Newest Higgs Results from the CMS Experiment

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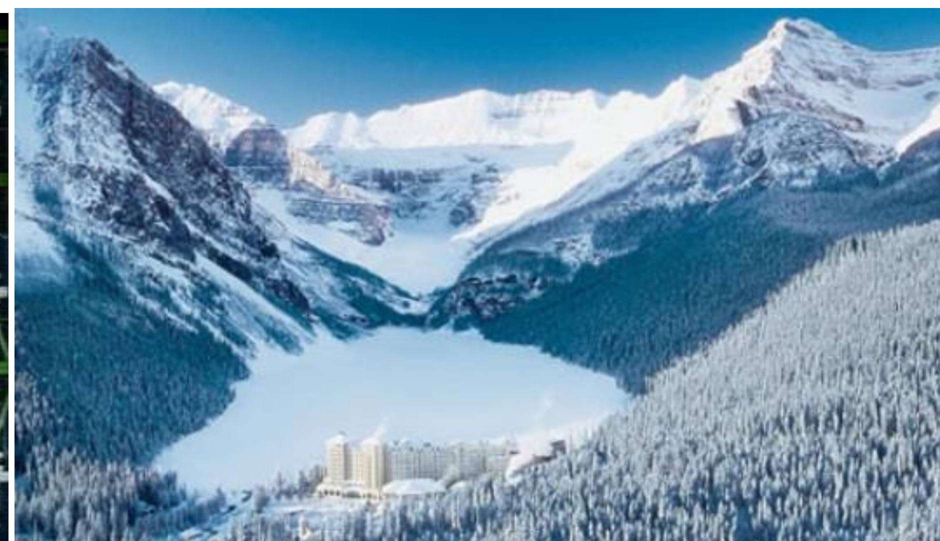
On behalf of the CMS Collaboration

February 20, 2023



10 Years with the Higgs Boson

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A portrait of the Higgs boson by the CMS experiment ten years after the discovery

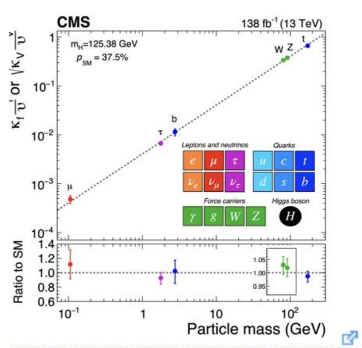
The CMS Collaboration

Nature **607**, 60–68 (2022) | Cite this article

Abstract

In July 2012, the ATLAS and CMS experiments at the CERN Large Hadron Collider announced the observation of a Higgs boson at a mass of around 125 gigaelectronvolts. Ten years later, and with the data corresponding to the production of a 30-times larger number of Higgs bosons, we have learnt much more about the properties of the Higgs boson. The CMS experiment has observed the Higgs boson in numerous fermionic and bosonic decay channels, established its spin–parity quantum numbers, determined its mass and measured its production cross-sections in various modes. Here the CMS Collaboration reports the most up-to-date combination of results on the properties of the Higgs boson, including the most stringent limit on the cross-section for the production of a pair of Higgs bosons, on the basis of data from proton–proton collisions at a centre-of-mass energy of 13 teraelectronvolts. Within the uncertainties, all these observations are compatible with the predictions of the standard model of elementary particle physics. Much evidence points to the fact that the standard model is a low-energy approximation of a more comprehensive theory. Several of the standard model issues originate in the sector of Higgs boson physics. An order of magnitude larger number of Higgs bosons, expected to be examined over the next 15 years, will help deepen our understanding of this crucial sector.

- Over this decade a transition from discovery to precision measurements



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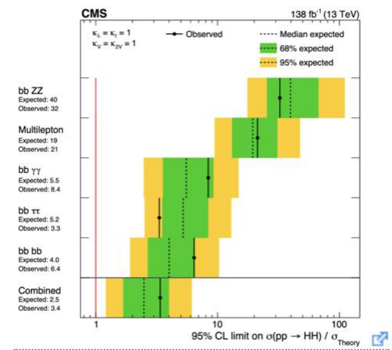
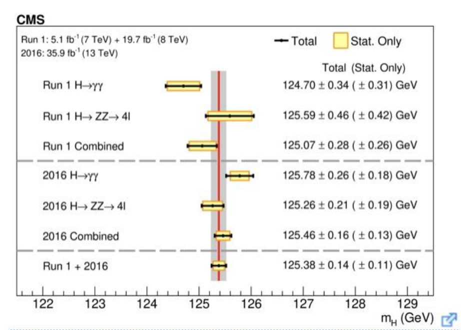
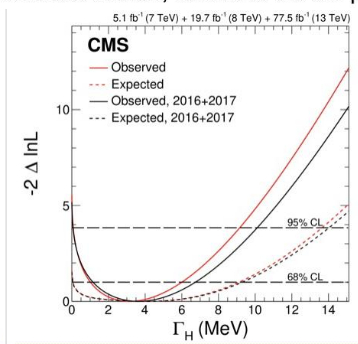


Expected and observed 95% CL upper limits on the HH production cross section, relative to the SM prediction,



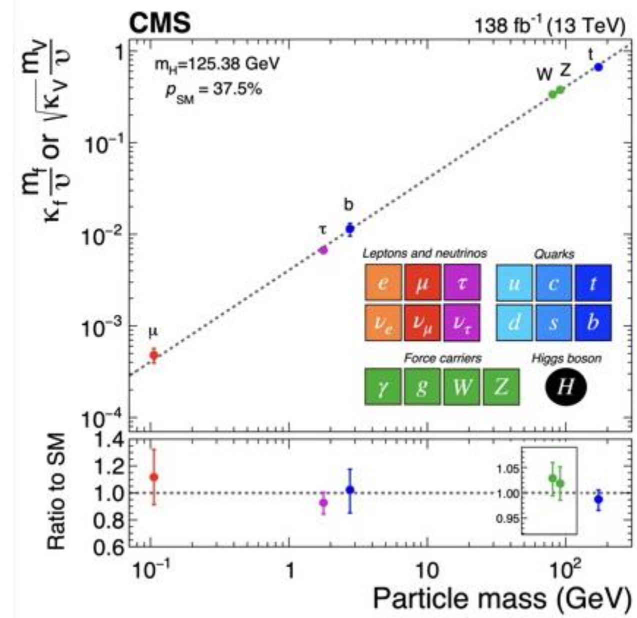
Summary of the measured Higgs boson mass in the H→γγ and H→ZZ→4ℓ decay channels, and the combination of the two: png

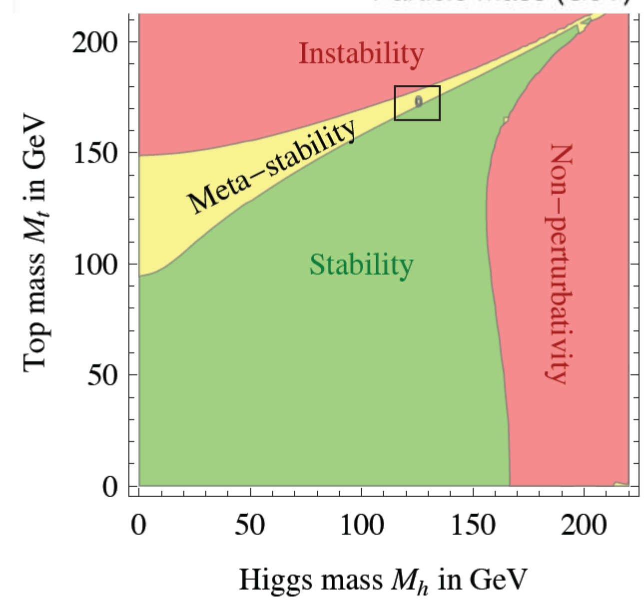


Likelihood scan versus the ΓH variable: png

Precision Measurements

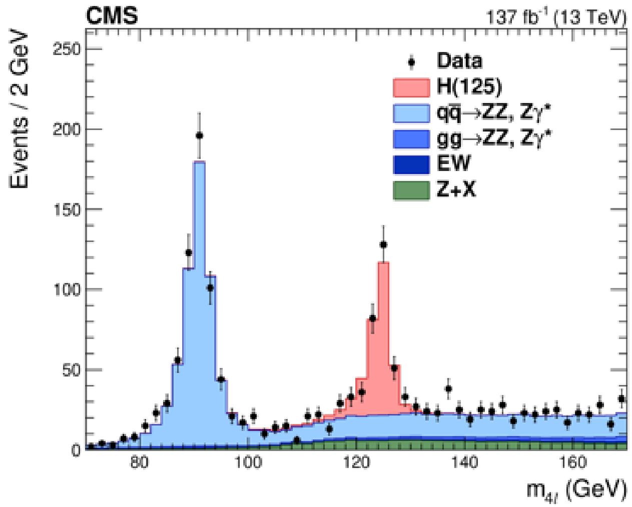
- Important for quantifying the mechanism of the electroweak symmetry breaking
  - In the SM Higgs sector, m_H is the only free parameter, so needs to be measured
  - Couplings: sensitivity comes both through production and decay modes
- A window into the unknown:
  - Small deviations of couplings from SM predictions would indicate presence of new physics
    - Much like the insight from the LEP-era measurements at Z mass
  - What is the shape of the Higgs potential? Is our vacuum even stable?
    - How do we know that we won’t explode tomorrow if the Universe transitions to the true vacuum?



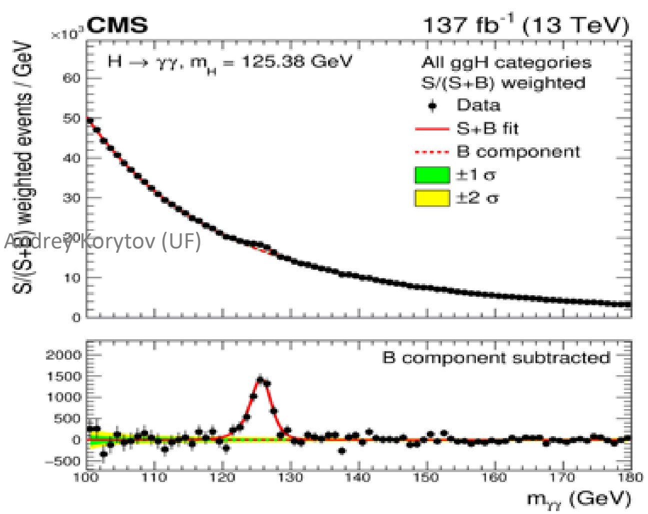


Higgs Boson Stats: Mass

$H \to ZZ \to 4\ell$ [Run 2]



$H \to \gamma\gamma$ [Run 2]



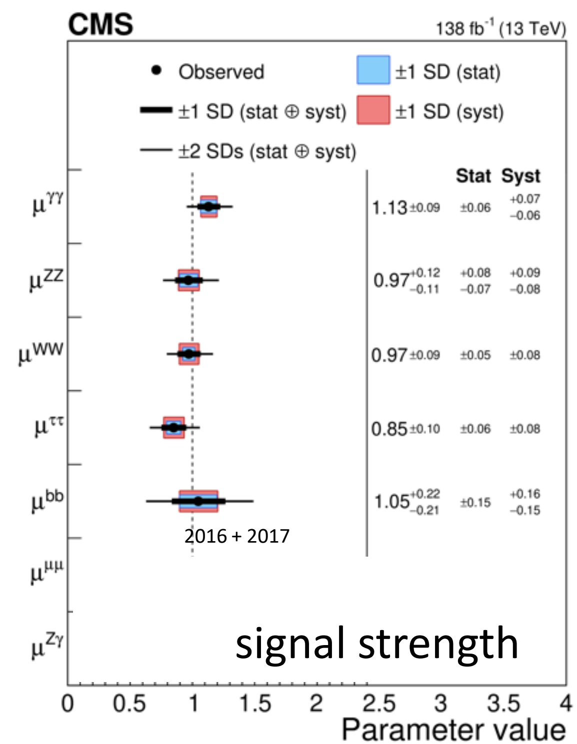
- $H \to ZZ \to 4\ell$ and $H \to \gamma\gamma$ are workhorse channels
  - Run 1 + 2016 results: 125.38 ± 0.14 GeV
    - PLB 805 (2020) 135425
- Still the most precise
  - $H \to ZZ \to 4\ell$: 125.26 ± 0.20(stat) ± 0.08(syst) GeV
    - JHEP11 (2017) 047
  - $H \to \gamma\gamma$: 125.78 ± 0.18(stat) ± 0.18(syst) GeV
    - PLB 805 (2020) 135425
- Statistical powers of the two channels are similar
  - Emerging challenge in $H \to \gamma\gamma$: syst. uncertainties become a limiting factor
- Run 2: Results in 2023, expect precision <100 MeV
- Outlook @HL-LHC: expected precision ~20 MeV
  - CMS PAS FTR-21/007, -21/008

Higgs Boson Stats: Decay Modes

SM Higgs

bb	WW	ττ	cc	ZZ	γγ	Zγ	μμ	“hopeless”: gg, qq, ee
58%	21%	6.3%	2.9%	2.6%	0.23%	0.15%	0.022%	9%

- Green: five well-established decay modes (>5σ)
  - They comprise ~90% of the total SM Higgs width.
  - All event rates are compatible with the SM predictions
  - The overall signal strength μ = 1.002 ± 0.057
- Emerging challenge: experimental statistical uncertainties are becoming comparable to experimental systematics and theory uncertainties
  - E.g. the overall combined signal strength
  - μ = 1.002 ± 0.036(stat) ± 0.029(exp) ± 0.033 (theory)
- In gray: three decay modes being searched for…



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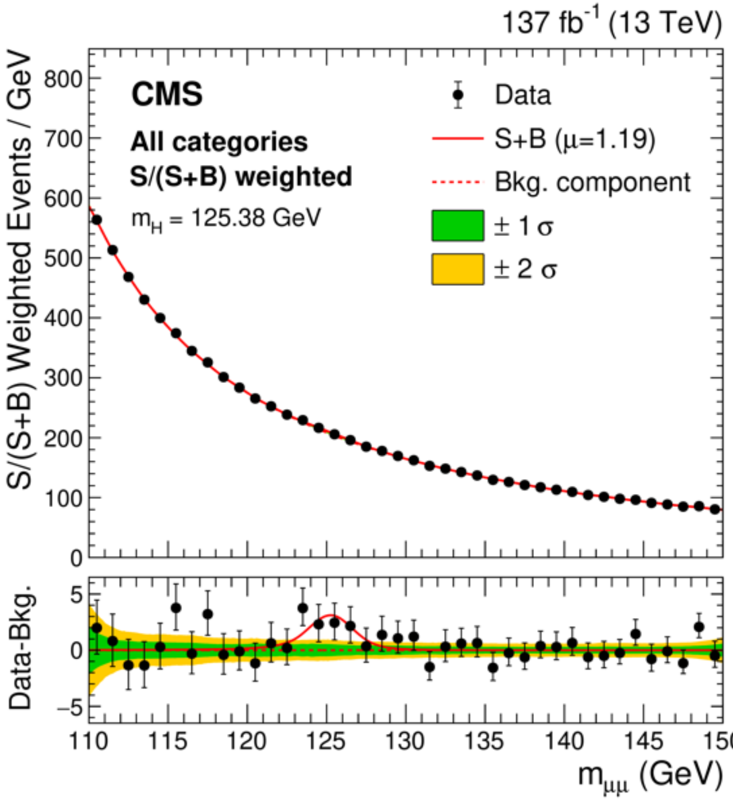
Jul 4, 2022

Search for $H \to \mu\mu$

JHEP 01 (2021) 148
Jan 25, 2021
[Run 2]

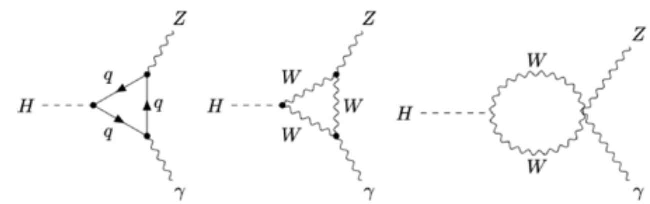
- **SM**: $B(H \to \mu\mu) \approx 0.02\%$
  - Probing Higgs coupling to the second-generation fermions
- Analysis:
  - Two prompt muons
  - ggF, VBF, and VH categories
  - Look for a small bump in the dimuon invariant mass at mμμ ~ 125 GeV
- Significance: 3.0 (evidence)
  - Signal strength: μ = 1.2 ± 0.4 (consistent with SM)
- Outlook: assuming SM H, we need ~4 times more data to establish this decay mode with 5σ



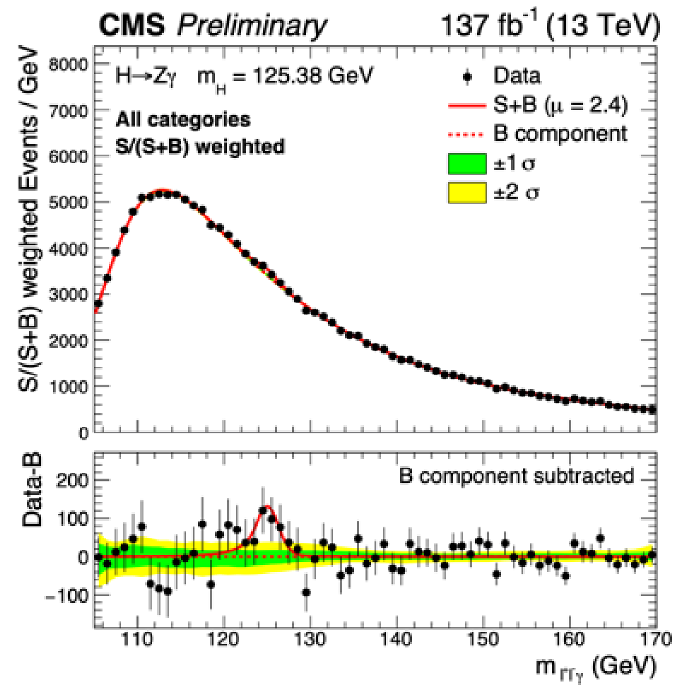
Search for $H \to Z\gamma$

CMS PAS HIG-19-014
Apr 26, 2022
[Run 2]

- **SM**: $B(H \to Z\gamma)B(Z \to ee/\mu\mu) \approx 0.01\%$
  - A loop-induced rare decay -> potential sensitivity to BSM



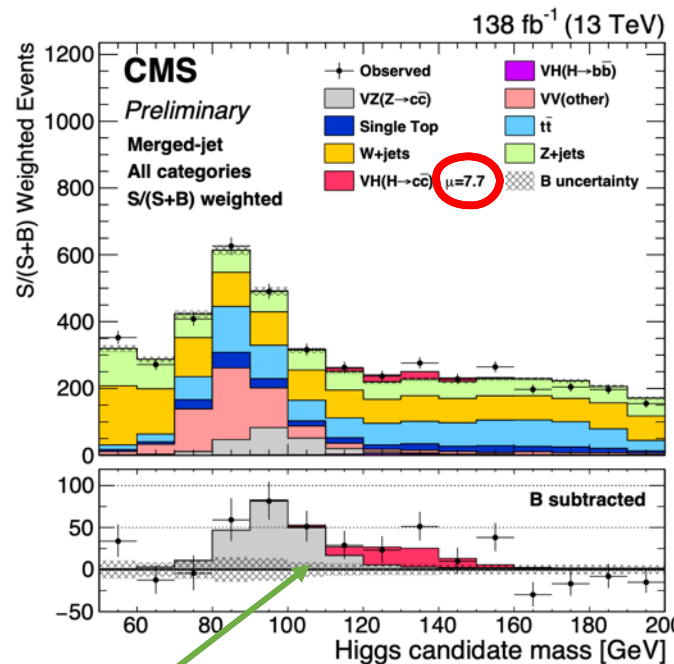
- Analysis:
  - Two prompt leptons with $m_{\ell\ell} \sim m_Z$
  - VBF, VH, and ttH categories + (ggF with $D_{kin}(\ell\ell\gamma)$)
  - Look for a small bump in the dimuon invariant mass at $m_{\ell\ell\gamma} \sim 125$ GeV
- Significance: 2.7
  - Signal strength: μ = 2.4 ± 0.9
    - An excess, but still well consistent with SM
- Outlook: Assuming SM H, will need ~20 times more data to establish this decay mode with 5σ



Search for $H\rightarrow cc$

- **SM**: $B(H \rightarrow cc) \approx 3\%$
  - Probing Higgs coupling to the second-generation fermions
- Search mode:
  - V+H(cc), including high-pT H (merged c-quark jets)
- One needs to fight:
  - V+jets, huge cross section (not picking in m(jj))
  - VH, H→bb (20 times the H→cc rate!)
  - Need a two-sided discriminant: q/g-jet vs c-jet vs b-jet
- 95% CL limit: μ < 14 (7.6 expected)
  - Signal strength: μ = 7.7 ± 3.7
- Outlook: naively, one would need >100 times more data to see an evidence for this SM H decay with 3σ
  - Advanced ML/AI techniques are now being employed and provide significant improvements in such discrimination

CMS PAS HIG-21-008
May 10, 2022
[Run 2]



“*standard candle*” $VZ, Z \rightarrow cc$
μ = 1.0 ± 0.2
significance 5.7

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Just out: search for high-p_T H(cc)
CMS-HIG-21-012 (Nov 25, 2022)
95%CL limit: μ<47 (39 expected)

Established Production Modes

SM Higgs (σ=55.7 pb at 13 TeV)

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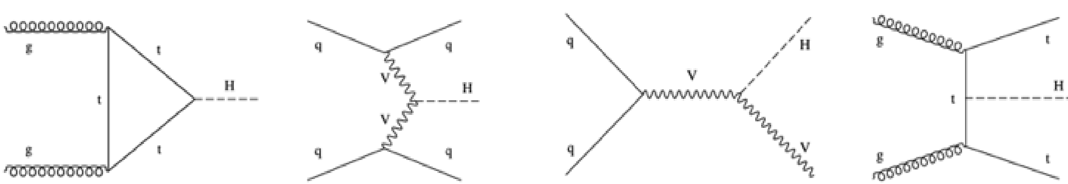
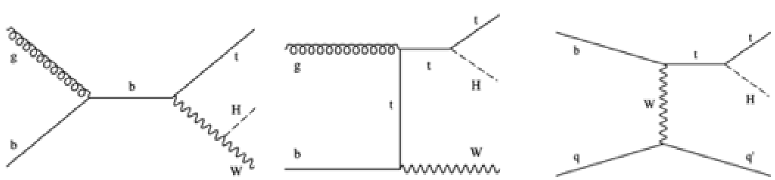
gg	VBF	WH	ZH	ttH	tH	bbH
87.2%	6.8%	2.5%	1.6%	0.9%	0.2%	0.9%

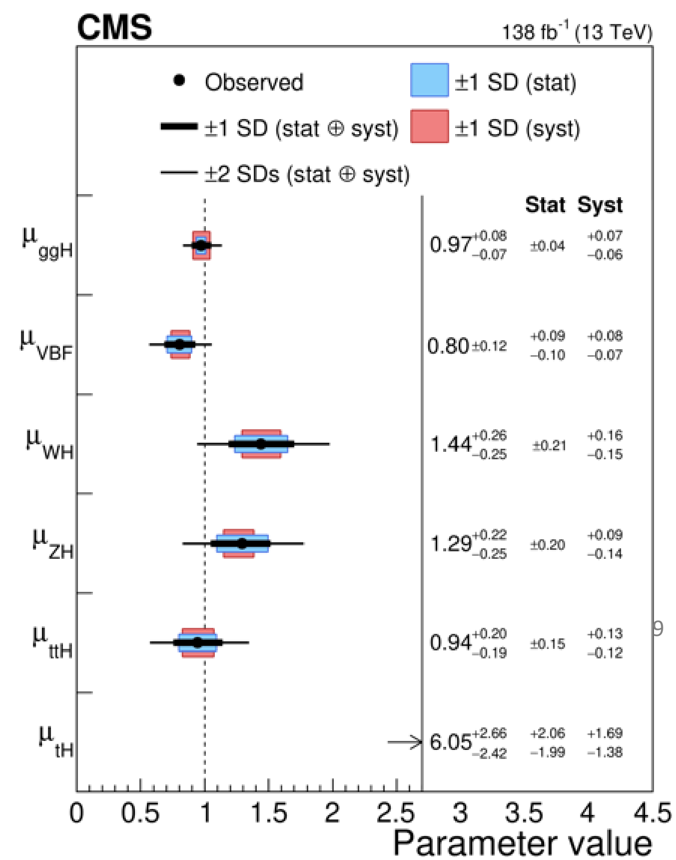
- Green are five well stablished production modes ($> 5\sigma$)
- All event rates are compatible with the SM predictions



gg-fusion VBF WH, ZH ttH, bbH

tH





Combined Fit: Coupling Modifiers

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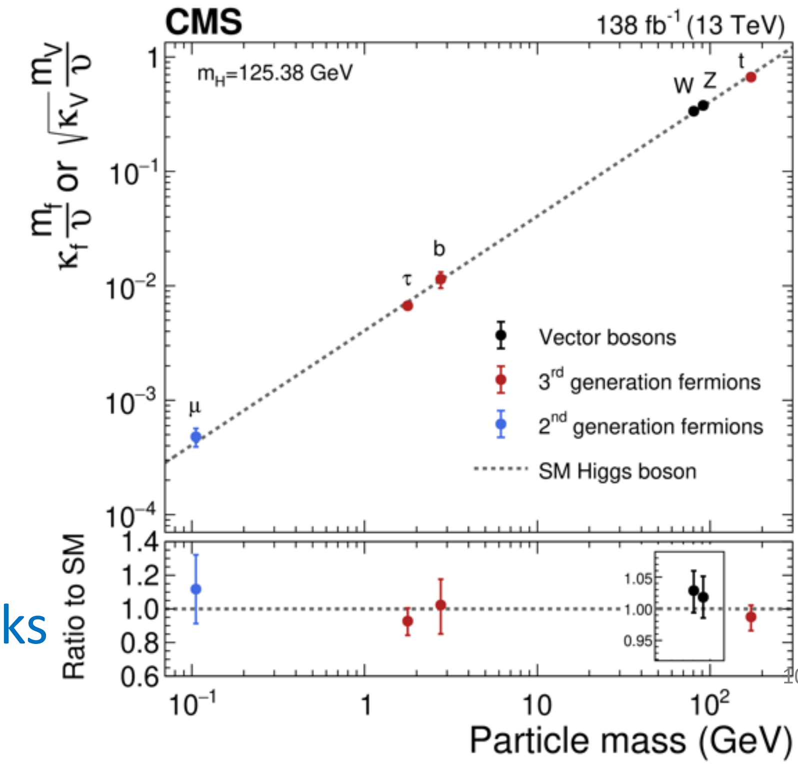
- Fit for six Higgs coupling modifiers: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$
- Event rate for $ii \rightarrow H \rightarrow ff$:

$$\sigma_i \mathcal{B}^f = \frac{\sigma_i(\vec{\kappa})\Gamma^f(\vec{\kappa})}{\Gamma_H(\vec{\kappa})}$$

- Assumptions:
  - No “new physics” in loop-driven couplings ($H \rightarrow \gamma\gamma$, gg$\rightarrow H$)
  - No BSM decays (invisible, not observed)
  - Couplings to the 1st/2nd–gen. quarks and electrons are SM-like
    - i.e., small and hence having a negligible effect on the fit)
  - Impressive agreement with SM over three orders of magnitude in coupling strengths



Next Step: Higgs Self-Coupling

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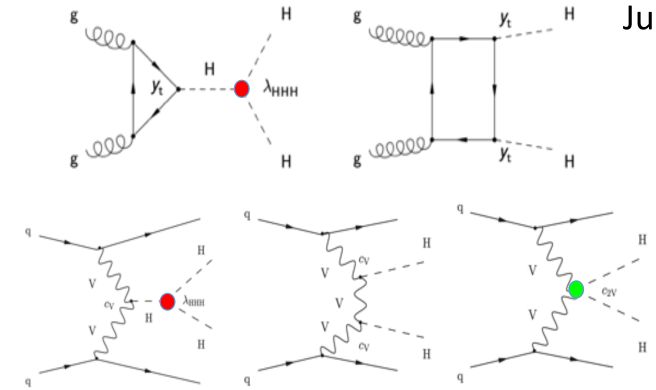
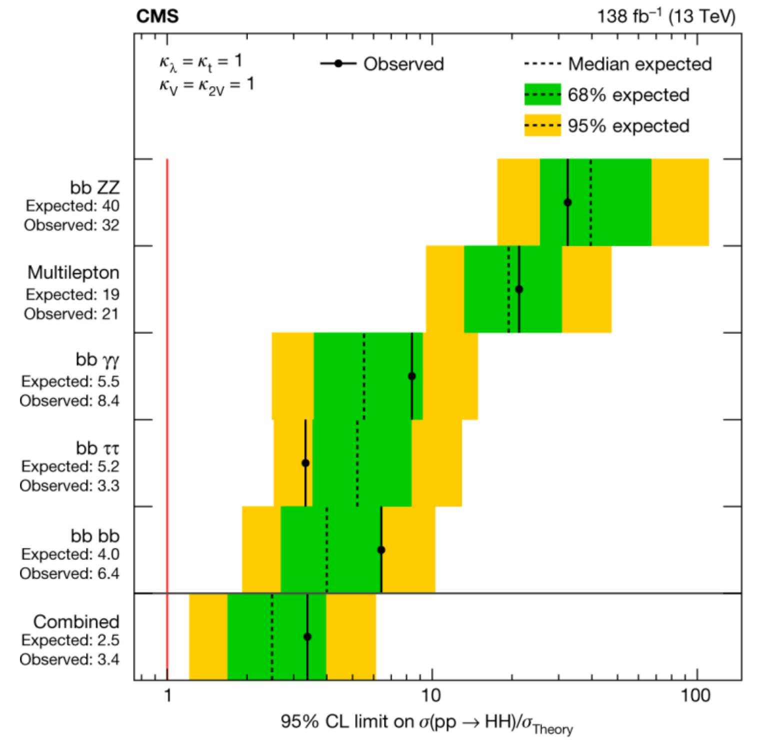
[Run 2]

- Challenging: In SM, $\boldsymbol{\sigma(HH):\sigma(H)\sim 1:1000}$
- Three most sensitive decay modes:
  - HH→ $(bb)(bb)$
  - HH→ $(bb)(\tau\tau)$
  - HH→ $(bb)(\gamma\gamma)$
- Production modes tags:
  - VBF
  - Untagged (ggF)
- Results (95% CL limits):
  - HH production signal strength $\mu < 3.4$
  - HHH coupling: $-1.2 < \kappa_\lambda < 6.5$
  - VVHH quartic coupling: $0.7 < \kappa_{2V} < 1.4$
    - k_{2V}=0 excluded at 6.6σ(!)





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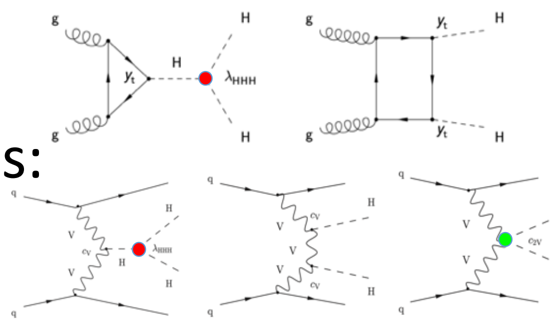

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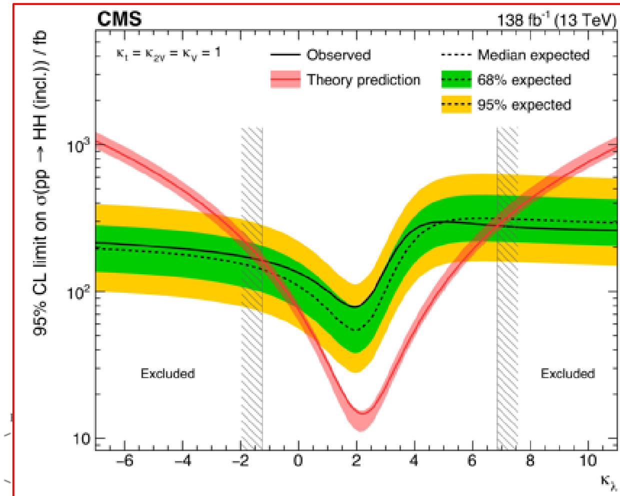
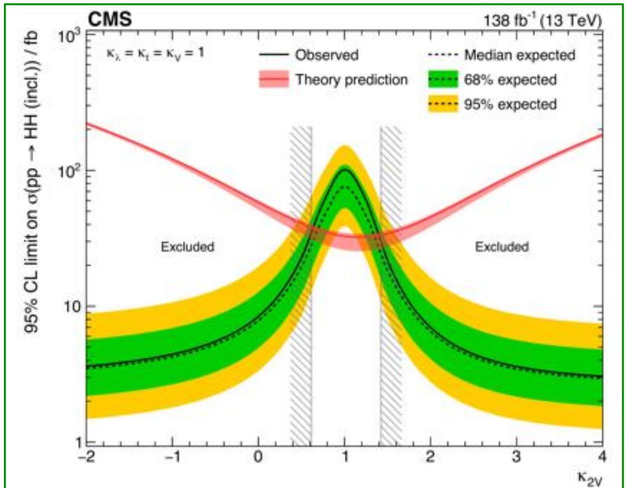
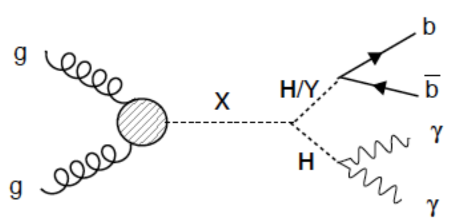
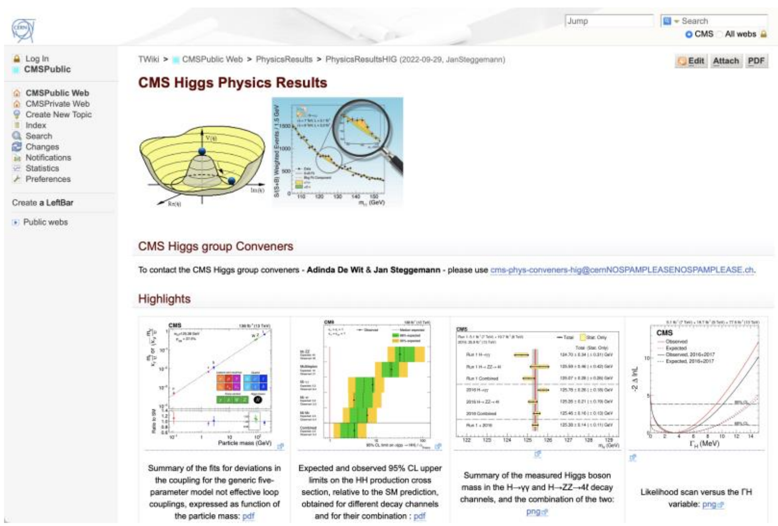




Direct Searches Beyond SM

- Many scenarios of new physics under investigation at CMS:
  - Non-SM couplings: $t \to q\mathrm{H}$
  - Unaccounted BSM decay modes: H width, H → invisible, H → $\ell\ell'$(CLFV), H → BSM particles
  - Additional (pseudo-) scalars: heavy higgs $\mathrm{H} \to \mathrm{h(125)h(125)}$ or $\mathrm{h(125)} \to \mathrm{aa}$
    - Or new heavy particles, e.g. graviton: $X \to \mathrm{HH}$
  - Charged Higgs: H±, H±±





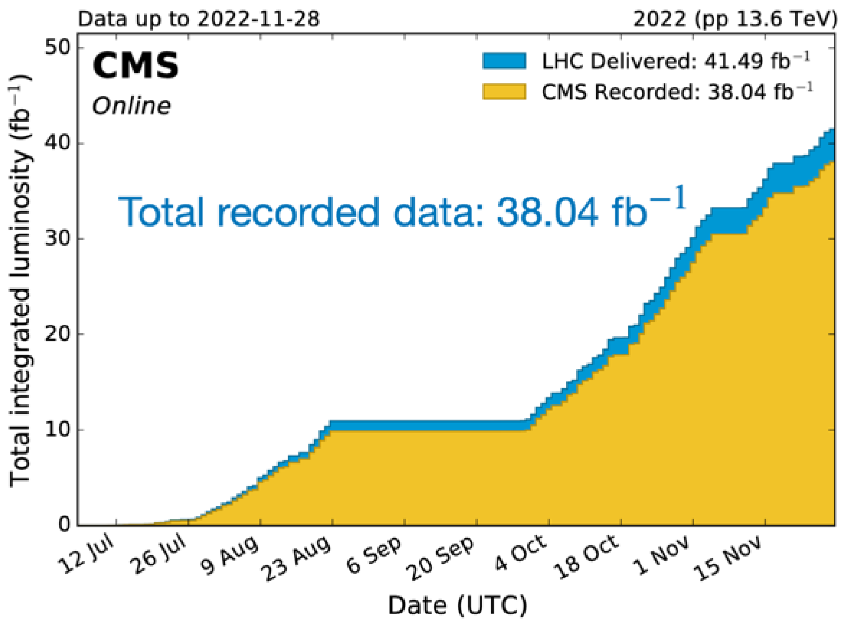
- For full details, see
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Conclusions

- Transition to the true higgs boson precision measurements era is well under way
  - Accuracy of coupling measurements is under 10% for most couplings
  - Combined invisible BR<16 % at 95% C.L.
- Focus on comprehensive understanding
  - Requires combined analysis of multiple complementary measurements
- Progress in self-coupling measurements is much ahead of earlier preliminary expectations
  - Many improvements in data analysis techniques
- Further improvements in precision with the large increases in the size of the datasets following Run-3
  - Better understanding of systematics will be important as statistical uncertainties go down

Run 3 status

- Energy: 13.6 TeV
- 2022 (start-up year): 38 fb–1 (recorded, 92% efficiency)



- 2023 – 2025 (main period): 300 fb–1 by 2025 (planned)
- 2023 (war realities): LHC running time has been cut from 20 to 13 weeks due to the energy crisis
- New projection for Run 3 lumi: wait and see

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