



The Current Higgs-Boson Portrait by the CMS Experiment

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on behalf of the CMS Collaboration

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2023-10-10



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Experimental Setup



Large Hadron Collider (LHC)



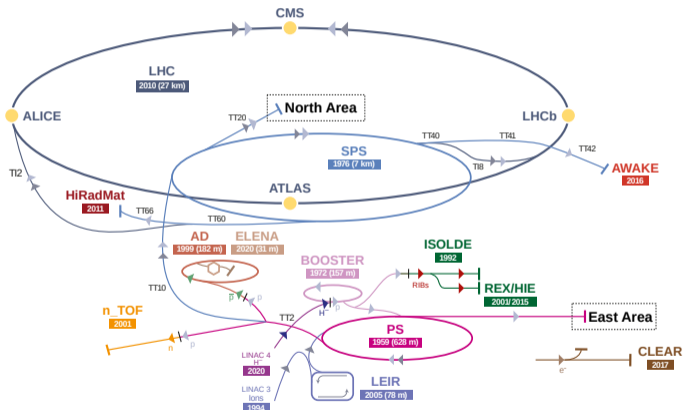
CERN accelerator complex

Data delivered @ \sqrt{s} :

R1	6.1 fb ⁻¹ @7 TeV	2011
R1	23.3 fb ⁻¹ @8 TeV	2012
R2	4.3 fb ⁻¹ @13 TeV	2015
R2	41.6 fb ⁻¹ @13 TeV	2016
R2	49.8 fb ⁻¹ @13 TeV	2017
R2	67.9 fb ⁻¹ @13 TeV	2018
R3	42.0 fb ⁻¹ @13.6 TeV	2022
R3	31.4 fb ⁻¹ @13.6 TeV	2023

266.4 fb⁻¹ and grows

- $\mathcal{L}_{\max} = 2.5 \cdot 10^{34} \frac{\text{Hz}}{\text{cm}^2}$ ($\mathcal{L}_{\text{proj}} = 10^{34} \frac{\text{Hz}}{\text{cm}^2}$)
- Collisions $\sim 52/\text{Hz}$





Detector: Compact Muon Solenoid

CMS detector with cut (phase 0)

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm^2) -1 m² -66M channels
Microstrips (80-180 μm) -200 m² -9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying -18,000 A

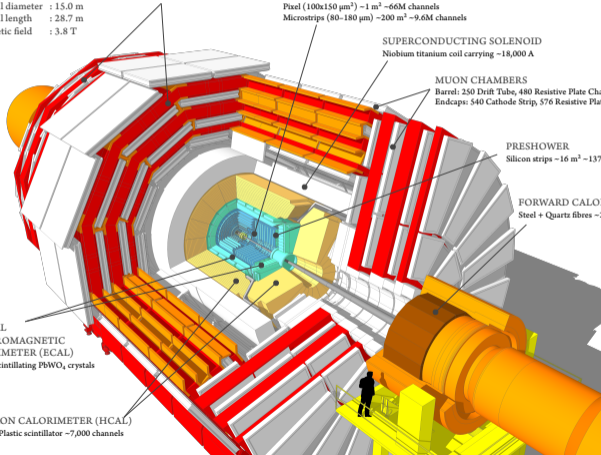
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
Silicon strips -16 m² -137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres -2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
-76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator -7,000 channels



40 MHz

×

20-52 p-p collisions

×

p-p = ~500 final particles

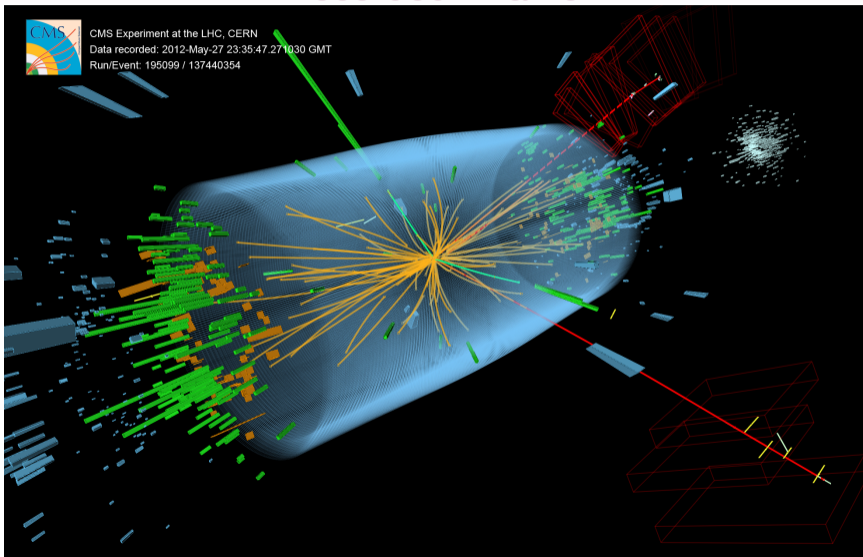
=

~50 Tb/s

Final state	Resolution
γ	1.5-5% @ 60 GeV
e	2-4% @ 10 GeV
μ	1-1.5% @ 10 GeV
j	o(10)%



Recorded "Frame"





The Discovery of 2012



PHYSICS LETTERS B

Abstracted/Indexed in: Current Contents: Physical, Chemical & Earth Sciences/INSPEC/Zentralblatt MATH/MathSciNet.
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Volume 716, issue 1

17 September 2012

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0370-2693(20120917)716:1;1-H

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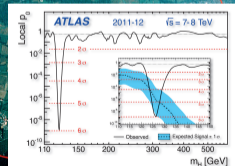
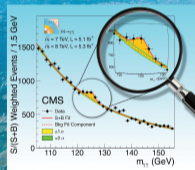
Volume 716, Issue 1, 17 September 2012

ISSN 0370-2693



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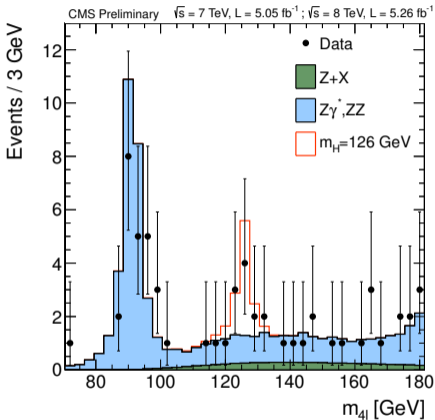
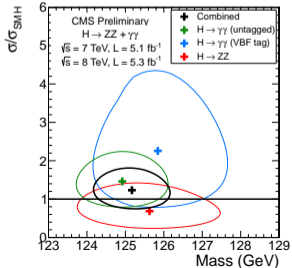
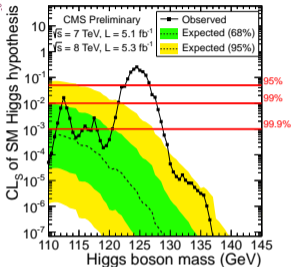
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Highlights from 2012



- Both ATLAS and CMS have announced significant excesses at invariant masses of around 125 GeV.
- Results of further studies were consistent with the SM Higgs boson.

Combined p -value $\sim 5 \sigma$



François Englert Peter Higgs

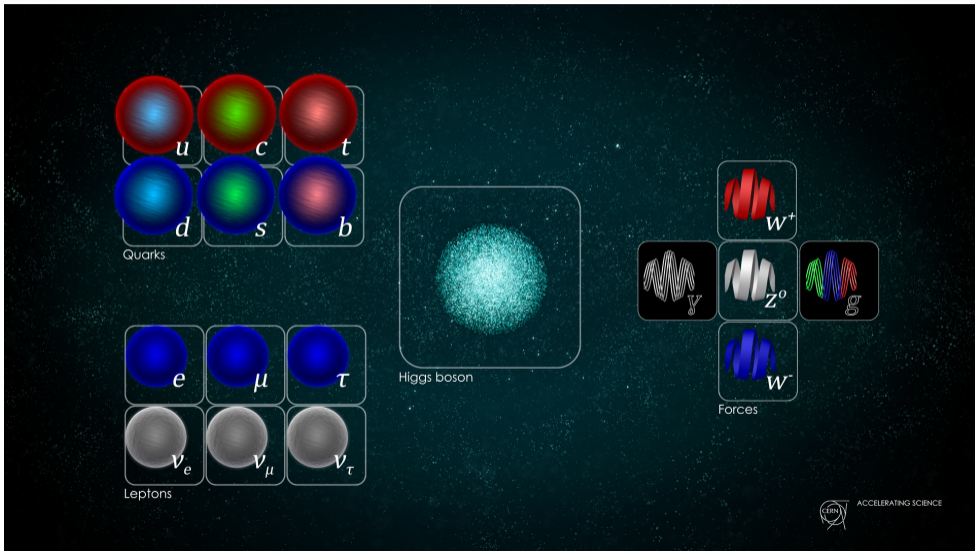


Nobel Prize in 2013





The Central Piece of the Standard Model

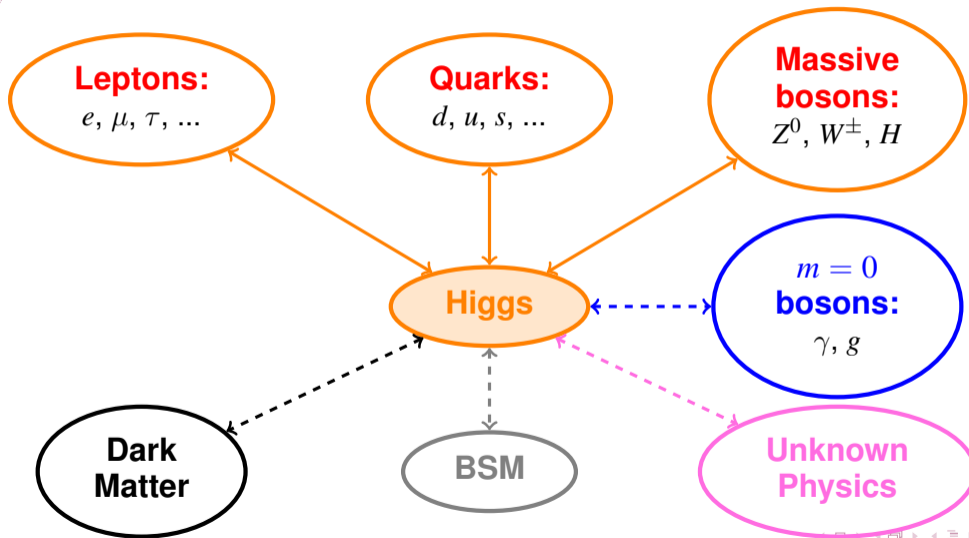




Higgs Studies: The Big Picture

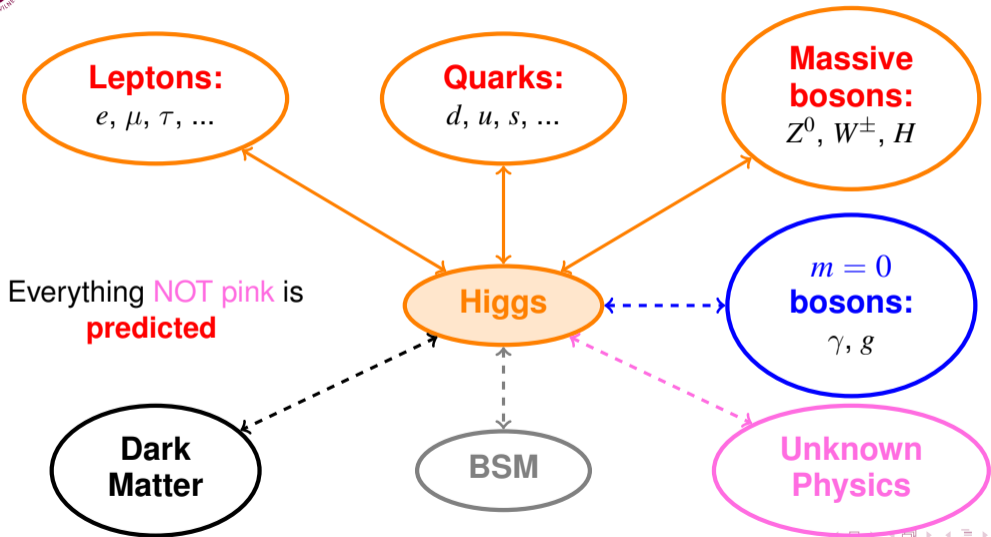


Higgs as a Probe and Vice Versa



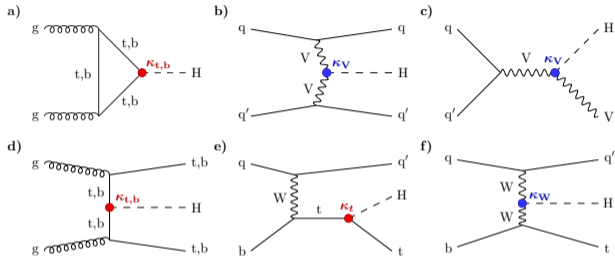


Higgs as a Probe and Vice Versa

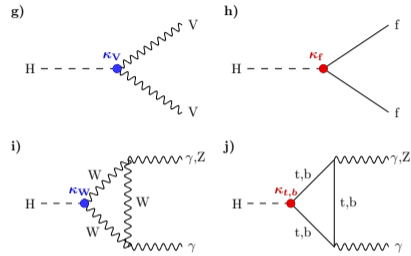




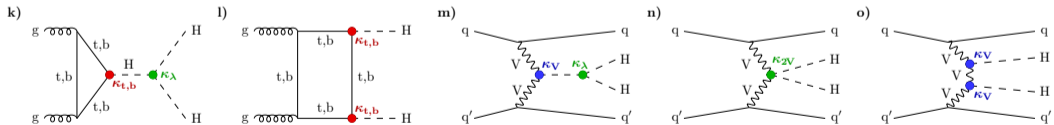
Higgs boson production modes



Higgs boson decay channels



Higgs boson pair production

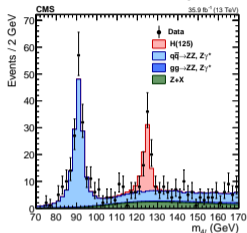




“Direct” Measurements



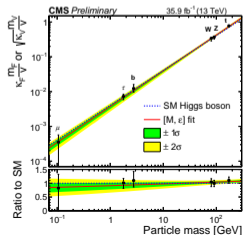
1. Look for bumps:



Integrated cross-section measurements:

- Select your favorite channel
- Full story in *one* number
- For predicted processes
- Depend on model assumptions

2. Extract signal:



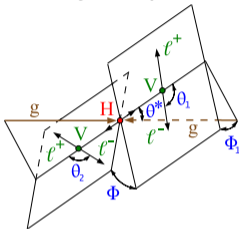
Currently:

- So far, so good: SM holds well

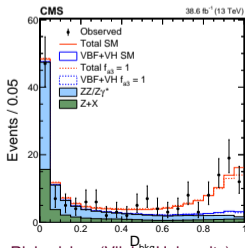


“Indirect” Measurements

1. Pick your space:



2. Do your MVA:



Differential measurements:

- Angular correlations:
 - Spin-parity
 - Exotic couplings
- Differential phase space:
 - Boosted decays
 - Jet multiplicity
 - p_T, \dots
 - EFT
- Multiple channels
- ...

Quite some possibilities for variations

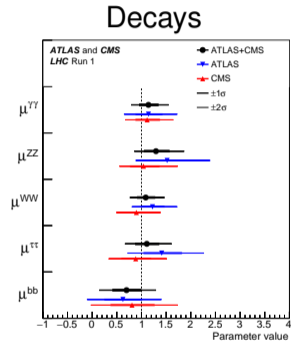
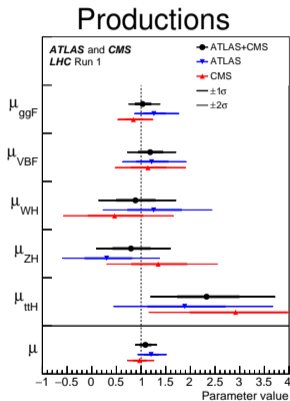
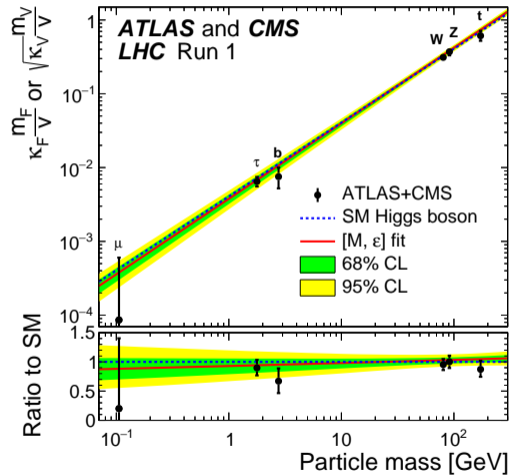


Overview of the Higgs Studies

10 Years After the Discovery



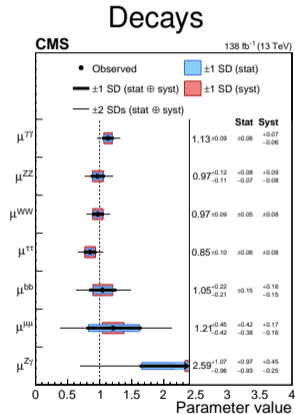
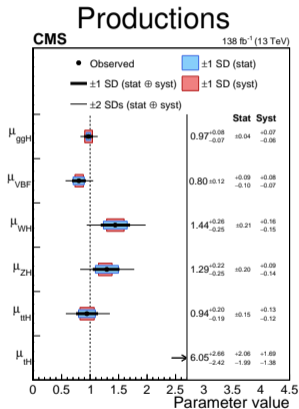
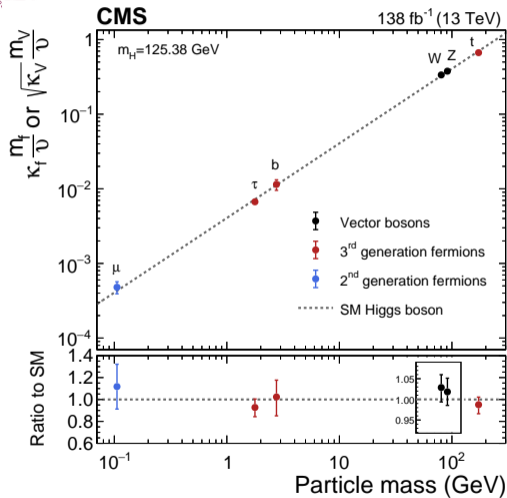
Summary of LHC Run 1



JHEP 08, 045 (2016)



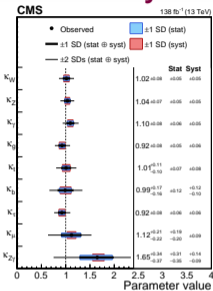
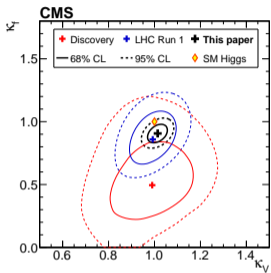
Summary of LHC Run 2 (1/2)



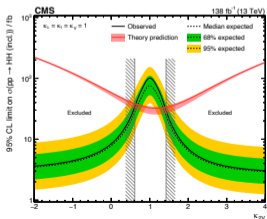
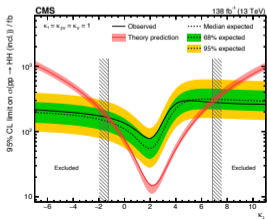
Nature **607**, no.7917, 60-68 (2022)



Summary of LHC Run 2 (2/2)

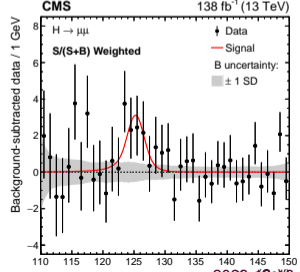
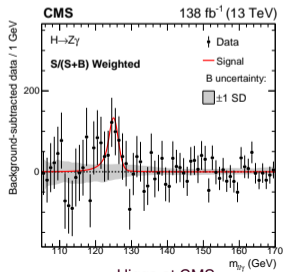
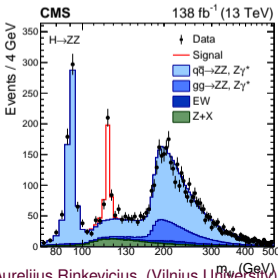
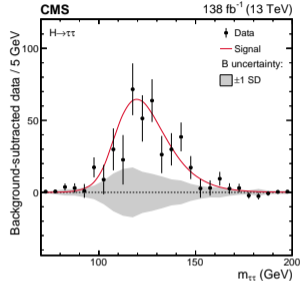
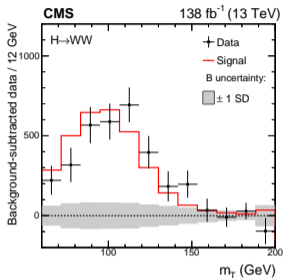
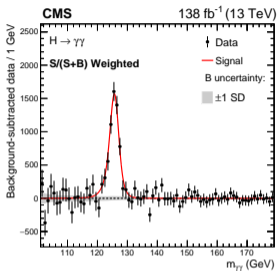


- Improved resolution WRT Run 1
 - CMS alone!
- Rare channels become visible
 - $t\bar{t}H$, $\mu\mu$, $Z\gamma$, ...
- H self-coupling (HH) on the horizon
- Data is consistent with the SM





Prominent Signal in Many Modes — Further Studies Possible

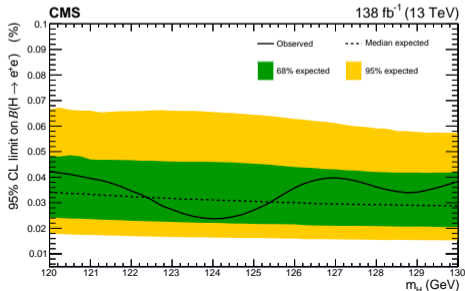
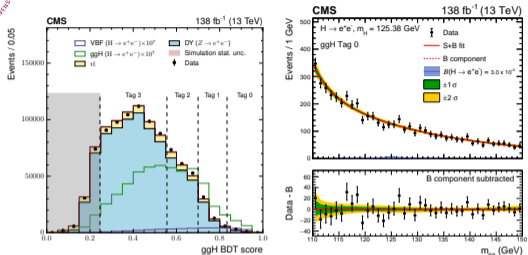




Recent Higgs-Boson Studies



Search for the Higgs Boson Decay to a Pair of Electrons

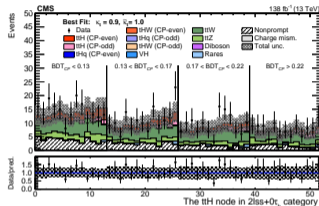
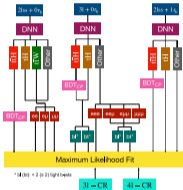


- Very low cross section
 - The weakest SM coupling
- BDT tagging helps with DY
- Miniscule signal \Rightarrow BR limit study
- $\mathcal{B}_{\text{SM}} \sim o(10^{-9})$

Phys. Lett. B **846**, 137783 (2023)

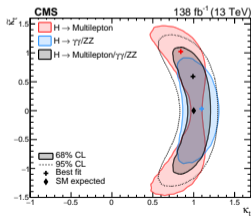
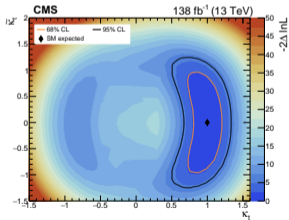


Search for CP Violation in $t\bar{t}H$ and tH Production in Multilepton Channels



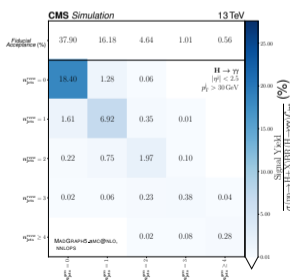
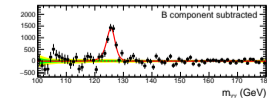
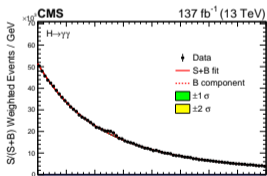
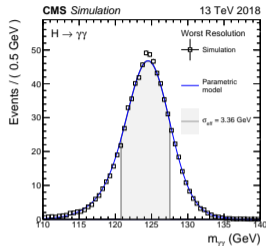
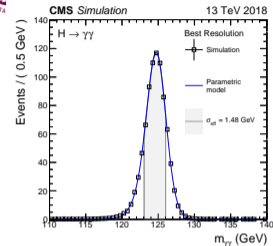
- A prominent $t\bar{t}H$ measurement
- Many backgrounds
 - Multiclass ANN to separate
- CP separation by BDT
- Consistent with the SM

JHEP 07, 092 (2023)





Inclusive and Differential Fiducial Cross Sections in $H \rightarrow \gamma\gamma$ (1/2)

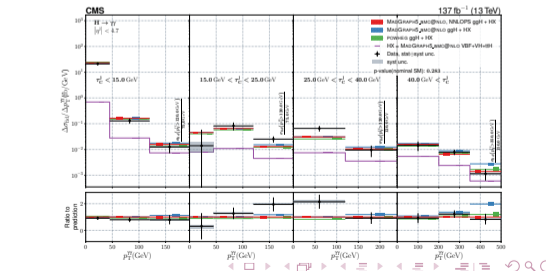
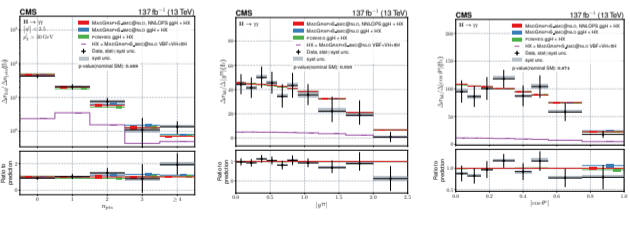
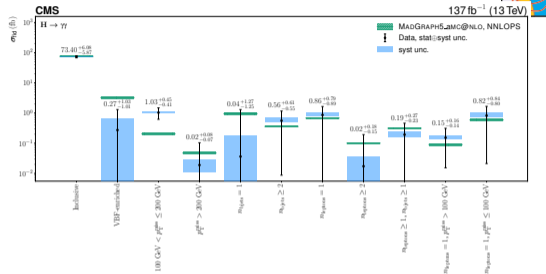
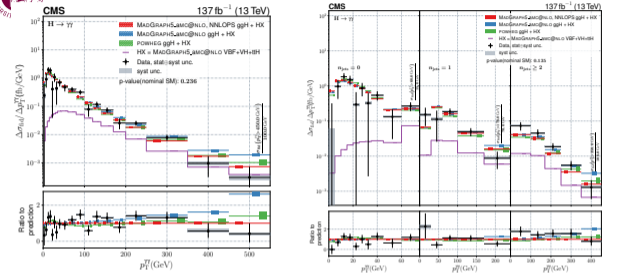


- High resolution final state
- Fiducial selection
- Double differential measurements
- $\sigma_{fid} = 73.4^{+5.4}_{-5.3}(\text{stat})^{+2.4}_{-2.2}(\text{syst}) \text{ fb}$
- $\sigma_{SM} = 75.4 \pm 4.1 \text{ fb}$
- Consistent with the SM

JHEP 07, 091 (2023)

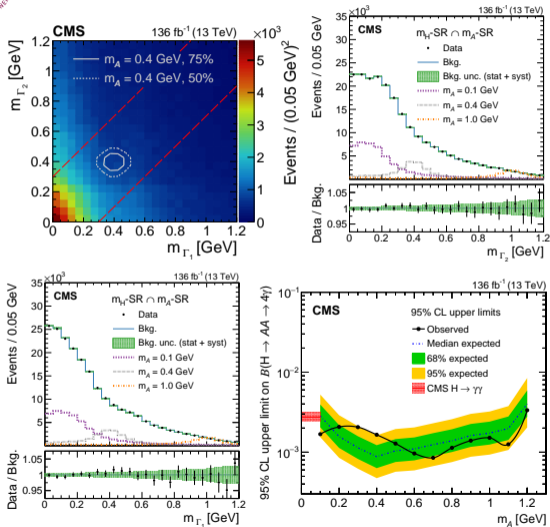


Inclusive and Differential Fiducial Cross Sections in $H \rightarrow \gamma\gamma$ (2/2)





Search for Exotic $H \rightarrow \mathcal{A}\mathcal{A} \rightarrow 4\gamma$

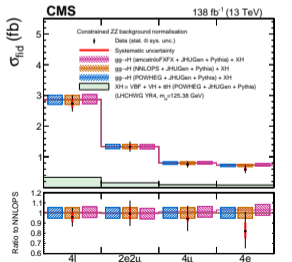
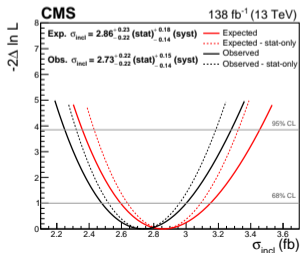
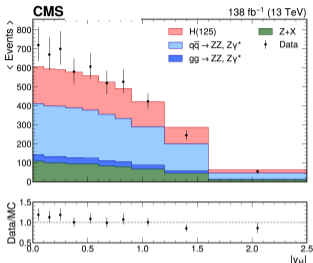
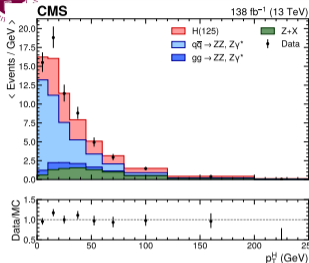


- Γ : merged diphoton
- \mathcal{A} : low-mass spin-0 particle
- Used new reconstruction to get Γ
- BR limits consistent with the SM

Phys. Rev. Lett. **131**, 101801 (2023)



Inclusive and Differential $H \rightarrow 4\ell$

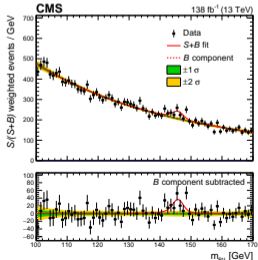
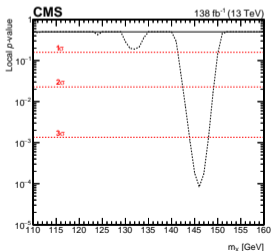
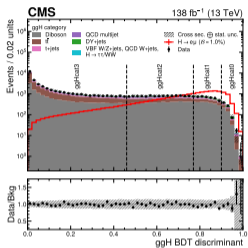
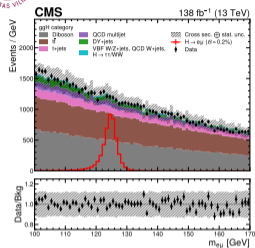


- Well-measurable final state
- Rich differential program
- Pushing event-generator limits
- Consistent with the SM

JHEP 08, 040 (2023)



Search for Lepton-Flavor Violating H in $e\mu$ Final State

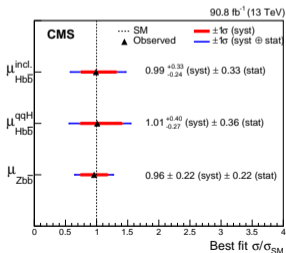
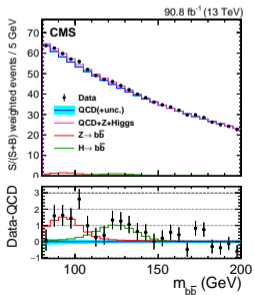
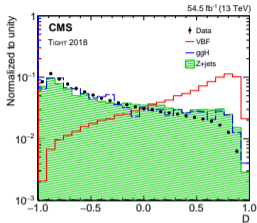
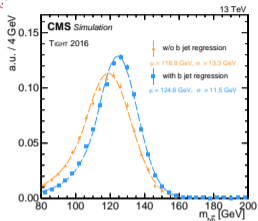


- Analysis in ggH and VBF cats.
- Energy scales \Rightarrow main uncertainties
- 3.8σ (2.8) deviation $m_{\chi} = 146$ GeV
- Consistent with the SM @125 GeV

HIG-22-002



Measurement of VBF $H \rightarrow b\bar{b}$

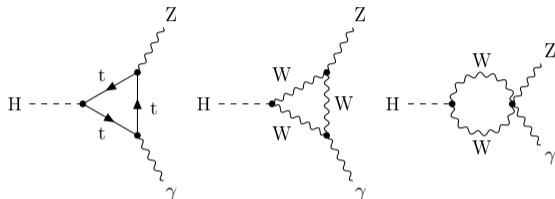


- Major background: QCD
- Major irreducible background: Z+jets
- Other backgrounds: $t\bar{t}$, t/\bar{t} , W +jets
- VBF: 3 tight categories on BDT
- Significance (qqH): 2.4 (2.7) SDs
- Consistent with the SM

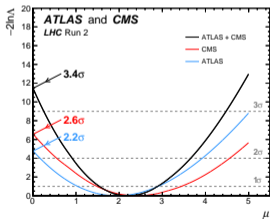
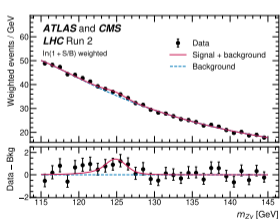
HIG-22-009



Evidence for $H \rightarrow Z\gamma$ at the LHC



- Dominant backgrounds: $DY+\gamma$, $DY+jet$
 - Misidentified jet \rightarrow “ γ ”
- $\mu = 2.2 \pm 0.6$ (stat.) $_{-0.2}^{+0.3}$ (syst.)
- $\mu_{SM} = 1.0 \pm 0.6$ (stat.) ± 0.2 (syst.)
- Significance: 3.4 (1.6) SDs
- Consistent with the SM



HIG-23-002



Summary



Summary

- Run 2 resulted in a variety of the Higgs boson studies
- Deeper probing of the Higgs boson continues
- So far studies are consistent with the SM Higgs boson



Backup



$$\tau_C^j = \max_{k \in \text{jets}} \left(\frac{\sqrt{E_k^2 - p_{z,k}^2}}{2 \cosh(y_k - y_H)} \right) \quad (1)$$