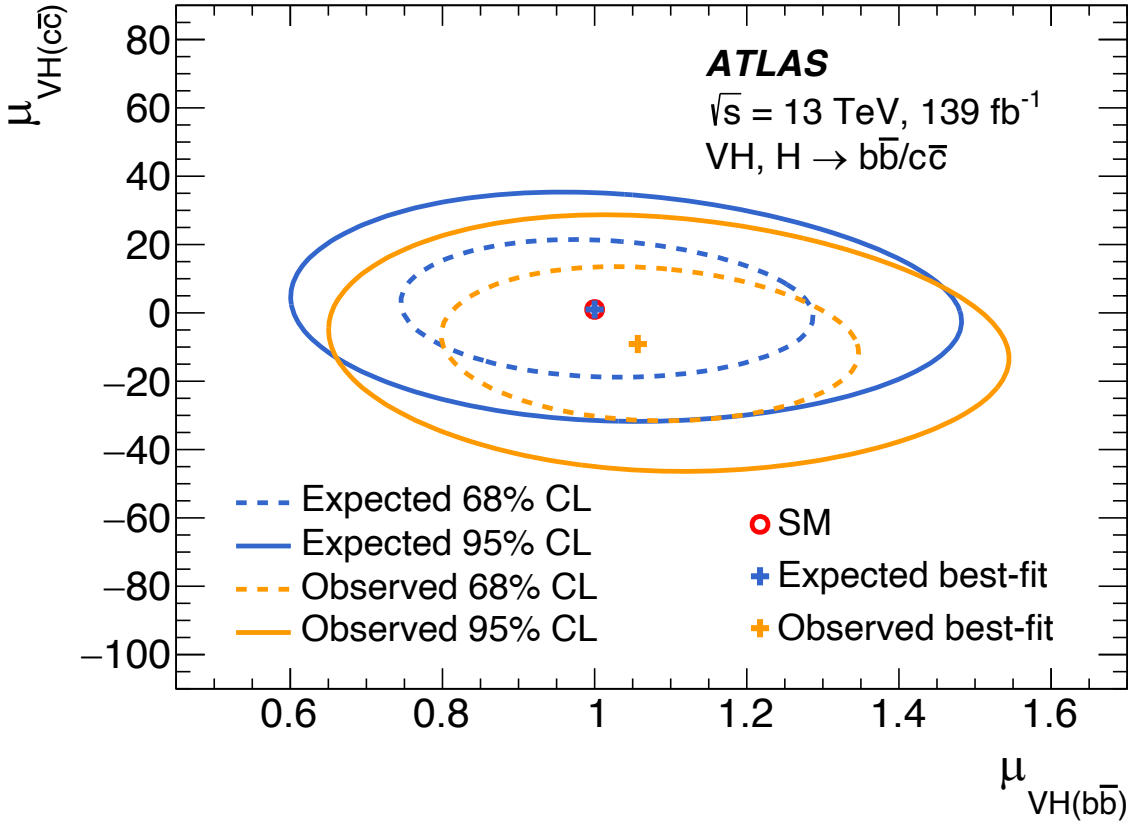
ATLAS: Phys. Lett. B 819 (2021) 136412

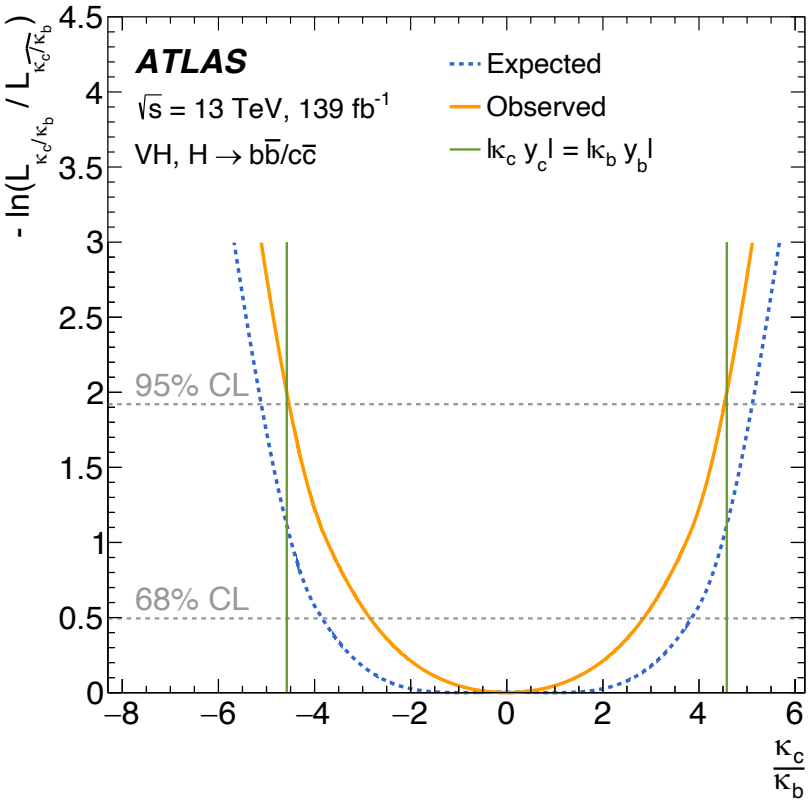


Category	Events	S_{90}	B_{90}^{N}	$B_{H\to\gamma\gamma}$	f_{90} [%]	Z_{90}
ee resolved VBF-enriched	10	0.4	1.6	0.009	20	0.3
ee merged VBF-enriched	15	0.8	2.0	0.07	27	0.5
$\mu\mu$ VBF-enriched	33	1.3	5.9	–	18	0.5
ee resolved high-$p_{\mathrm{T}t}$	86	1.1	12	0.02	9	0.3
ee merged high-$p_{\mathrm{T}t}$	162	2.5	18	0.2	12	0.6
$\mu\mu$ high-$p_{\mathrm{T}t}$	210	4.0	34	–	11	0.7
ee resolved low-$p_{\mathrm{T}t}$	3713	22	729	0.5	2.9	0.8
ee merged low-$p_{\mathrm{T}t}$	5103	29	942	2	3.0	1.0
$\mu\mu$ low-$p_{\mathrm{T}t}$	9813	61	1750	–	3.4	1.4

Higgs boson decay to a pair of charm quarks

ATLAS: arXiv:2201.11428 Submitted to EPJC, CMS: CMS-PAS-HIG-21-008

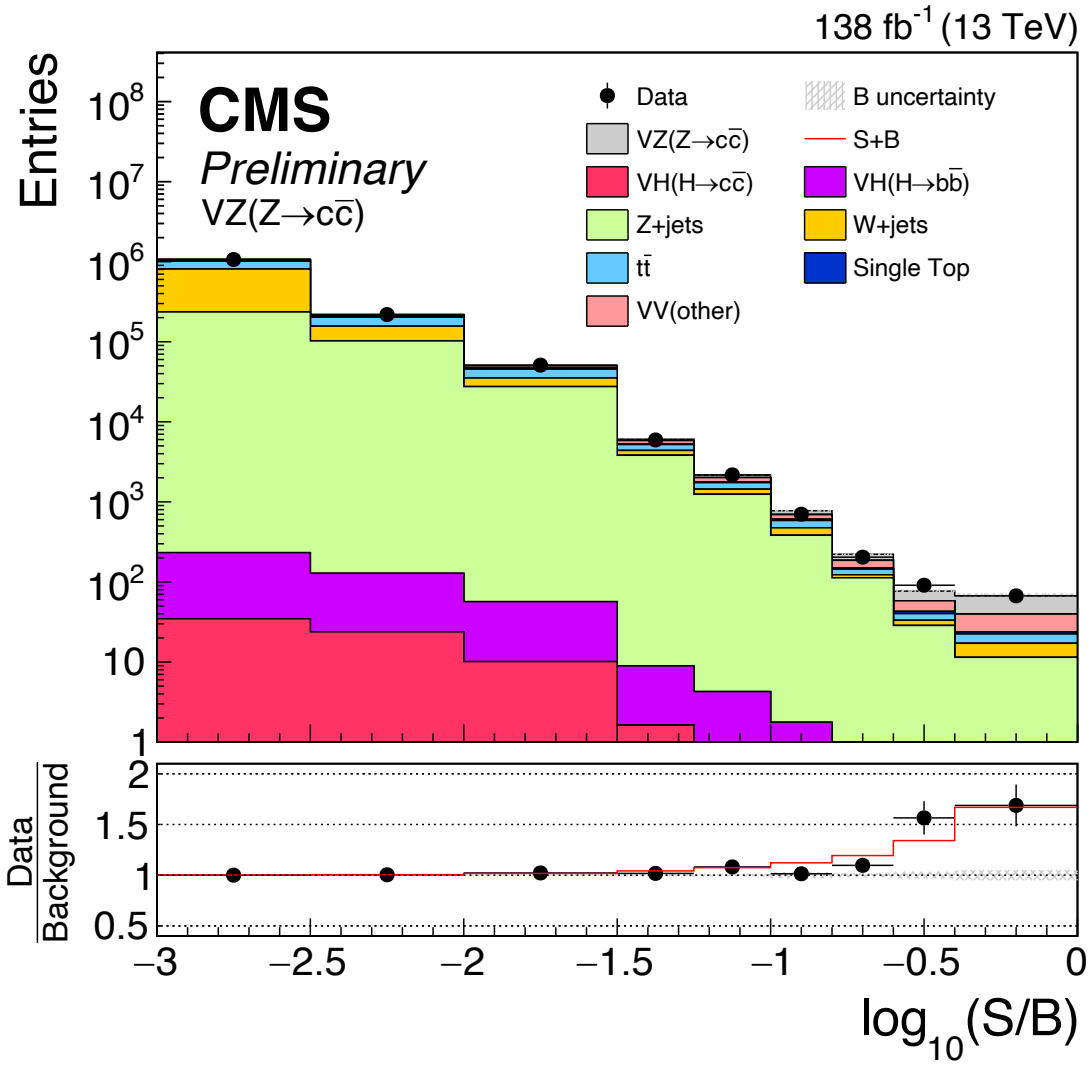


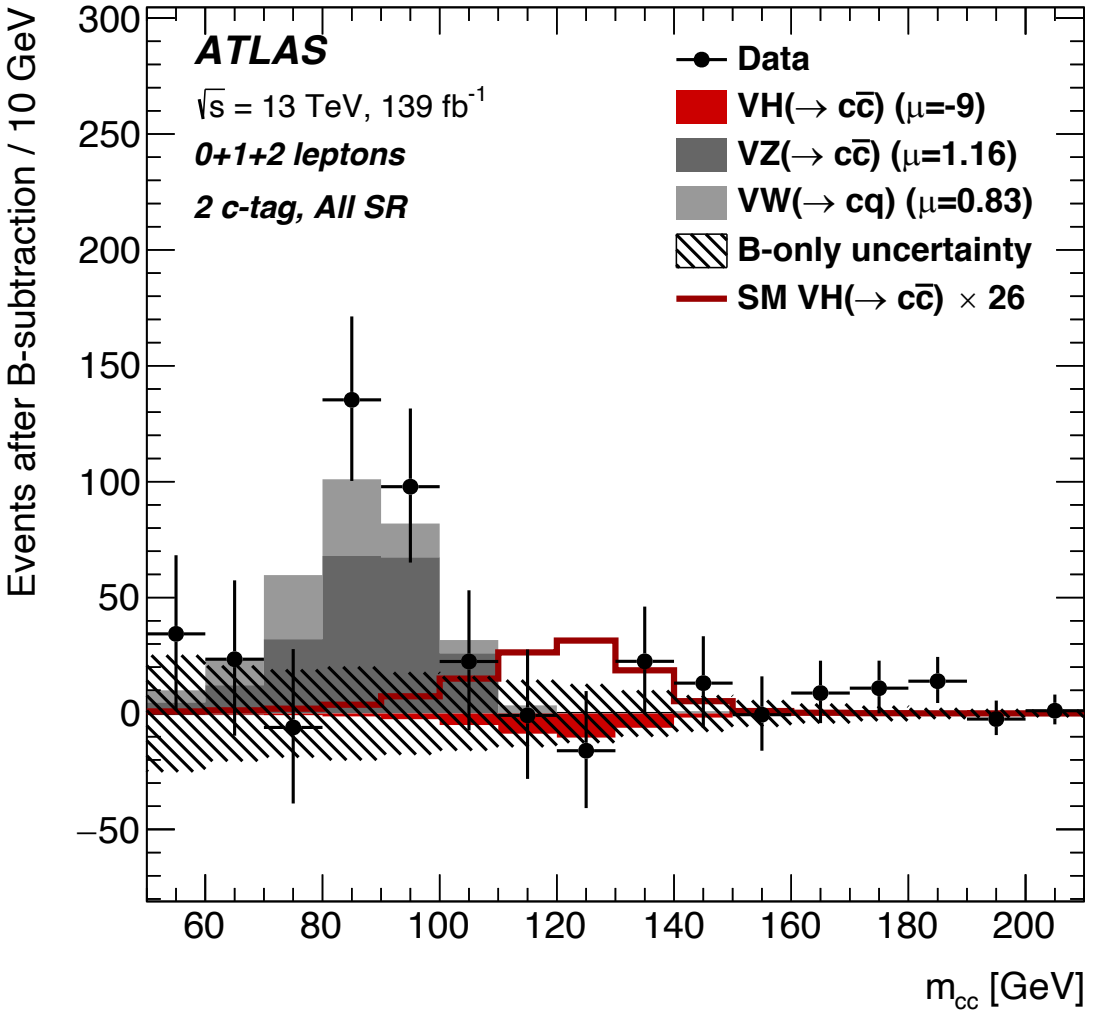


- ATLAS: the value of (|kc/kb|<) 4.5 is less then than the ratio of the b- and c-quark masses, which constrains the coupling of the Higgs to the c-quark to be weaker than the coupling of the Higgs boson to the b quark at 95% CL

Higgs boson decay to pair of charm quarks: Analysis

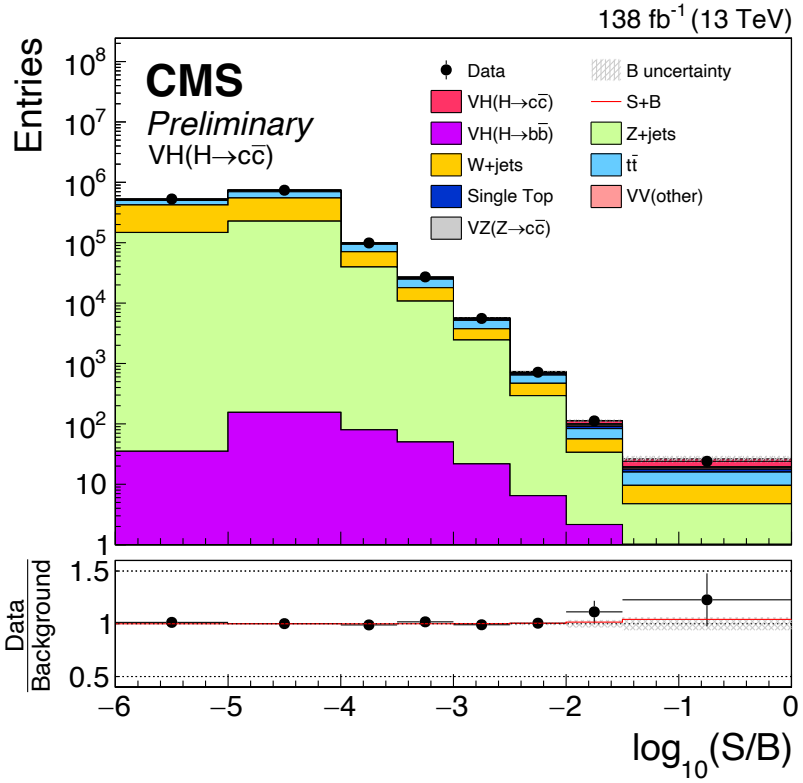
ATLAS: arXiv:2201.11428 Submitted to EPJC, CMS: CMS-PAS-HIG-21-008

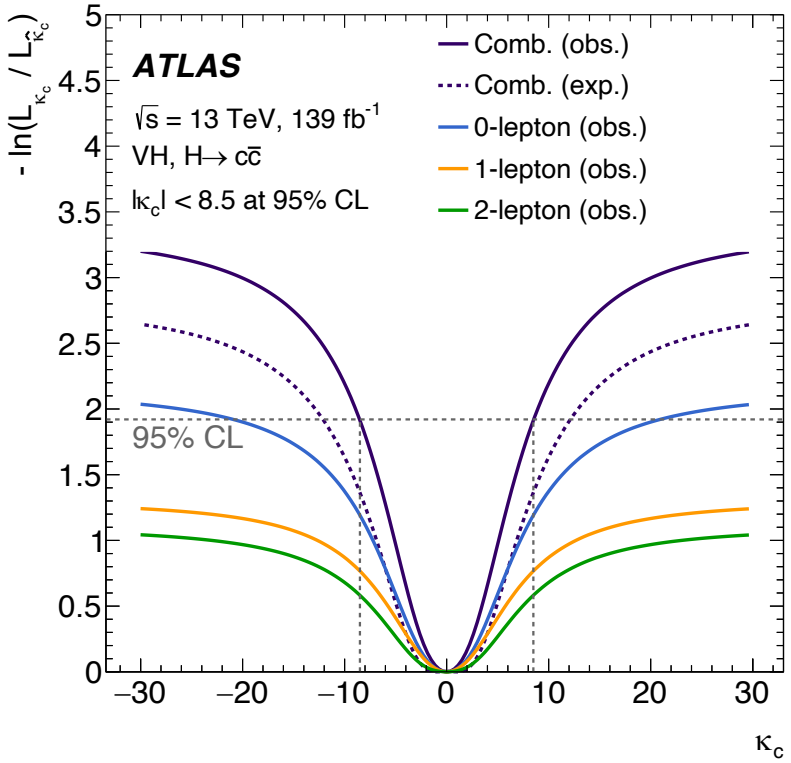


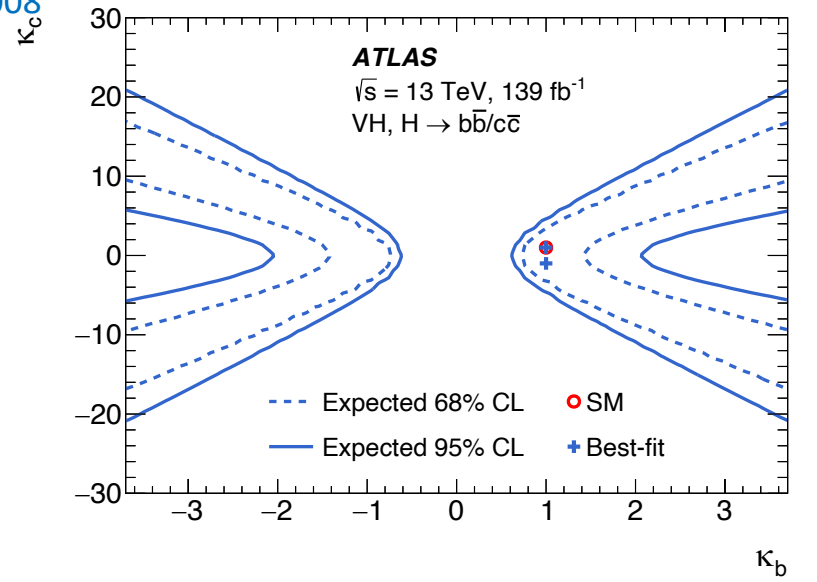


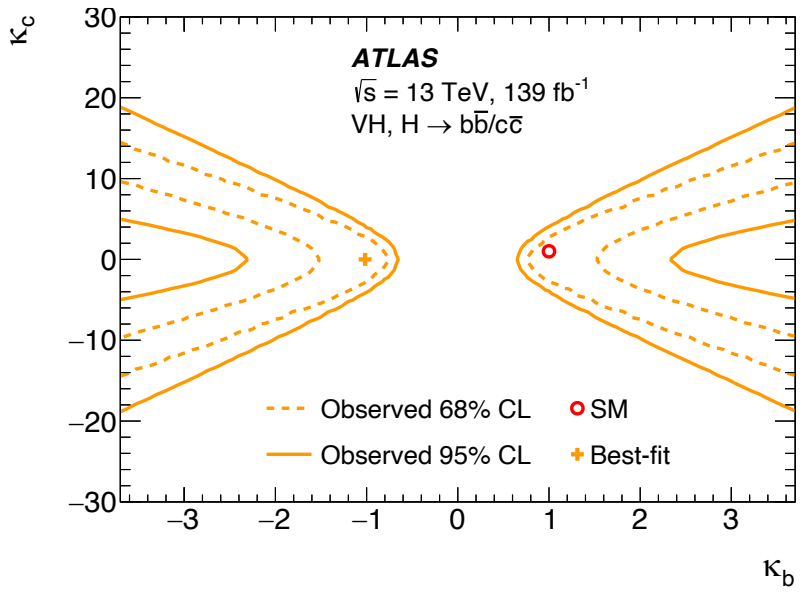
Higgs boson decay to pair of charm quarks

ATLAS: arXiv:2201.11428 Submitted to EPJC, CMS: CMS-PAS-HIG-21-008





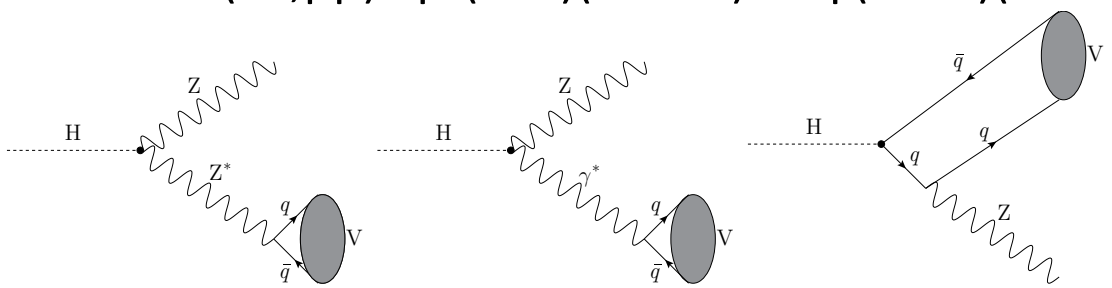




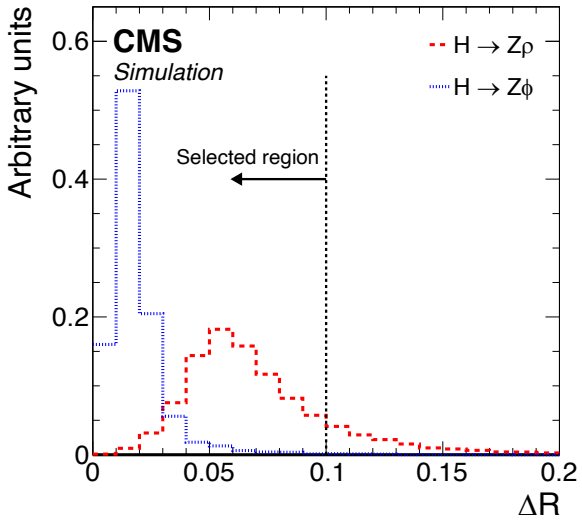
Higgs boson decay to a Z boson and ρ or ϕ meson

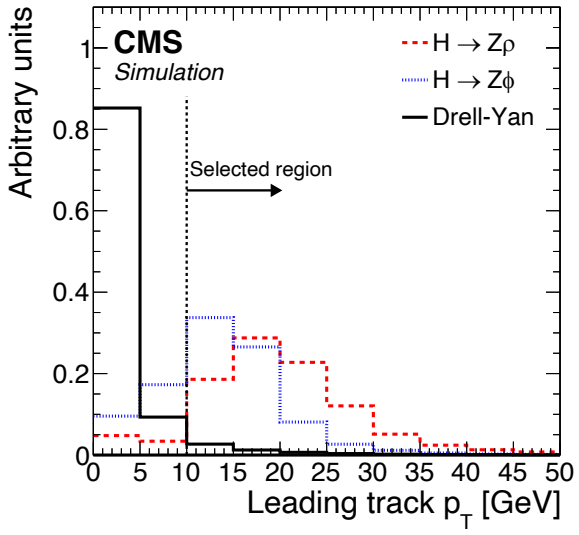
CMS: JHEP11 (2020) 039

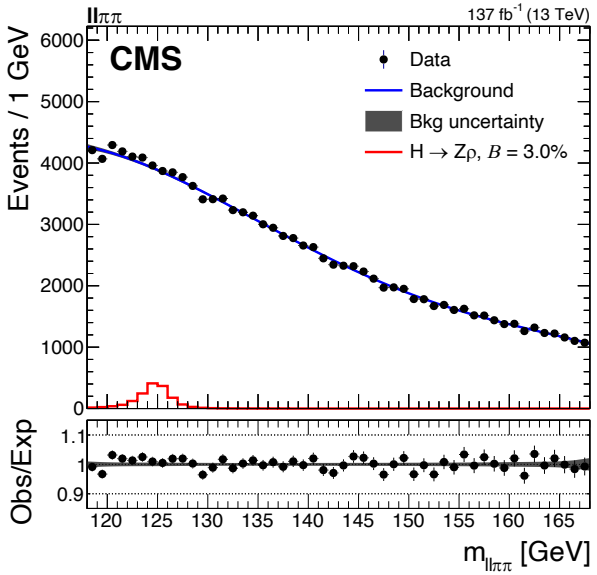
- CMS: H->Z(ee,μμ)+ $\rho^0(770)(\to\pi^+\pi^-)$ or $\phi(1020)(\to K^+K^-)$

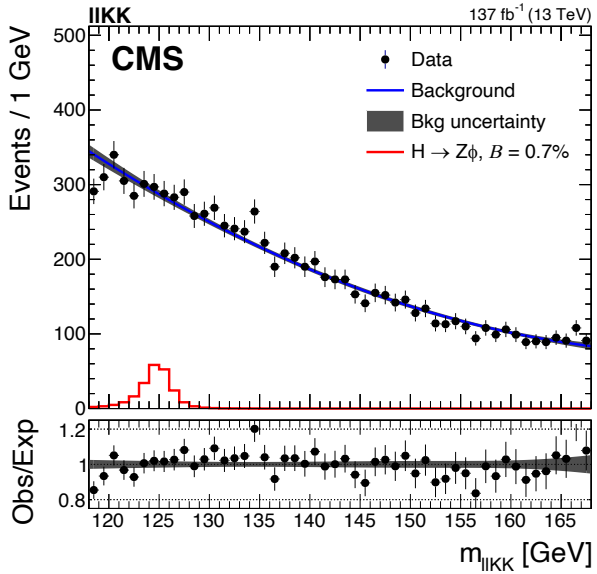


- Direct production suppressed in SM by factor of m_q^2/m_H^2 relative to indirect, but can be enhanced in BSM models
- Main bkg: Drell-Yan Z prod. w/ genuine or mis-ID meson









- Small angular separation(ΔR) between two meson tracks, leading meson track p_T > 10 GeV reduce the background

Polarization state	Effect on yield			
	$\mu\mu\pi\pi$	$\mu\mu$KK	ee$\pi\pi$	eeKK
Longitudinally polarized	+16%	+17%	+23%	+21%
Transversely polarized	−8%	−9%	−11%	−11%

- UL on B(H->Zρ) in range 1.04-1.31% or 740-940 x SM exp
- UL on B(H->Zϕ) in range 0.31-0.40% or 730-950 x SM exp

Higgs boson decay to a Z boson and ρ or ϕ meson

CMS: JHEP11 (2020) 039