Higgs2023 | Beijing
Rare Higgs boson decays with the CMS experiment

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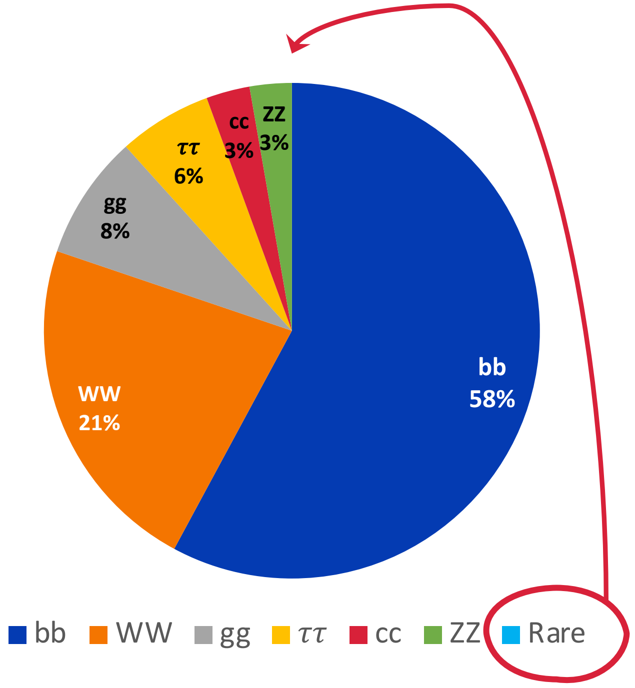
Introduction to Higgs rare decays

Are the properties of the Higgs boson exactly as forseen by the Standard Model?

Decay channel	Branching fraction (%)
bb	57.63 ± 0.70
WW	22.00 ± 0.33
gg	8.15 ± 0.42
$\tau\tau$	6.21 ± 0.09
cc	2.86 ± 0.09
ZZ	2.71 ± 0.04
$\gamma\gamma$	0.227 ± 0.005
$Z\gamma$	0.157 ± 0.009
ss	0.025 ± 0.001
$\mu\mu$	0.0216 ± 0.0004

Nature 607 (2022) 60



A way to test it → **Higgs boson rare decays**

- Experimentally **challenging:**
  - Small branching ratios
  - Low signal/bkg
- Several ATLAS and CMS results in the 10 years after discovery:
  - **Couplings** up to **2nd generation of fermions**
  - Search for **New Physics**
  - constraint on the H boson **invisible** width
- Today I will focus mostly on **SM rare decays**

today

- $H \to Z\gamma$
- $H \to ee$
- $H \to Z\,J/\psi$ and J/ψ or Υ pairs
- $H \to \gamma\,\psi'$
- $H \to$ invisible (rare SM+BSM)

Introduction to Higgs rare decays

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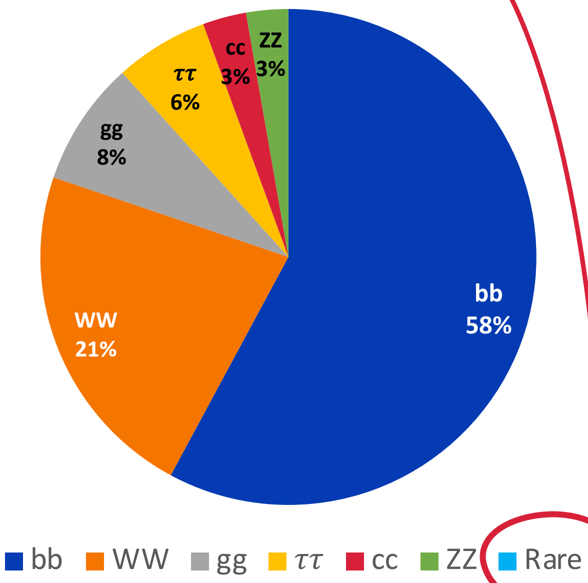


today

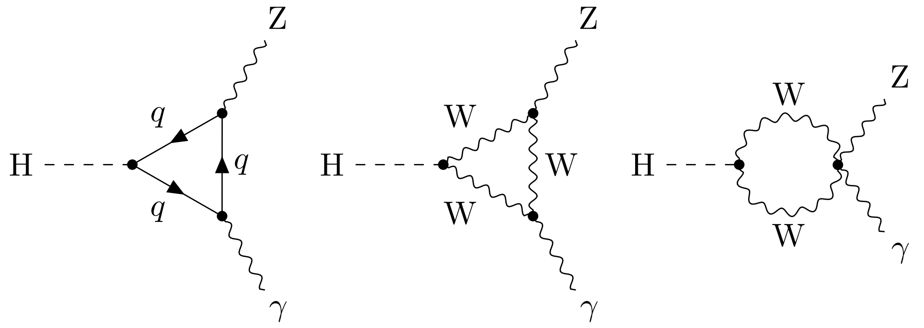
- H → $Z\gamma$
- H → ee
- H → Z J/ψ and J/ψ or ϒ pairs
- H → γ ψ′
- H → invisible (rare SM+BSM)

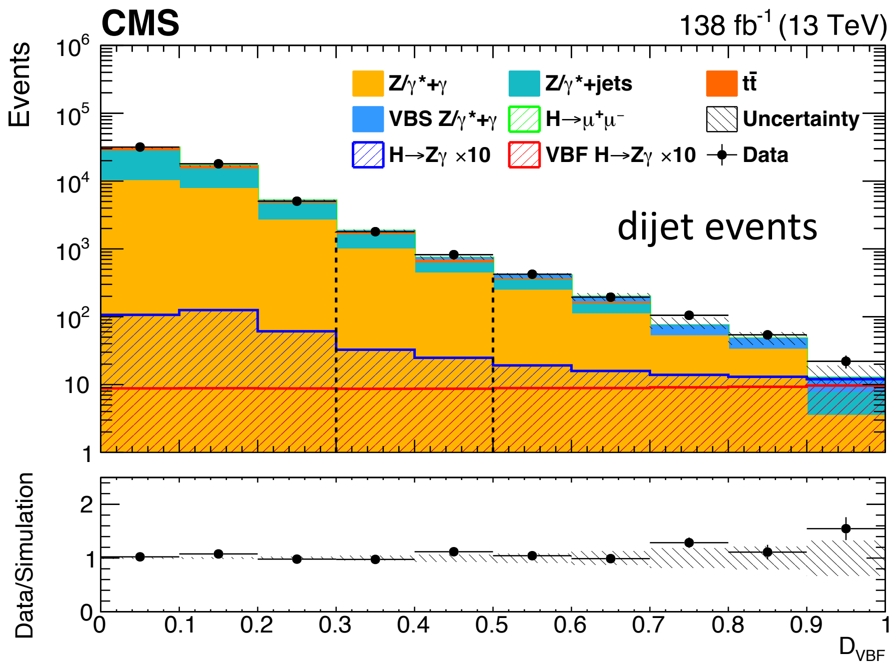
$H \to Z\gamma$

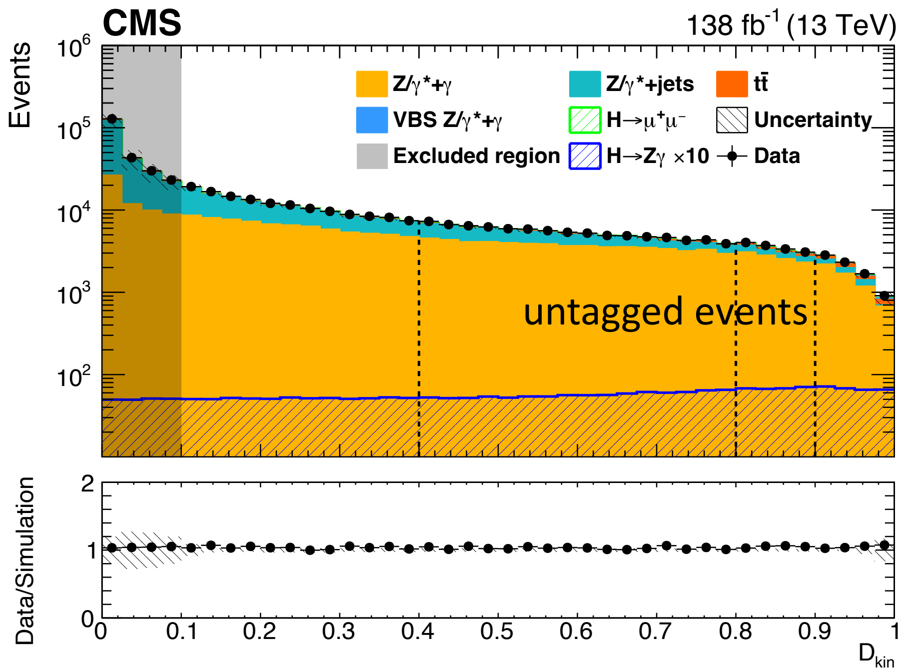
JHEP 05 (2023) 233

SM $\mathcal{B}(H \to Z\gamma) = (1.57 \pm 0.09) \cdot 10^{-3}$
$\mathcal{B}(Z \to ee/\mu\mu) \backsim 6.8\%$

- Sensitive to **potential BSM Physics** models: BSM can shift $B(H \to Z\gamma)$ and $B(H \to \gamma\gamma)$ differently
- Search for $\boldsymbol{e^+e^-\gamma}$ and $\boldsymbol{\mu^+\mu^-\gamma}$ final states
- Most relevant bkg: $\boldsymbol{Z\gamma}$ and **Z+jets** (jet fakes a photon)
- **FSR** recovery
- kinematic fit to improve mass resolution
- **8 event categories:**
  - lepton tag categories (VH and ttH)
  - dijet events (mainly VBF): MVA discriminant $\mathcal{D}_{\mathrm{VBF}}$ categories
  - untagged events (mainly ggH): MVA discriminant $\mathcal{D}_{\mathrm{kin}}$ categories







$H \to Z\gamma$

JHEP 05 (2023) 233

SM $\mathcal{B}(H \to Z\gamma) = (1.57 \pm 0.09) \cdot 10^{-3}$
$\mathcal{B}(Z \to ee/\mu\mu) \backsim 6.8\%$

- Significance of **2.7 σ**
- observed signal strength $\mu = 2.4 \pm 0.9$
- $\frac{B(H\to Z\gamma)}{B(H\to \gamma\gamma)} = 1.54^{+0.65}_{-0.58}$ compatible with SM at 1.5σ

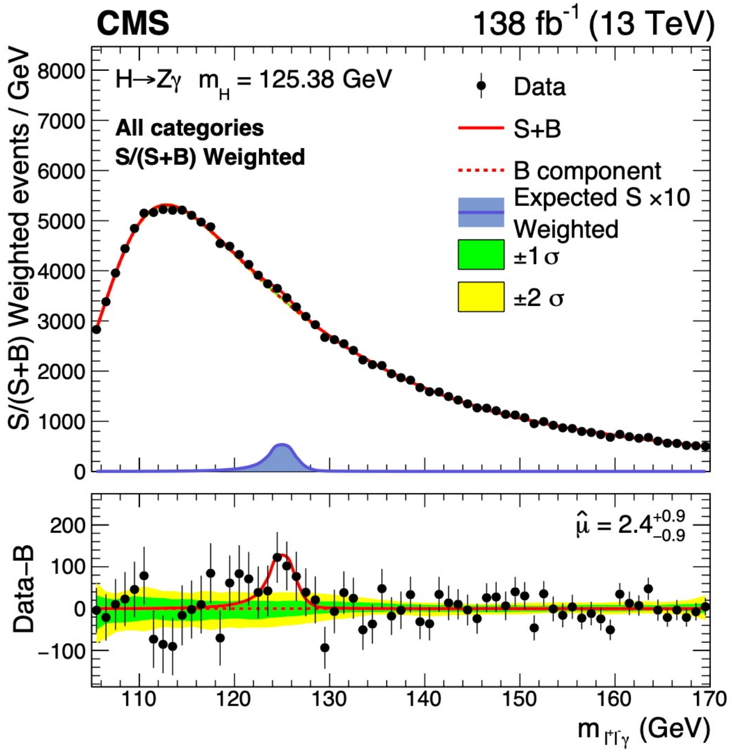


Figure: Sum over all categories of the data points and signal-plus-background model after the simultaneous fit to each $m_{\ell\ell\gamma}$ distribution.

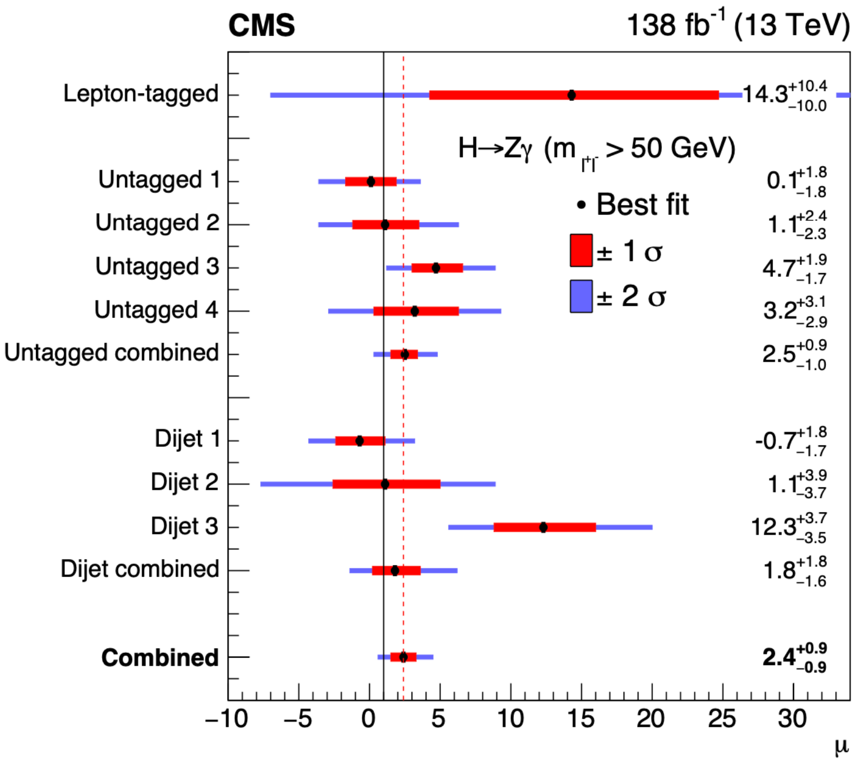


Figure: Observed signal strength μ for a SM Higgs boson with $m_{\ell\ell\gamma} = 125.38$ GeV.

$H \to Z\gamma$ CMS and ATLAS combination

Submitted to PRL

- Significance of **3.4 σ**
- observed signal strength $\mu = 2.2 \pm 0.7$
- observed $\mathcal{B}(\mathrm{H} \to \mathrm{Z}\gamma) = (3.4 \pm 1.1) \cdot 10^{-3}$

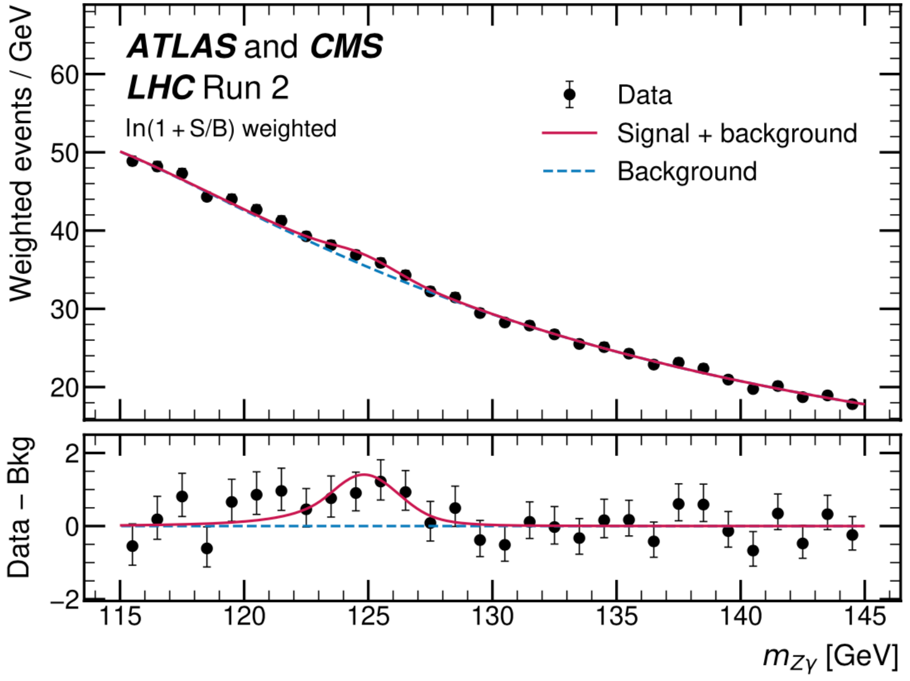


Figure: The $Z\gamma$ invariant mass distribution of events from all ATLAS and CMS analysis categories.

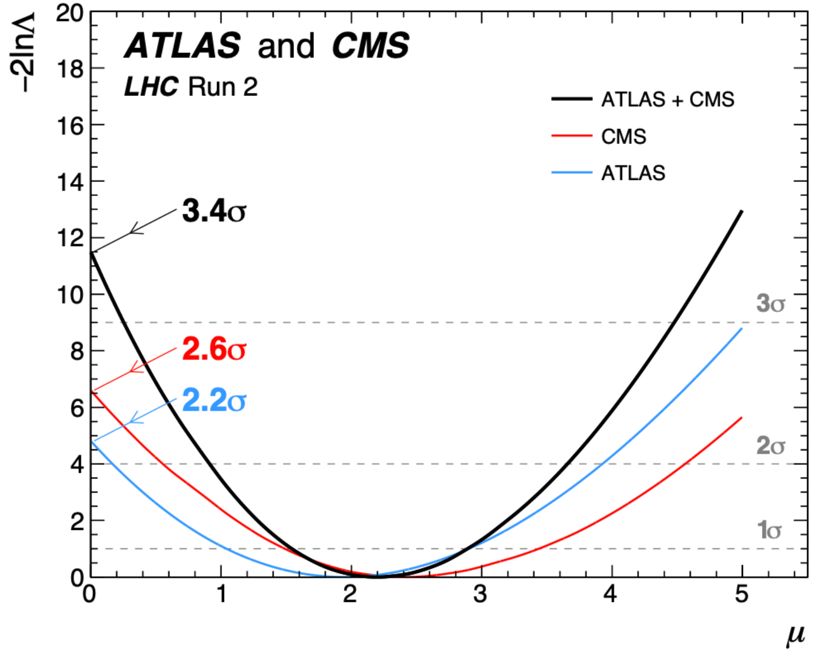


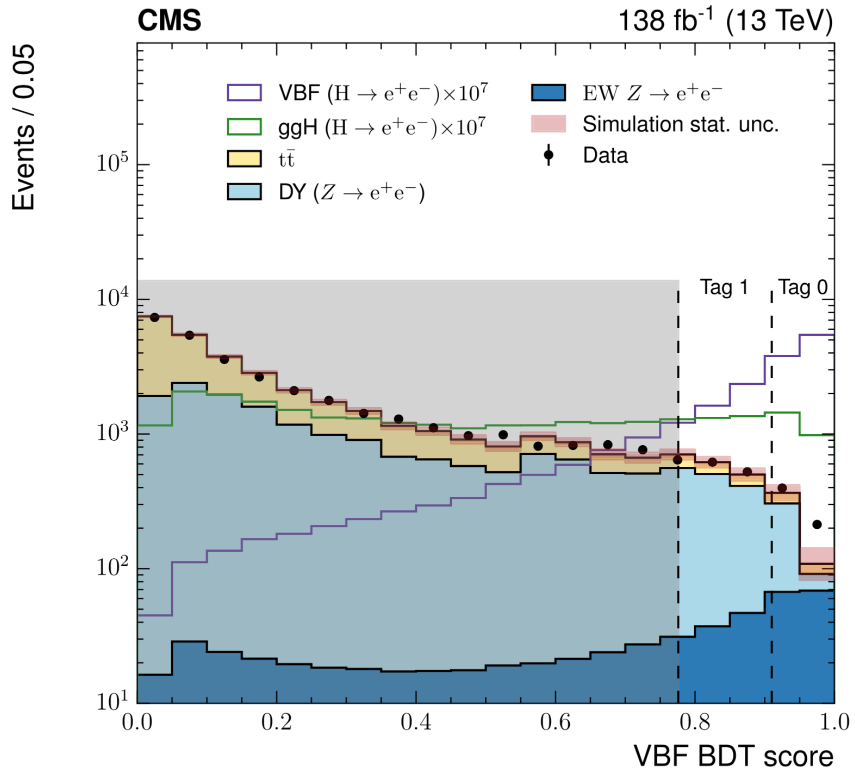
Figure: Negative profile log-likelihood scan of the signal strength μ.

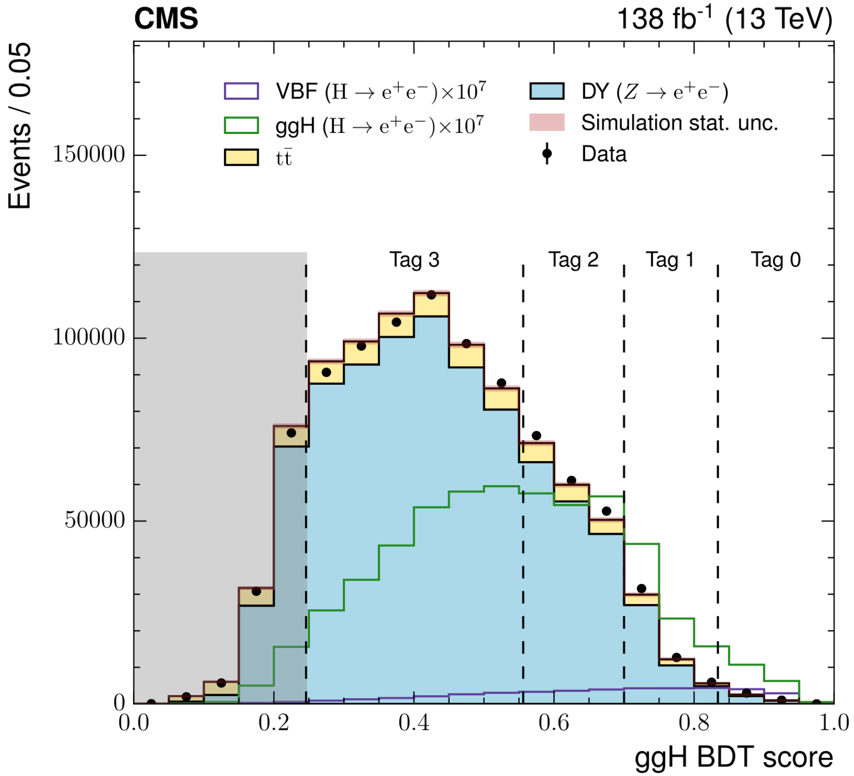
Search for $H \to ee$

PLB 846 (2023) 137783

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

- CMS probed the H coupling to 2nd gen of leptons in the $H \to \mu\mu$ channel
- $H \to ee$: coupling to **1st generation** of fermions
- Analysis targets **ggH** and **VBF** (most sensitive)
- **MVA-based categories** to suppress bkg (DY mainly, $t\bar{t}$ with di-lepton + jets final states)
- **parametric fit** to the *ee* invariant mass distribution performed simultaneously in all categories





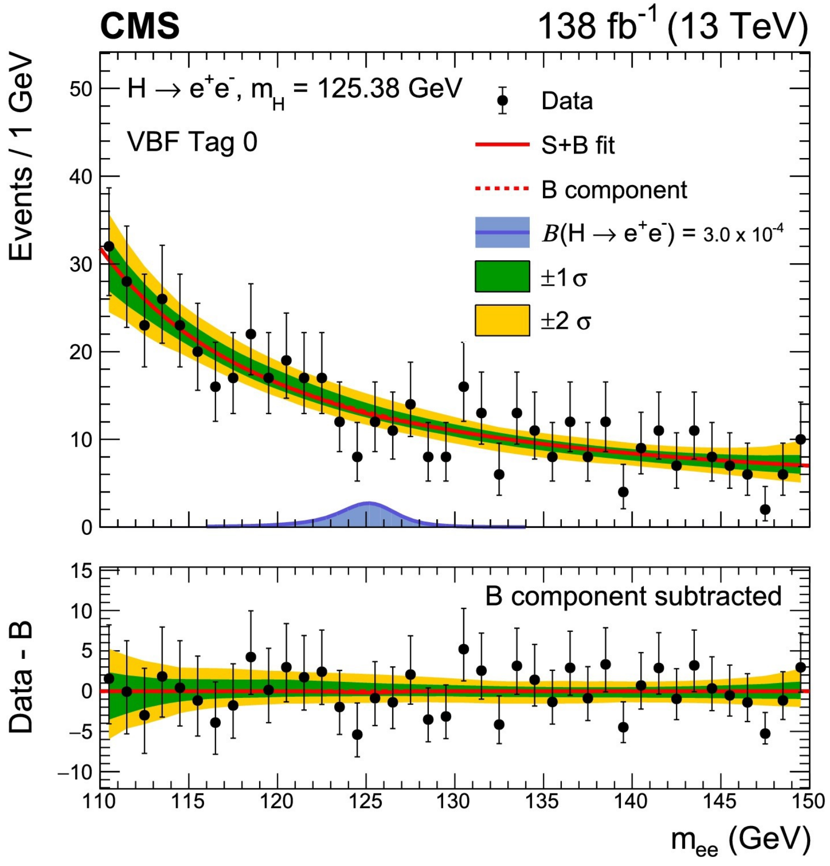
Search for $H \to ee$

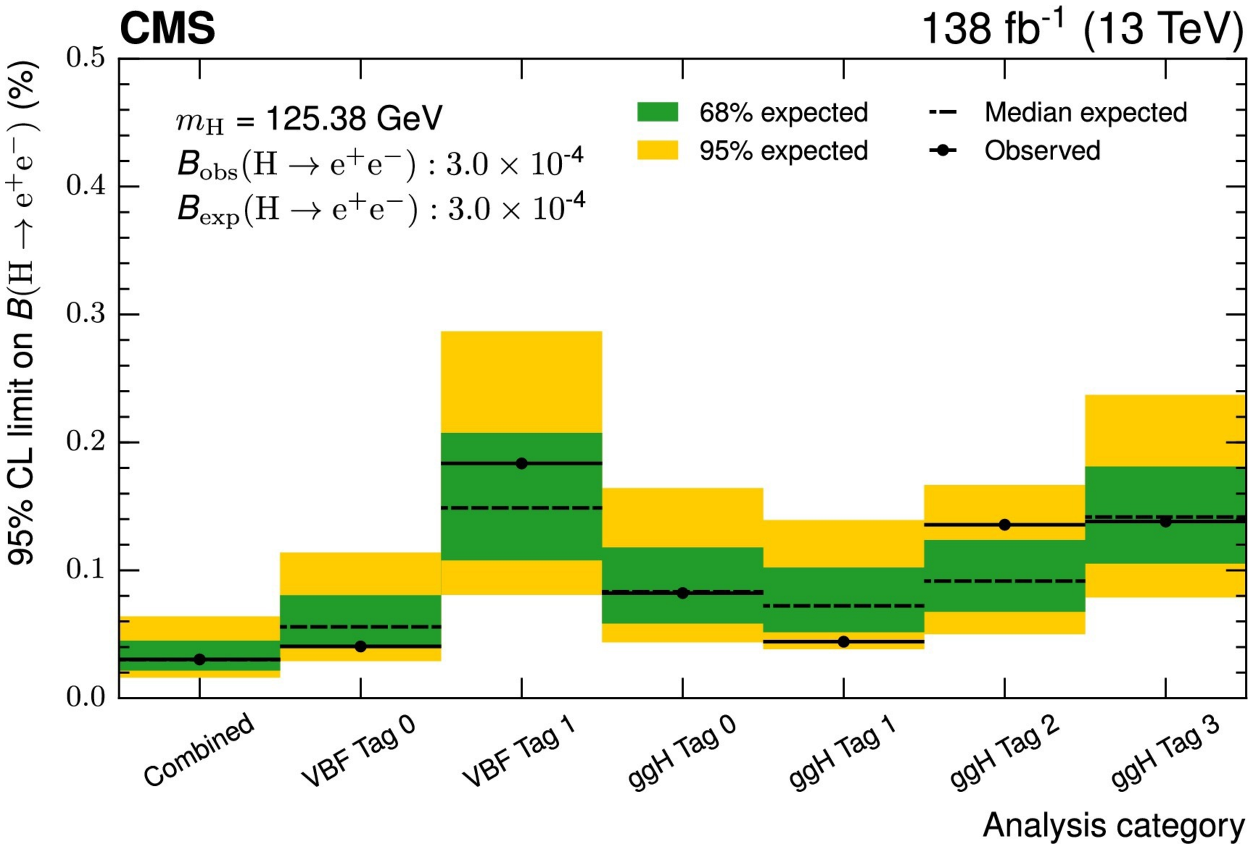
PLB 846 (2023) 137783

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

Observed (expected) 95 % CL **upper limit**:

- $\mathcal{B}(H \to ee) < 3.0(3.0) \cdot 10^{-4}$





Search for H → Z J/ψ and J/ψ or Υ pairs

SM $\mathcal{B}(\mathrm{H} \to \mathrm{Z\,J/\psi}) = (2.3 \pm 0.11) \cdot \mathbf{10^{-6}}$
SM $\mathcal{B}(\mathrm{H} \to \mathrm{Z\,\psi(2S)}) = 1.7 \cdot \mathbf{10^{-6}}$
SM $\mathcal{B}(\mathrm{H} \to \mathrm{J/\psi J/\psi}) = 1.5 \cdot \mathbf{10^{-10}}$
SM $\mathcal{B}(\mathrm{H} \to \Upsilon\Upsilon) = 2 \cdot \mathbf{10^{-9}}$

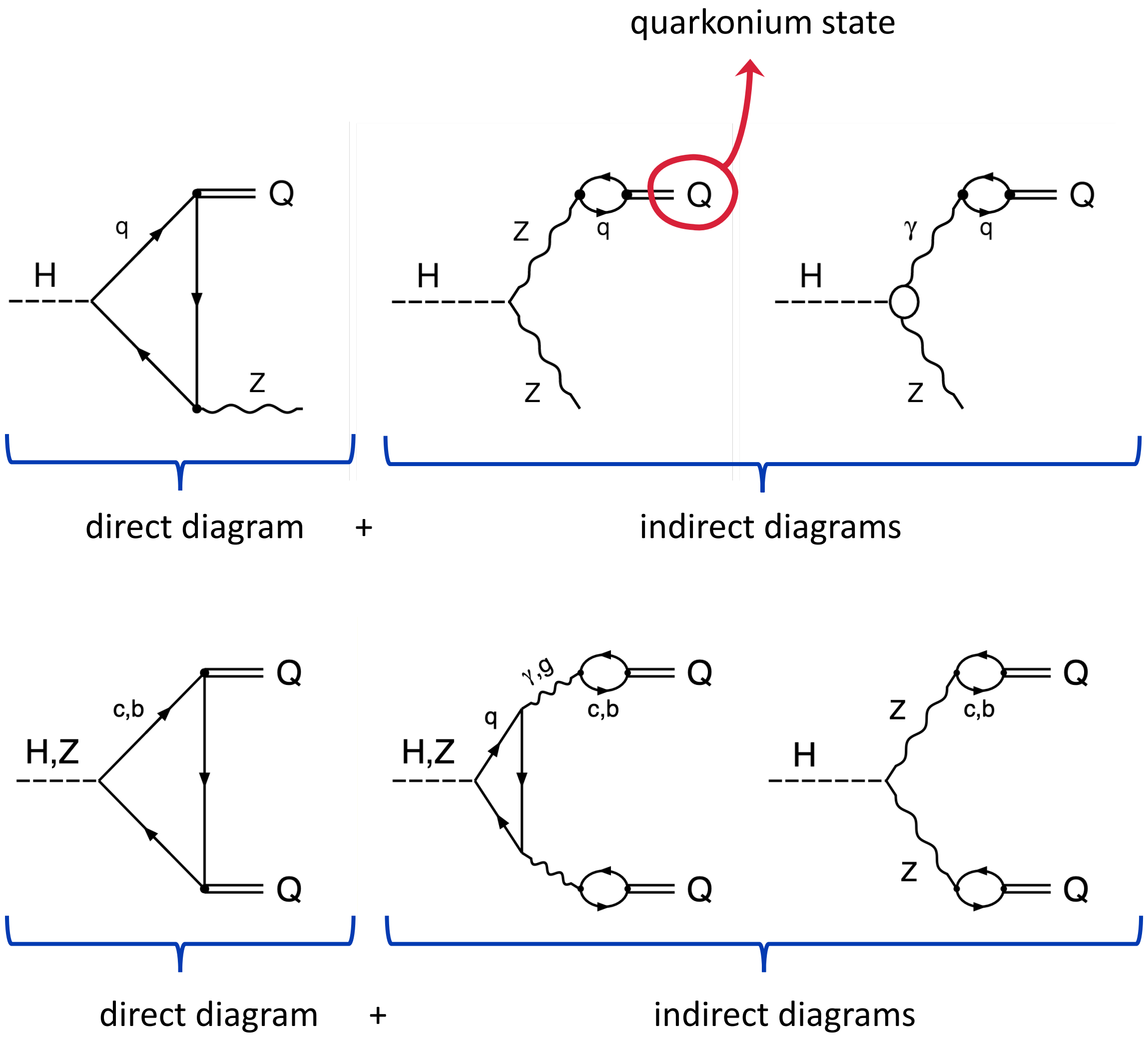
Phys. Lett. B 842 (2023) 137534

BSM physics:

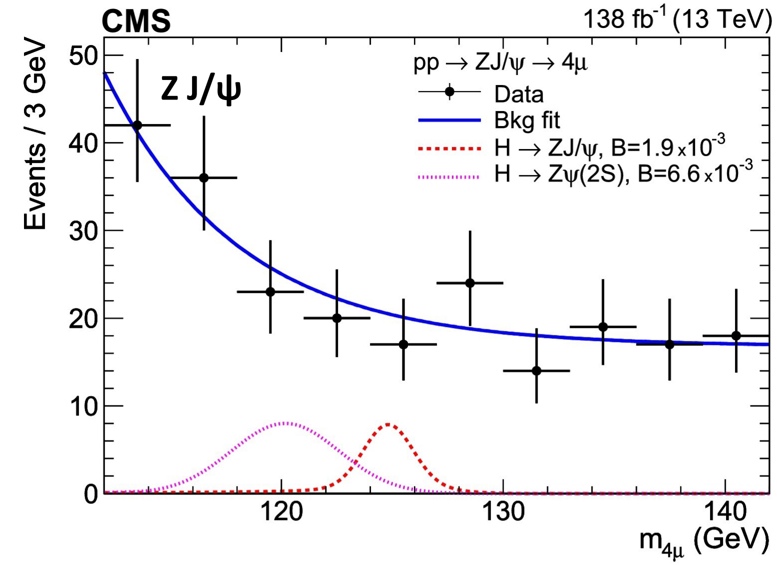
- could modify $\mathcal{B}$ through loops and alter the interference
- may enhance Yukawa couplings to light quarks

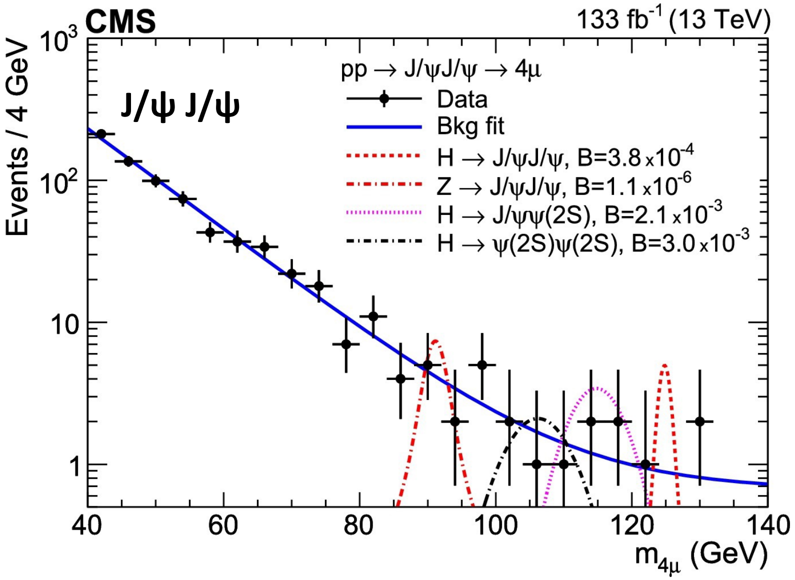
Analysis strategy:

- *ee* or $\mu\mu$ **final states** from Z and $\mu\mu$ final state from J/ψ or Υ
- single lepton triggers for Z J/ψ channel
- specific triggers for the di-meson channels
- **Main bkg**: $\mathrm{H} \to \mathrm{ZZ}^*$
- **feed-down** transitions of ψ(2S) or Υ(nS) into J/ψ included
- Same decay channels **from a Z** included in the results



Search for H → Z J/ψ and J/ψ or ϒ pairs





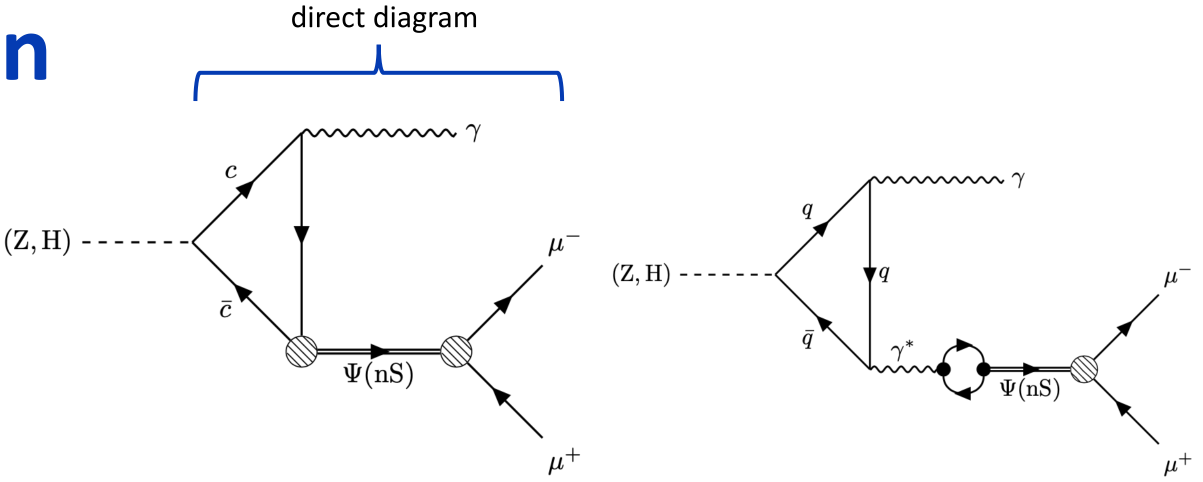
[Phys. Lett. B 842 (2023) 137534]

Process	Observed Longitudinal	Expected Longitudinal
$\mathcal{B}(H \to ZJ/\Psi)$	1.9×10^{-3}	$(2.6^{+1.1}_{-0.7}) \times 10^{-3}$
$\mathcal{B}(H \to Z\Psi(2S))$	6.6×10^{-3}	$(7.1^{+2.8}_{-2.0}) \times 10^{-3}$
$\mathcal{B}(H \to J/\Psi J/\Psi)$	3.8×10^{-4}	$(4.6^{+2.0}_{-0.6}) \times 10^{-4}$
$\mathcal{B}(H \to \Psi(2S)J/\Psi)$	2.1×10^{-3}	$(1.4^{+0.6}_{-0.4}) \times 10^{-3}$
$\mathcal{B}(H \to \Psi(2S)\Psi(2S))$	3.0×10^{-3}	$(3.3^{+1.5}_{-0.9}) \times 10^{-3}$
$\mathcal{B}(H \to \Upsilon(nS)\Upsilon(mS))$	3.5×10^{-4}	$(3.6^{+0.2}_{-0.3}) \times 10^{-4}$
$\mathcal{B}(H \to \Upsilon(1S)\Upsilon(1S))$	1.7×10^{-3}	$(1.7^{+0.1}_{-0.1}) \times 10^{-3}$
$\mathcal{B}(Z \to J/\Psi J/\Psi)$	11×10^{-7}	$(9.5^{+3.8}_{-2.6}) \times 10^{-7}$
$\mathcal{B}(Z \to \Upsilon(nS)\Upsilon(mS))$	3.9×10^{-7}	$(4.0^{+0.3}_{-0.3}) \times 10^{-7}$
$\mathcal{B}(Z \to \Upsilon(1S)\Upsilon(1S))$	1.8×10^{-6}	$(1.8^{+0.1}_{-0.0}) \times 10^{-6}$

$H/Z \to \psi'$ and a photon

$$\text{SM } \mathcal{B}(H \to \gamma\ J/\psi) = 2.99^{+0.16}_{-0.15} \cdot 10^{-6}$$
$$\text{SM } \mathcal{B}(H \to \gamma\ \psi') = 1.03^{+0.06}_{-0.06} \cdot 10^{-6}$$
$$\text{SM } \mathcal{B}(Z \to \gamma\ J/\psi) = 8.96^{+1.51}_{-1.38} \cdot 10^{-8}$$
$$\text{SM } \mathcal{B}(Z \to \gamma\ \psi') = 4.83^{+1.02}_{-0.91} \cdot 10^{-8}$$

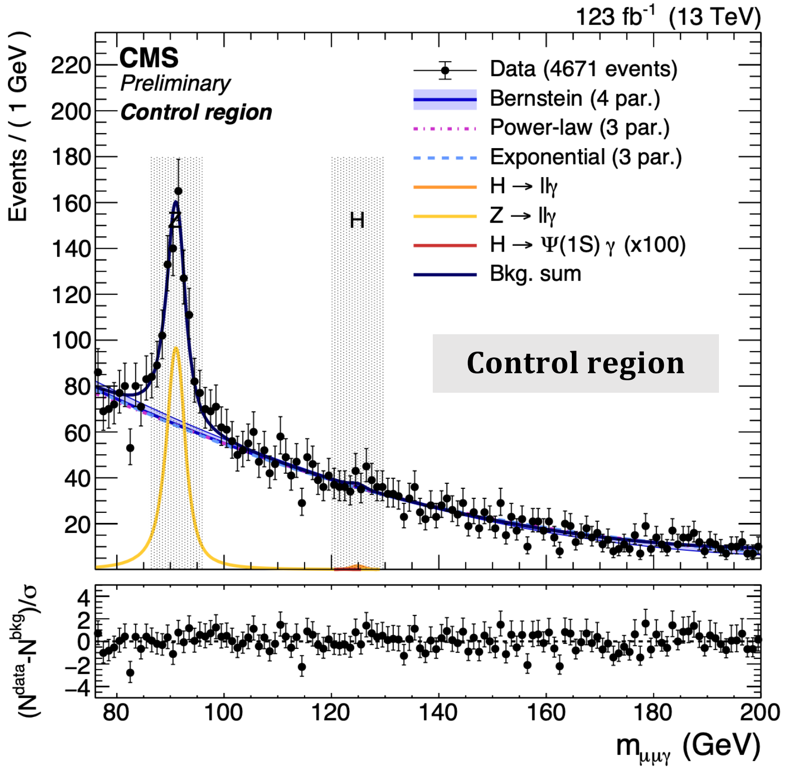
NEW



- Process via a **charm quark loop**
- well established for the Z, not yet observed for the Higgs

Analysis strategy

- ***μμ*** meson final state considered
- single muon + photon trigger
- **$m_{\mu\mu}$ requirements** to select ψ(1S) or ψ(2S)
- Complementary $m_{\mu\mu}$ region (**control region**) used to constrain the resonant bkg estimation
- bkg separated into two classes:
  1. EW-induced: H Dalitz decays and Z → μμ with FSR-photon **Resonant** bkg modeled in MC
  2. QCD multijet production: **nonresonant** bkg modeled directly from data



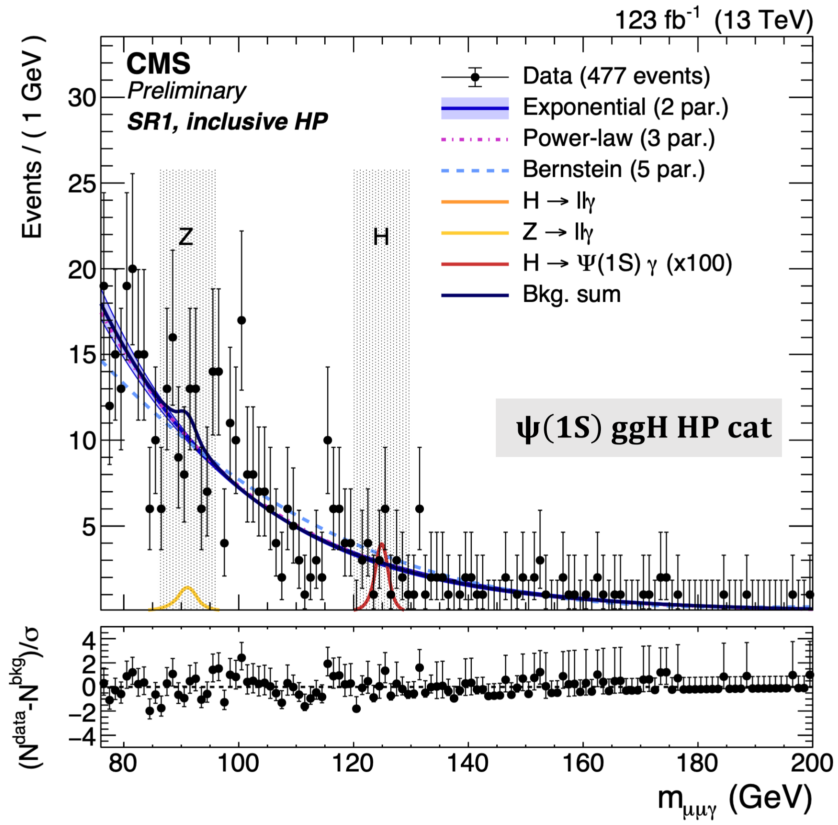
$H/Z \to \psi'$ and a photon

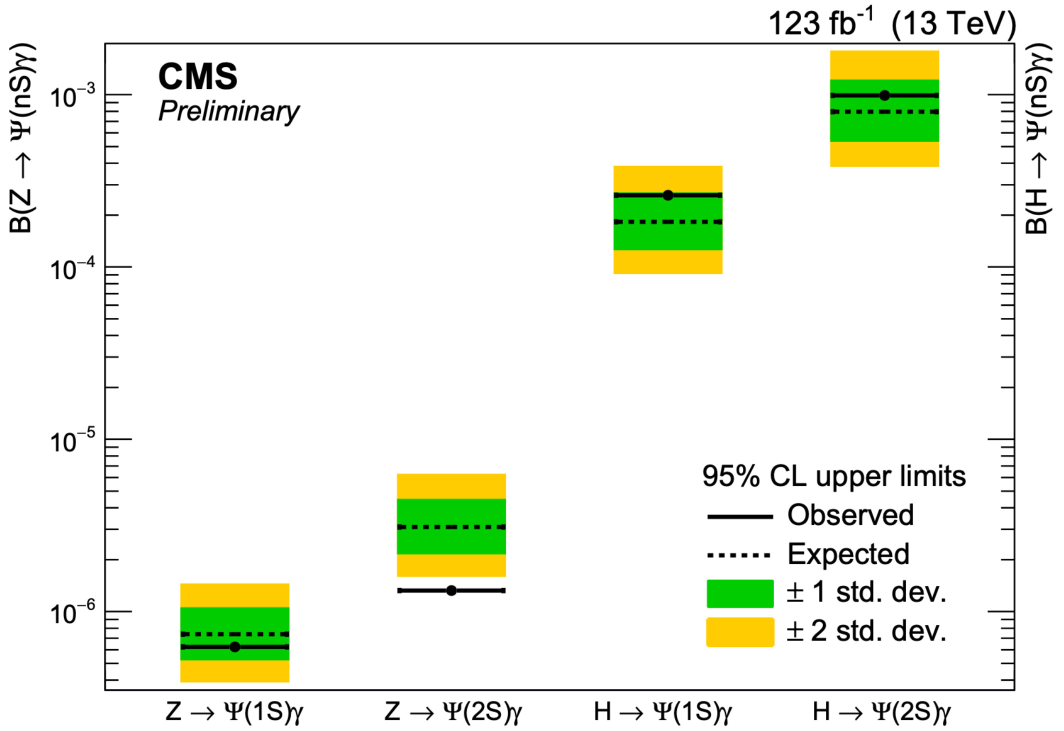
NEW

Categorization for Higgs analysis

- **1** inclusive category for ψ(2S)
- **4** exclusive categories for ψ(1S):
  - **2 ggH** categories high and low purity (HP or LP):
  - **VBF**
  - **High flavor lepton** (HFL): at least 1 b-jet

Process	This paper (123 fb^{-1})		
	$\mu_{obs}(\mu_{exp})$	$\sigma_{obs}(\sigma_{exp})$ [pb]	$\mathcal{B}_{obs}(\mathcal{B}_{exp})$
$Z \to \Psi(1S)\gamma$	7.2 $\left(8.6^{+4.1}_{-2.7}\right)$	3.8 $\left(4.4^{+1.9}_{-1.3}\right) \times 10^{-2}$	0.6 $\left(0.7^{+0.3}_{-0.2}\right) \times 10^{-6}$
$Z \to \Psi(2S)\gamma$	29 $\left(68^{+36}_{-22}\right)$	8 $\left(19^{+8}_{-6}\right) \times 10^{-2}$	1.3 $\left(3.1^{+1.4}_{-0.9}\right) \times 10^{-6}$
$H \to \Psi(1S)\gamma$	88 $\left(62^{+30}_{-19}\right)$	1.4 $\left(1.0^{+0.5}_{-0.3}\right) \times 10^{-2}$	2.6 $\left(1.8^{+0.9}_{-0.6}\right) \times 10^{-4}$
$H \to \Psi(2S)\gamma$	970 $\left(781^{+417}_{-259}\right)$	5.5 $\left(4.4^{+2.3}_{-1.5}\right) \times 10^{-2}$	9.9 $\left(8.0^{+4.2}_{-2.6}\right) \times 10^{-4}$

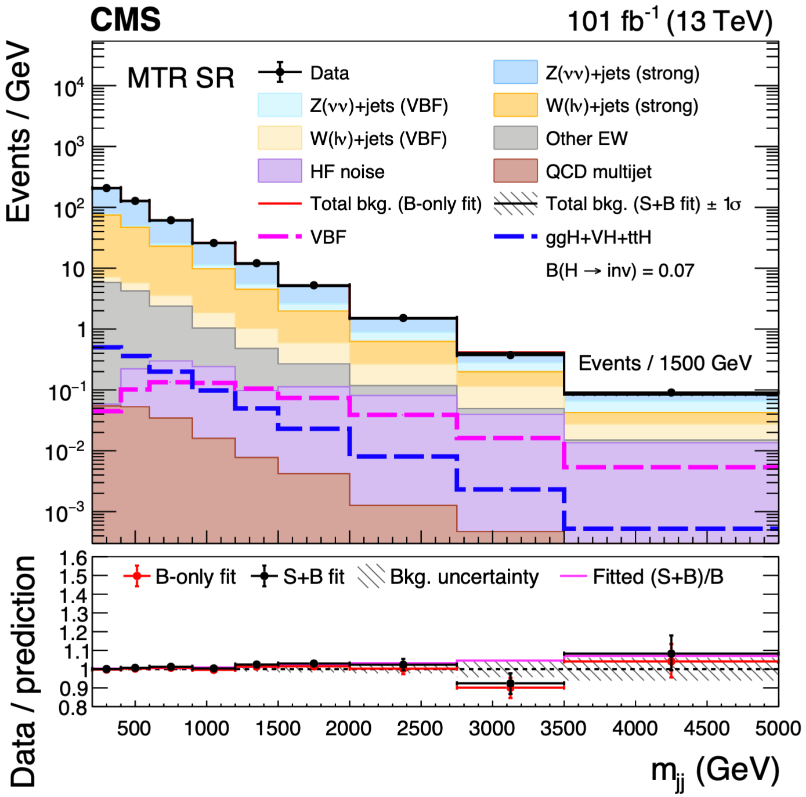


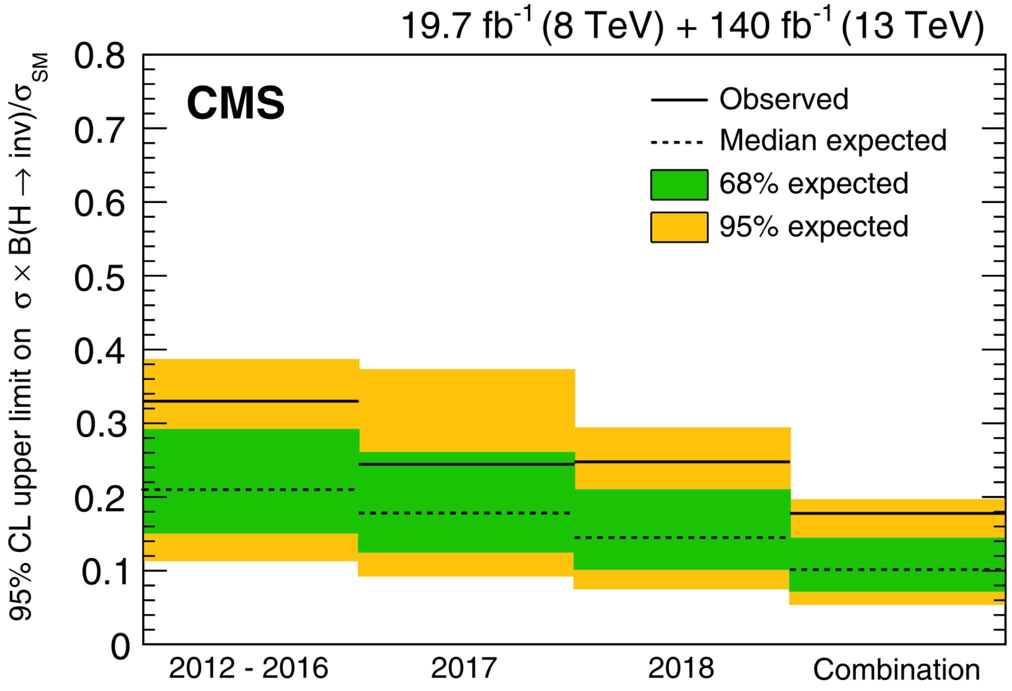


H to invisible

Phys. Rev. D 105 (2022) 092007 for VBF
Eur. Phys. J. C 83 (2023) 933 for ttH and VH (and VBF combination)

- **2022** publication for **VBF** production
- recent results (**2023**) for **ttH** and **VH** productions combined with VBF results
- **VBF** analysis:
  - selection based on two high p_T **VBF-like jets** and well separated p_T^{miss}
  - bkg: $\mathbf{Z} \to \ \boldsymbol{\nu\nu}$ and $\mathbf{W} \to \boldsymbol{l\nu}$, but also **noise** from the hadronic calorimeter (suppressed using jet shape cuts)
  - **simultaneous fit** of signal region and 5 control regions: 1 e/μ , 2 e/μ , photon + jets

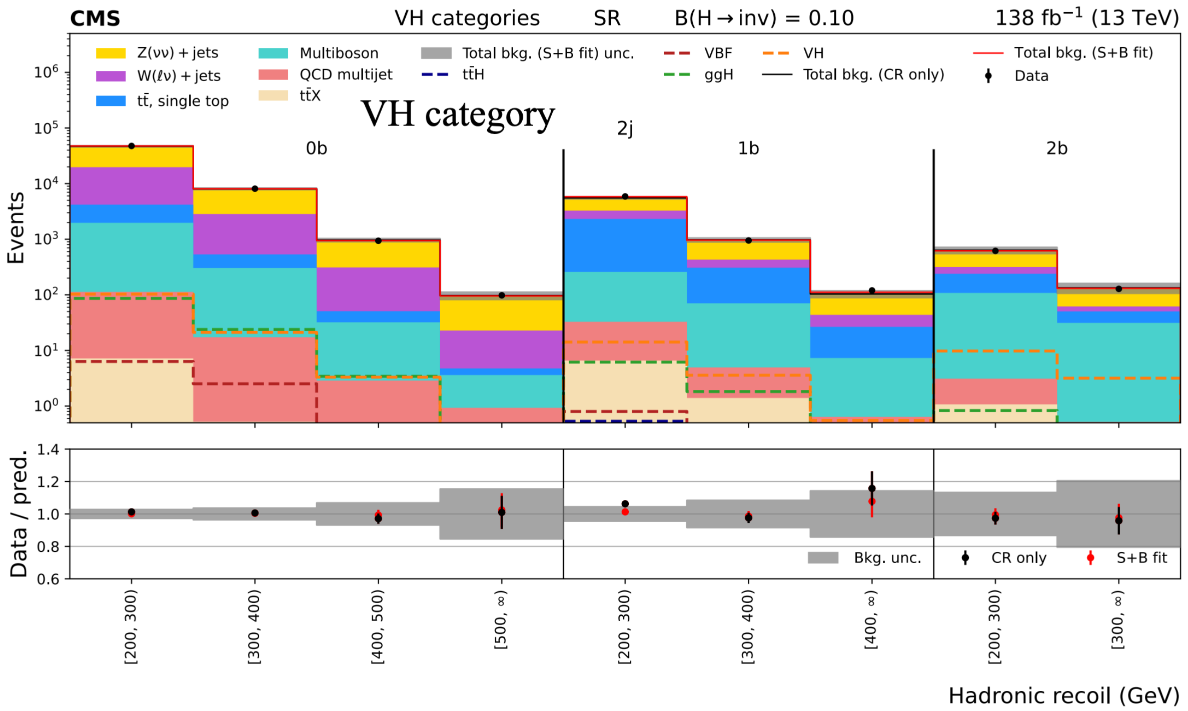


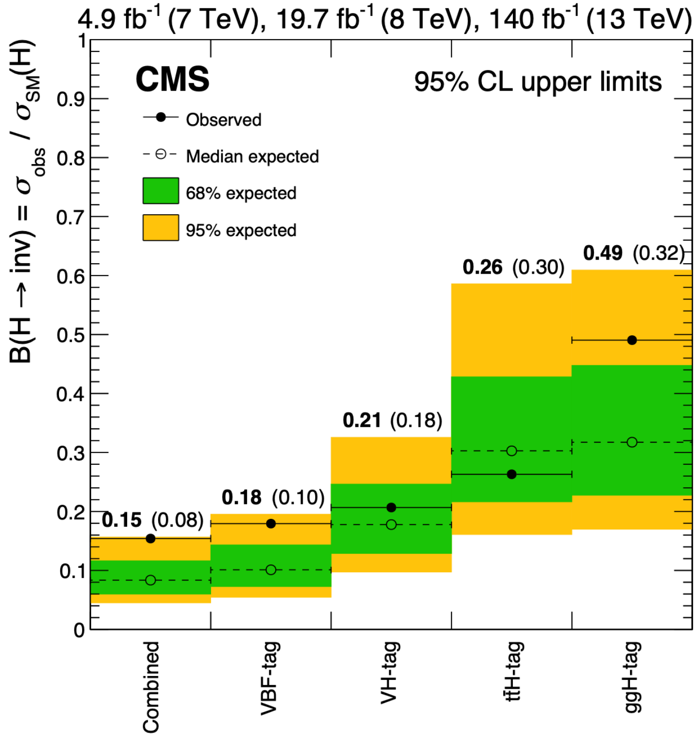


H to invisible

[Phys. Rev. D 105 (2022) 092007](#) for VBF
[Eur. Phys. J. C 83 (2023) 933](#) for ttH and VH (and VBF combination)

- **VH** and **ttH** analysis:
  - considers **fully hadronic channels**
  - **dominating bkg**: $Z \to \nu\nu$ + jets, lost leptons from tt+jets, single top, W+jets
  - signal is extracted in a simultaneous fit of hadronic recoil distribution in bins of n b-jets in SR and CR
- Combination: Observed (expected) 95 % c.l. **upper limit** $\mathcal{B}(\mathrm{H} \to \mathrm{inv}) < 15\,\%\ (8\%)$

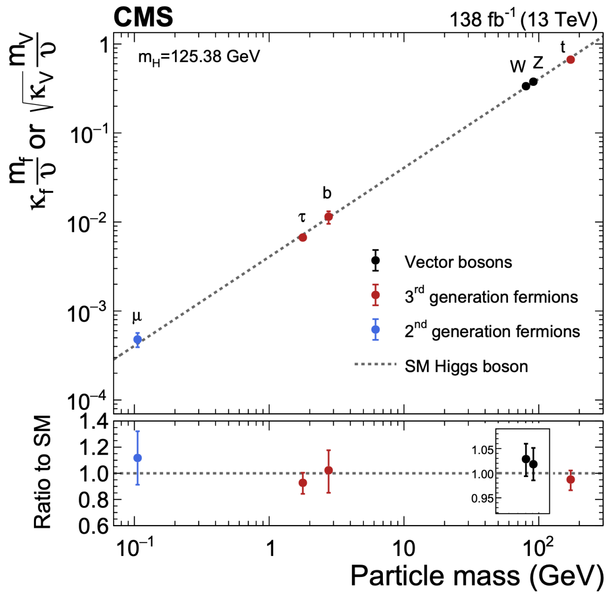




Conclusions

Summary

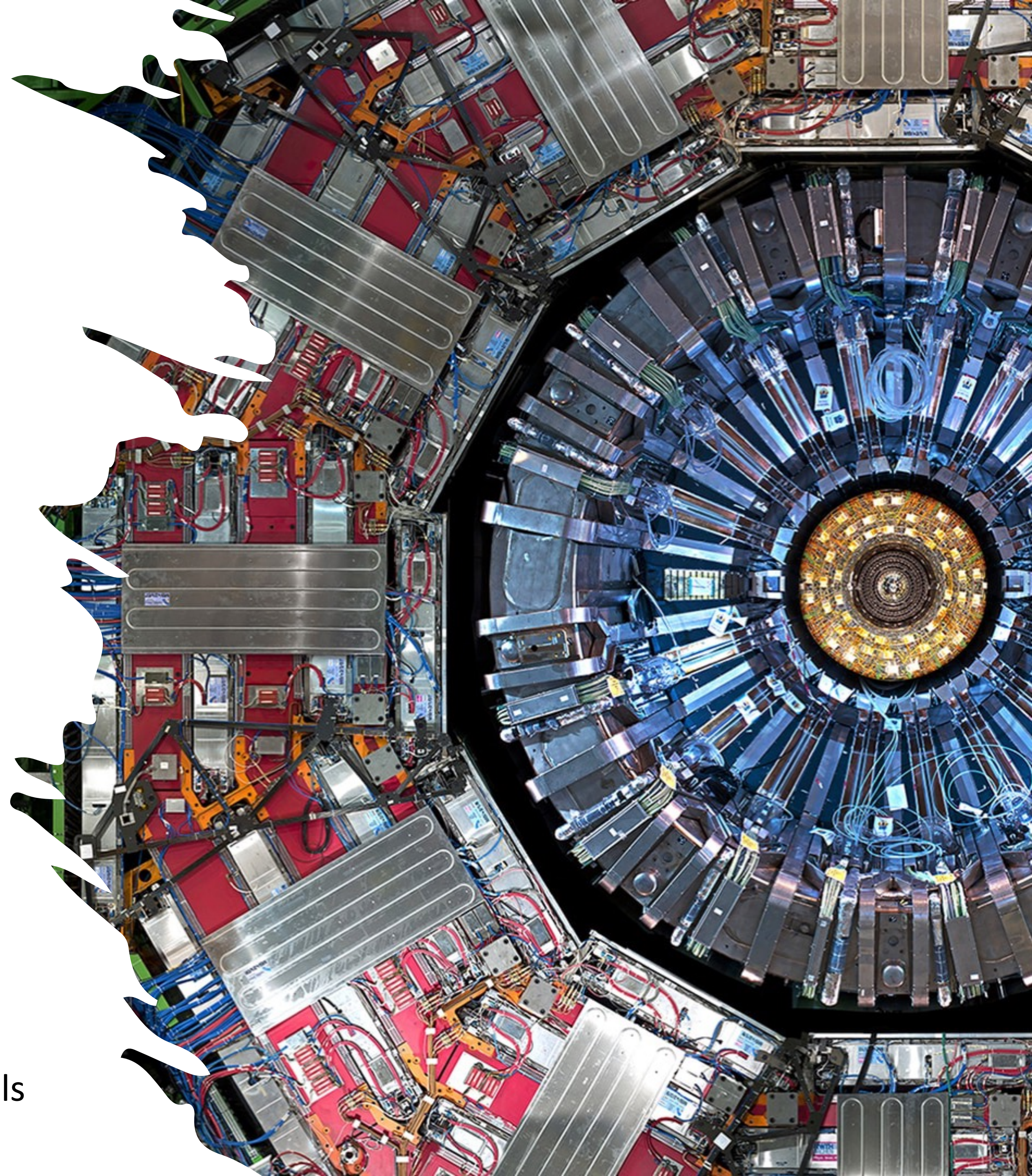
- Several **recent results** of CMS explored
- **confirmation** of the SM prediction, so far…



Nature 607 (2022) 60

Run3

- **improvement in sensitivity** for the analyses not systematically limited
- more precise testing of **H boson properties**
- consolidation of the **evidence** in some decay channels



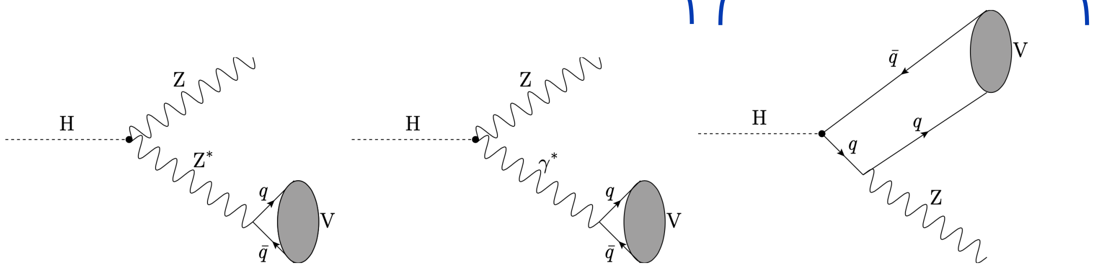
BACKUP

$H \rightarrow Z\rho$ or $Z\phi$

SM $\mathcal{B}(\mathrm{H} \rightarrow \mathrm{Z}\rho) \sim 1.4 \cdot 10^{-5}$
SM $\mathcal{B}(\mathrm{H} \rightarrow \mathrm{Z}\phi) \sim 4 \cdot 10^{-6}$

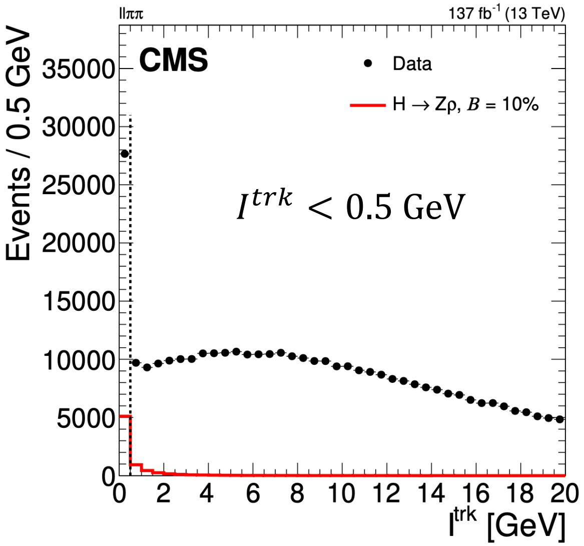
JHEP 11 (2020) 039

direct diagrams + indirect diagram

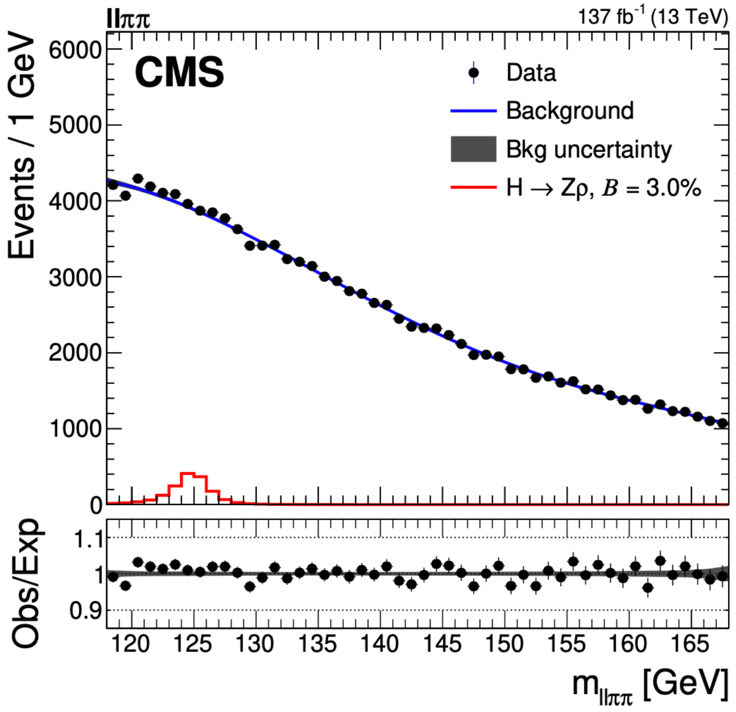


- Higgs **coupling to 1st and 2nd generation of quarks**
- **BSM**: if light quark Yukawa coulplings are enhanced wrt in the SM

- Search for resonances in $\boldsymbol{m_{llKK}}$ and $\boldsymbol{m_{ll\pi\pi}}$, where $l = e, \mu$
- KK or ππ **isolation** (activity in a cone around the meson direction) to enhance the signal and bkg separation



Upper limits @ 95 % c.l.
- Zρ: 740 ÷ 940 · SM
- Zϕ: 730 ÷ 950 · SM



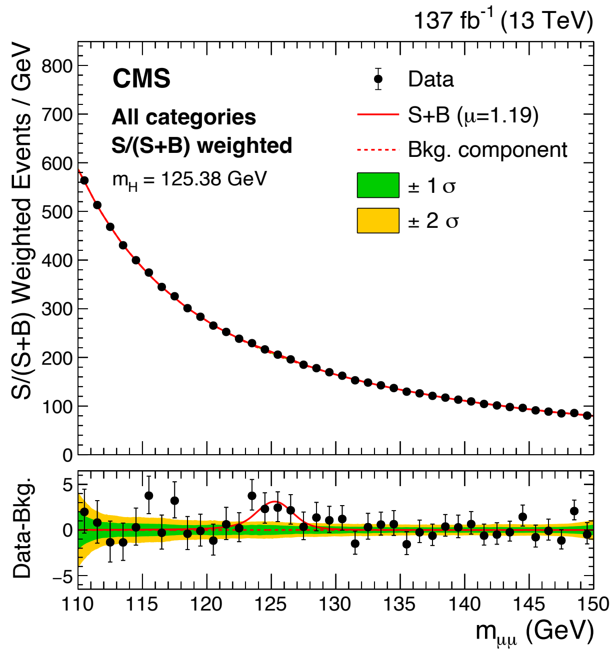
Search for $H \to \mu\mu$ | CMS

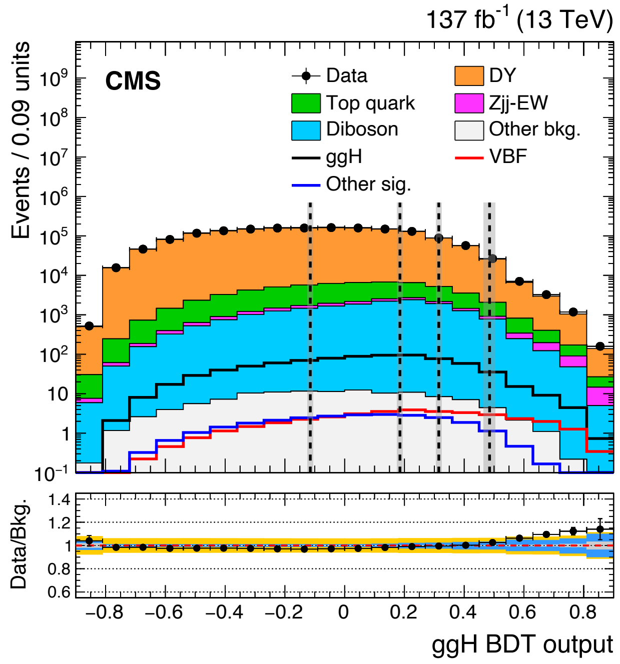
JHEP 01 (2021) 148

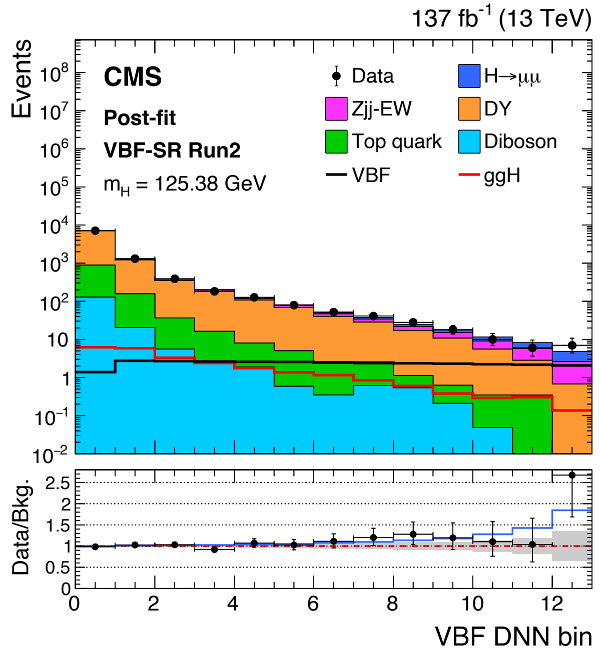
$\text{SM BR}(H \to \mu\mu) \sim 2 \cdot 10^{-4}$

Features

- **Divide-n-fit** strategy to enhance analysis performance for each category
- … except for the **VBF**: **DNN** discriminator with $\mathbf{m_{\mu\mu}}$
- bkg parametrization using a ***core* shape** (shared between categories) and a per-category Chebyshev pdf







Search for $H \to \mu\mu$ | CMS

JHEP 01 (2021) 148

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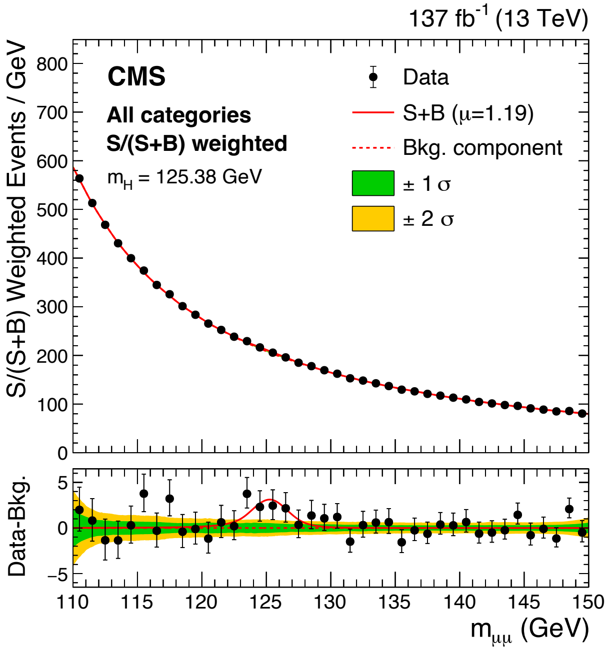
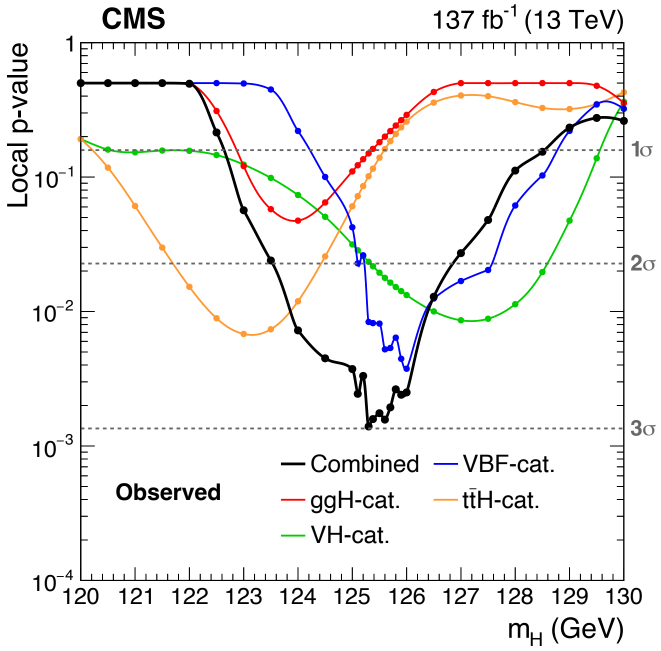
Features

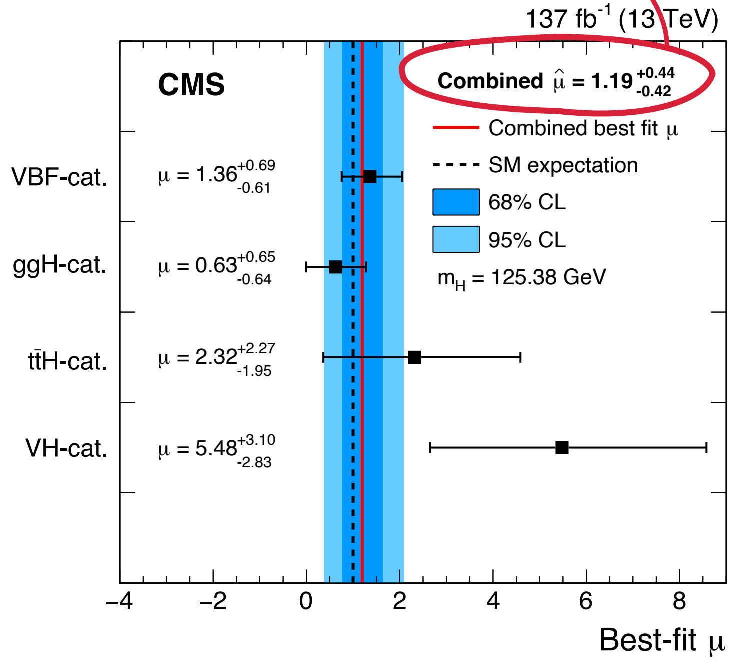
- **Divide-n-fit** strategy to enhance analysis performance for each
- … except for the **VBF**: **DNN** discriminator with $\mathbf{m_{\mu\mu}}$
- bkg parametrization using a ***core* shape** (shared between categ and a per-category Chebyshev pdf

Observed (expected) signal:
- $\mathbf{3.0\sigma\ (2.5\sigma)}$

Signal strength:
- $\hat{\mu} = 1.19^{+0.44}_{-0.42}$







Search for $H \to \mu\mu$ | CMS

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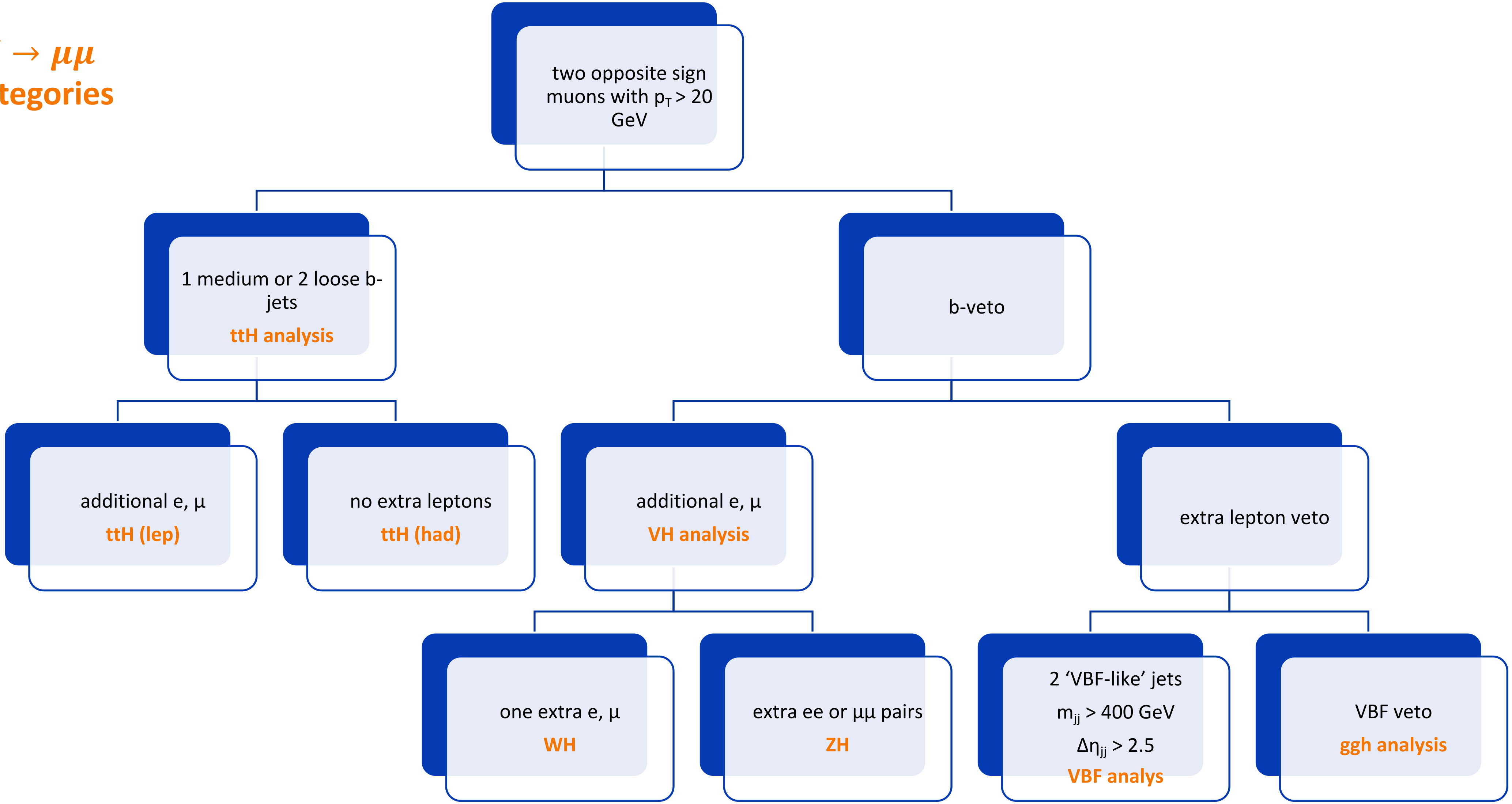
$H \to \mu\mu$ categories



Search for $H \to \mu\mu$ | CMS

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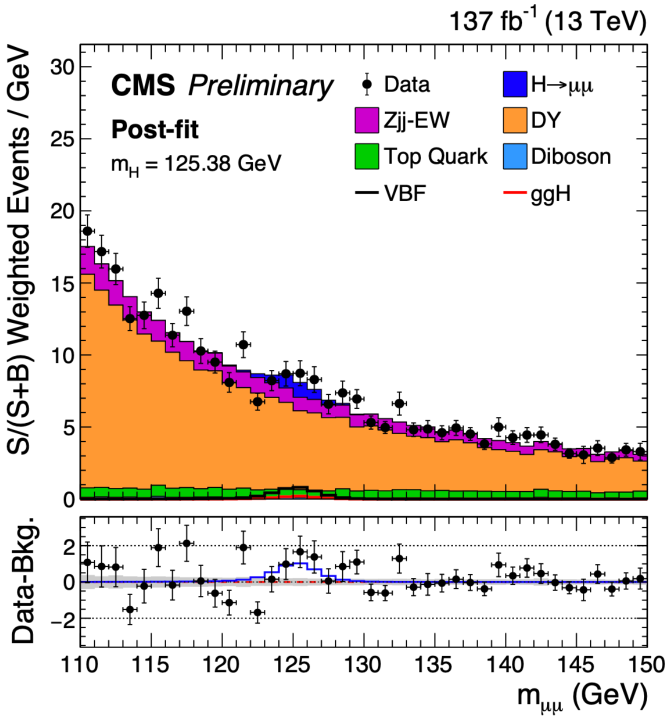
- VBF analysis: events weighted by S/(S+B) of the corresponding bin or a *mass-decorrelated* DNN



- Major sources of uncertainty in the measurement of the signal strength μ and their impact

Uncertainty source	$\Delta\mu$	
Post-fit uncertainty	+0.44	−0.42
Statistical uncertainty	+0.41	−0.40
Systematic uncertainty	+0.17	−0.16
Experimental uncertainty	+0.12	−0.11
Theoretical uncertainty	+0.10	−0.11
Size of simulated samples	+0.07	−0.06

- Observed and expected significances for the incompatibility with the background-only hypothesis

Production category	Observed (expected) signif.	Observed (expected) UL on μ
VBF	2.40 (1.77)	2.57 (1.22)
ggH	0.99 (1.56)	1.77 (1.28)
$t\bar{t}$H	1.20 (0.54)	6.48 (4.20)
VH	2.02 (0.42)	10.8 (5.13)
Combined $\sqrt{s} = 13$ TeV	2.95 (2.46)	1.94 (0.82)
Combined $\sqrt{s} = 7, 8, 13$ TeV	2.98 (2.48)	1.93 (0.81)

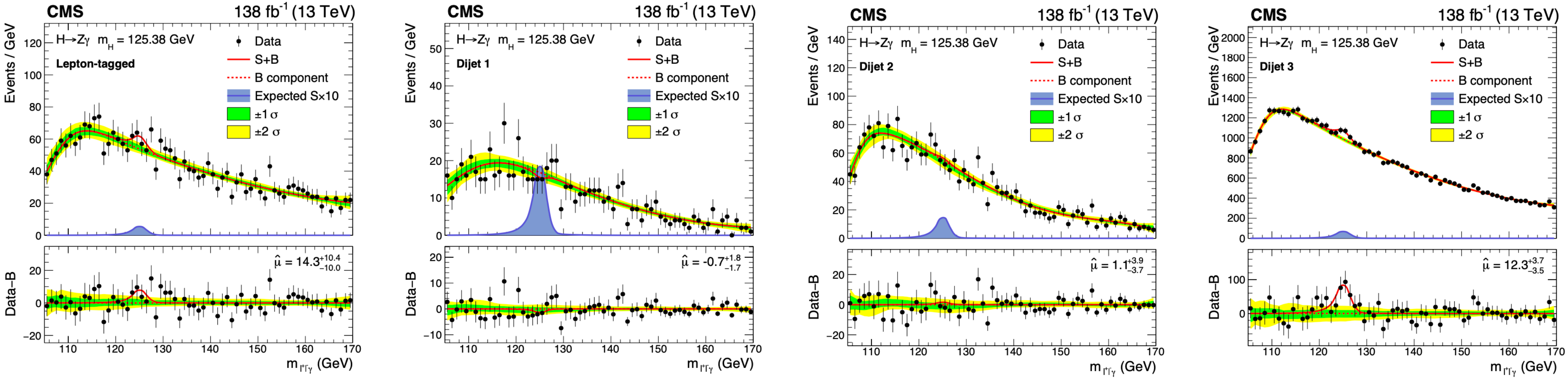
Search for $H \to Z\gamma$ | CMS

arXiv:2204.12945

Summary of the category definitions

- The **lepton-tagged** category requires at least one additional electron or muon
- **Dijet** categories are defined by regions of $\mathbf{D_{VBF}}$
- **untagged** categories are defined by regions of $\mathbf{D_{kin}}$.

Lepton	Dijet 1	Dijet 2	Dijet 3	Untagged 1	Untagged 2	Untagged 3	Untagged 4
≥ 1 e, μ	$\mathcal{D}_{\mathrm{VBF}}$ selection			$\mathcal{D}_{\mathrm{kin}}$ selection			
	0.5–1.0	0.3–0.5	0.0–0.3	0.9–1.0	0.8–0.9	0.4–0.8	0.1–0.4



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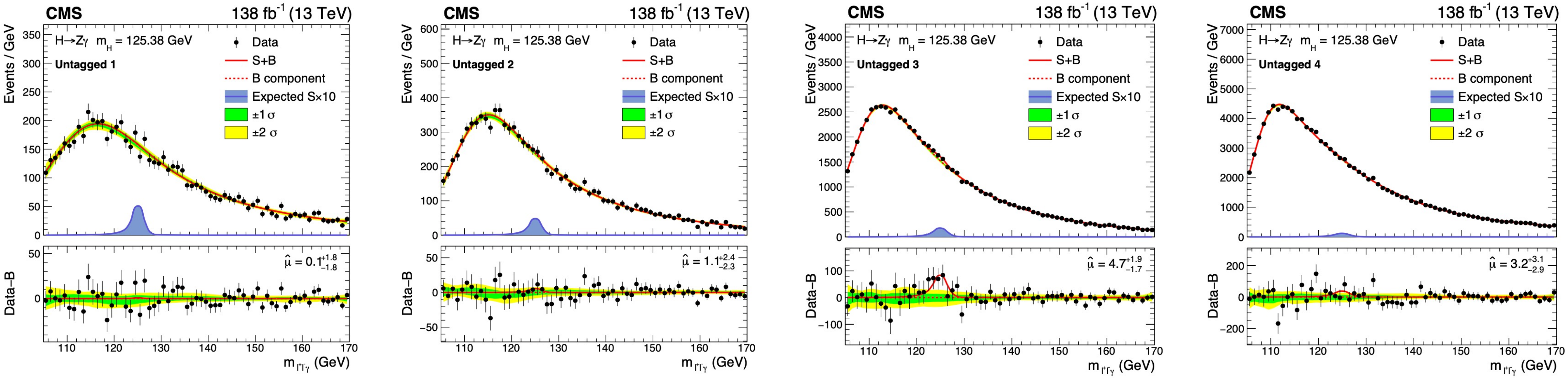

Search for $H \to Z\gamma$ | CMS

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Systematic uncertainties

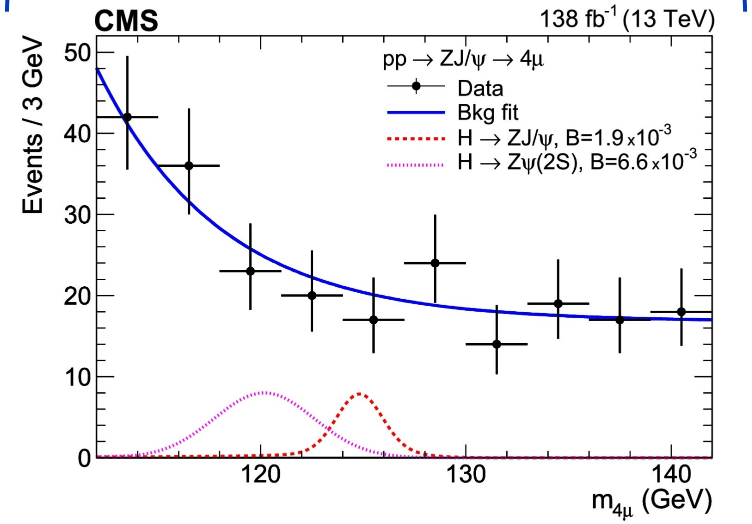
Systematic uncertainties originate from imperfect knowledge of the detector and imperfect signal modeling:

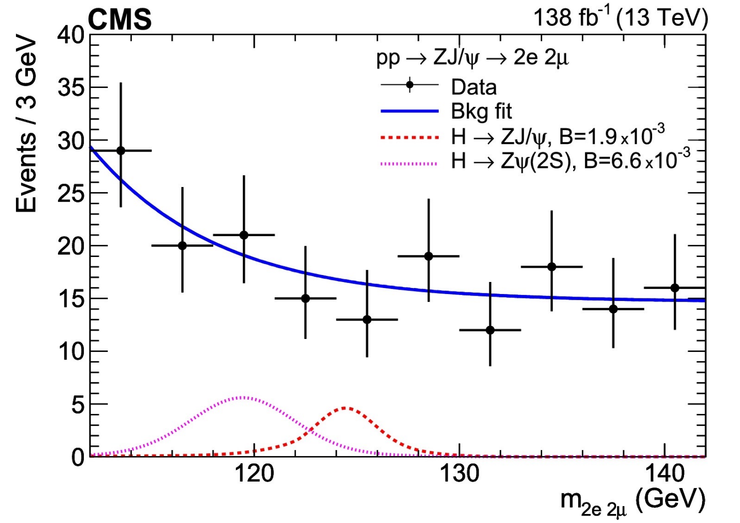
1. **Theoretical cross section calculations**: effects of the **choice of PDFs**, value of the **strong coupling constant**, effect of **missing higher orders** in the perturbative cross section calculations
2. **Integrated luminosity**: overall uncertainty for the **2016–2018** period of **1.6%**
3. **L1 trigger:** During the 2016 and 2017 data-taking periods, a gradual **shift in the timing** of the inputs of the ECAL L1 trigger in the $\eta > 2.4$ region led to a specific inefficiency. A correction of approximately **1%** is applied to the simulation
4. **Trigger**: Uncertainties for the **corrections applied to the simulation** to match the trigger efficiencies measured in data
5. **Photon identification and isolation**: Uncertainties are evaluated for the **corrections applied to the simulation** to match the selection efficiencies in data measured with $Z \to e^+e^-$ events.
6. **Lepton identification and isolation**: Uncertainties are evaluated for the **corrections applied to the simulation** to match electron and muon selection efficiencies in data measured with $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ events.
7. **Pileup modeling**: uncertainty in the description of the pileup in the signal simulation is estimated by varying the total inelastic cross section **by 4.6%**
8. **Kinematic BDT**: uncertainties in the photon and lepton energy and the **correction of the photon MVA discriminant** are propagated to D_{kin}
9. **VBF BDT**: uncertainties in the jet energy and the uncertainty in D_{kin} are propagated to D_{VBF}
10. **Photon energy scale and resolution**: The photon energy in the simulation is varied due to the **ECAL energy scale and resolution uncertainties**, and the effects on the signal mean and resolution parameters are propagated to the fits.
11. **Lepton momentum scale and resolution**: The lepton momentum in the simulation is varied due to the **lepton momentum scale and resolution uncertainties**, and the effects on signal mean and resolution parameters are propagated to the fits.

Search for $\mathbf{H \rightarrow Z\,J/\psi}$ and $\mathbf{J/\psi}$ or $\mathbf{\Upsilon}$ pairs

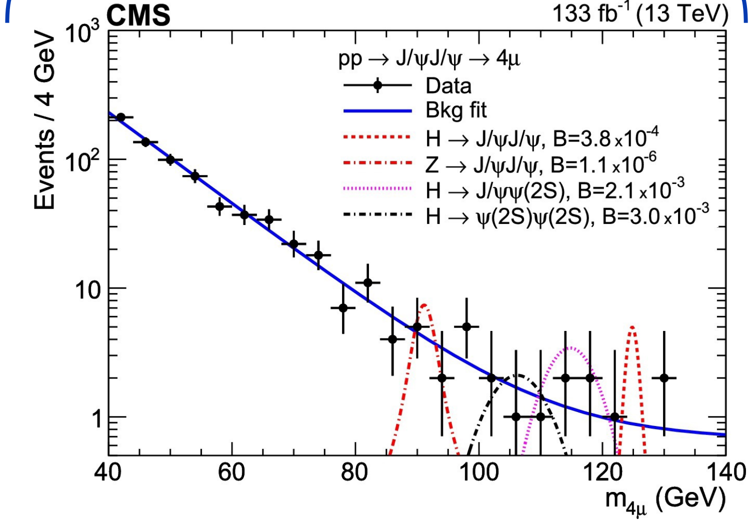
[Phys. Lett. B 842 (2023) 137534](https://doi.org/10.1016/j.physletb.2023.137534)

Z J/ψ and Z ψ(2S) channels



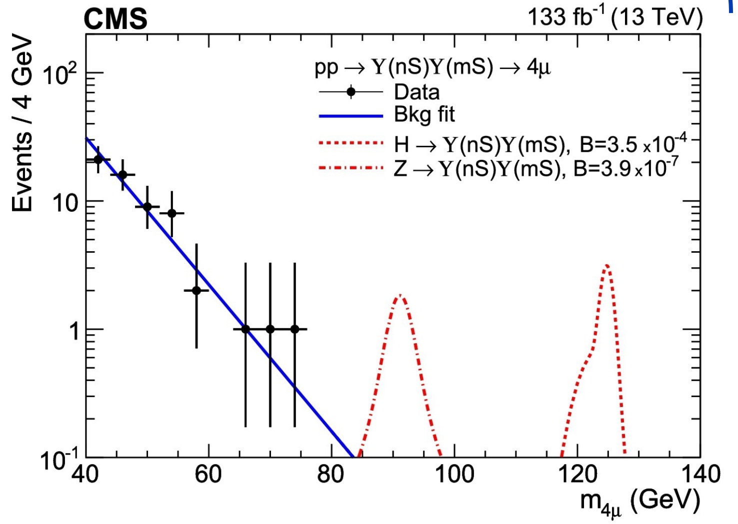


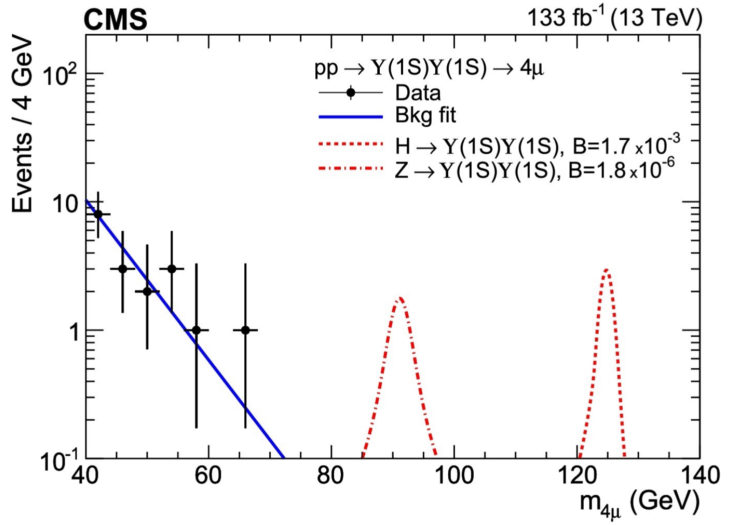
J/ψ and ψ(2S) pairs



Process	Observed Longitudinal	Expected Longitudinal
$\mathcal{B}(H \rightarrow ZJ/\Psi)$	1.9×10^{-3}	$(2.6^{+1.1}_{-0.7}) \times 10^{-3}$
$\mathcal{B}(H \rightarrow Z\Psi(2S))$	6.6×10^{-3}	$(7.1^{+2.8}_{-2.0}) \times 10^{-3}$
$\mathcal{B}(H \rightarrow J/\Psi J/\Psi)$	3.8×10^{-4}	$(4.6^{+2.0}_{-0.6}) \times 10^{-4}$
$\mathcal{B}(H \rightarrow \Psi(2S)J/\Psi)$	2.1×10^{-3}	$(1.4^{+0.6}_{-0.4}) \times 10^{-3}$
$\mathcal{B}(H \rightarrow \Psi(2S)\Psi(2S))$	3.0×10^{-3}	$(3.3^{+1.5}_{-0.9}) \times 10^{-3}$
$\mathcal{B}(H \rightarrow \Upsilon(nS)\Upsilon(mS))$	3.5×10^{-4}	$(3.6^{+0.2}_{-0.3}) \times 10^{-4}$
$\mathcal{B}(H \rightarrow \Upsilon(1S)\Upsilon(1S))$	1.7×10^{-3}	$(1.7^{+0.1}_{-0.1}) \times 10^{-3}$
$\mathcal{B}(Z \rightarrow J/\Psi J/\Psi)$	11×10^{-7}	$(9.5^{+3.8}_{-2.6}) \times 10^{-7}$
$\mathcal{B}(Z \rightarrow \Upsilon(nS)\Upsilon(mS))$	3.9×10^{-7}	$(4.0^{+0.3}_{-0.3}) \times 10^{-7}$
$\mathcal{B}(Z \rightarrow \Upsilon(1S)\Upsilon(1S))$	1.8×10^{-6}	$(1.8^{+0.1}_{-0.0}) \times 10^{-6}$

ϒ(nS) and ϒ(1S) pairs





Search for H to quarkonia | CMS

$$\text{SM BR}(H \to ZJ/\psi) \sim 2 \cdot 10^{-6}$$
$$\text{SM BR}(H \to J/\psi J/\psi) \sim 2 \cdot 10^{-10}$$

Systematic uncertainties

Systematic uncertainties originate from imperfect knowledge of the detector and imperfect signal modeling:

1. **integrated luminosities:** overall uncertainty for the 2016–2018 period is 1.6%
2. The **differences between data and simulation** for the **trigger**, offline **muon reconstruction**, **identification**, and **isolation** efficiencies are corrected by reweighting the simulated events with data-to-simulation correction factors, which are obtained with the tag-and-probe method using J/ψ events: less than **2(2)**, **0.5(0.5)** and **1(3)%** for the ZJ/ψ (QQ) channel. Analogously, the uncertainty in the **electron** reconstruction, identification and trigger efficiency is found to be about **2%**
3. The relative difference in the **four-lepton vertex criterion** between data and simulation is evaluated with ZJ/ψ (J/ψ pair) event samples. It is found to be less than **2(3)%** for the ZJ/ψ (QQ) channel.
4. Differences in the **lepton momentum scale** and **resolution** in data and simulation are estimated from J/ψ and Z dilepton signals and extrapolated to the four-lepton signals. The systematic uncertainty is estimated as the relative change in the upper limit when varying the signal mass mean and width by these differences. They are found to be **less than 1(3)%** in the 4μ (2e2μ) channel.
5. The theoretical uncertainties in the **production cross section for the H** (Z boson) are **3.2%** (1.7%) due to the choice of the PDF and the value of the strong coupling constant
6. A **common parameterization for each signal model** is used for the entire run period. The relative uncertainty in the signal model due to the change in detector conditions in each year is determined to be **1(2)%** for the ZJ/ψ (QQ) channels.
7. The background is alternatively parameterized with a **second order Chebyshev polynomial or a power law function**. The relative uncertainty due to the choice of the background function is found to be **negligible**

$H/Z \to \psi'$ and a photon

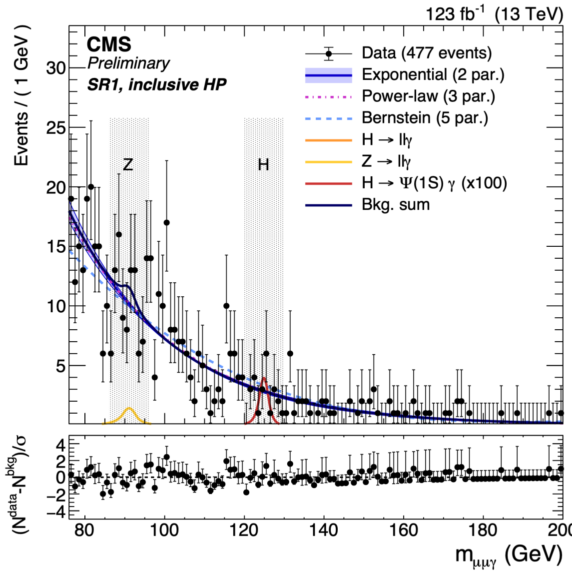
SM $\mathcal{B}(\mathrm{H} \to \gamma\ \mathrm{J}/\psi) \sim 3 \cdot 10^{-6}$
SM $\mathcal{B}(\mathrm{H} \to \gamma\ \psi(2S)) \sim 1 \cdot 10^{-6}$
SM $\mathcal{B}(\mathrm{Z} \to \gamma\ \mathrm{J}/\psi) \sim 9 \cdot 10^{-8}$
SM $\mathcal{B}(\mathrm{Z} \to \gamma\ \psi(2S)) \sim 5 \cdot 10^{-8}$

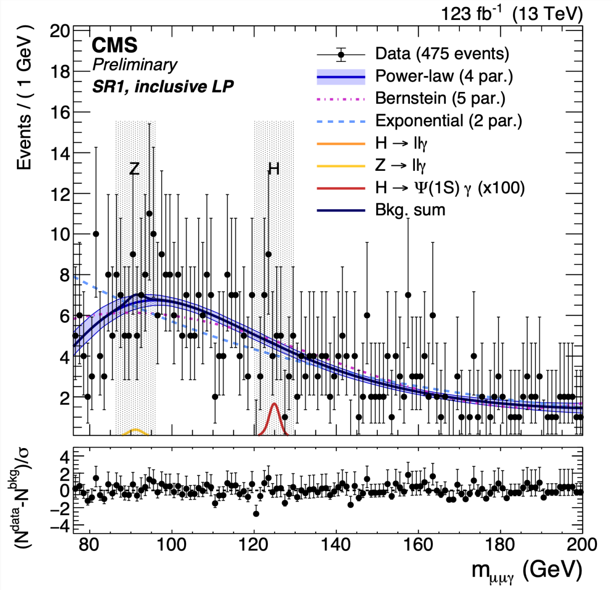
NEW

Categorization for Higgs analysis

- **1** inclusive category for $\psi(2S)$
- **4** exclusive categories for $\psi(1S)$:
  - **2 ggH** categories high and low purity (HP or LP): based on the angle between the ψ and γ direction in the H rest frame
  - **VBF**
  - **High flavor lepton** (HFL): at least 1 b-jet

Process	This paper (123 fb^{-1}) $\mu_{obs}(\mu_{exp})$	$\sigma_{obs}(\sigma_{exp})$ [pb]	$\mathcal{B}_{obs}(\mathcal{B}_{exp})$
$Z \to \Psi(1S)\gamma$	$7.2\ (8.6^{+4.1}_{-2.7})$	$3.8\ (4.4^{+1.9}_{-1.3}) \times 10^{-2}$	$0.6\ (0.7^{+0.3}_{-0.2}) \times 10^{-6}$
$Z \to \Psi(2S)\gamma$	$29\ (68^{+36}_{-22})$	$8\ (19^{+8}_{-6}) \times 10^{-2}$	$1.3\ (3.1^{+1.4}_{-0.9}) \times 10^{-6}$
$H \to \Psi(1S)\gamma$	$88\ (62^{+30}_{-19})$	$1.4\ (1.0^{+0.5}_{-0.3}) \times 10^{-2}$	$2.6\ (1.8^{+0.9}_{-0.6}) \times 10^{-4}$
$H \to \Psi(2S)\gamma$	$970\ (781^{+417}_{-259})$	$5.5\ (4.4^{+2.3}_{-1.5}) \times 10^{-2}$	$9.9\ (8.0^{+4.2}_{-2.6}) \times 10^{-4}$





ψ(2S) cat