CERN 10 *years* **HIGGS boson** *discovery*

Rare Higgs boson decays

Andrea Carlo Marini

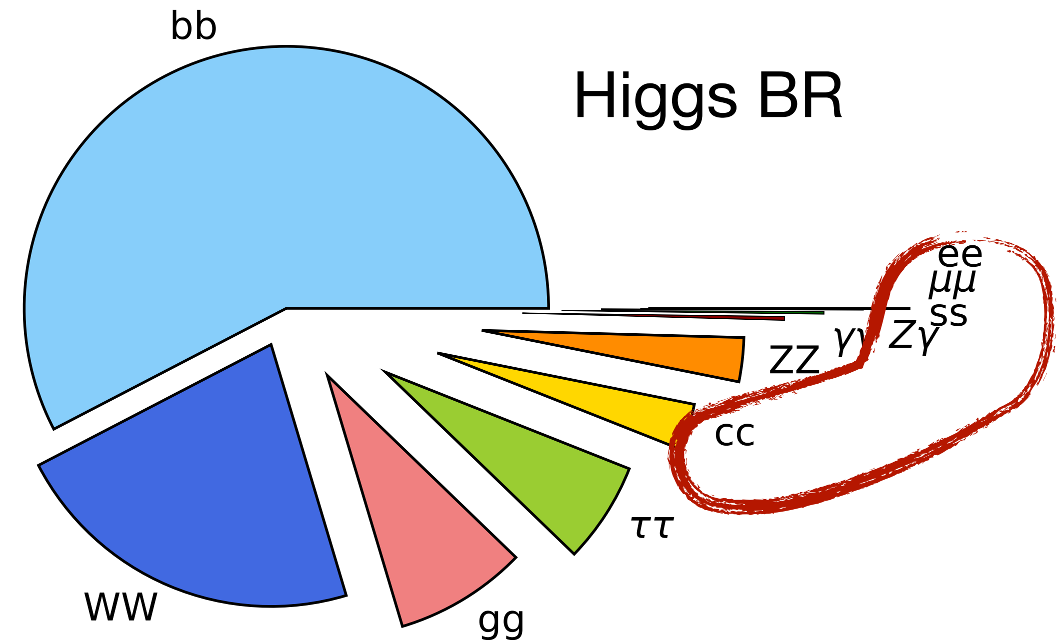
on behalf of the
ATLAS and CMS Collaborations

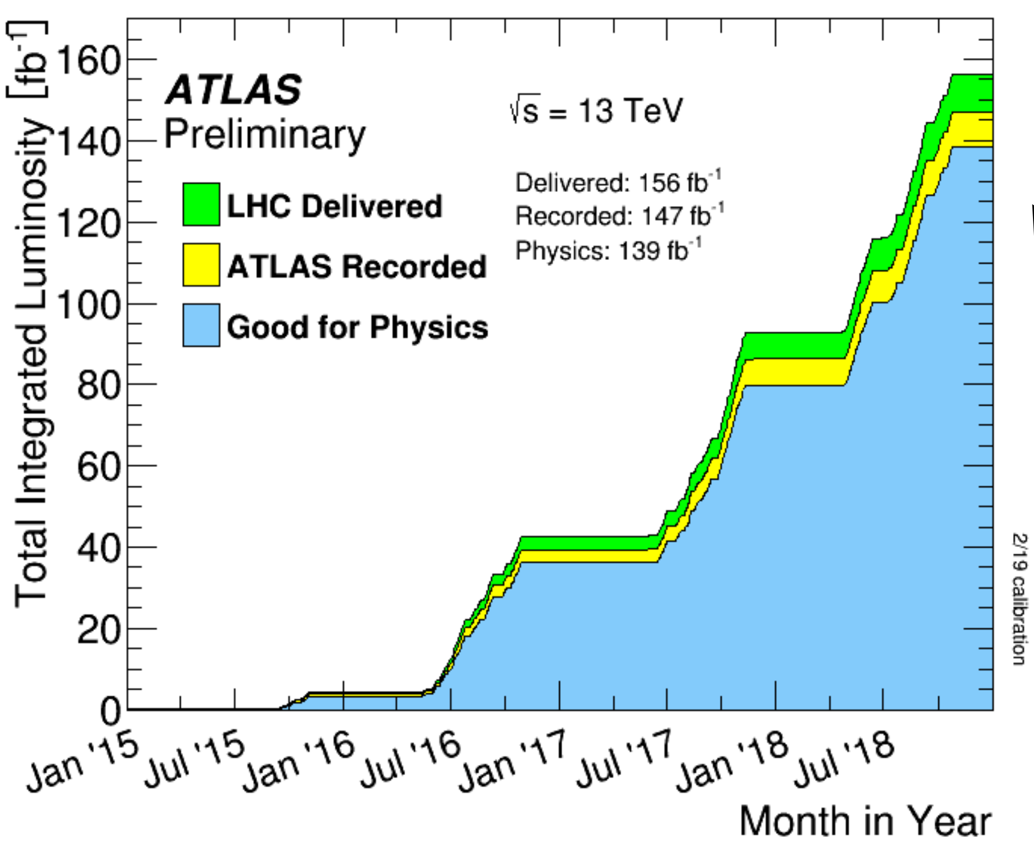
Introduction

What's rare?

- Higgs to cc
- Higgs to Zγ
- Higgs to μμ
- Higgs to ee
- Higgs to bound states
- …

ATLAS and CMS released analyses on the full Run 2 dataset





Full Run 2

Full Run2 ~140 fb^{-1}

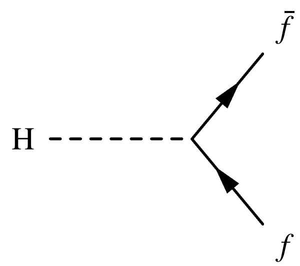
Experimentally challenging:

- Small BR
- Low S/B

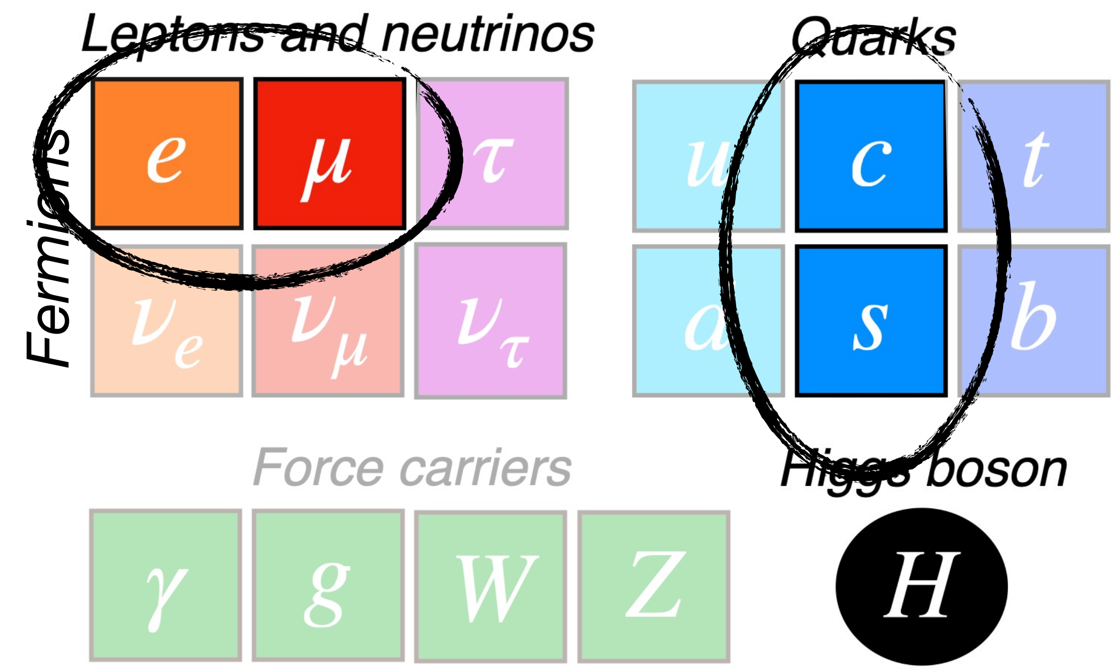
Decay channel	Branching fraction (%)
bb	57.63
WW	22.00
gg	8.15
$\tau\tau$	6.21
cc	2.86
ZZ	2.71
$\gamma\gamma$	0.227
$Z\gamma$	0.157
ss	0.025
$\mu\mu$	0.0216
ee	$5\ 10^{-9}$

Motivations

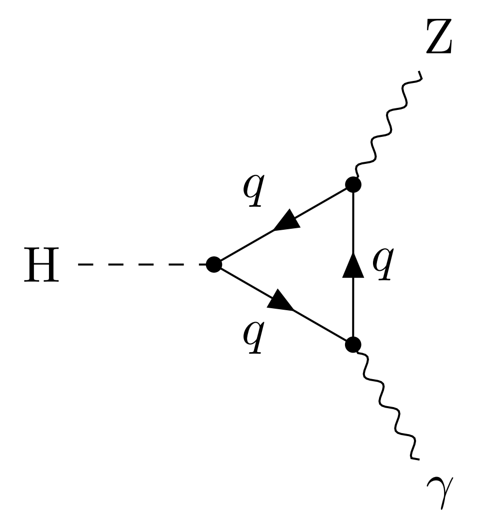
- The fermionic sector is characterised by Yukawa couplings to the Higgs boson
  - Proportional to the fermion mass!



$$\mathcal{B} \propto m_F^2$$



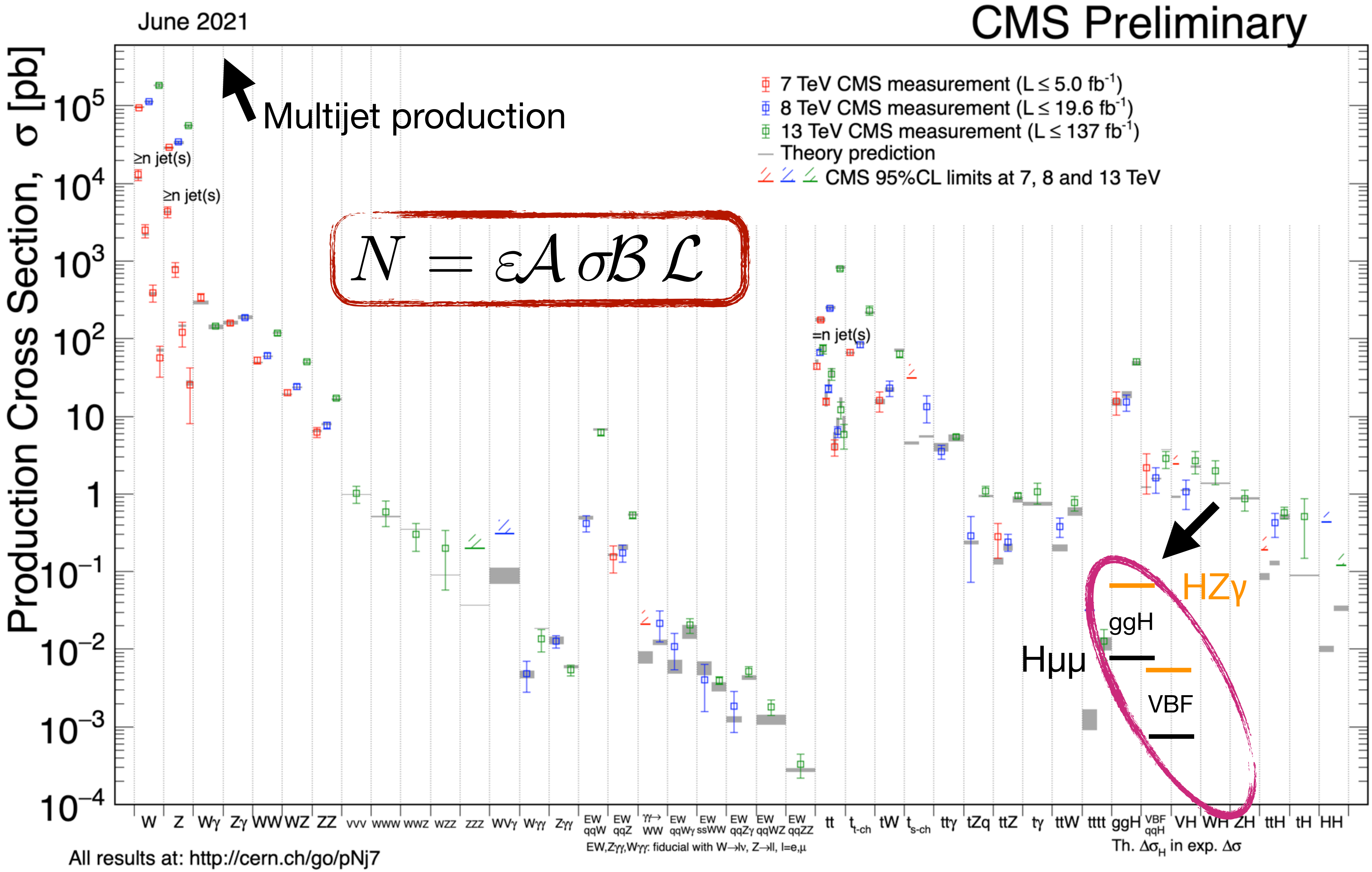
- New physics can affect differently the different fermion **generations**.
  - Precision mapping of the couplings is key to understand the nature of the Higgs boson
  - Asymmetries in the leptonic vs the quark sector



Rare decays happen also through **quantum loops**:

- Precise measurements give indications on the couplings and particles in the loop, and therefore are sensitive to new structures and particles

- Comparison to Standard Model



H→cc — ATLAS

arXiv:2201.11428

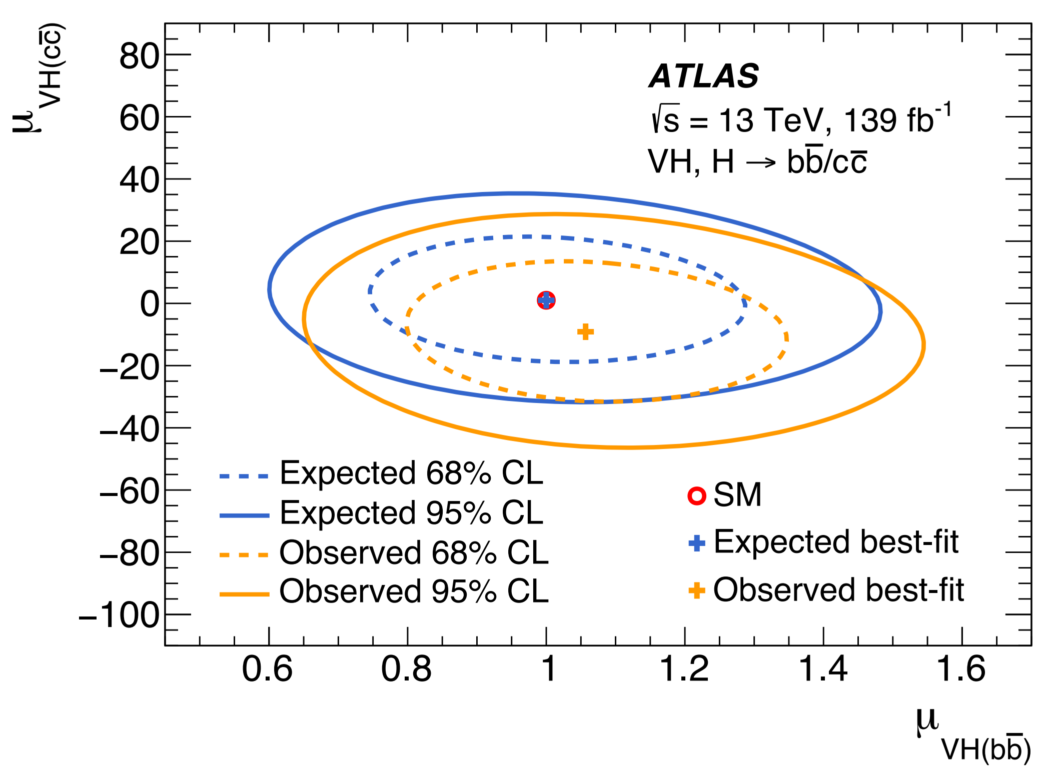
- Probing the charm Yukawa coupling.

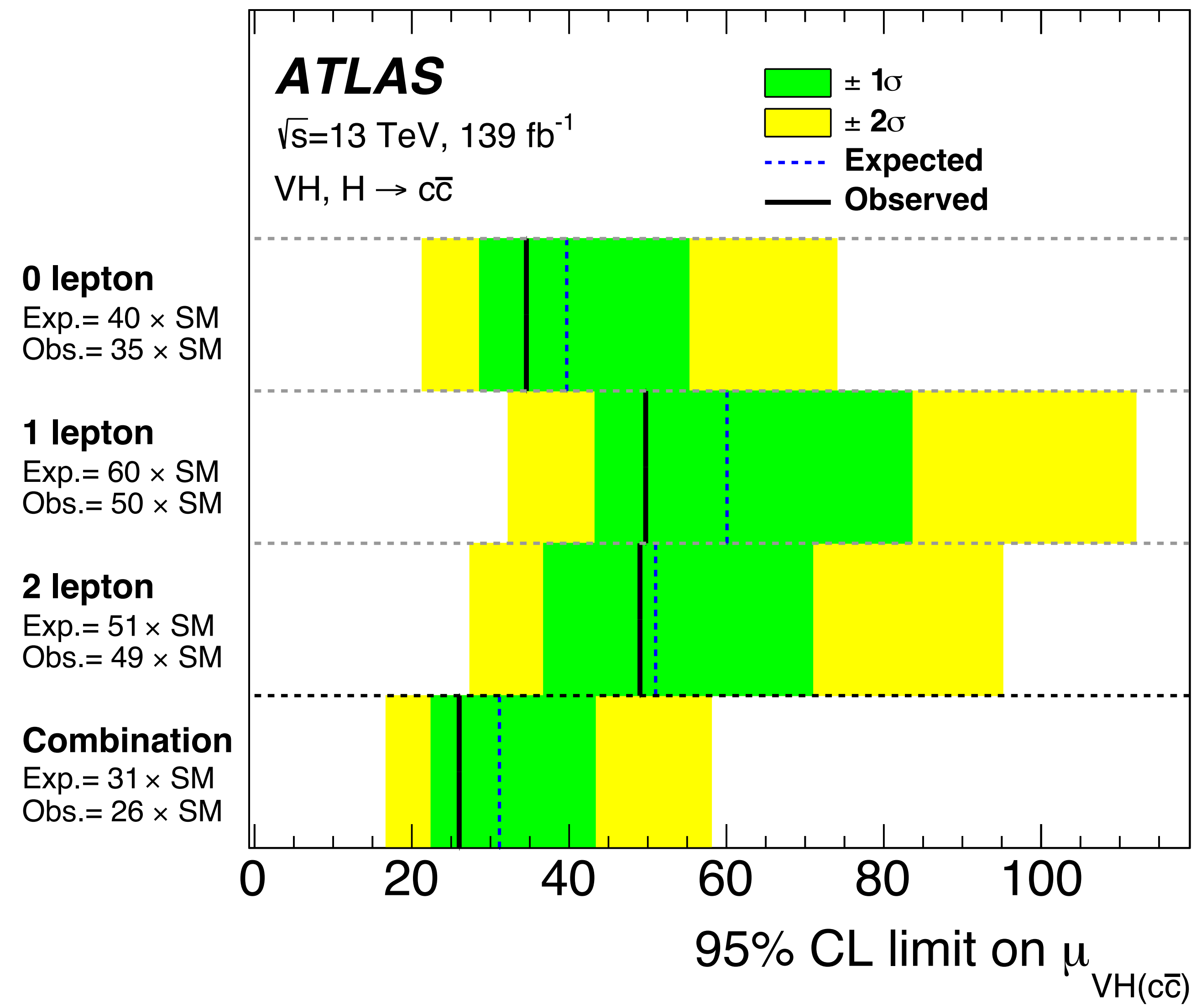
SM $\mathcal{B}$(H→cc) = 2.8%

- VH production: V=W, Z and leptonic (ℓ=e,μ) or invisible decays (ν)
- Small branching fraction and very large hadronic background
- The associated V boson allow for good online selection (trigger) of the events.

Analysis of the Run 2 datasets.

- 3 Categories: 0 lepton (E_T^{miss} >150 GeV), 1 lepton, and 2 lepton targeting Z→νν, W→ℓν, and Z→ℓℓ
- 1c- and 2c-tagged categories
  - c-tagging: orthogonal to b-tagging





H→ cc — CMS

HIG-21-012

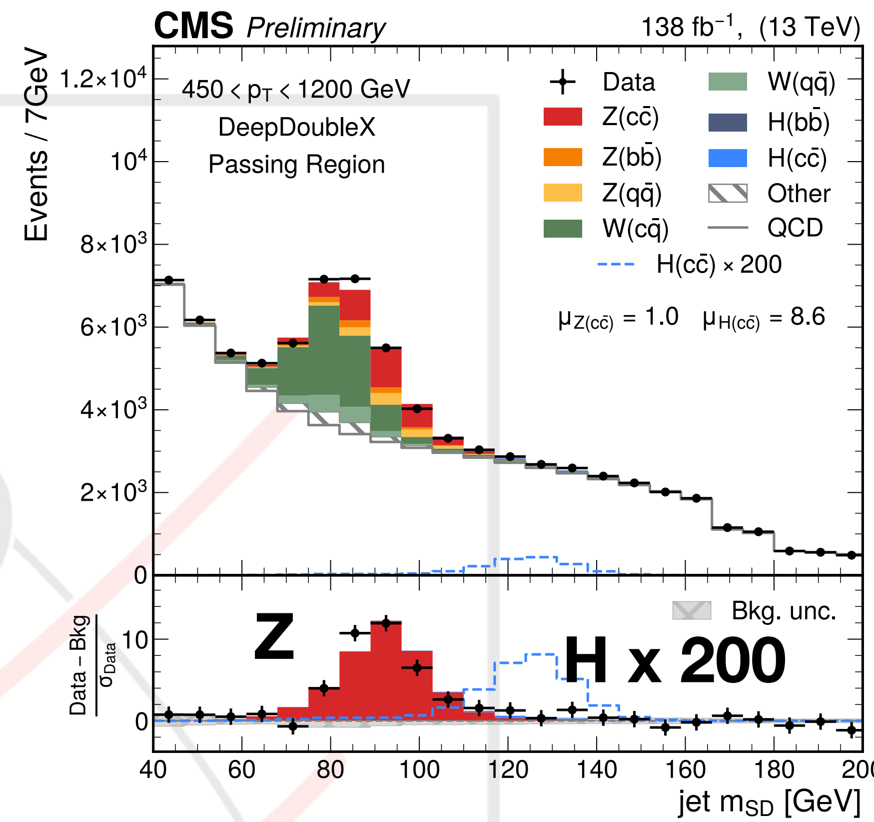
arXiv:2205.05550

ggH Analysis

- Boosted cc system in the final state

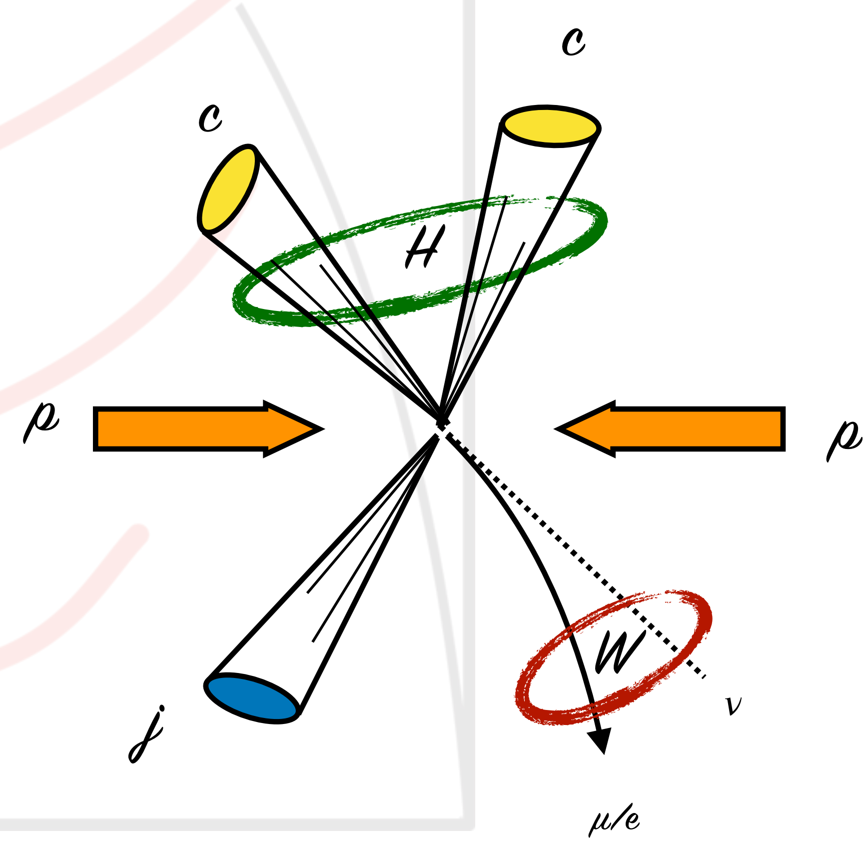
$$\mu_{\rm H} = 8.6^{+19.9}_{-19.4},$$

45 (38) at the 95% CL.



VH Analysis of the Run 2 datasets

- Higgs to charm reconstructed both in the **boosted** (p_T>300 GeV) and **resolved** regimes



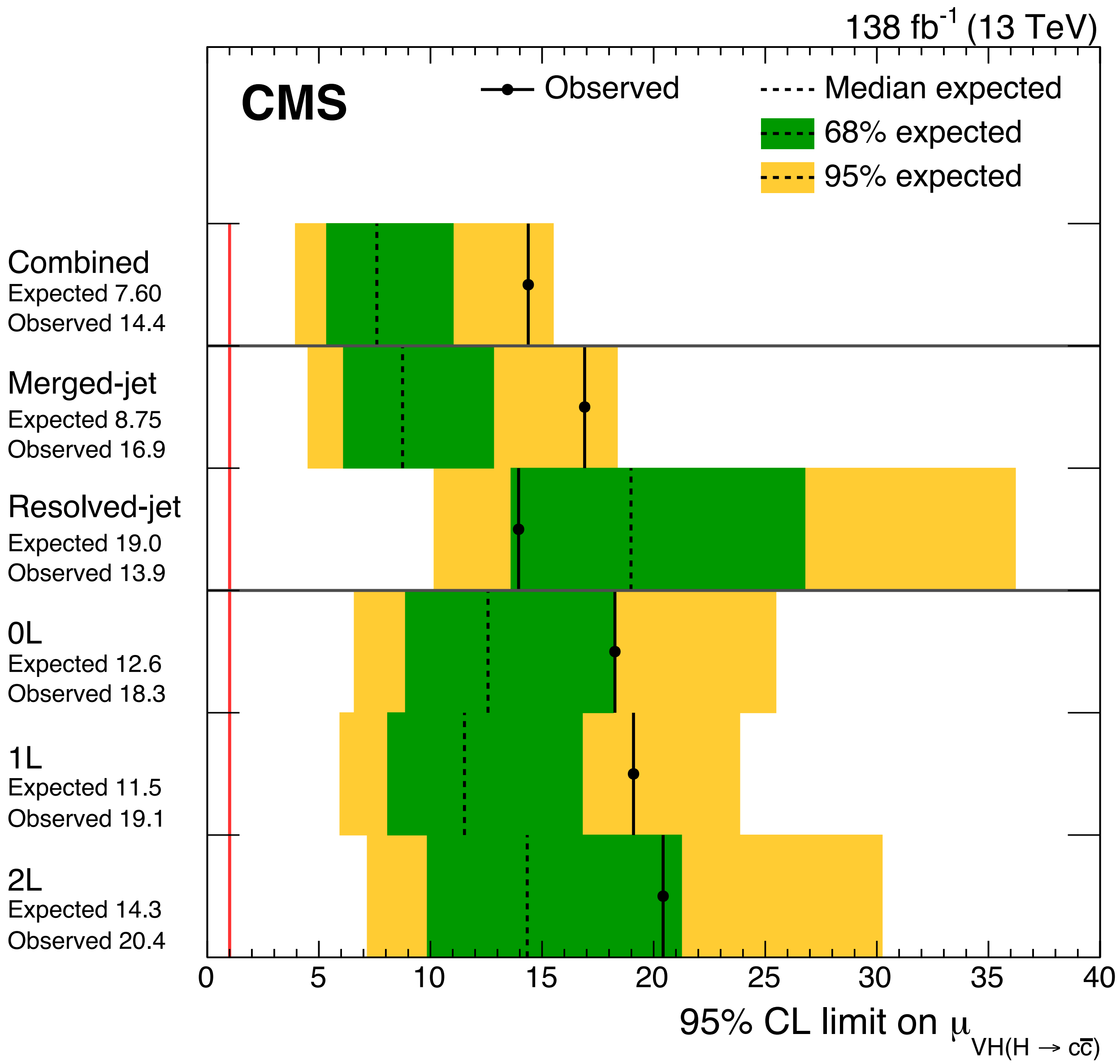
Resolved regime:

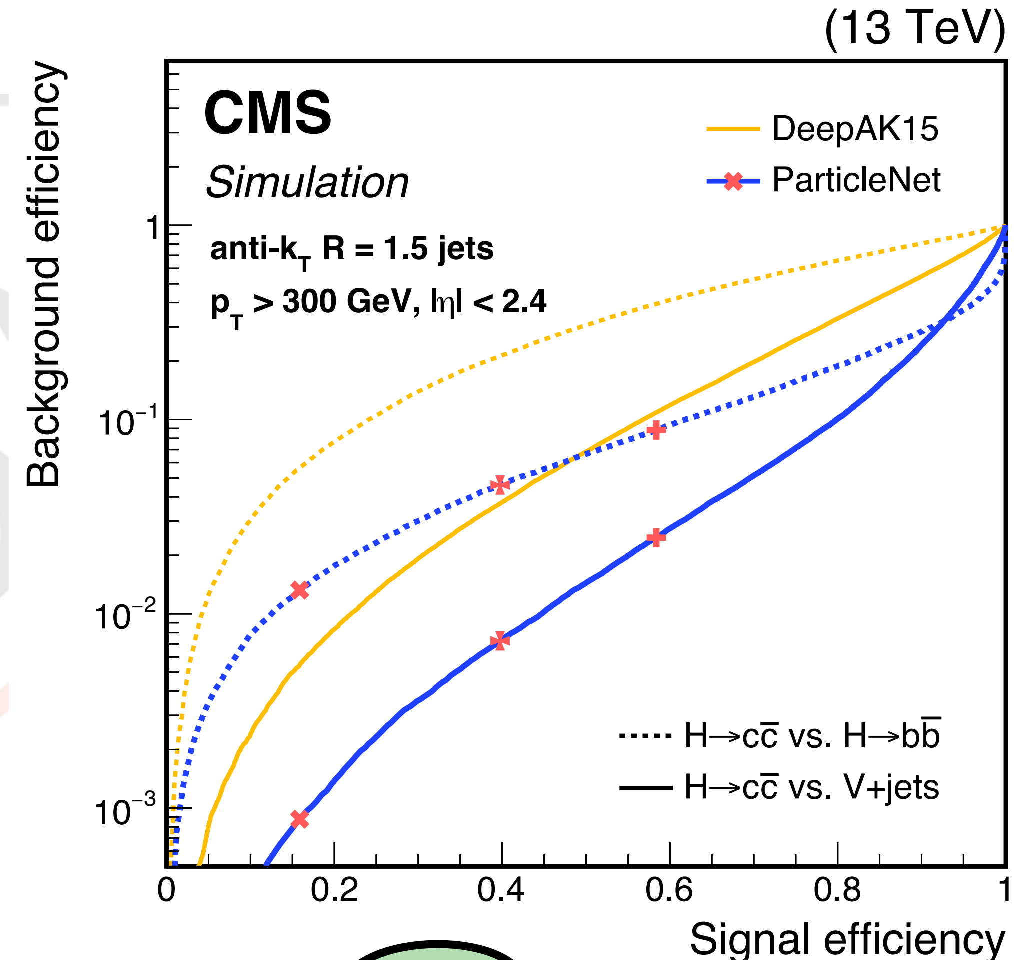
- Using deep neural network to improve rejection of light quarks vs b jets (DeepJet)
- Dedicated energy regression
- 3 Categories: 0 lepton, 1 lepton, and 2 lepton targeting Z→νν, W→ℓν, and Z→ℓℓ

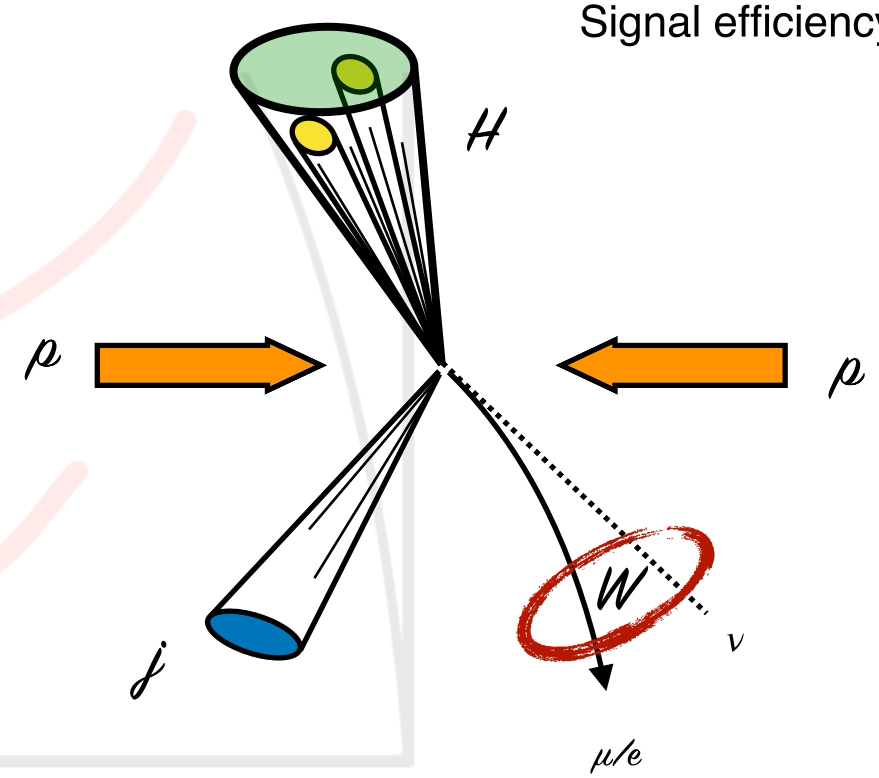
arXiv:2205.05550

Boosted regime

- Major backgrounds are the corresponding V+jets productions
- Charm tagging boosted region: **ParticleNet**, a multiclass graph network for jet identification and mass estimation.



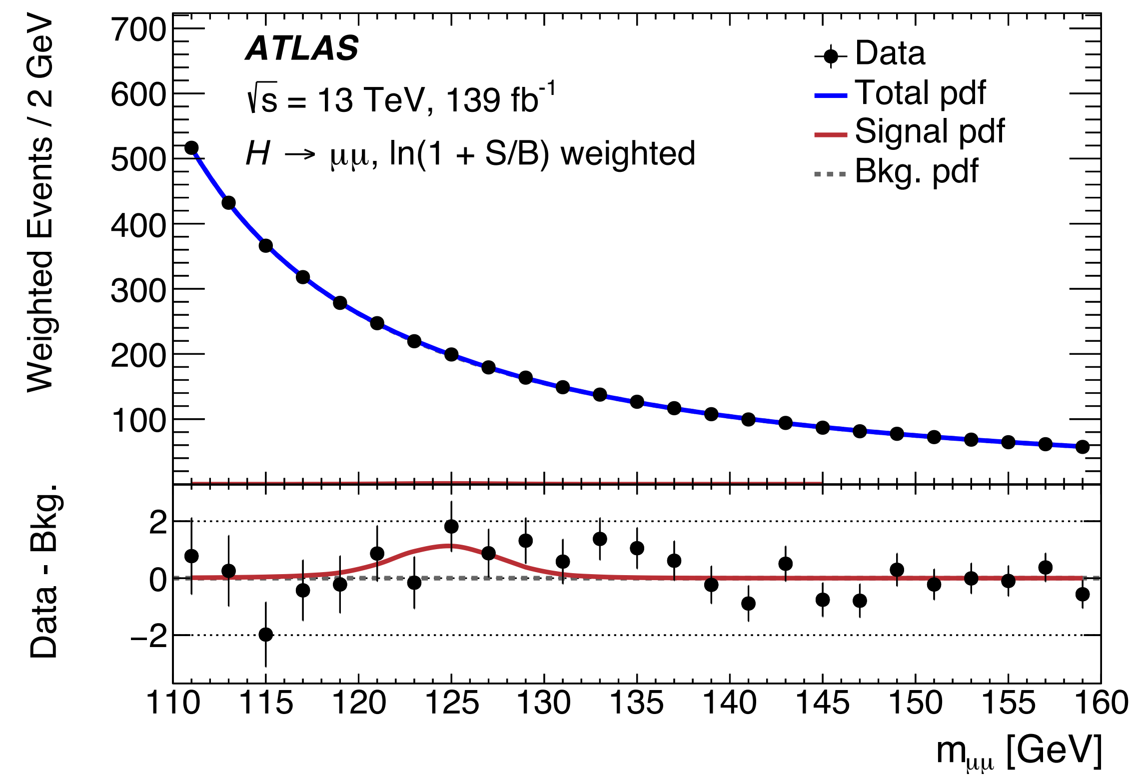




H→μμ — ATLAS

PLB 812 (2021) 135980

SM $\mathcal{B}(H \to \mu\mu) \sim 2.2 \times 10^{-4}$



large SM irreducible DY → μμ background
– S/B ~ 0.1% for inclusive events at 125 GeV
Improvements to increase sensitivity:

- Targeting all production modes
- MVA categorisation to select events at high S/B, e.g. from VBF
- γ-FSR recovery to improve $\sigma(m_{\mu\mu})$

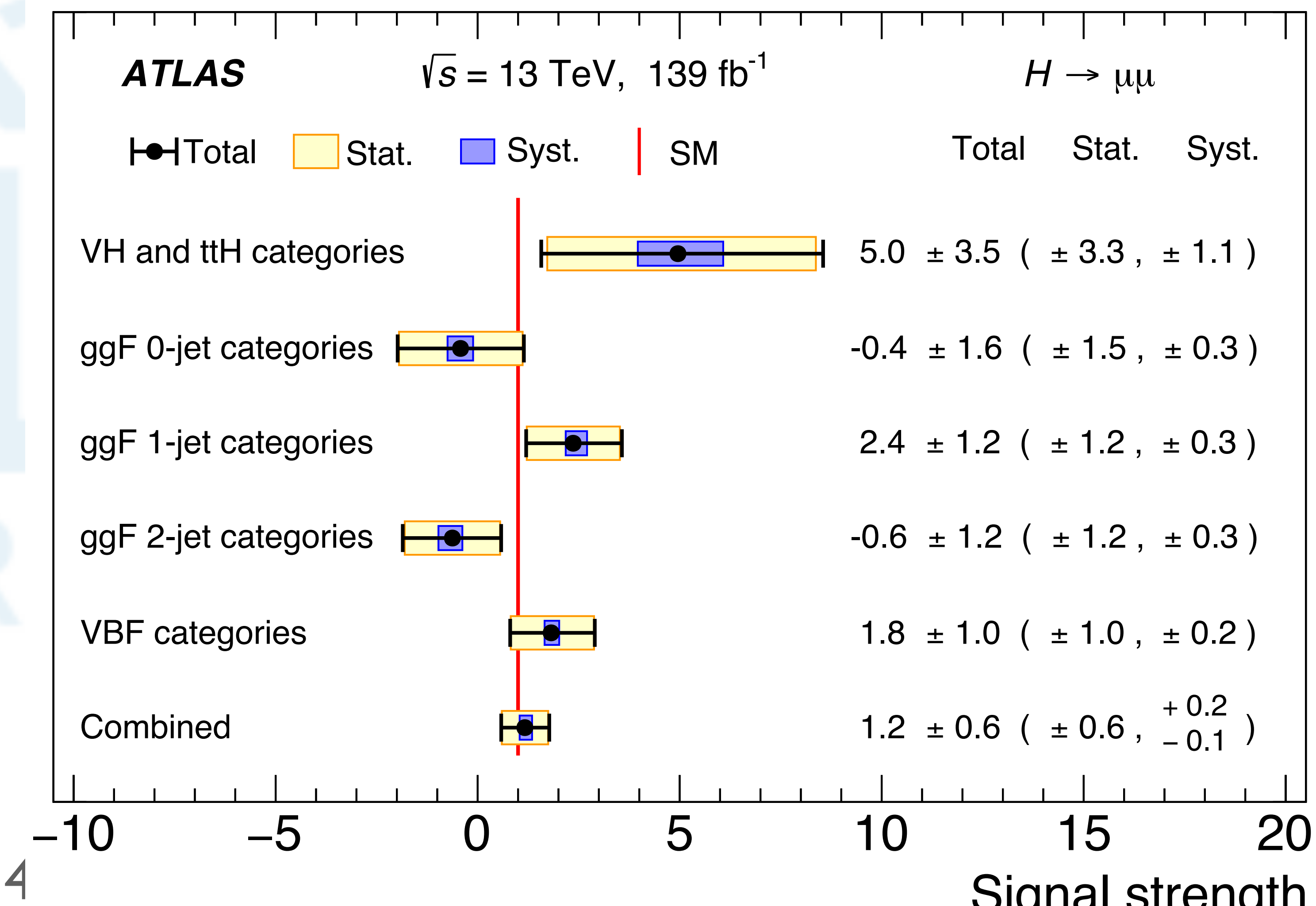
Signal extraction from $m_{\mu\mu}$ fit
Background parametrisation:

- Common "core" pdf + per-category empirical function

μ = 1.2 ± 0.6

Observed (expected) **significance**

$$2.0\sigma\ (1.7\sigma)$$



H→μμ — CMS

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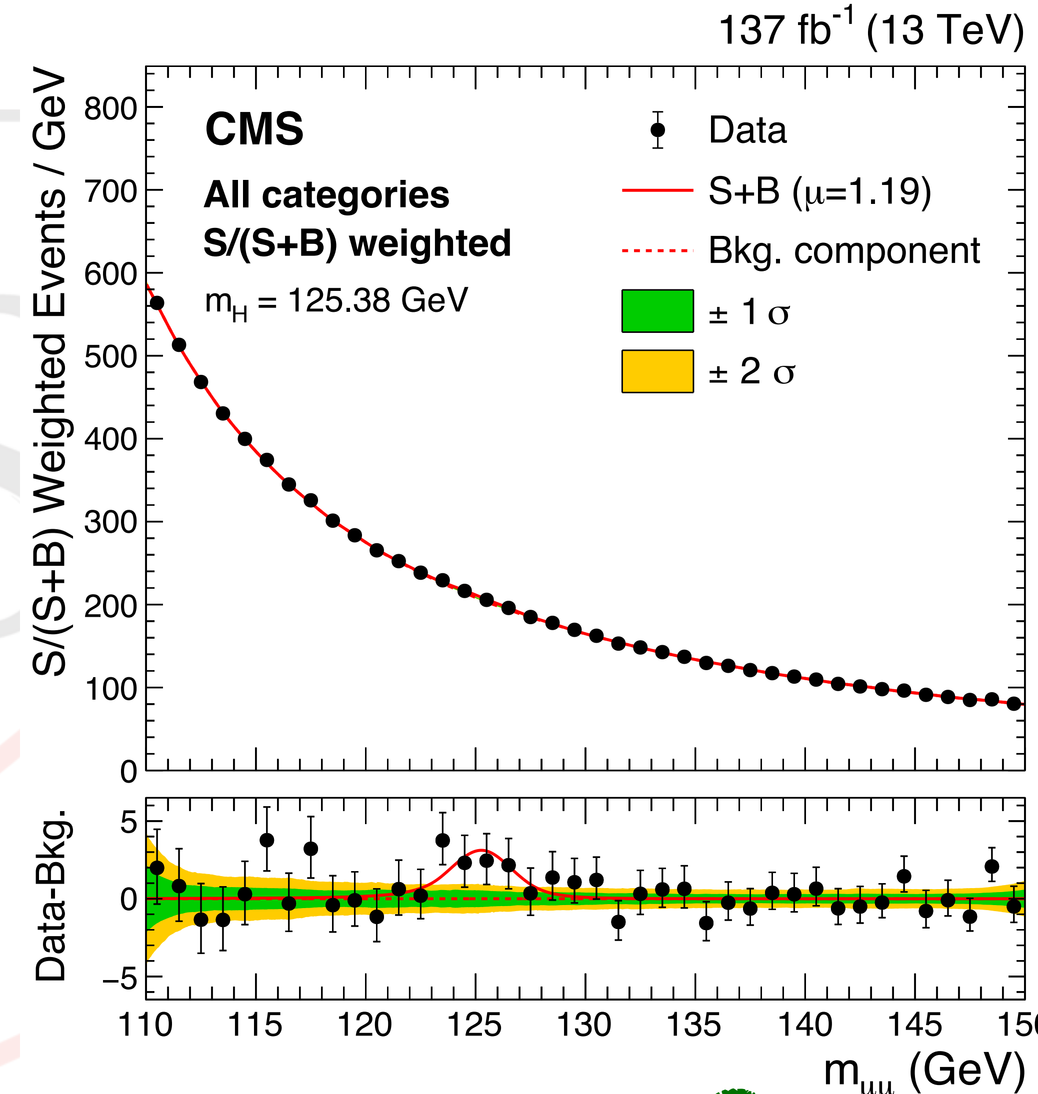
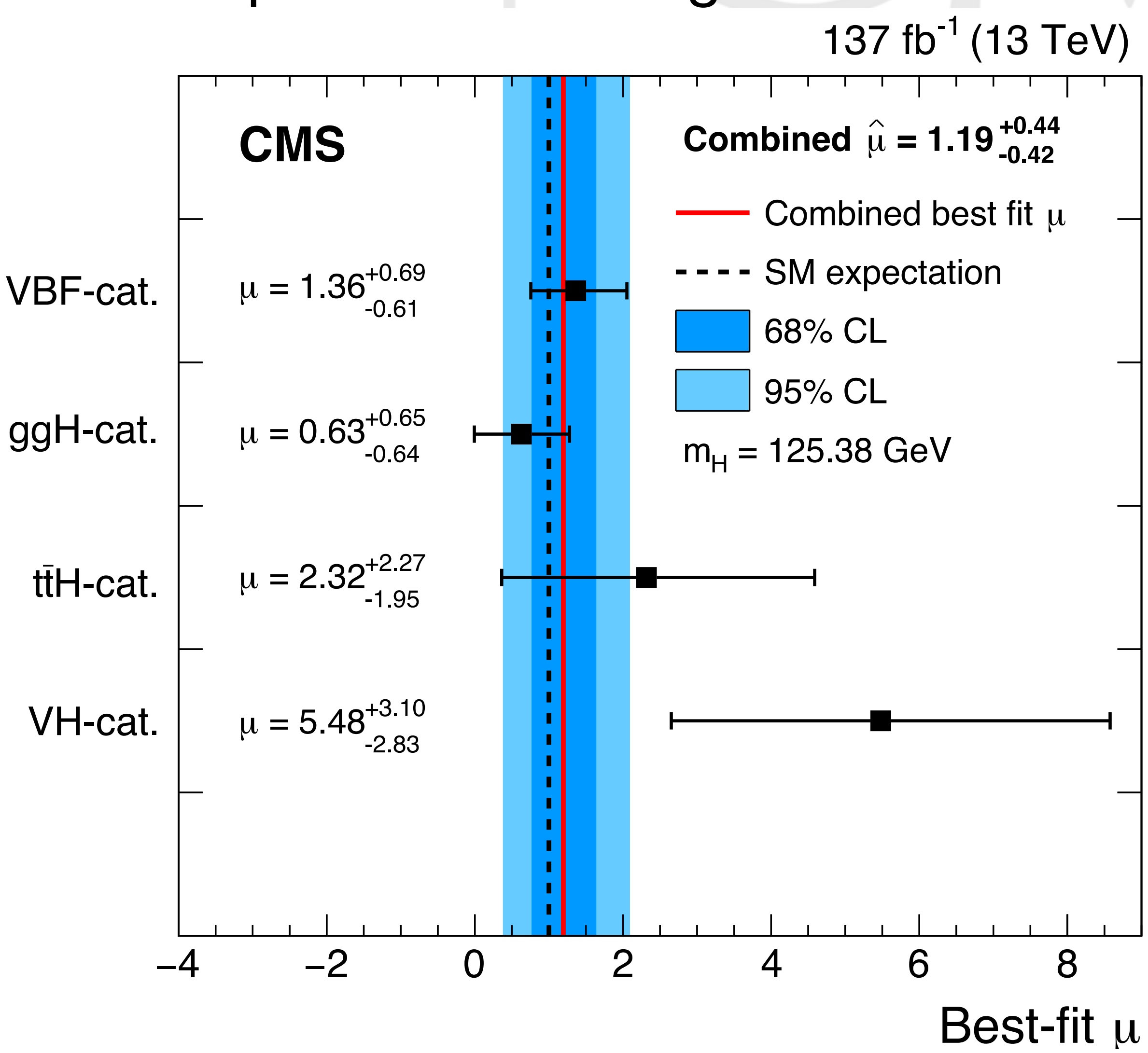
- Dedicated MVA to enhance sensitivity in all the production modes
- γ-FSR and in situ Z calibration
- VBF background prediction from MC simulation
  - DNN discriminator with mass as feature
- ggH, ttH, VH analytical fit to the invariant mass:
  - core pdf for the background estimation





- $\mu = 1.19^{+0.44}_{-0.42}$
- **Evidence for H→μμ 3.0σ (2.5σ)**

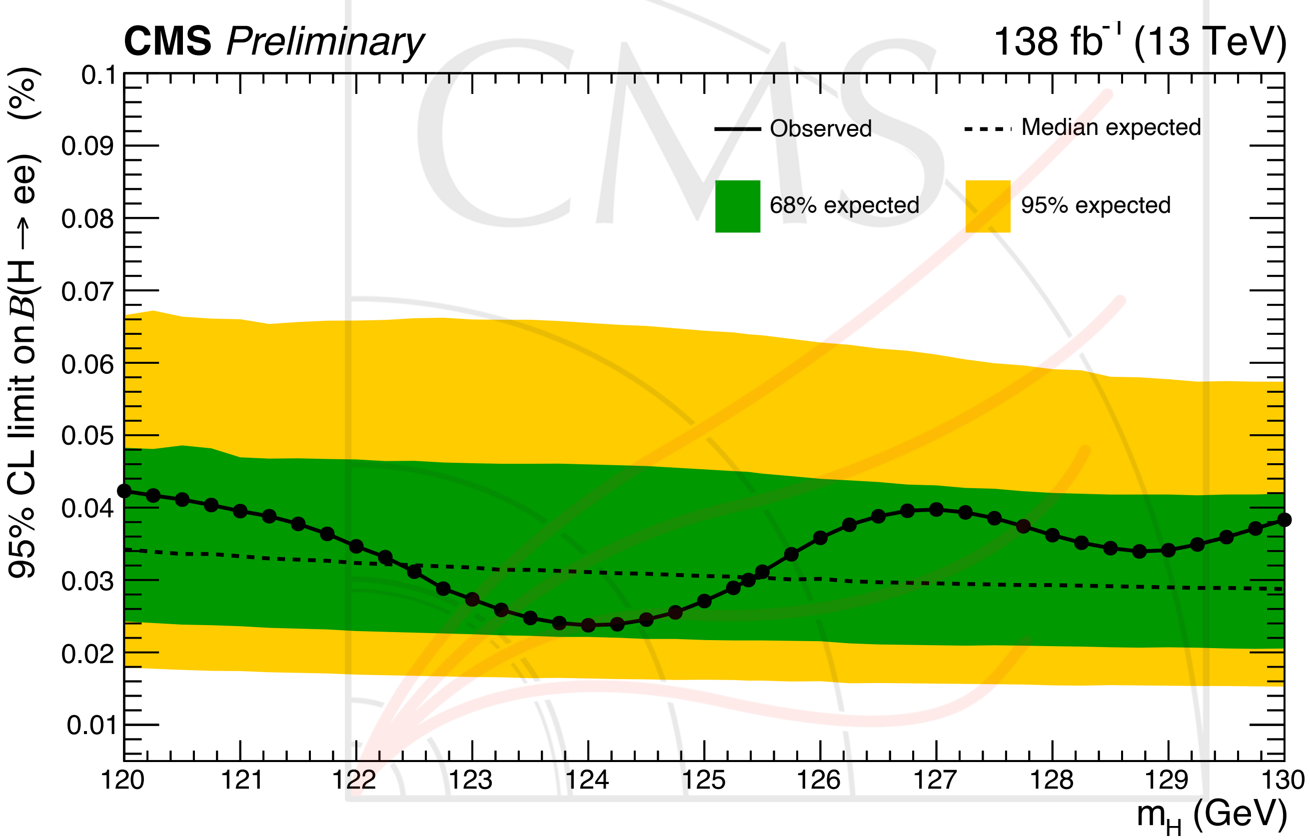
- Direct probe of the Higgs-electron Yukawa coupling

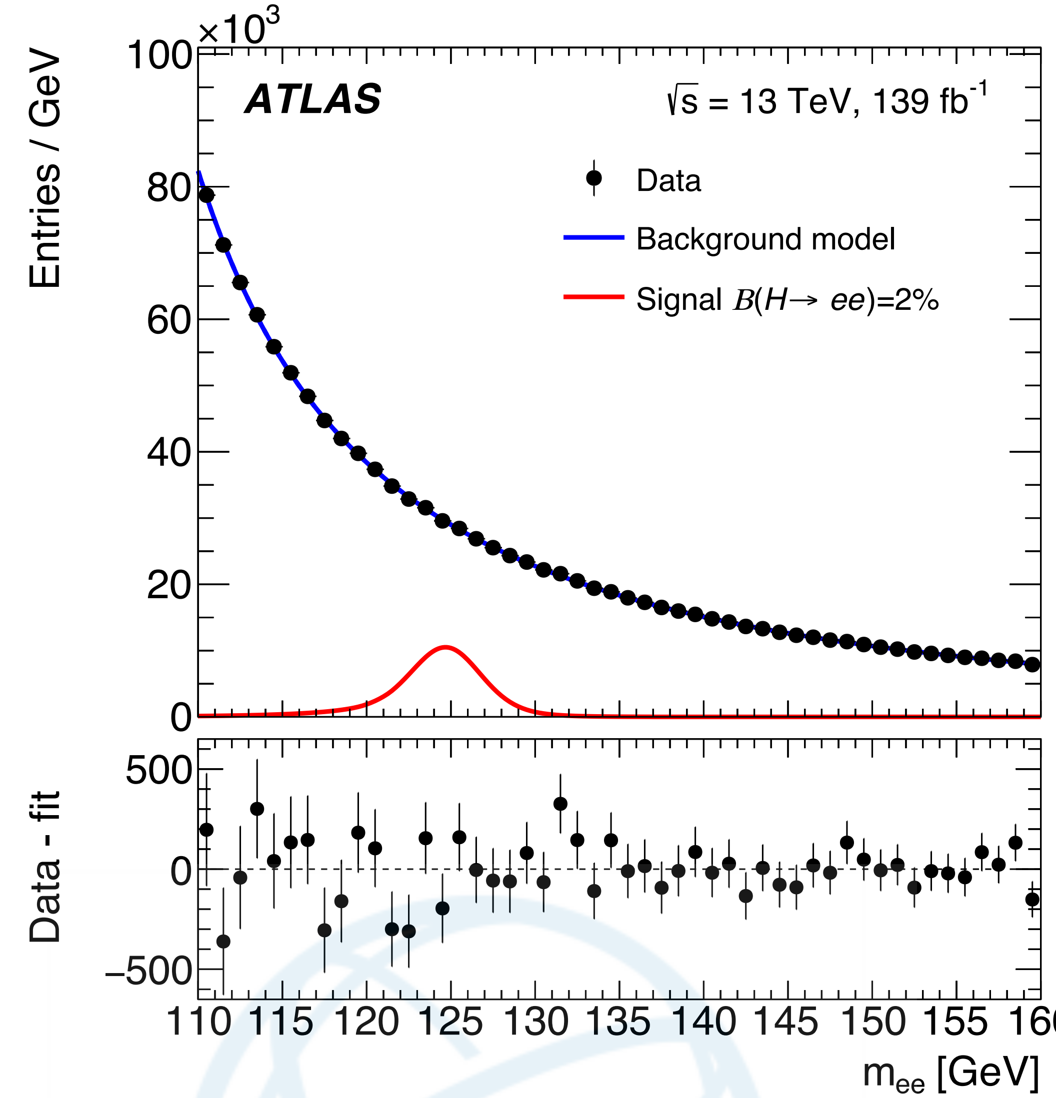
SM prediction for $\mathcal{B}(H\to ee) \sim 5 \times 10^{-9}$

- Several categories
- Most sensitive category is VBF (best S/B)
- Parametric fit to the invariant mass distribution simultaneously in all categories

CMS

- BR < 3×10^{-4} @ 95%CL





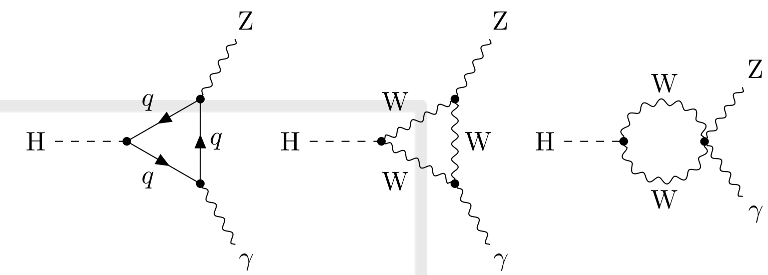
ATLAS

- BR < 3.6×10^{-4} @ 95%CL

H→Zγ — CMS

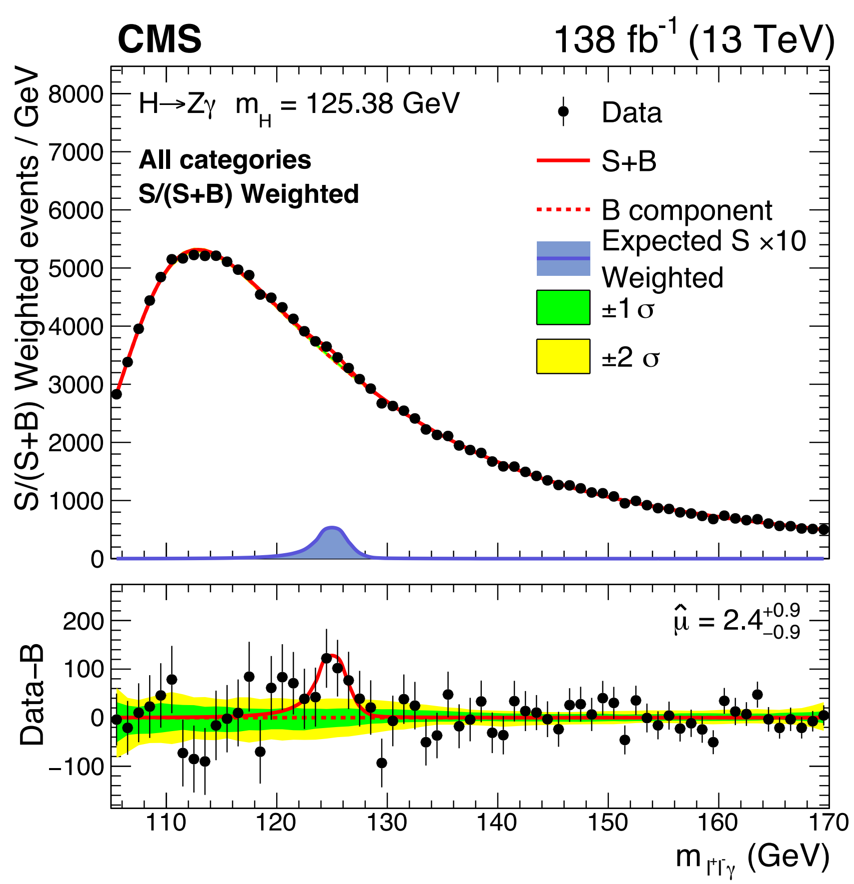
arXiv:2204.12945

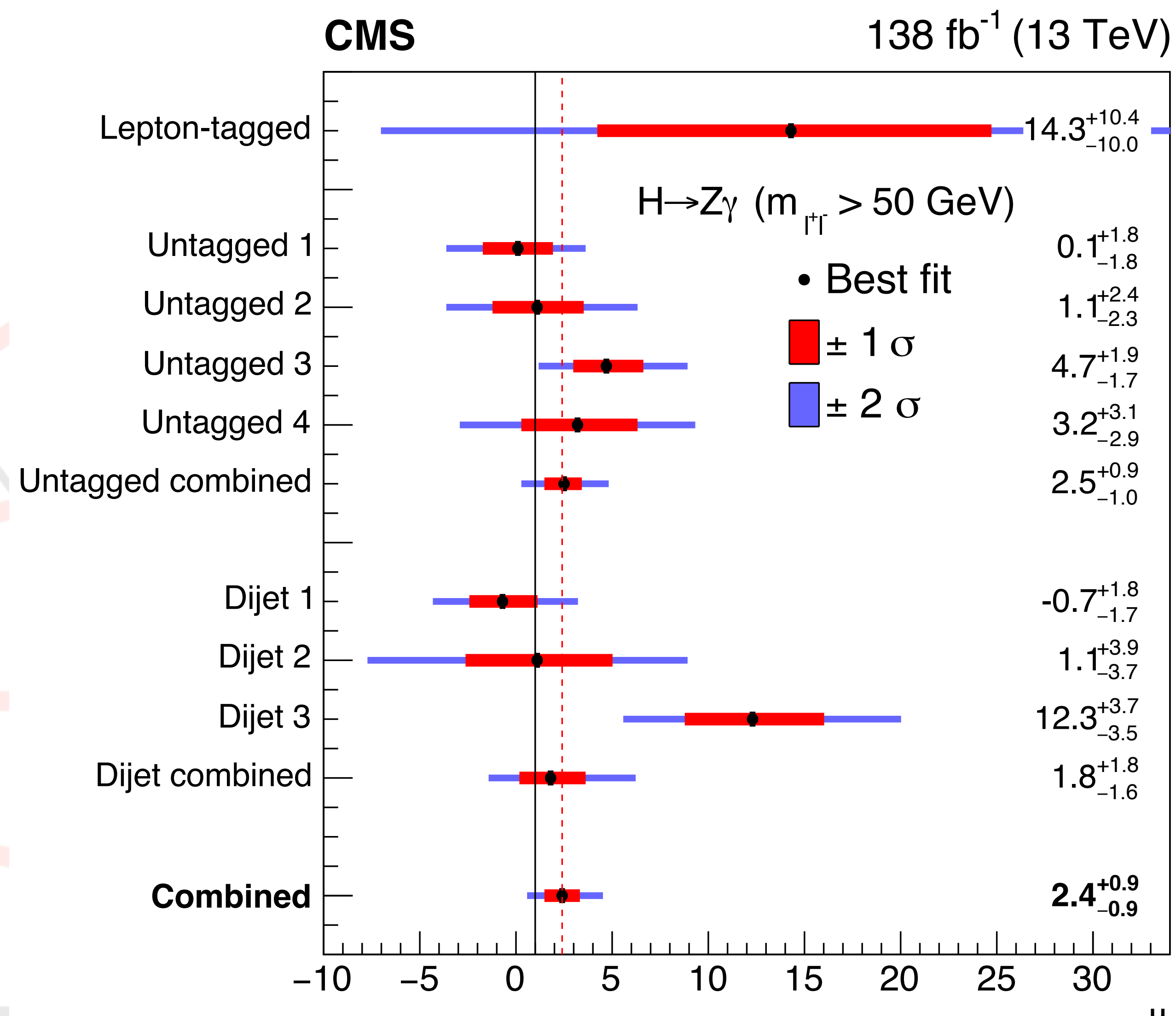
SM $\mathcal{B}$(H→Zγ) = 1.6 × 10^{-3}



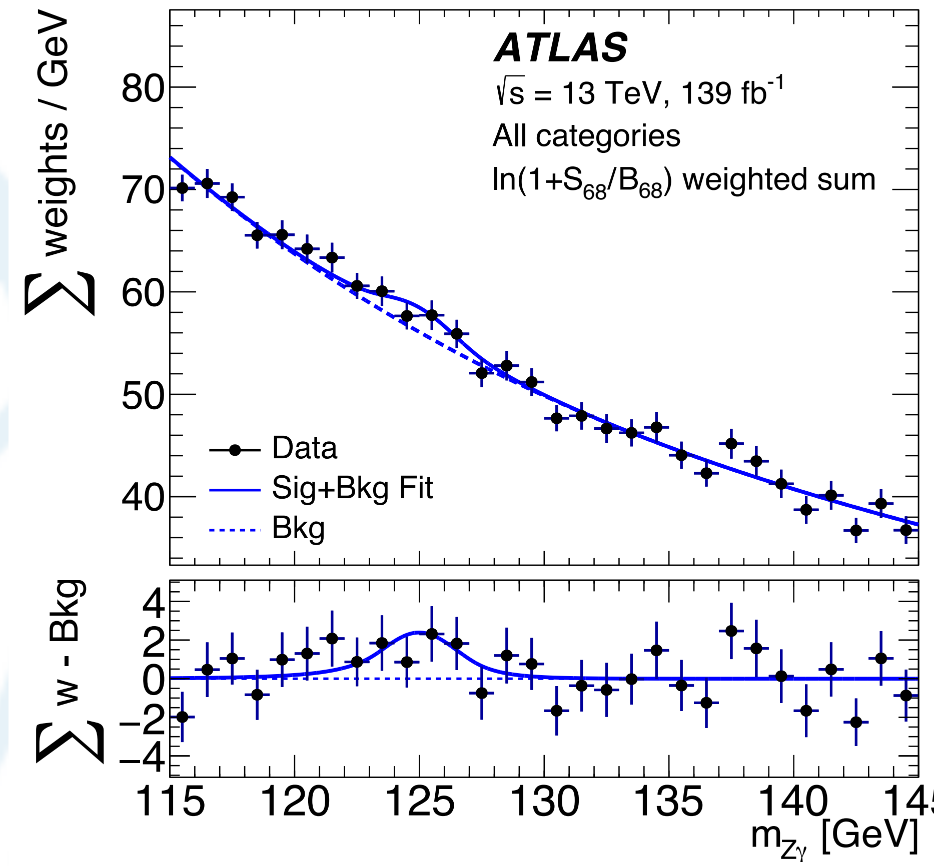
- Sensitivity to new physics in the difference between H→Zγ and H→γγ
- Selecting Z→ee and Z→μμ events and an additional photon
- Sensitivity to the different production modes: VH (lepton), VBF (dijet), ggH (Untagged)
- MVA to enhance event categorisation
- Parametric fit to the invariant mass

2.7 (1.2)σ obs (exp)





- Selecting Z→ee and Z→μμ events and an additional photon
  - $|m_{\ell\ell} - m_Z| < 10$ GeV
  - Kinematic fit and muon γ-FSR → mass resolution
- 6 categories:
  VBF enriched, and S/B based (high, low p_T) or resolution (p_T^{γ}) and lepton flavor
- Parametric fit to the invariant mass



$$\mu = 2.0 \pm 0.9(\text{stat.})^{+0.4}_{-0.3}(\text{syst.}) = 2.0^{+1.0}_{-0.9}(\text{tot.})$$

2.2 (1.2)σ obs (exp)

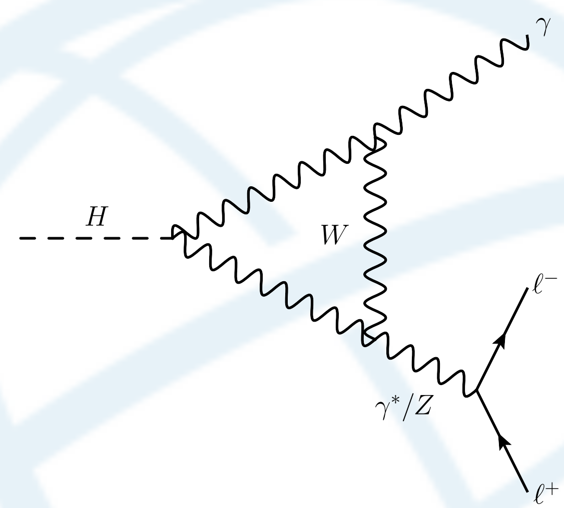
Category	μ	Significance
VBF-enriched	$0.5^{+1.9}_{-1.7}$ $(1.0^{+2.0}_{-1.6})$	0.3 (0.6)
High relative p_T	$1.6^{+1.7}_{-1.6}$ $(1.0^{+1.7}_{-1.6})$	1.0 (0.6)
High p_{Tt} ee	$4.7^{+3.0}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.7 (0.4)
Low p_{Tt} ee	$3.9^{+2.8}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.5 (0.4)
High p_{Tt} $\mu\mu$	$2.9^{+3.0}_{-2.8}$ $(1.0^{+2.8}_{-2.7})$	1.0 (0.4)
Low p_{Tt} $\mu\mu$	$0.8^{+2.6}_{-2.6}$ $(1.0^{+2.6}_{-2.5})$	0.3 (0.4)
Combined	$2.0^{+1.0}_{-0.9}$ $(1.0^{+0.9}_{-0.9})$	2.2 (1.2)

$H \to \gamma^*\gamma$ — ATLAS

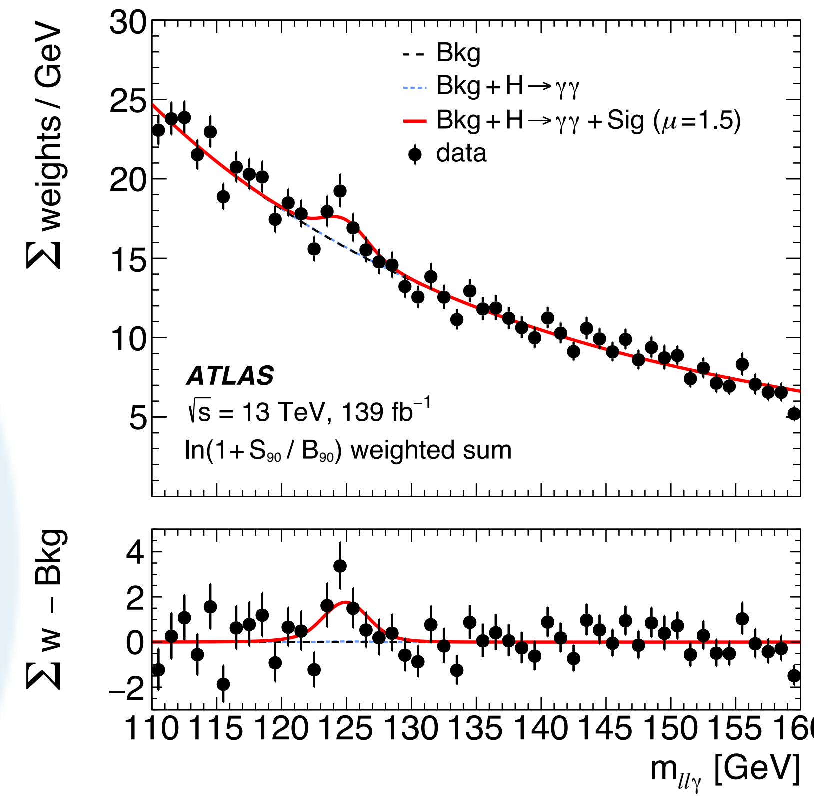
PLB 819 (2021) 136412

- Search for $H \to \gamma^*\gamma \to ee\gamma$ or $H \to \gamma^*\gamma \to \mu\mu\gamma$

SM $\mathcal{B}$($H \to ee\gamma$) = 7.2×10^{-5}
SM $\mathcal{B}$($H \to \mu\mu\gamma$) = 3.4×10^{-5}



- $m_{\ell\ell} < 30$ GeV
  - $p_T^{\mu} > 3$ GeV, $p_T^{e} > 5$ GeV
  - $p_T^{\gamma} > 20$ GeV

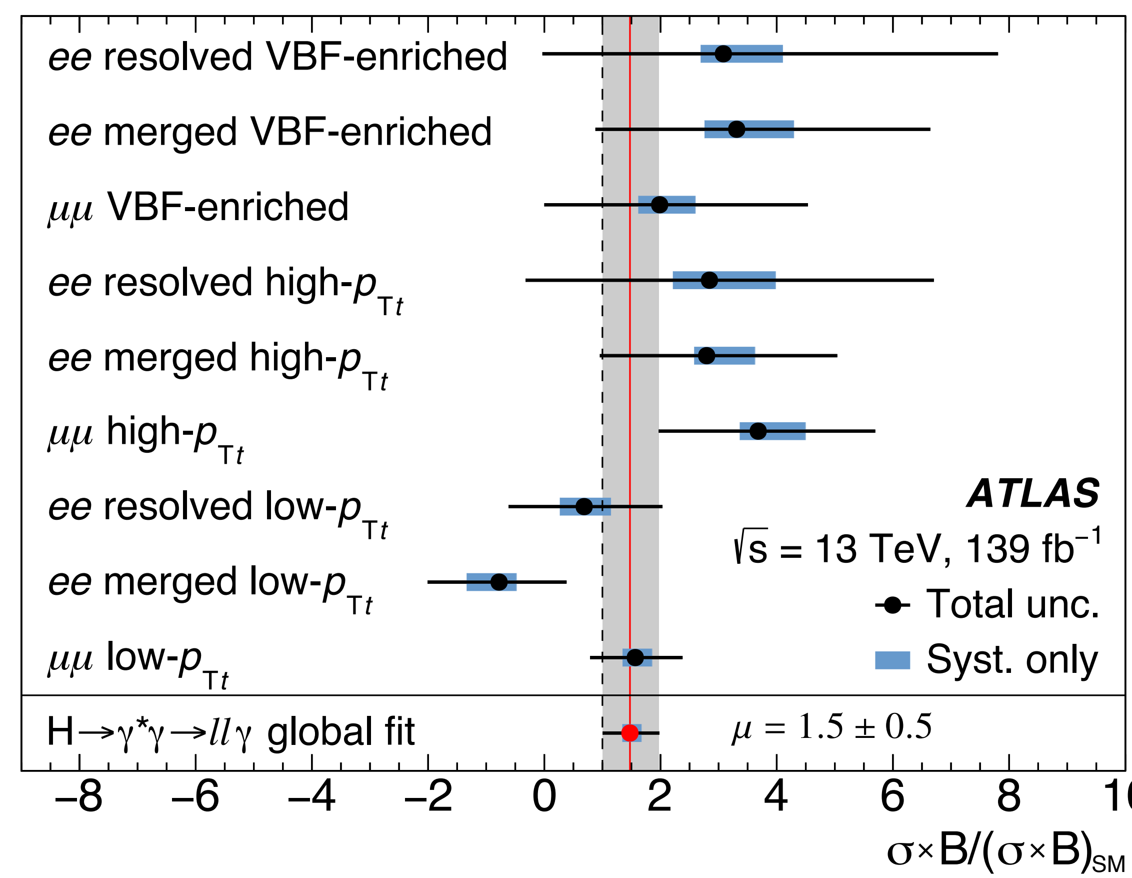


- A collection of triggers to keep high trigger efficiencies (~97%)
- Categories based on event topology and lepton flavor
- Both resolved and merged ee categories
  - Dedicated ID and calibration for the merged ee system

- $\mu = 1.5 \pm 0.5$

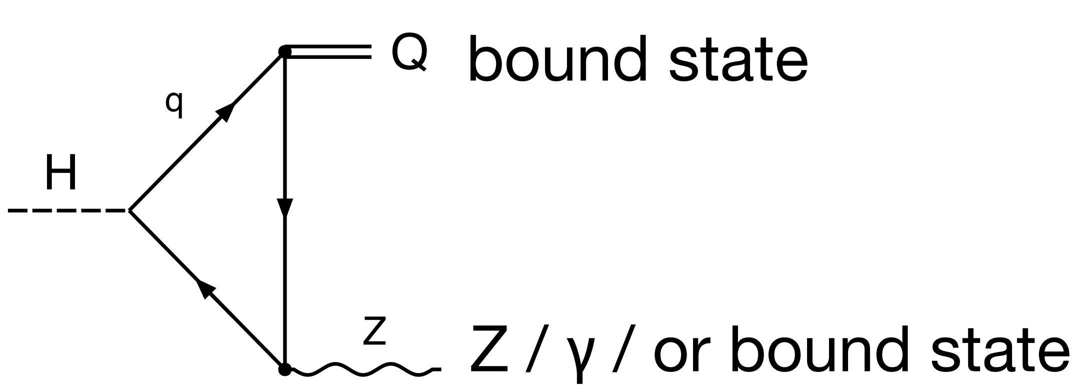
3.2 (2.1)σ obs (exp)

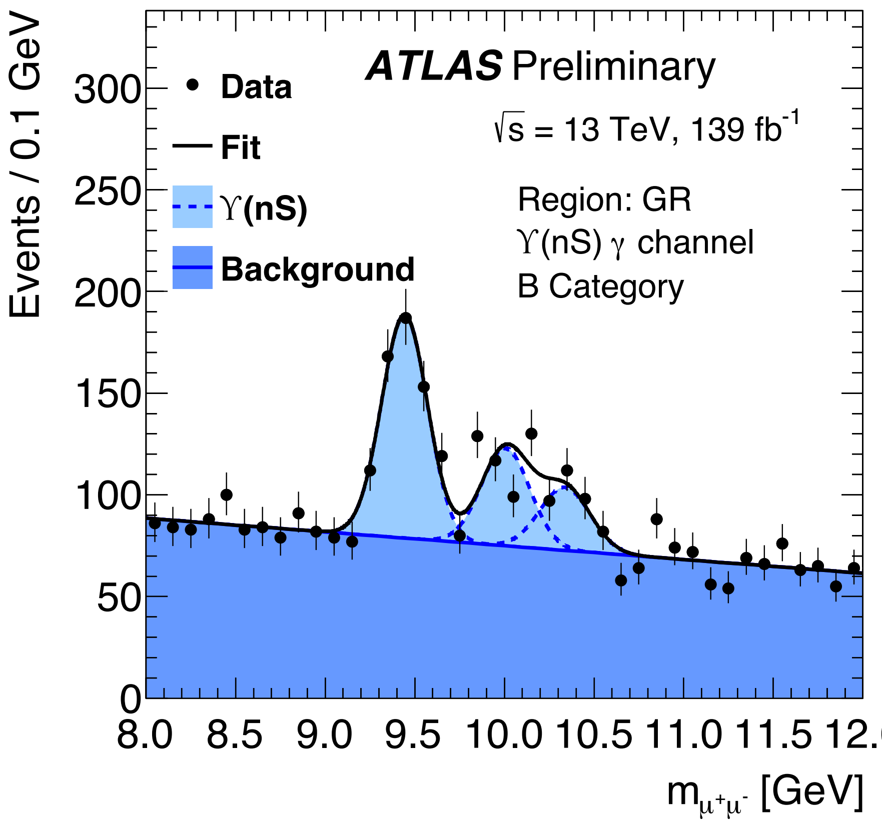
Evidence



Higgs decays to mesons

- Bound states are rare final state but can give insight on couplings to running particles
- Motivate the SM origin of the mass to light, charm, and bottom quarks





- The quarkonium (**J/ψ, ϒ**) decays into two muons leave a clear experimental signature inside the detectors.
- Alternatively, tracks have a good invariant mass resolution at low p_T ($K^{\pm}$, $\pi^{\pm}$). Bound states like (**ρ, ϕ**) in association with a Z boson, to trigger and reduce background.

Higgs decays to quarkonium

- In association with a photon

SM $\mathcal{B}$(H→ J/ψ γ) = 3 × 10^{-6}
SM $\mathcal{B}$(H→ ψ_{2S} γ) = 1 × 10^{-6}
SM $\mathcal{B}$(H→ Υ_{1S} γ) = 5.2 × 10^{-9}
SM $\mathcal{B}$(H→ Υ_{2S} γ) = 1.4 × 10^{-9}
SM $\mathcal{B}$(H→ Υ_{3S} γ) = 10^{-9}

CMS 95%CL Branching fraction limit

EPJ C79 (2019) 94

$H \to J/\psi\gamma$		
	Longitudinal	$1.2\ (1.4^{+0.6}_{-0.4}) \times 10^{-6}$
	Transverse	$7.6\ (5.2^{+2.4}_{-1.6}) \times 10^{-4}$

- In association with a Z boson

SM $\mathcal{B}$(H→ Z J/ψ) = 2.3 × 10^{-6}
SM $\mathcal{B}$(H→ Z ψ_{2S}) = 1.7 × 10^{-6}

ATLAS HDBS-2018-53

NEW

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

- Two quarkonium decays

SM $\mathcal{B}$(H→ J/ψ J/ψ) = 1.5 × 10^{-10}
SM $\mathcal{B}$(H→ ΥΥ) = 2 × 10^{-9}

CMS

arXiv:2206.03525

Process	Observed	Expected	Observed	
Higgs boson channel	Longitudinal	Longitudinal	Unpolarized	Transverse
$\mathcal{B}(H \to ZJ/\psi)$	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}

Higgs decays to vector mesons

SM $\mathcal{B}$(H→ ργ) = 1.7 × 10^{-5}
SM $\mathcal{B}$(H→ ϕγ) = 2.3 × 10^{-6}

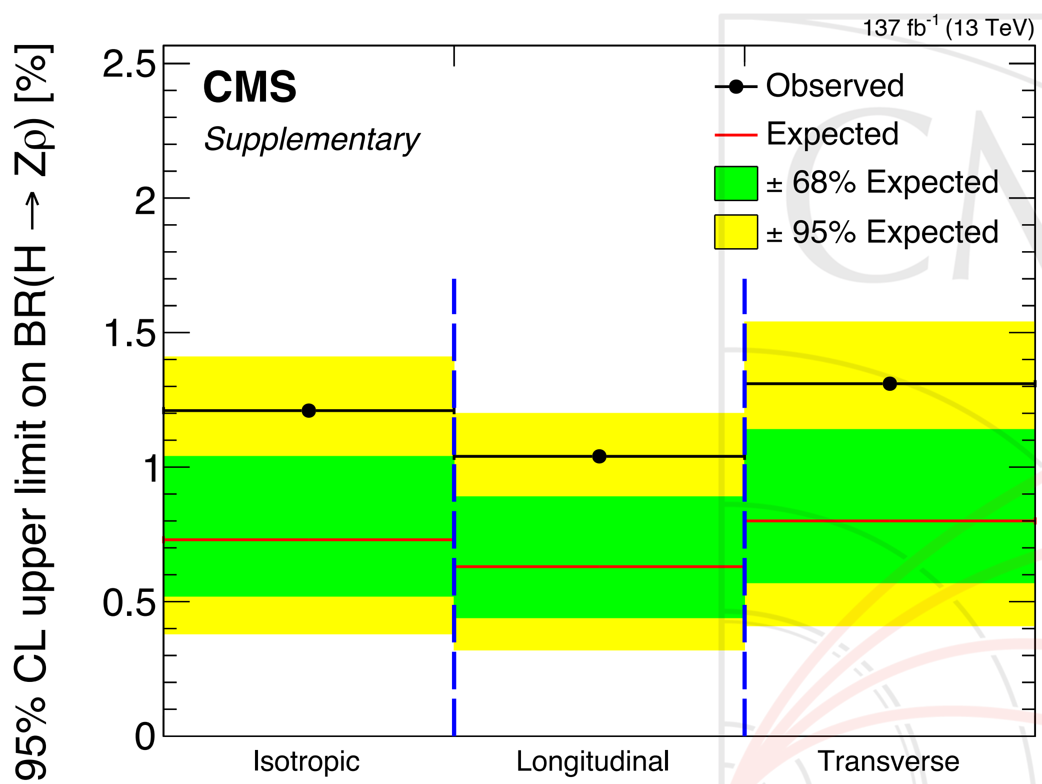
SM $\mathcal{B}$(H→ Zρ) = 1.4 × 10^{-5}
SM $\mathcal{B}$(H→ Zϕ) = 4.2 × 10^{-6}

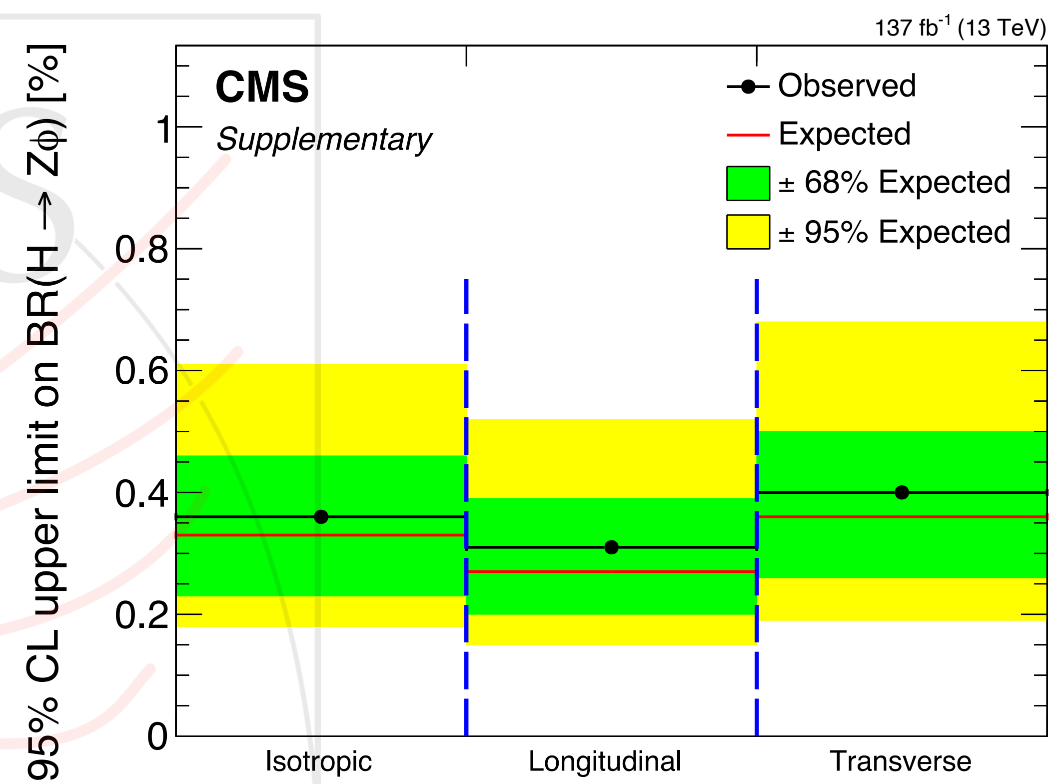
ATLAS JHEP 07 (2018) 127

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

- ϕ → $K^{\pm}K^{\pm}$, ρ → $\pi^{\pm}\pi^{\pm}$

CMS JHEP 11 (2020) 039





Summary

CMS and ATLAS have a large program to assess the rare decays of the Higgs boson

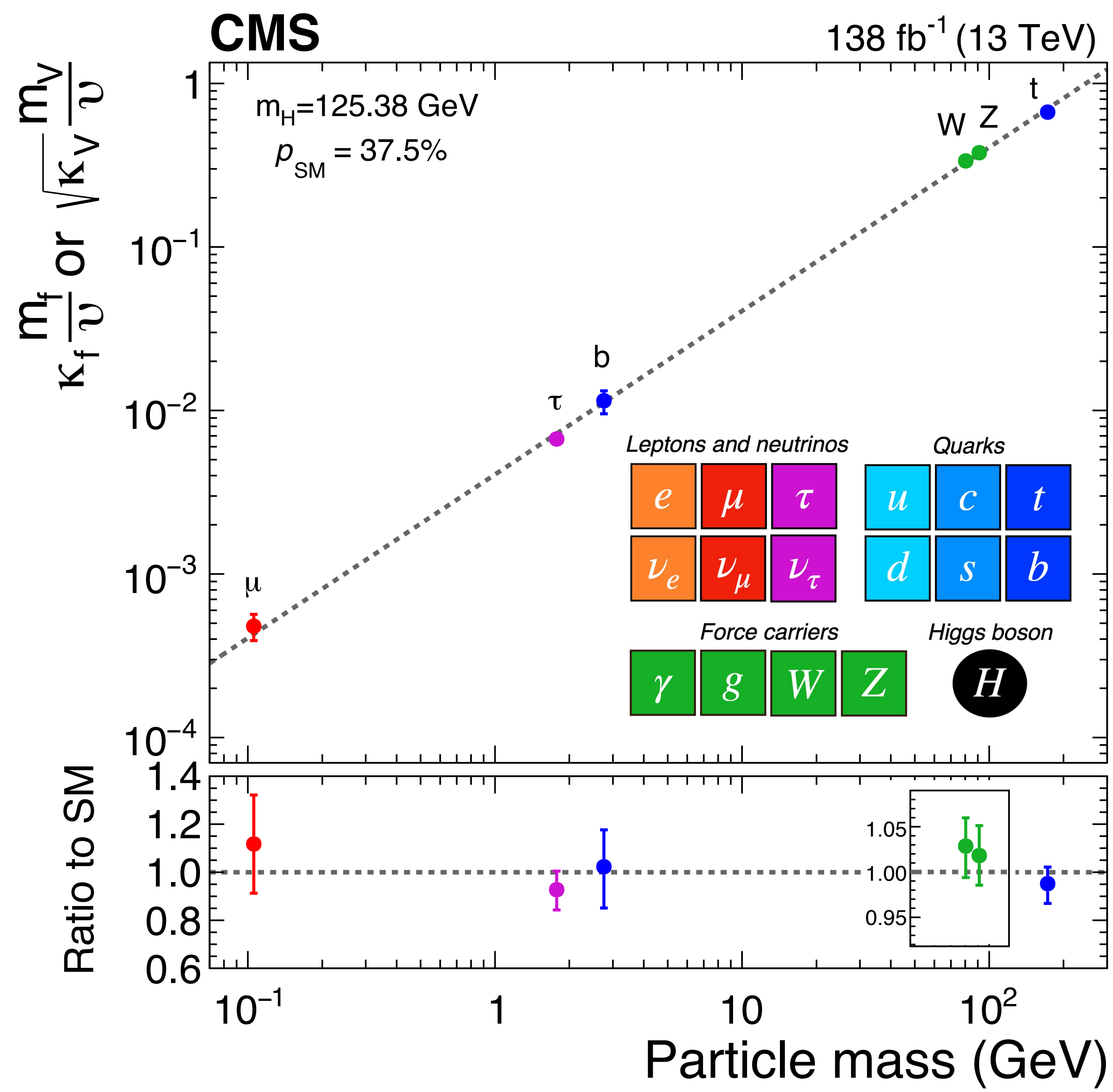
Direct Yukawa couplings:
Second generation sensitivity close to the SM:

Hμμ: CMS 3.0σ (2.5σ), ATLAS 2.0σ (1.7σ)

Hcc:

- $\sigma\mathcal{B} < 14.4$ (7.6) × SM **CMS**
- $\sigma\mathcal{B} < 31$ (26) × SM **ATLAS**

First fermion generation is out reach; looking for large deviations.



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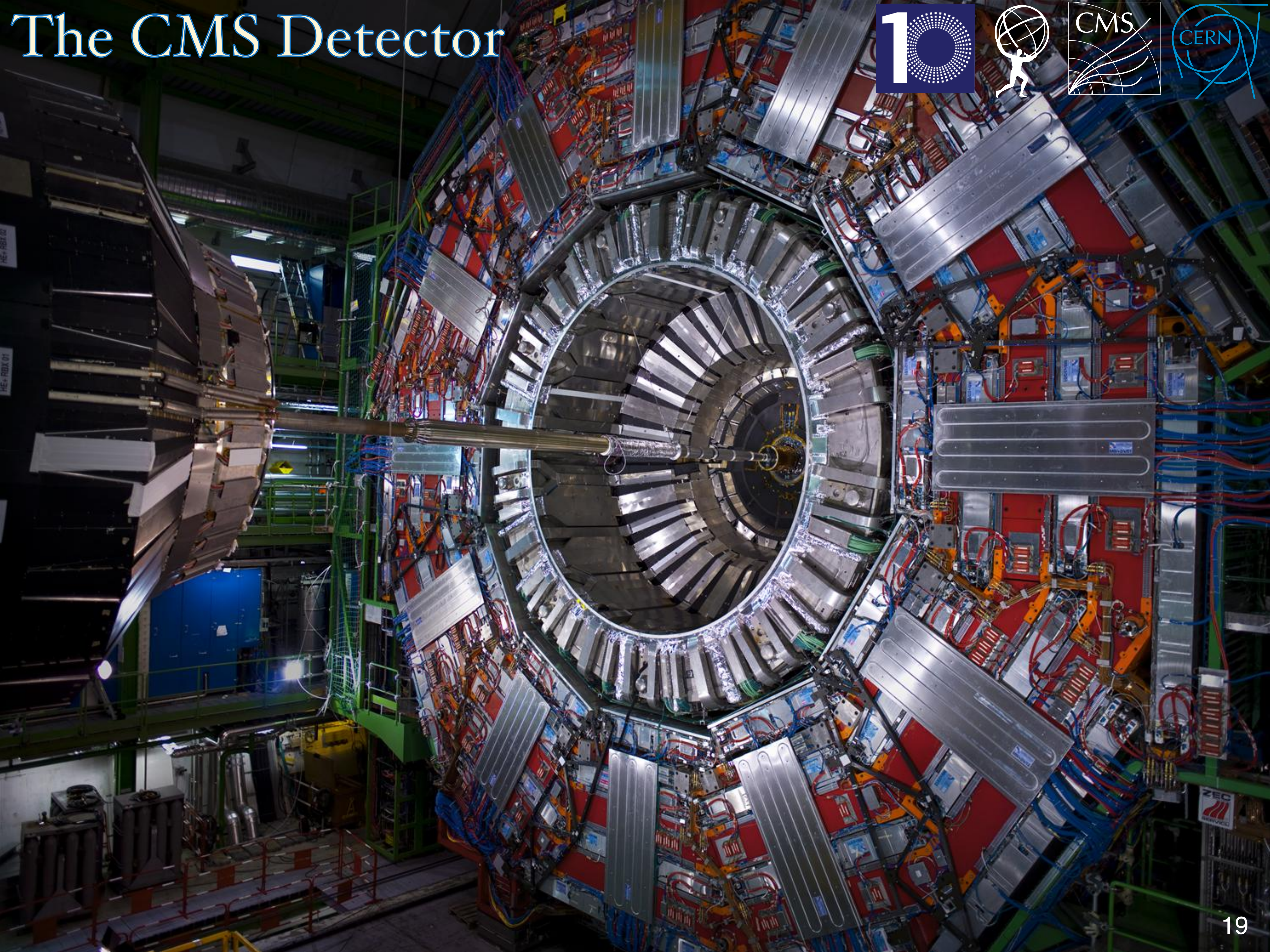
HZγ: Both experiments: a small excess in the Run2. CMS 2.7σ (1.2σ), ATLAS 2.2σ (1.2σ)

Searches for Higgs boson decays to **bound states** also probe unexplored couplings, having sensitivity to strange, charm, bottom couplings, but also to new physics in the loop

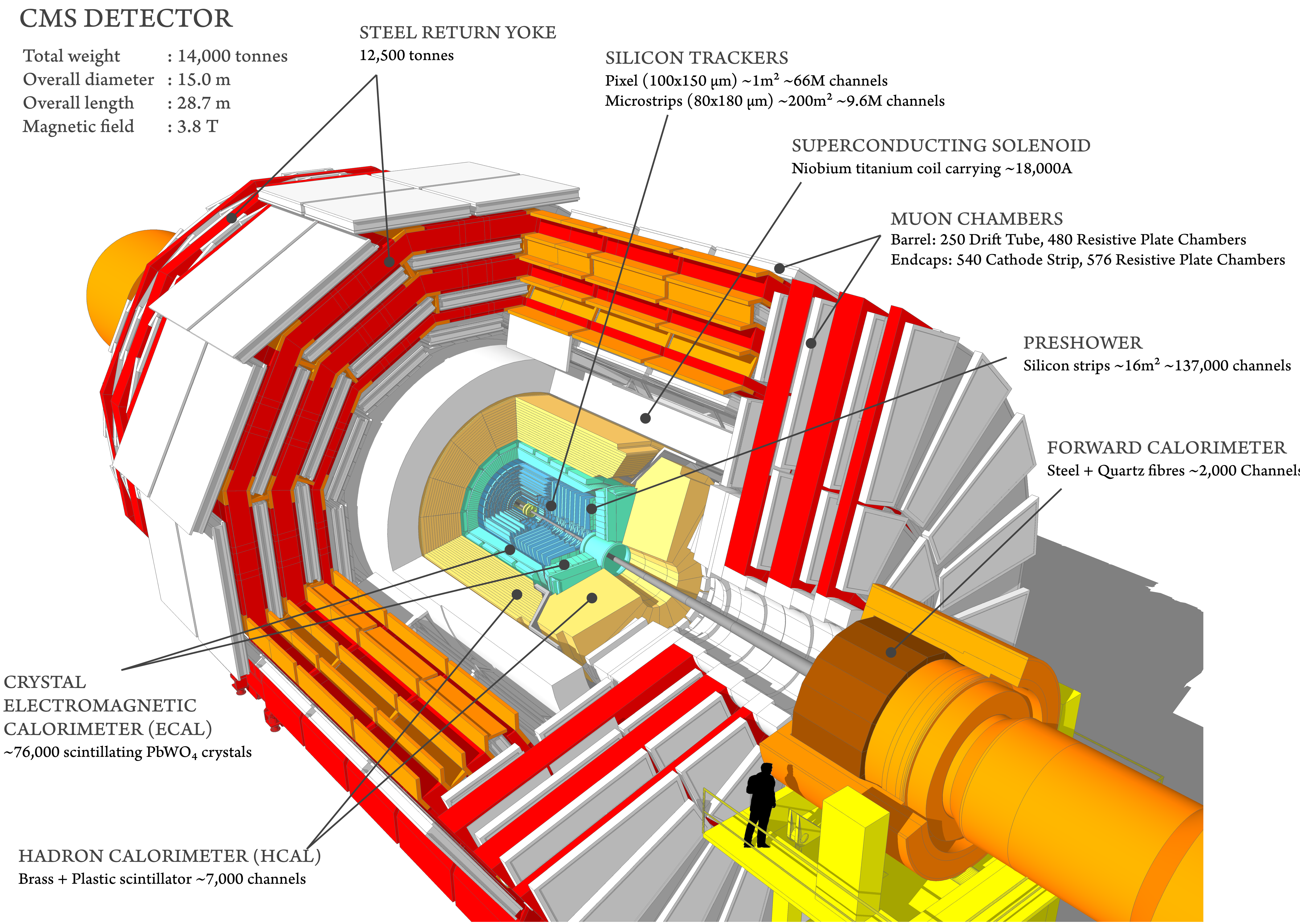
years
HIGGS boson
discovery

Thank you

The CMS Detector

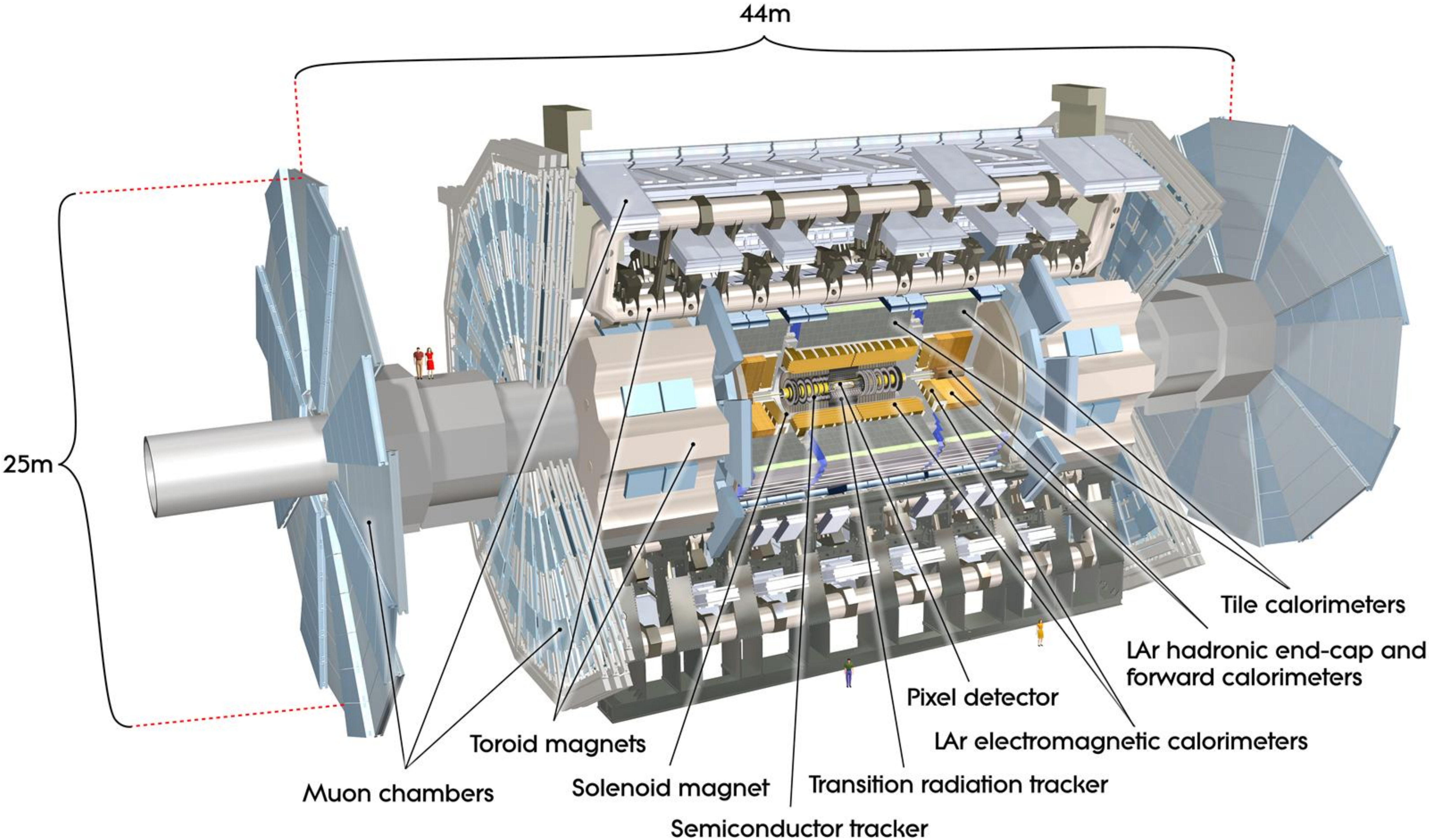


The CMS Detector

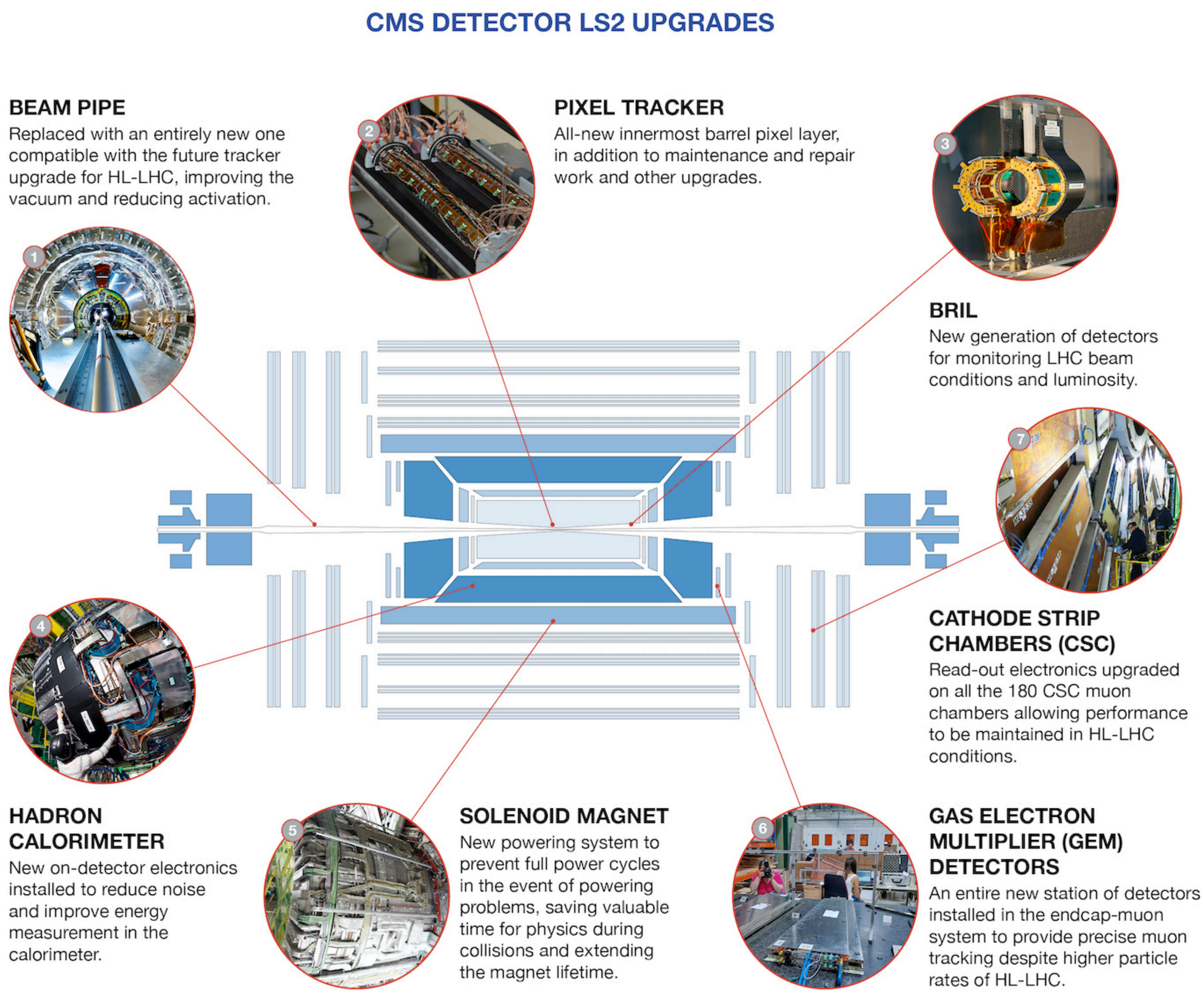


The ATLAS detector

The ATLAS detector



CMS Phase II upgrades



ATLAS Phase II Upgrades

ATLAS DETECTOR LS2 UPGRADES

MUON NEW SMALL WHEELS (NSW)

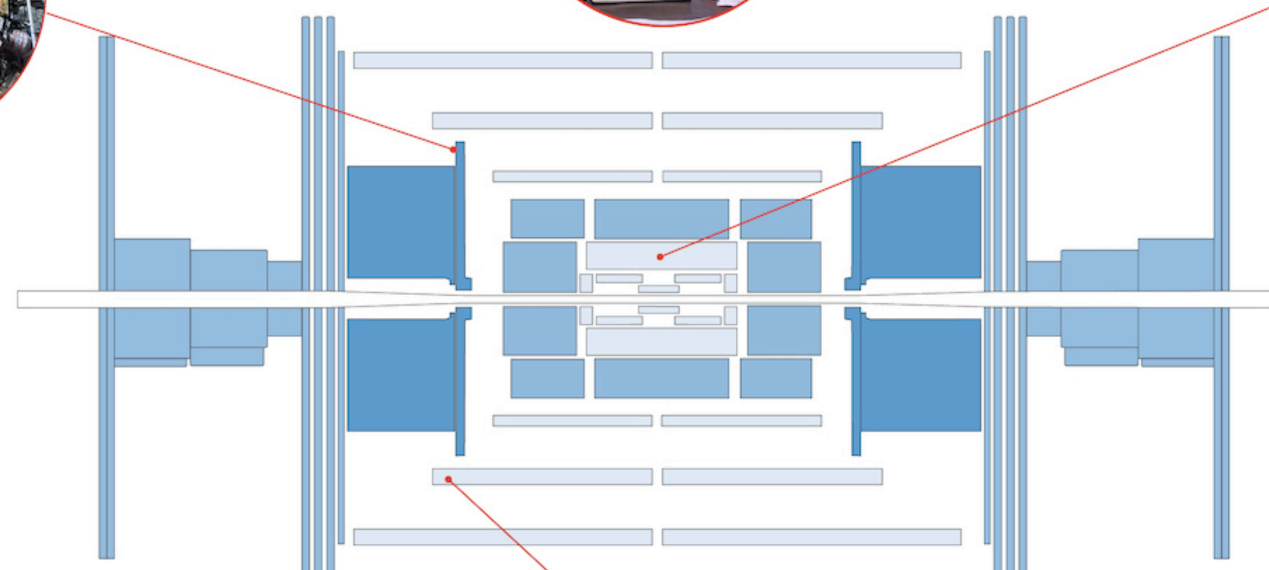
Installed new muon detectors with precision tracking and muon selection capabilities. Key preparation for the HL-LHC.

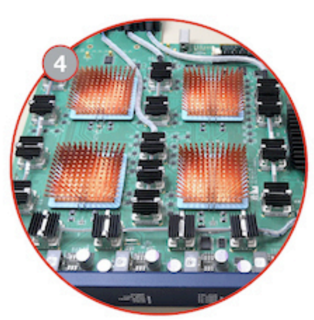
NEW READOUT SYSTEM FOR THE NSWs

The NSW system includes two million micromega readout channels and 350 000 small strip thin-gap chambers (sTGC) electronic readout channels.

LIQUID ARGON CALORIMETER

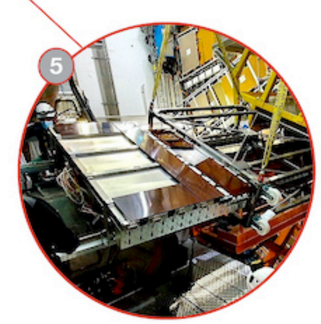
New electronics boards installed, increasing the granularity of signals used in event selection and improving trigger performance at higher luminosity.





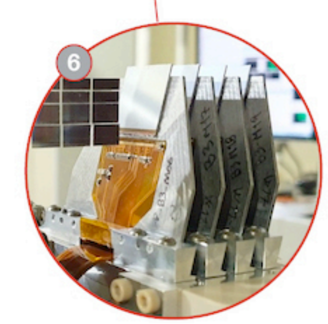
TRIGGER AND DATA ACQUISITION SYSTEM (TDAQ)

Upgraded hardware and software allowing the trigger to spot a wider range of collision events while maintaining the same acceptance rate.



NEW MUON CHAMBERS IN THE CENTRE OF ATLAS

Installed small monitored drift tube (sMDT) detectors alongside a new generation of resistive plate chamber (RPC) detectors, extending the trigger coverage in preparation for the HL-LHC.



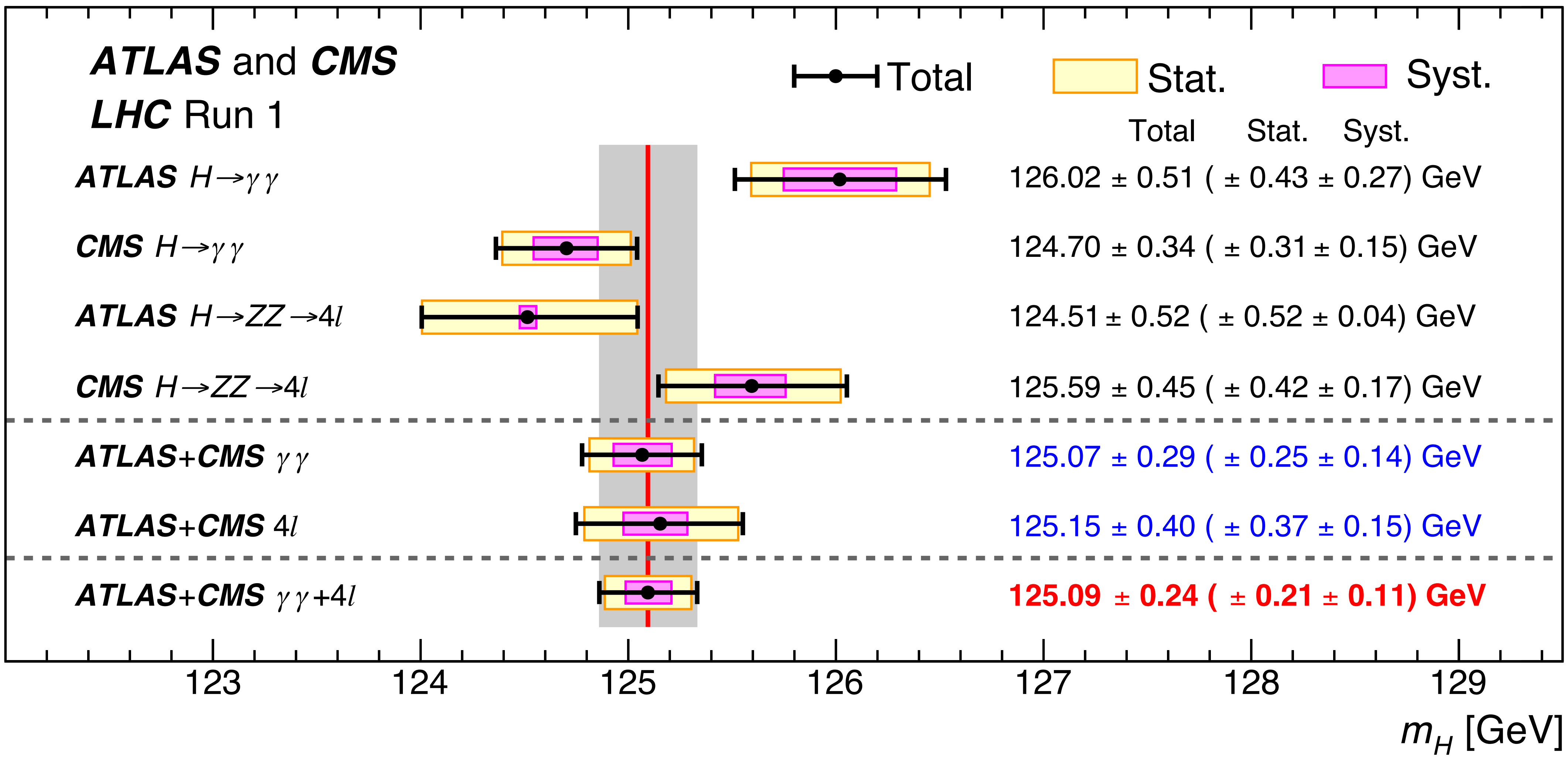
ATLAS FORWARD PROTON (AFP)

Re-designed AFP time-of-flight detector, allowing insertion into the LHC beamline with a new “out-of-vacuum” solution.

The Higgs boson mass

- Run I legacy measurement
  - CMS and ATLAS combination of the 7 and 8 TeV data

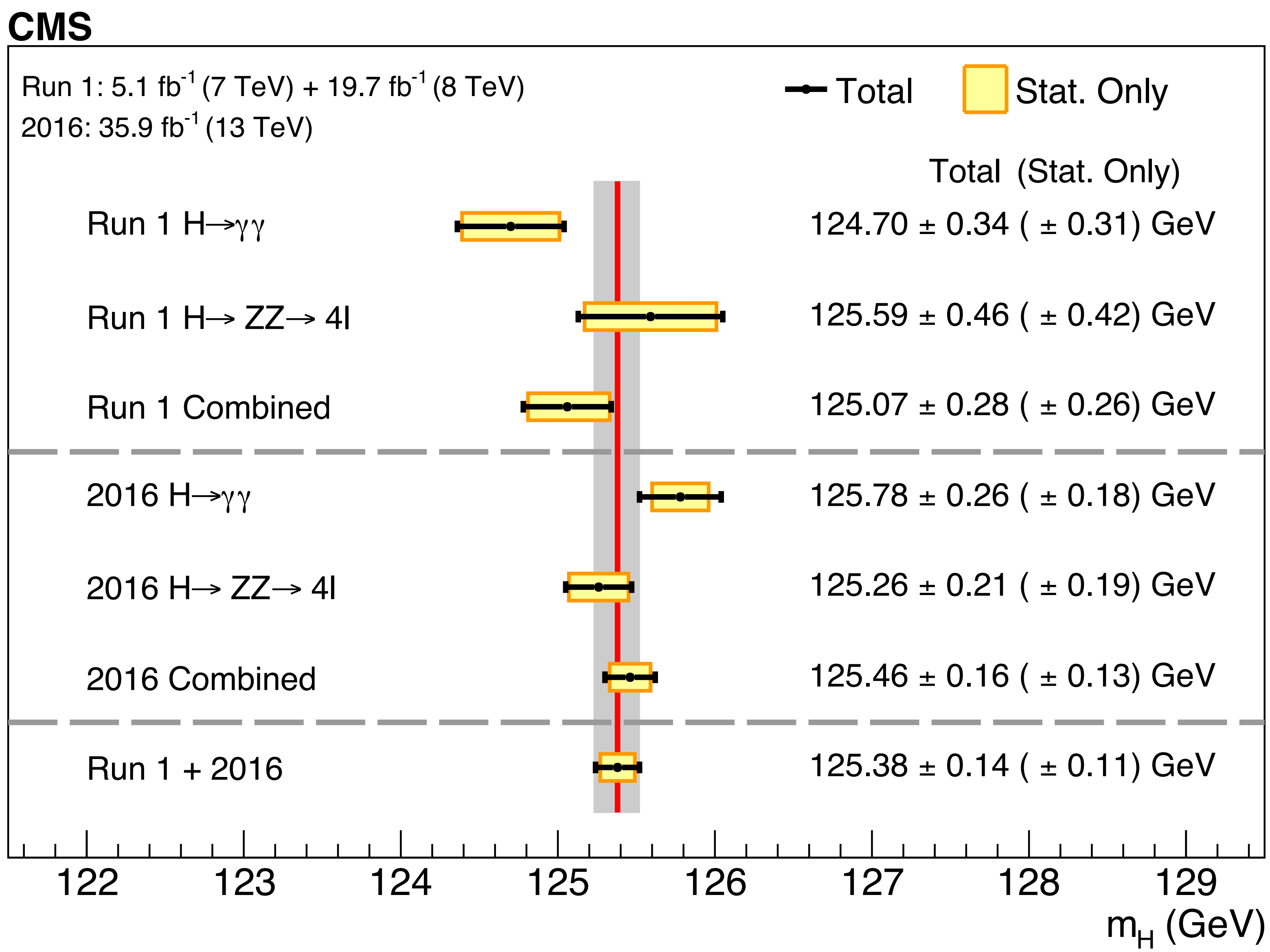
PRL 114 (2015) 191803



The Higgs boson mass

Precise measurement of the Higgs boson mass using the diphoton and ZZ (4-leptons) decay channels using 2016 data from CMS

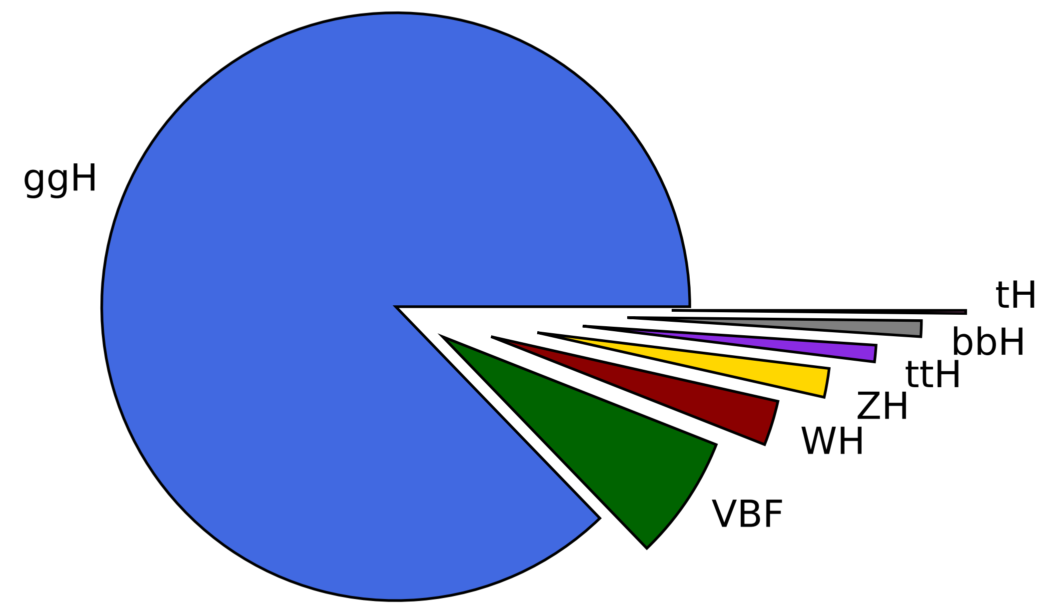
$m_H = 125.38 \pm 0.14$ GeV



PLB **802** (2020) 135425

Higgs production

- Different production mode of the Higgs boson

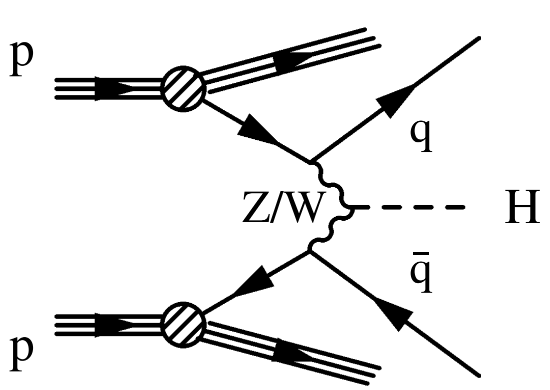


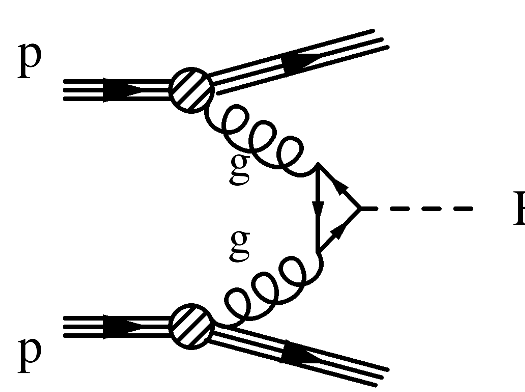
Vector-boson fusion
VBF

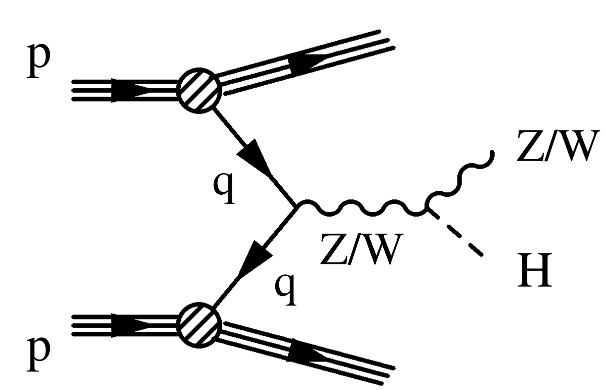
Gluon-gluon fusion
ggH

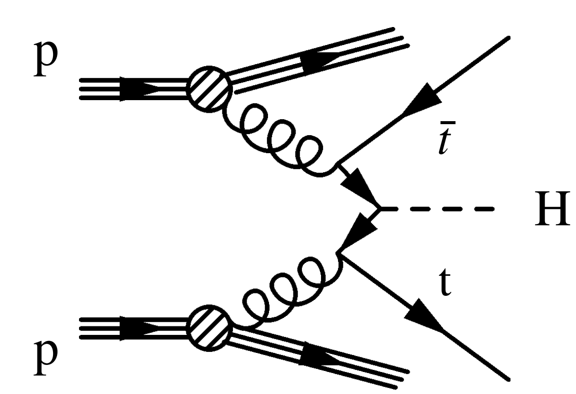
VH associate production
VH

Top quark pair associate production
ttH



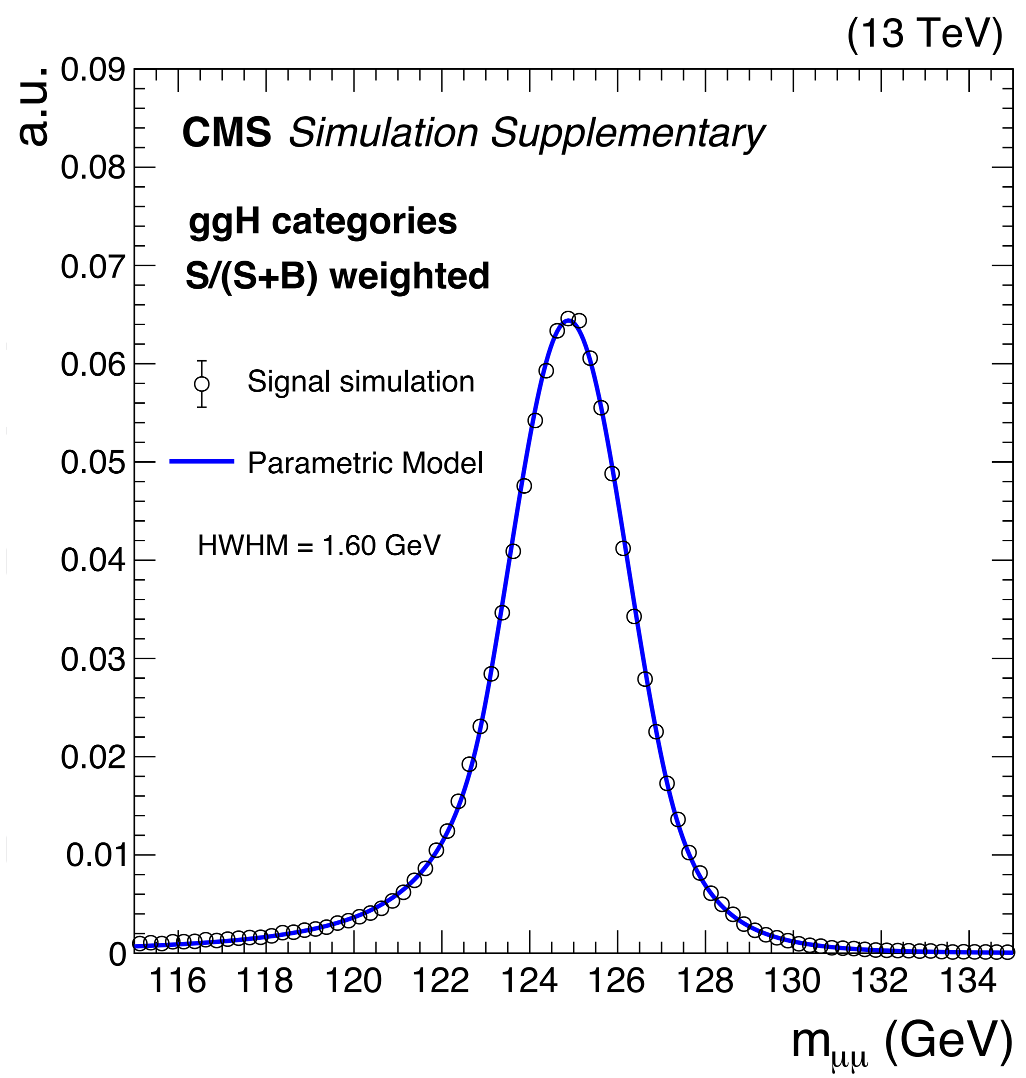


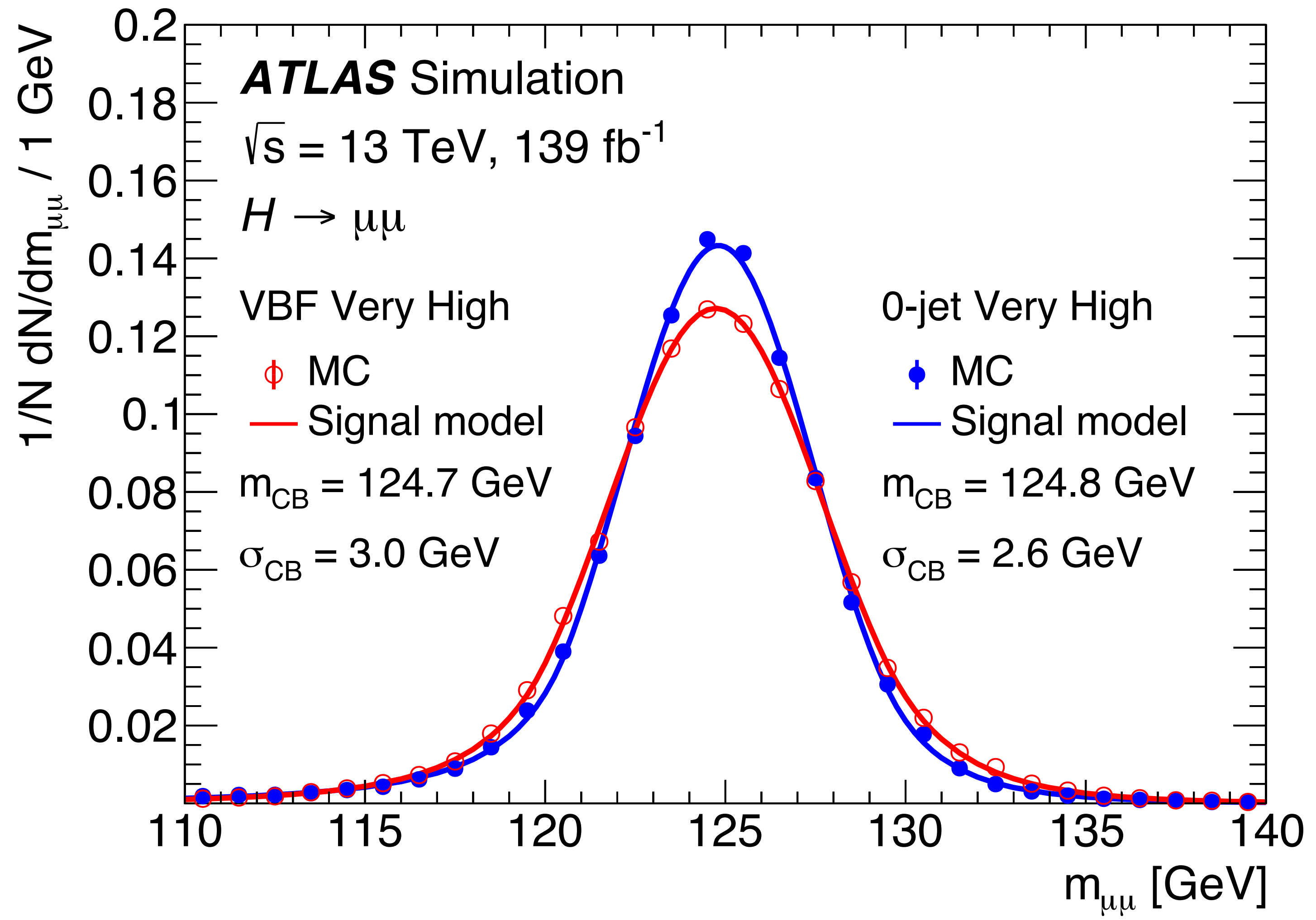




Hμμ invariant mass

- Invariant mass of the Hμμ peak in MC simulation





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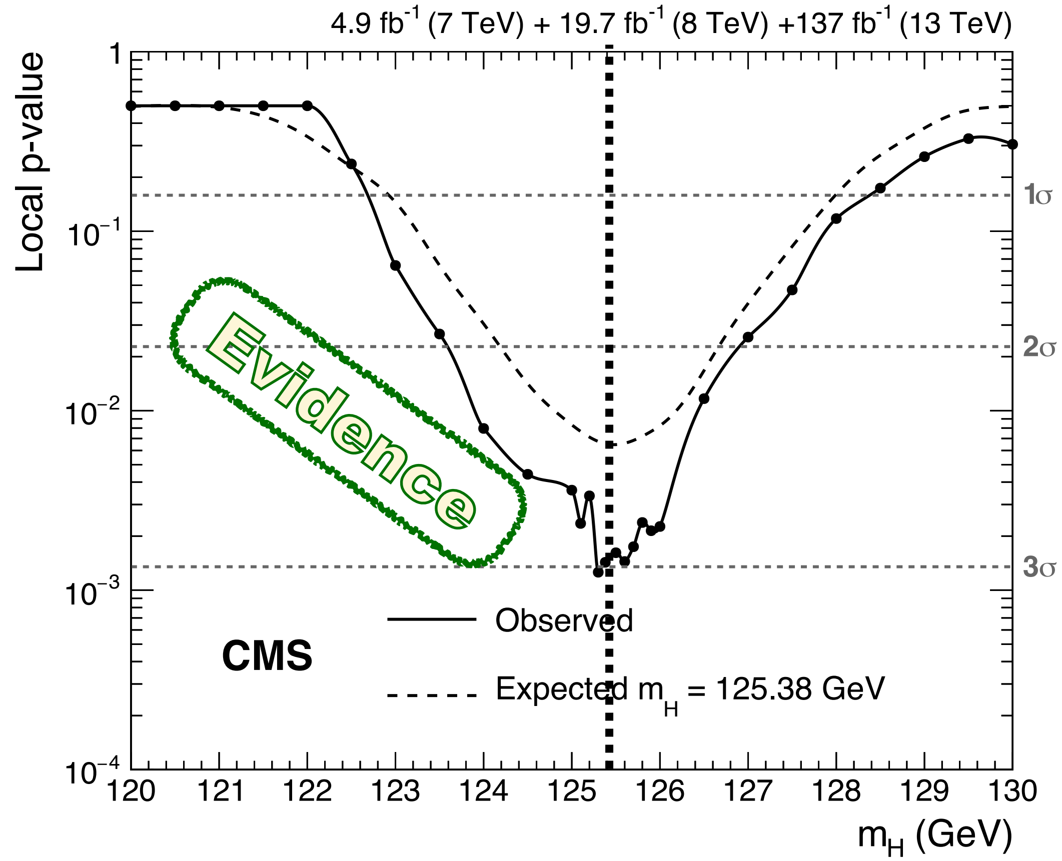
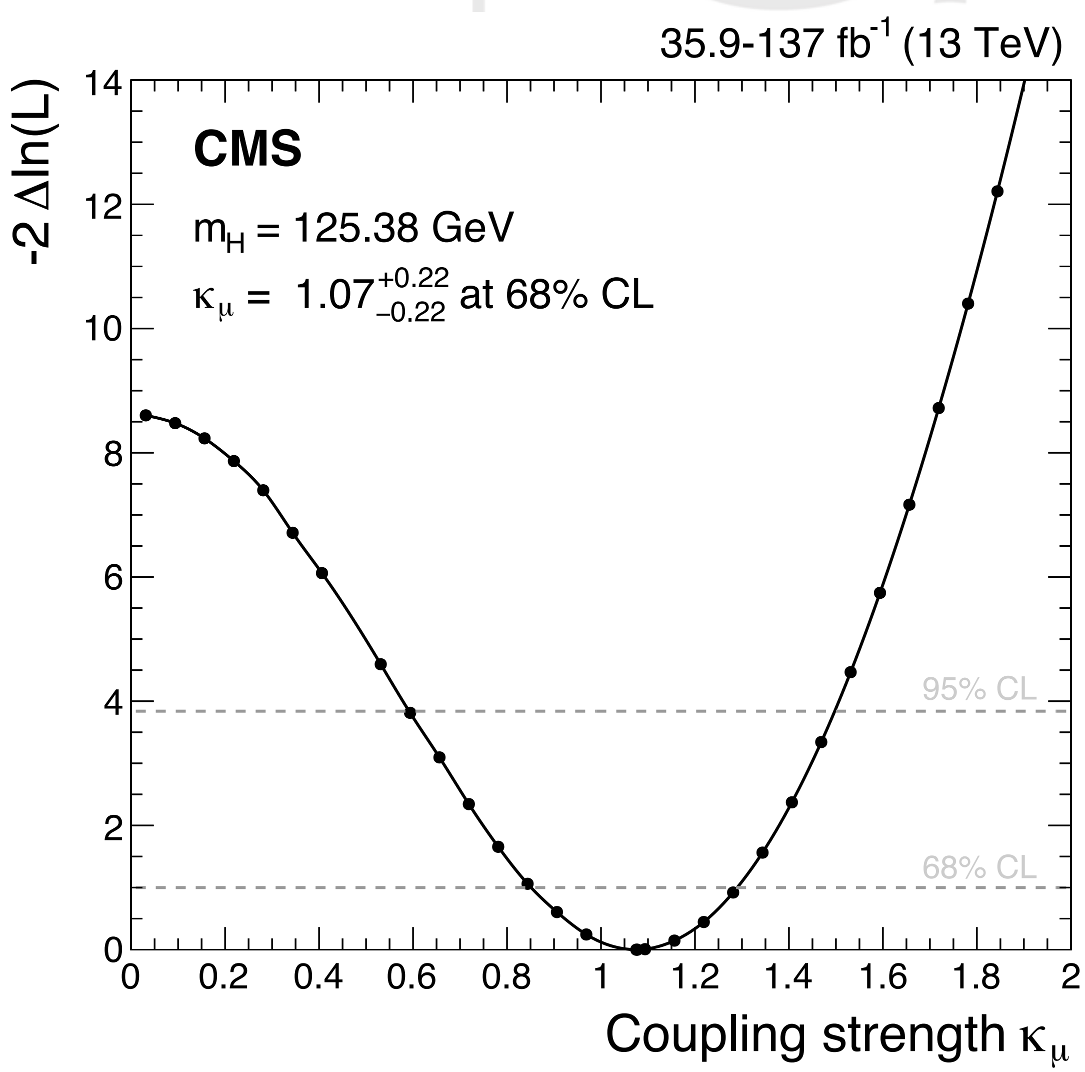
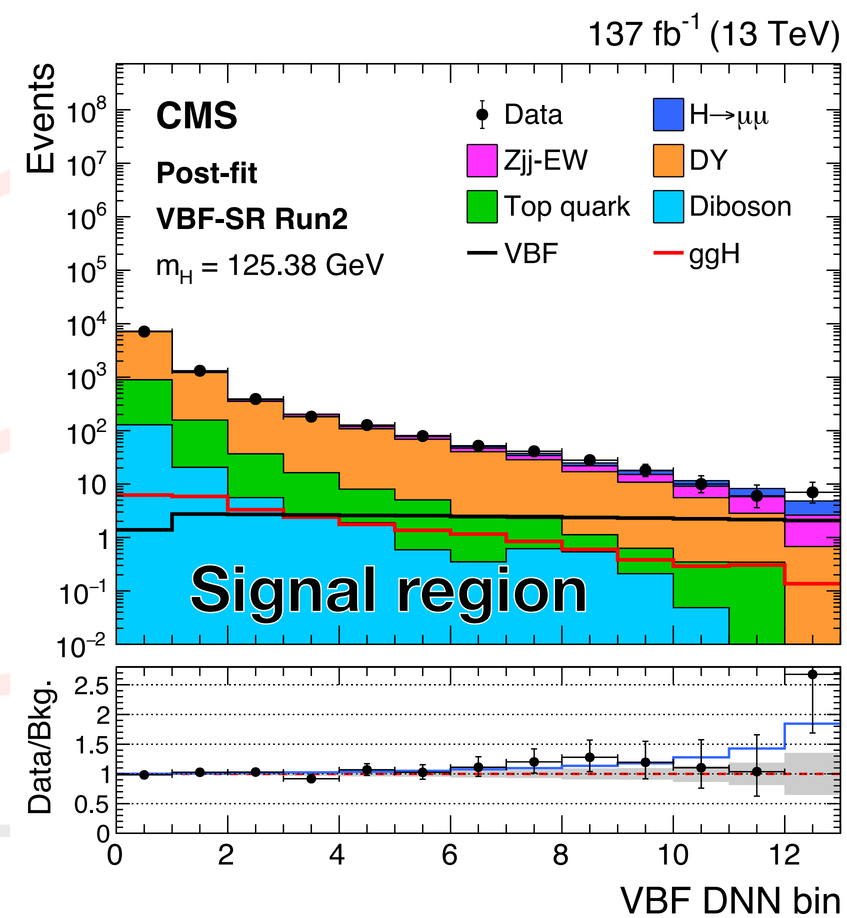
- Resulted reported at the best mass measurement m_H=125.38 GeV
- Strength 1.19 $^{+0.44}_{-0.42}$
- **Evidence for H→μμ 3.0σ (2.5σ)**
- Coupling measurement of κ_μ
  - With the inputs from EPJ **C79** (2019) 412

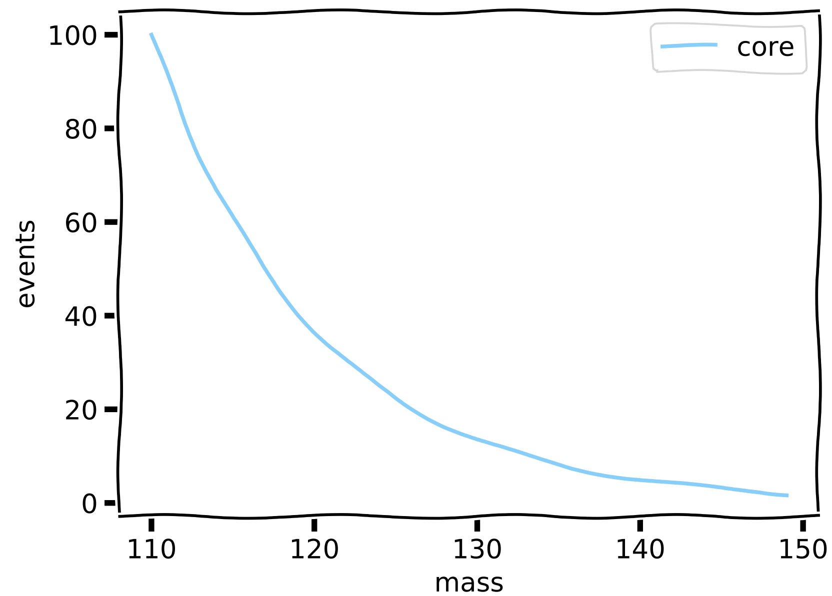






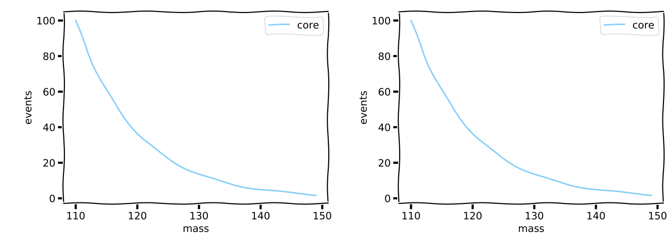
Core PDF — Hμμ CMS

- The background function is designed to minimise possible mismodels due to the choice of the analytical form



Discrete profile

Core: several functional forms used simultaneously on data



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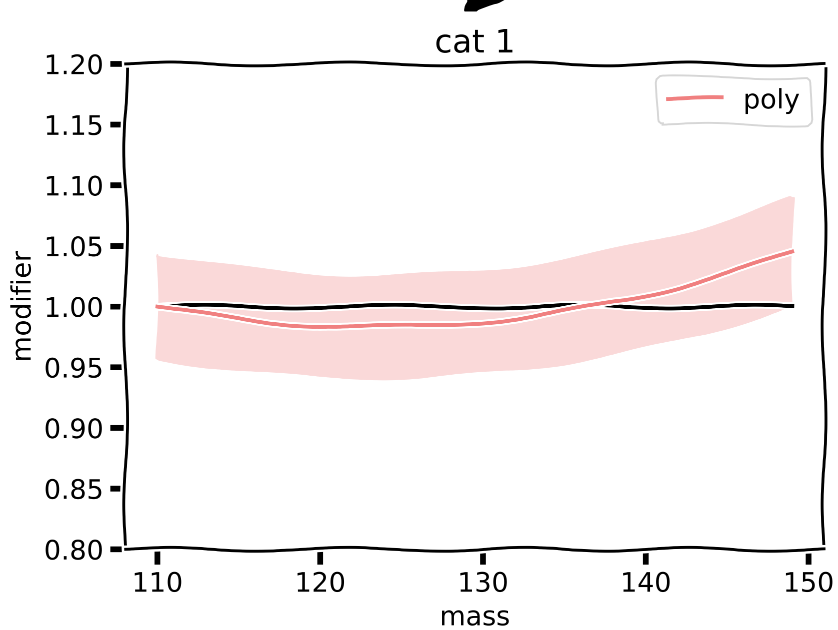
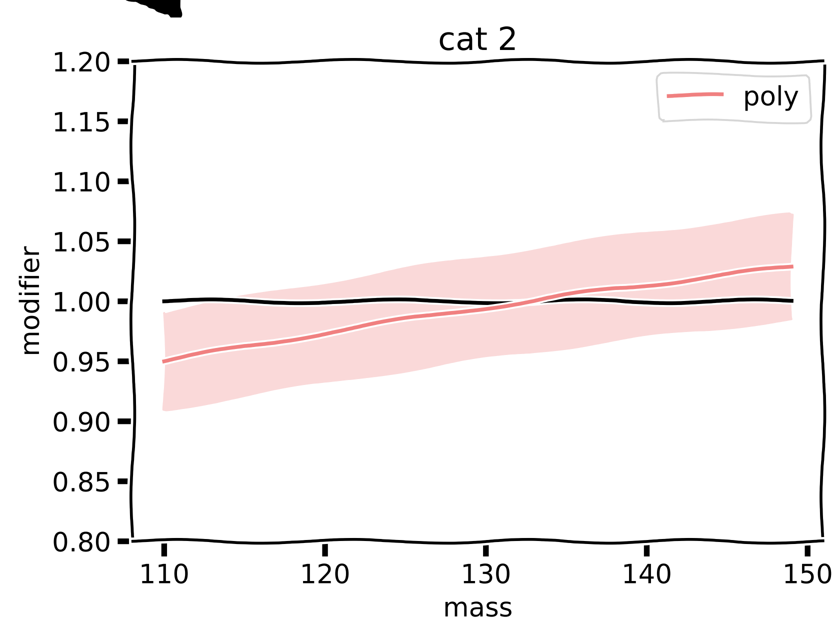
JINST **10** (2015) 04





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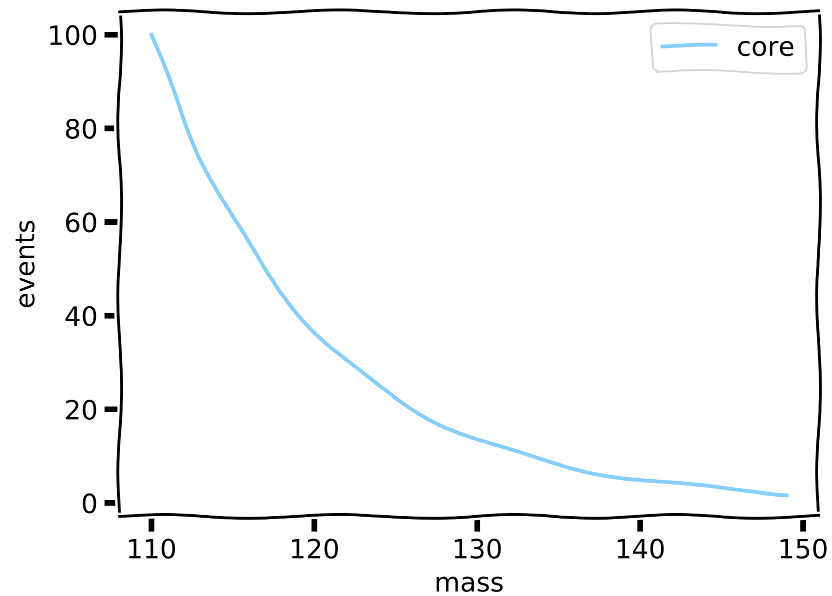
Core PDF — Hμμ CMS

- The background function is designed to minimise possible mismodels due to the choice of the analytical form



Discrete profile

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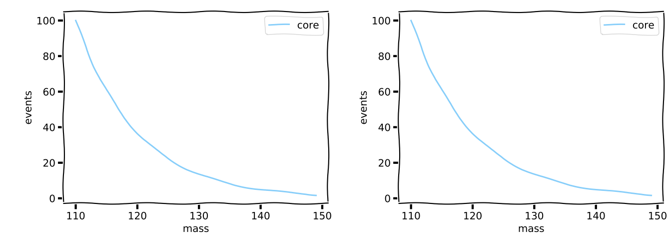
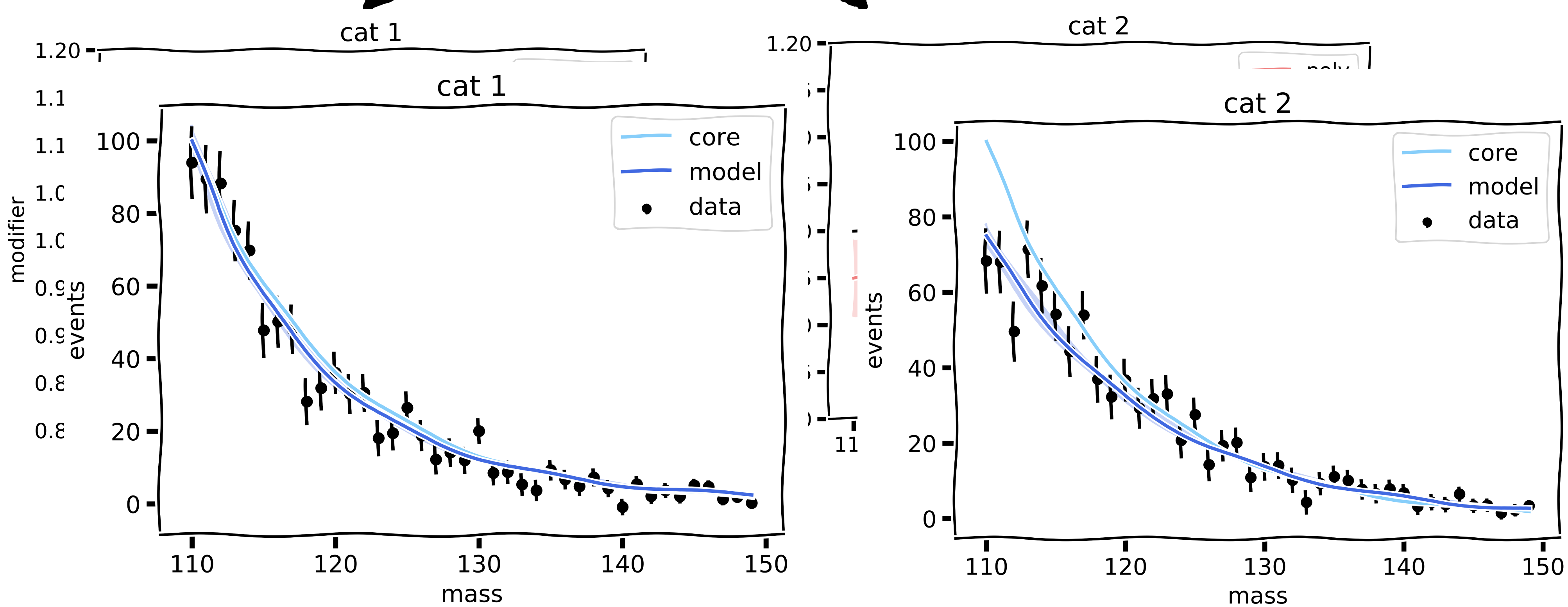
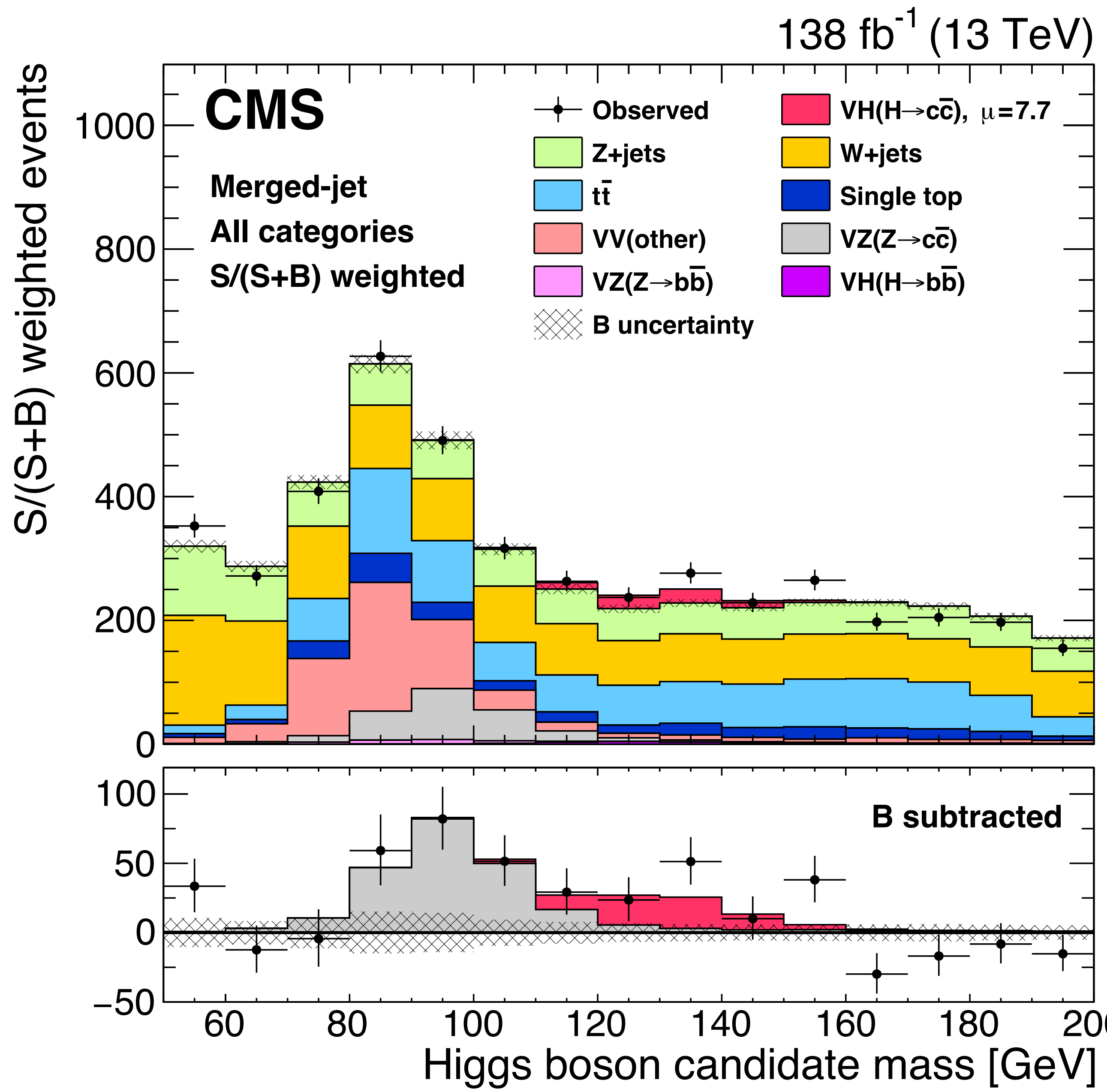


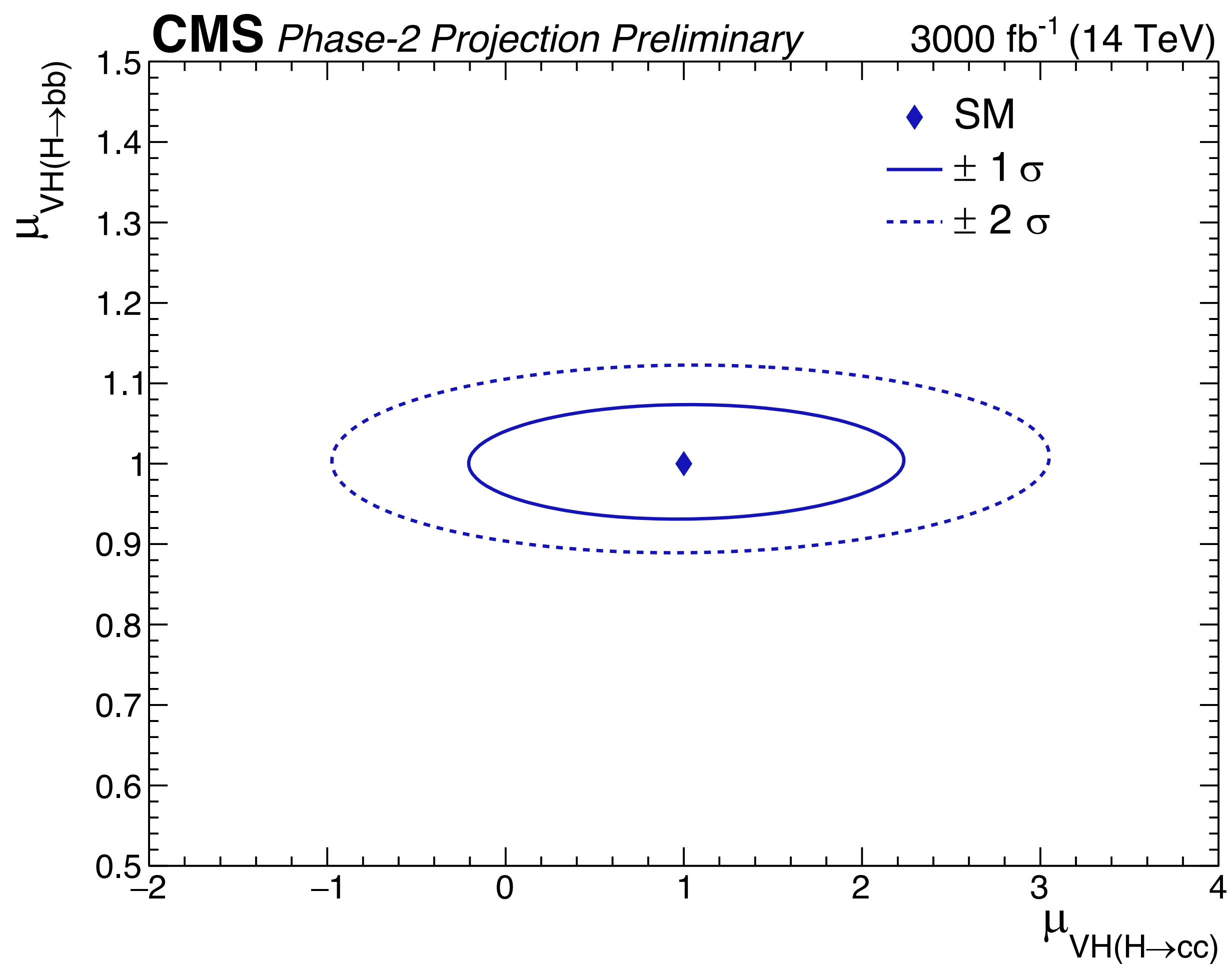
JINST **10** (2015) 04



VHcc mass — CMS

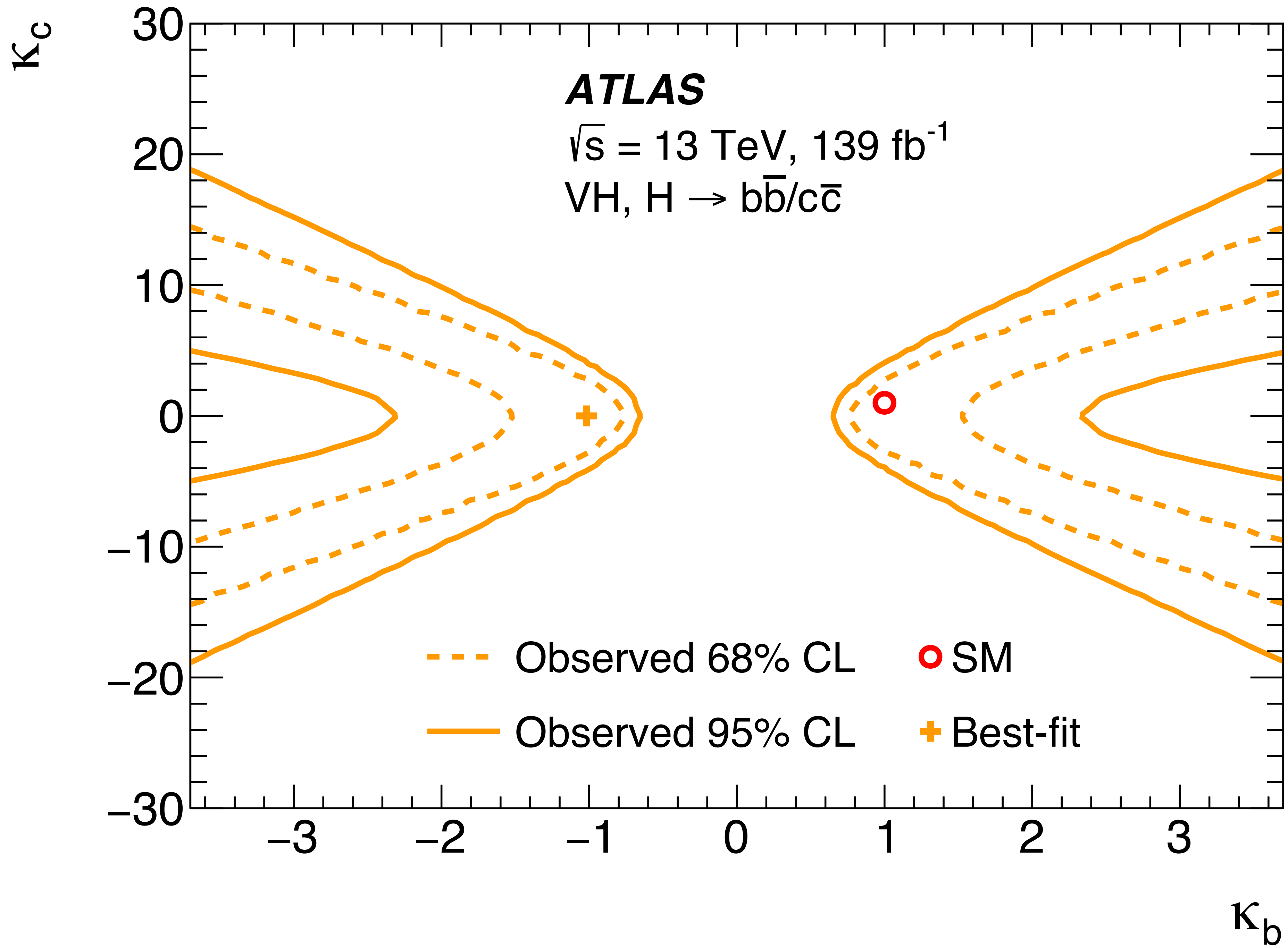


Prospects of VHcc at HL-LHC

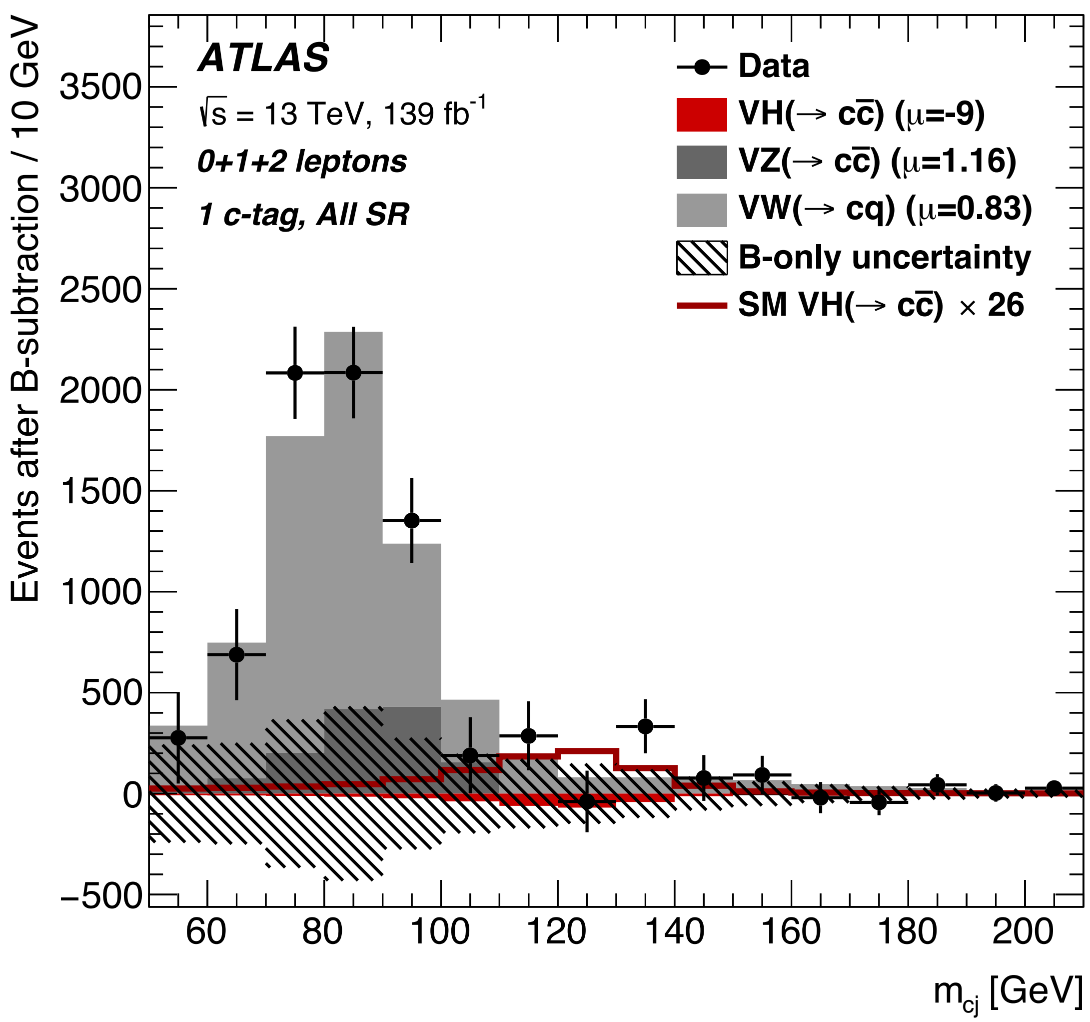


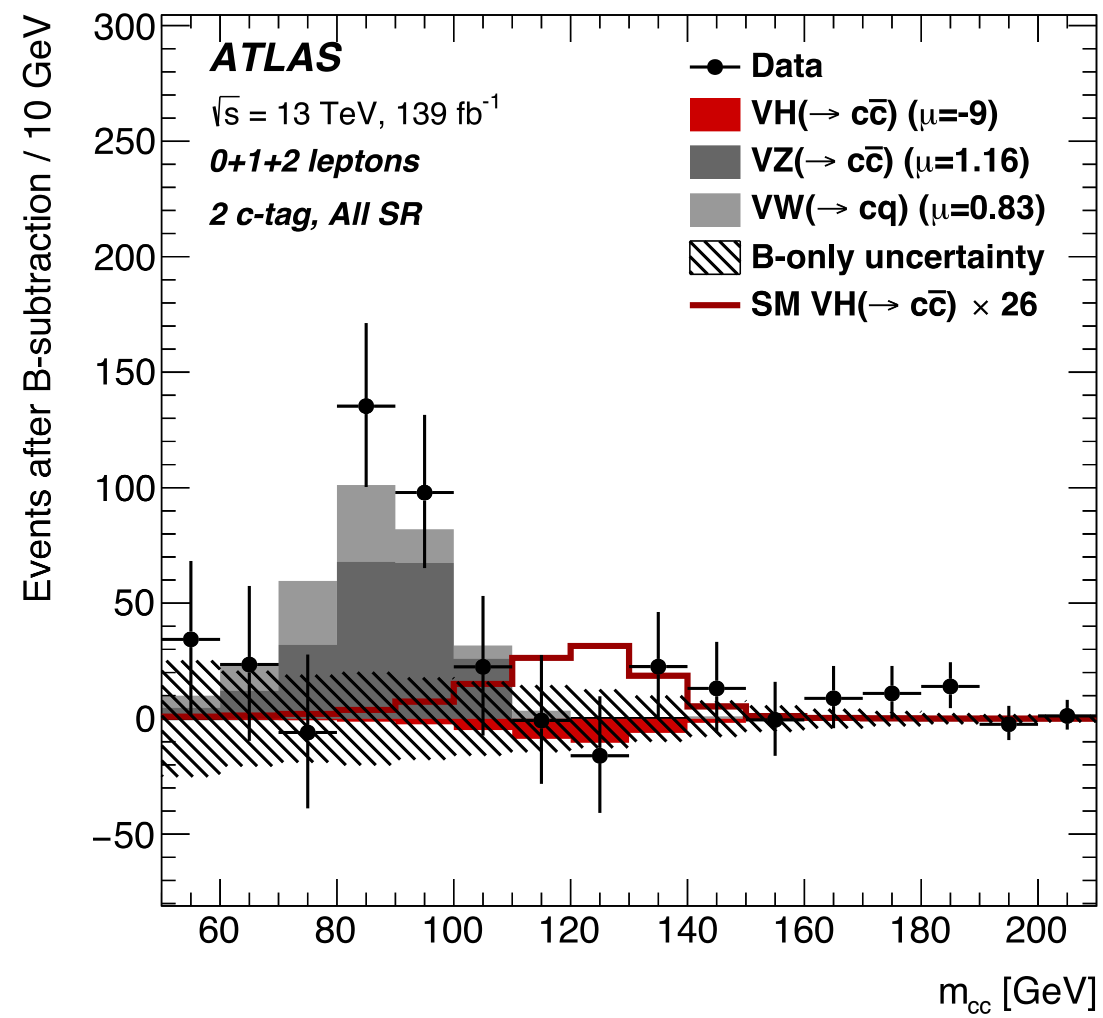
VHcc ATLAS

- Kappa b vs kappa c



VHcc mass — ATLAS Post-fit

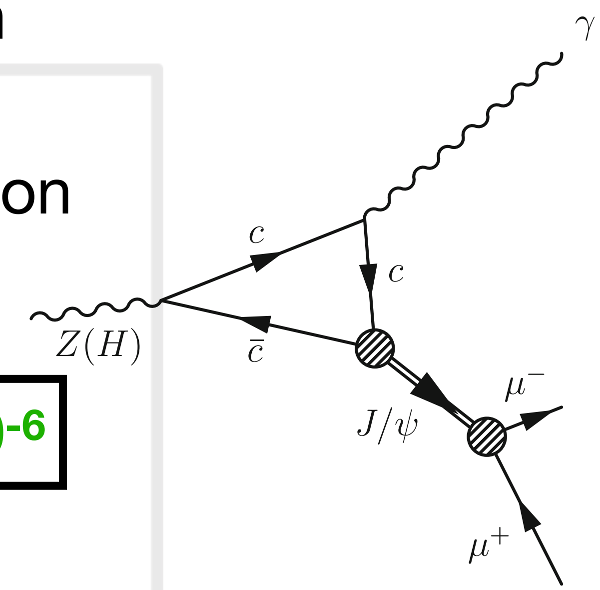




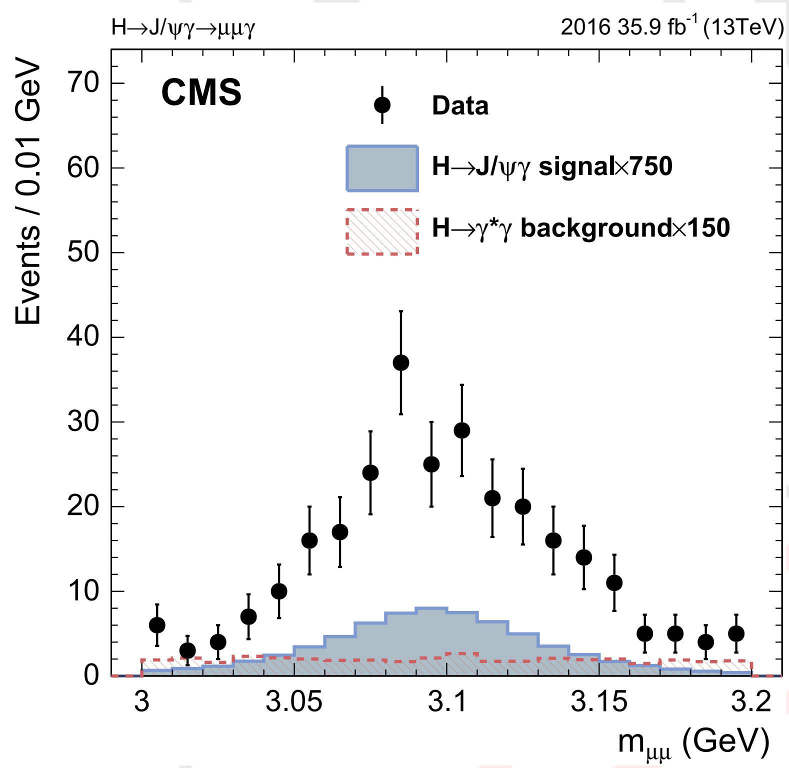
$H \rightarrow J/\psi\ \gamma$ — CMS

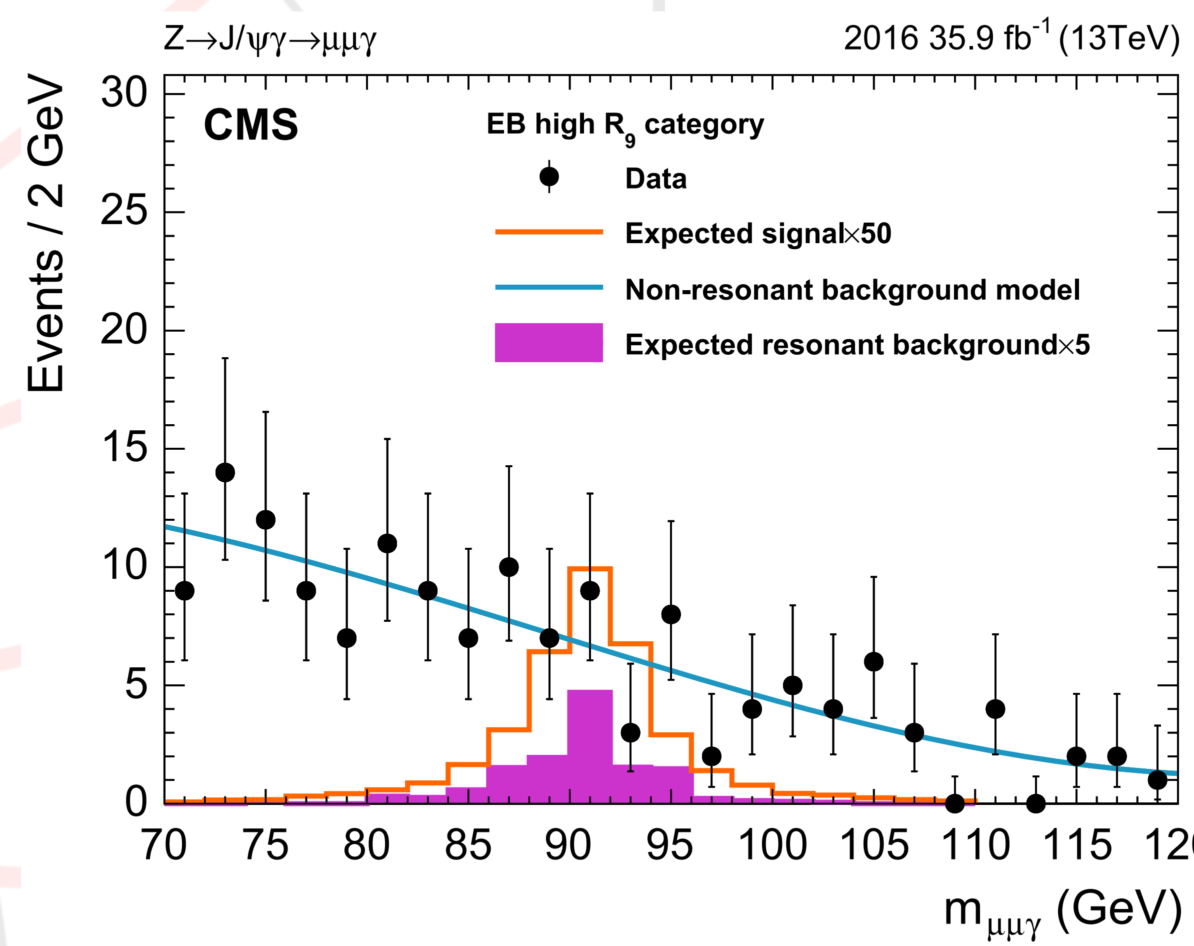
EPJ C79 (2019) 94

- Sensitivity to the coupling of the charm through a loop contribution
  - Many contributions to the loop (W, c)
- Non resonant ($m_{\mu\mu\gamma}$) background estimated with an analytical function
- Resonant background reduced with invariant mass window ($m_{\mu\mu}$) requirements



SM $\mathcal{B}$(H→ J/ψ γ) = 3 × 10⁻⁶





95%CL Branching fraction limit

$H \rightarrow J/\psi\,\gamma$	Longitudinal	$1.2\ (1.4^{+0.6}_{-0.4}) \times 10^{-6}$
	Transverse	$7.6\ (5.2^{+2.4}_{-1.6}) \times 10^{-4}$

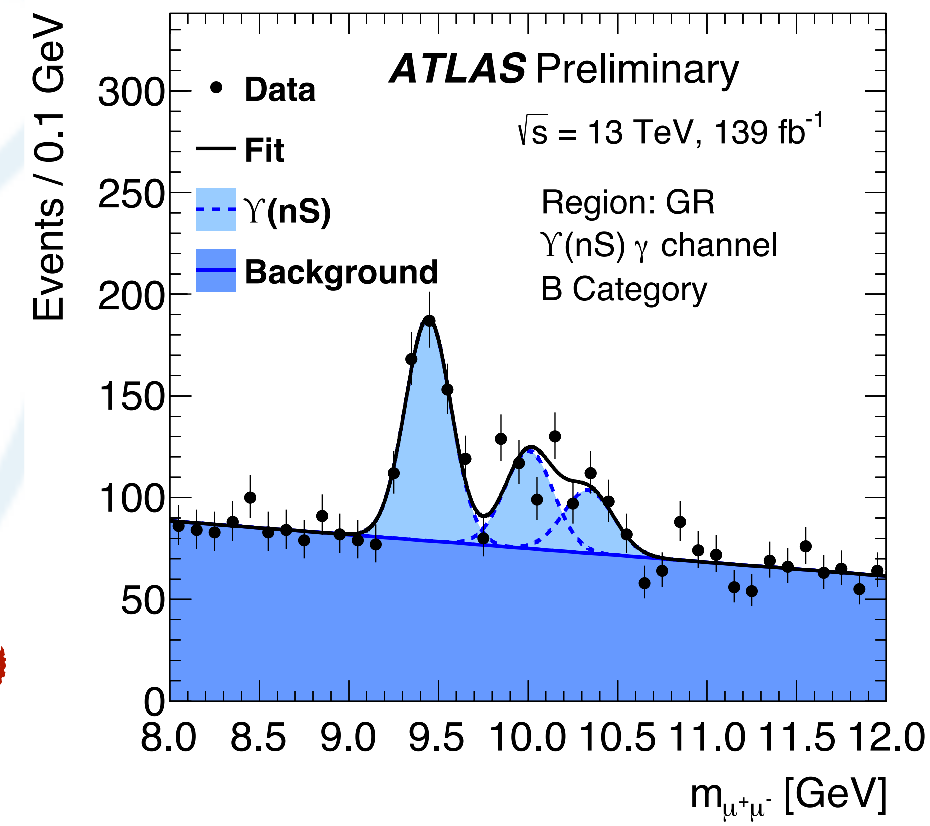
$H \to J/\psi\,\gamma,\ \psi(2s)\,\gamma, \Upsilon\gamma$ — ATLAS

SM $\mathcal{B}(H\to \psi_{2s}\gamma) = 1\times10^{-6}$	SM $\mathcal{B}(H\to \Upsilon_{2s}\gamma) = 1.4\times10^{-9}$
SM $\mathcal{B}(H\to \Upsilon_{1s}\gamma) = 5.2\times10^{-9}$	SM $\mathcal{B}(H\to \Upsilon_{3s}\gamma) = 10^{-9}$

HDBS-2018-53

- Sensitivity to the coupling of the charm through a loop contribution in the J/ψ γ
- And to the bottom in the Υγ and CP violation
- Kinematic requirements are applied in order to enhance the signal contribution
- Non parametric background model derived from Control regions and validated in dedicated regions
- 2D fit in $m_{\mu\mu}$ and $m_{\mu\mu\gamma}$

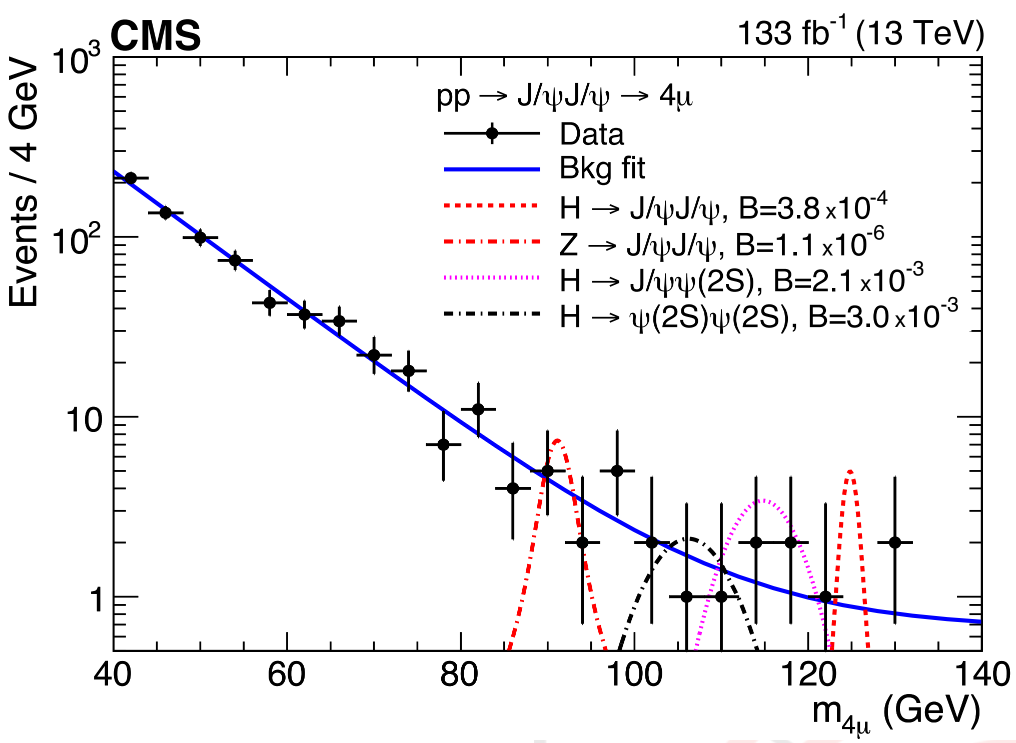
NEW

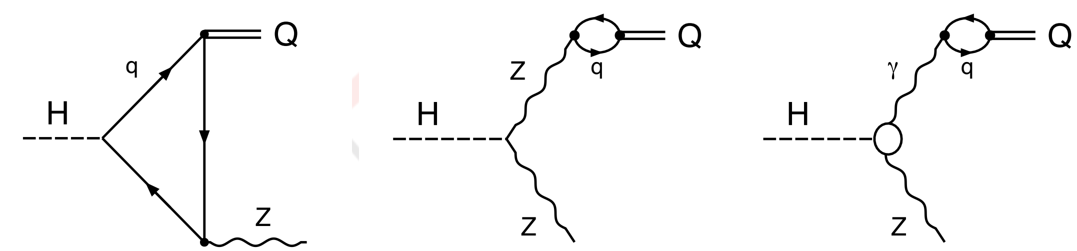


Decay channel	95% CL$_s$ upper limits: Branching fraction, Higgs boson [10^{-4}] Expected	Higgs boson [10^{-4}] Observed	Z boson [10^{-6}] Expected	Z boson [10^{-6}] Observed	$\sigma\times\mathcal{B}$: Higgs boson [fb] Observed	Z boson [fb] Observed
$J/\psi\,\gamma$	$1.9^{+0.8}_{-0.5}$	2.1	$0.6^{+0.3}_{-0.2}$	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

- J/ψ decays into muons
- Z decays into leptons (electron or muons)
- The ψ(2S) meson decays into a J/ψ + X, where X is not reconstructed

SM $\mathcal{B}$(H→ Z J/ψ) = 2.3 × 10^{-6}
SM $\mathcal{B}$(H→ Z ψ_{2S}) = 1.7 × 10^{-6}
SM $\mathcal{B}$(H→ J/ψ J/ψ) = 1.5 × 10^{-10}
SM $\mathcal{B}$(H→ ϒϒ) = 2 × 10^{-9}





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}

H→ γρ / γφ — ATLAS

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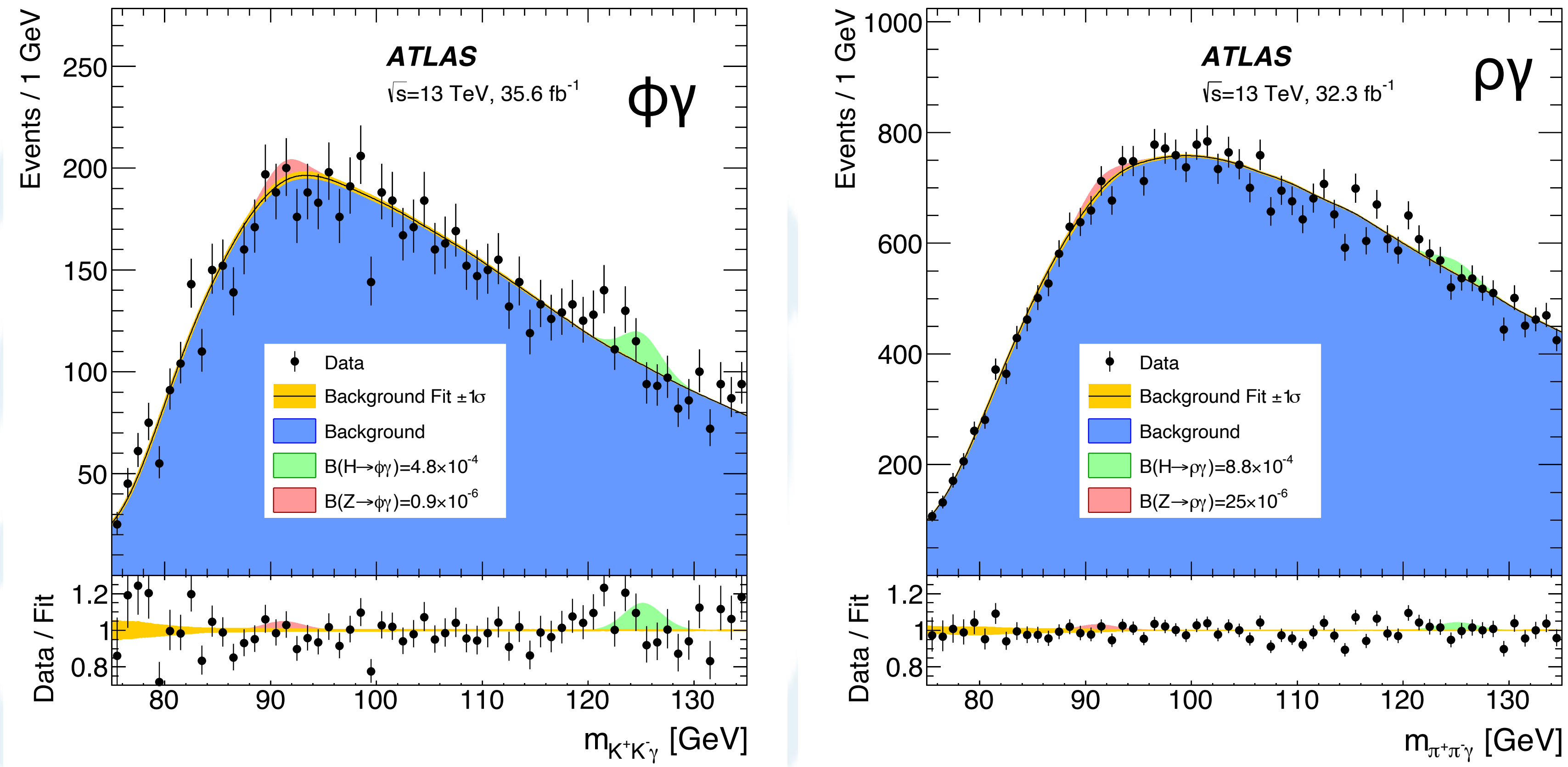
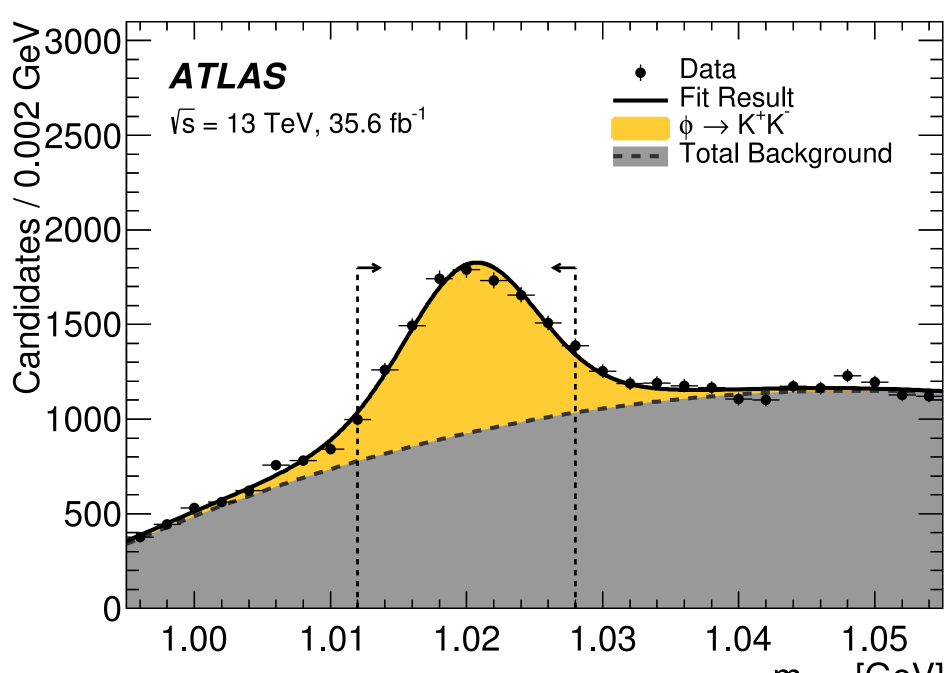
SM $\mathcal{B}$(H→ ργ) = 1.7 × 10^-5^
SM $\mathcal{B}$(H→ φγ) = 2.3 × 10^-6^



- Dedicated trigger
  - pTg > 35GeV
  - Isolated pair of tracks associated with a calorimetric cluster
- $\phi \rightarrow K^{\pm}K^{\pm}$, $\rho \rightarrow \pi^{\pm}\pi^{\pm}$
- Background is resampled from a control region inverting the isolation and validated in side-band regions



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

H→Zρ / Zϕ — CMS [JHEP 11 (2020) 039]

- Z → electron or muon
- ρ → $\pi^\pm\pi^\pm$
- ϕ → K±K±

SM $\mathcal{B}$(H→ Zρ) = 1.4 × 10-5
SM $\mathcal{B}$(H→ Zϕ) = 4.2 × 10-6