Higgs Results and Searches for More Scalars at CMS

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FERMILAB

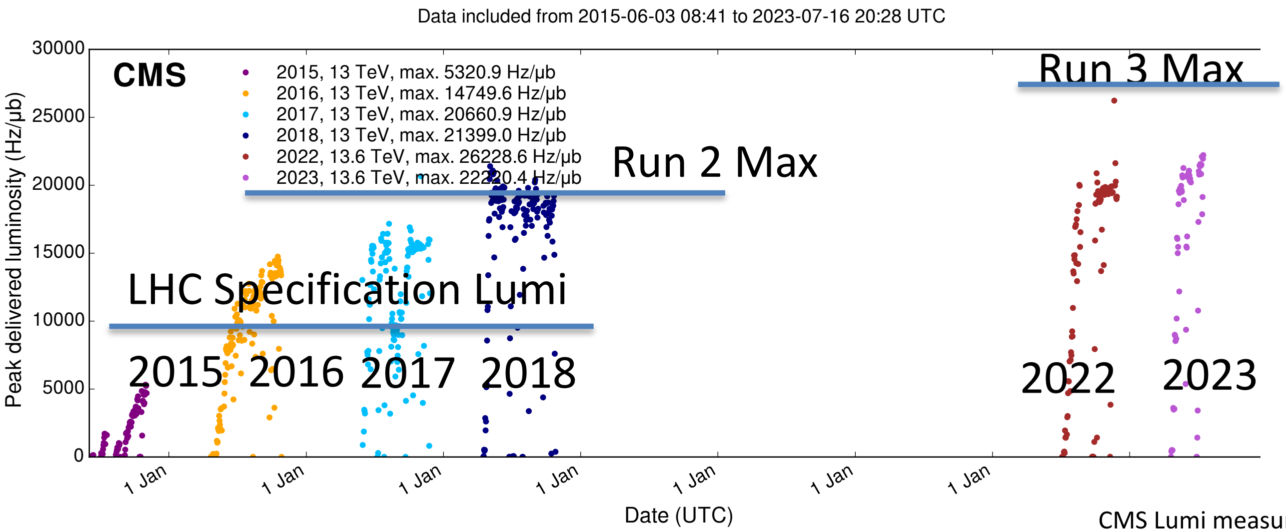
Scalars 2023

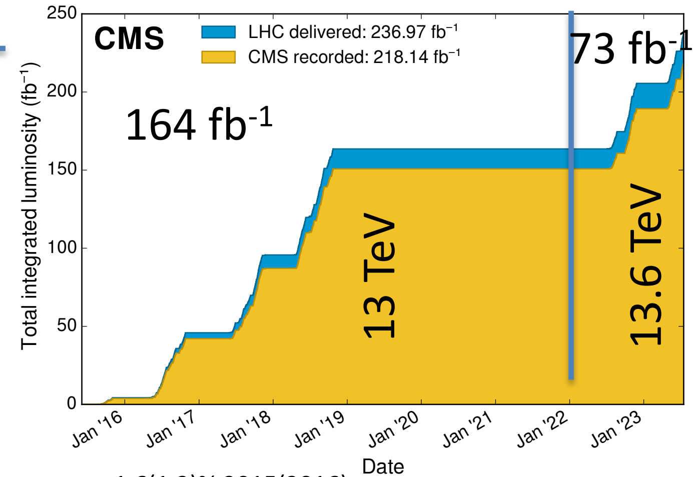
An opportunity to discuss various aspects of scalar particles.

13-16 September 2023
Warsaw (Ochota Campus)

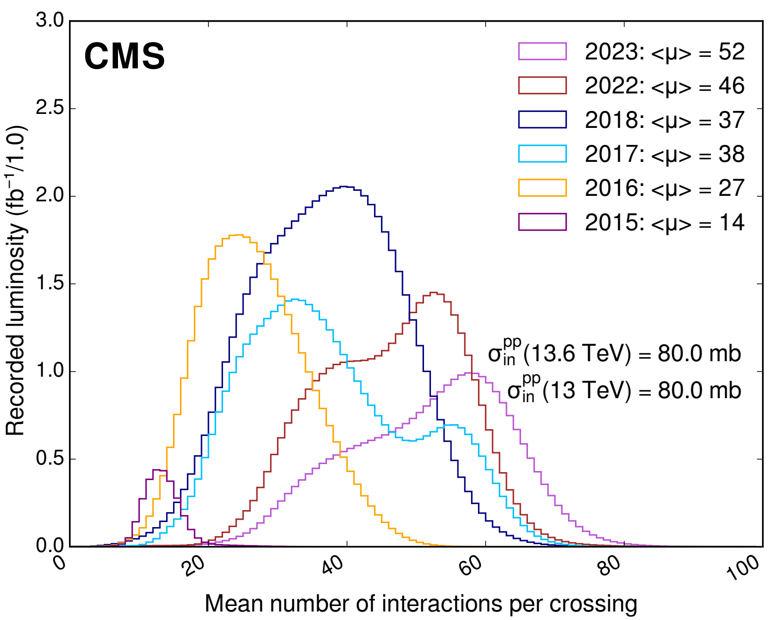
scalars2023.fuw.edu.pl

LHC in Run 2,3 (2015-2023) Highest Energy and Luminosity

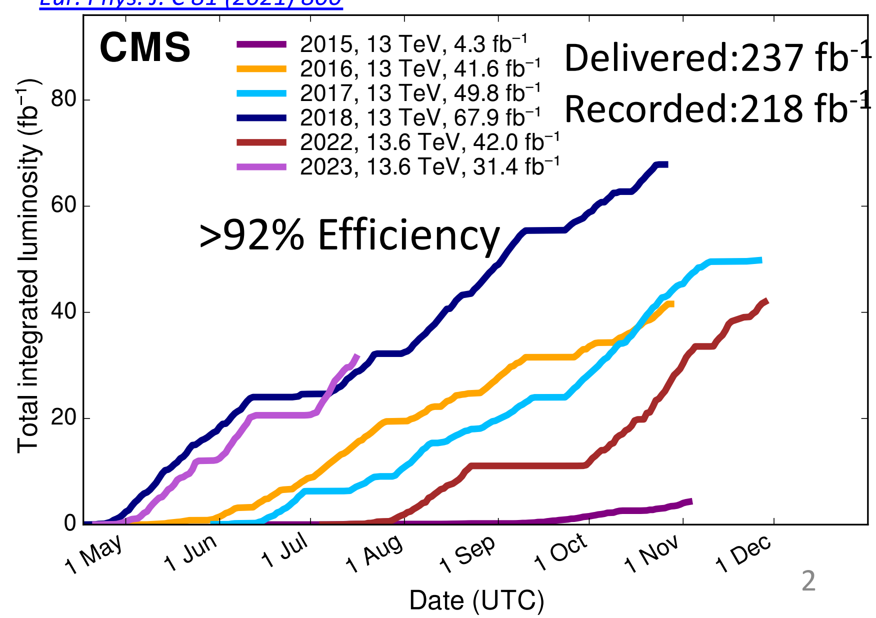




CMS Lumi measurements: 1.6(1.2)% 2015(2016)
Eur. Phys. J. C 81 (2021) 800



Focus on pp, but…
~150pb^{-1} of **PbPb,pPb**

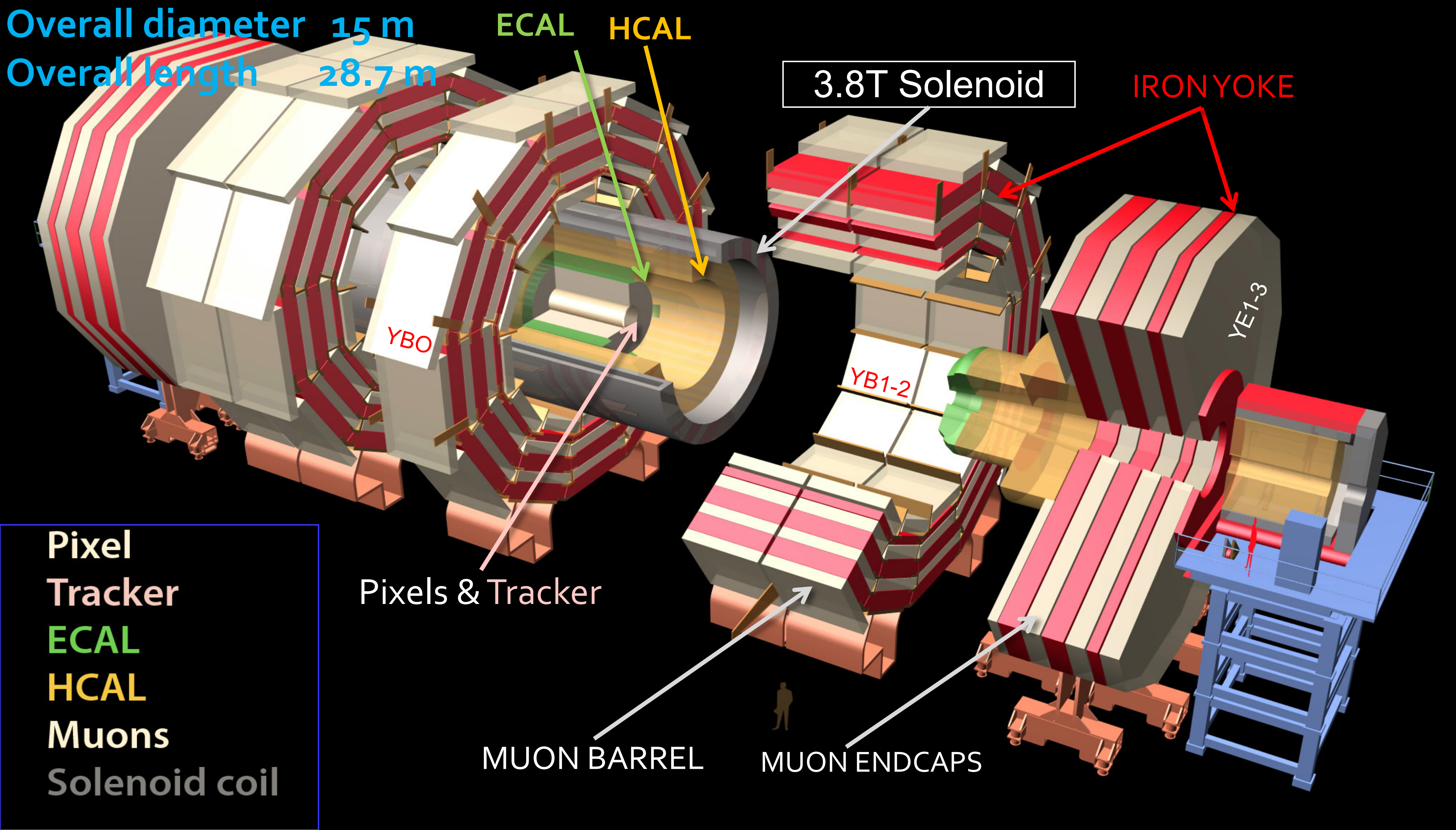


CMS Detector

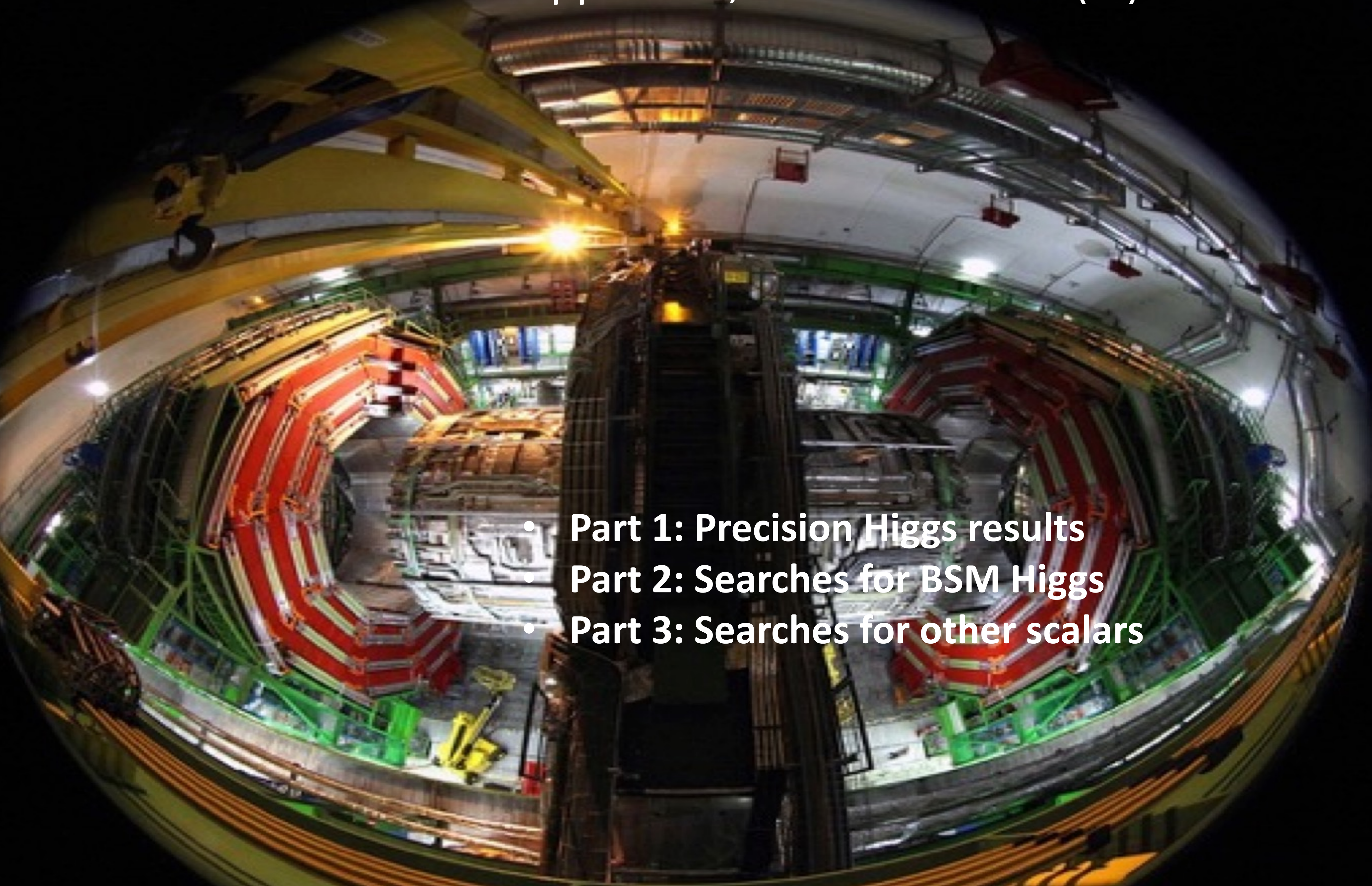
Total weight 14000 t

Overall diameter 15 m

Overall length 28.7 m



What has CMS seen in the pp Run 2,3 collisions at 13(.6)TeV?



- **Part 1: Precision Higgs results**
- **Part 2: Searches for BSM Higgs**
- **Part 3: Searches for other scalars**

Higgs Results 10+ y after Discovery

2012

Higgs Bosons — H^0 and $H^{\pm}$, Searches for

The July 2012 news about Higgs searches is described in the addendum to the Higgs review in the data listings, but is not reflected here.

The limits for H_1^0 and A^0 refer to the m_h^{max} benchmark scenario for the supersymmetric parameters.

H^0 Mass $m > 115.5$ and none 127–600 GeV, CL = 95%

***H_1^0* in Supersymmetric Models ($m_{H_1^0} < m_{H_2^0}$)**

Mass $m > 92.8$ GeV, CL = 95%

HTTP://PDG.LBL.GOV Page 4 Created: 6/18/2012 15:05

VII. Addendum

Updated July 12, 2012.

On July 4, 2012, the ATLAS and CMS collaborations simultaneously announced observation of a new particle produced in pp collision data at high energies [363–366]. The data samples used correspond to between 4.6 and 5.1 fb^{-1} of collision data collected at $\sqrt{s} = 7$ TeV in 2011, and between 5.3 and 5.9 fb^{-1} of collisions collected at $\sqrt{s} = 8$ TeV in 2012. The observed decay modes indicate that the new particle is a boson. The evidence is strong that the new particle decays to $\gamma\gamma$ and ZZ with rates consistent with those predicted for the Standard Model (SM) Higgs boson. There are indications that the new particle might also decay to W^+W^-, and decays to $b\bar{b}$ and $\tau^+\tau^-$ are being sought as well.

2023

$\boxed{H}$ $J = 0$

was H^0

Mass $m = 125.25 \pm 0.17$ GeV (S = 1.5)

Full width $\Gamma = 3.2^{+2.4}_{-1.7}$ MeV (assumes equal on-shell and off-shell effective couplings)

***H* Signal Strengths in Different Channels**

Combined Final States = 1.03 ± 0.04

$WW^* = 1.00 \pm 0.08$

$ZZ^* = 1.02 \pm 0.08$

$\gamma\gamma = 1.10 \pm 0.07$

$c\bar{c}$ Final State = 8 ± 22 (S = 1.9)

$b\bar{b} = 0.99 \pm 0.12$

$\mu^+\mu^- = 1.21 \pm 0.35$

$\tau^+\tau^- = 0.91 \pm 0.09$

$\gamma^*\gamma$ Final State = 1.5 ± 0.5

Fermion coupling (κ_F) = 0.95 ± 0.05

Gauge boson coupling (κ_V) = 1.035 ± 0.031

$t\bar{t}H$ Production = 1.10 ± 0.18

tH production = 6 ± 4

H Production Cross Section in pp Collisions at $\sqrt{s} = 13$ TeV = 56.9 ± 3.4 pb

Higgs Results 11 y after Discovery

2023

H

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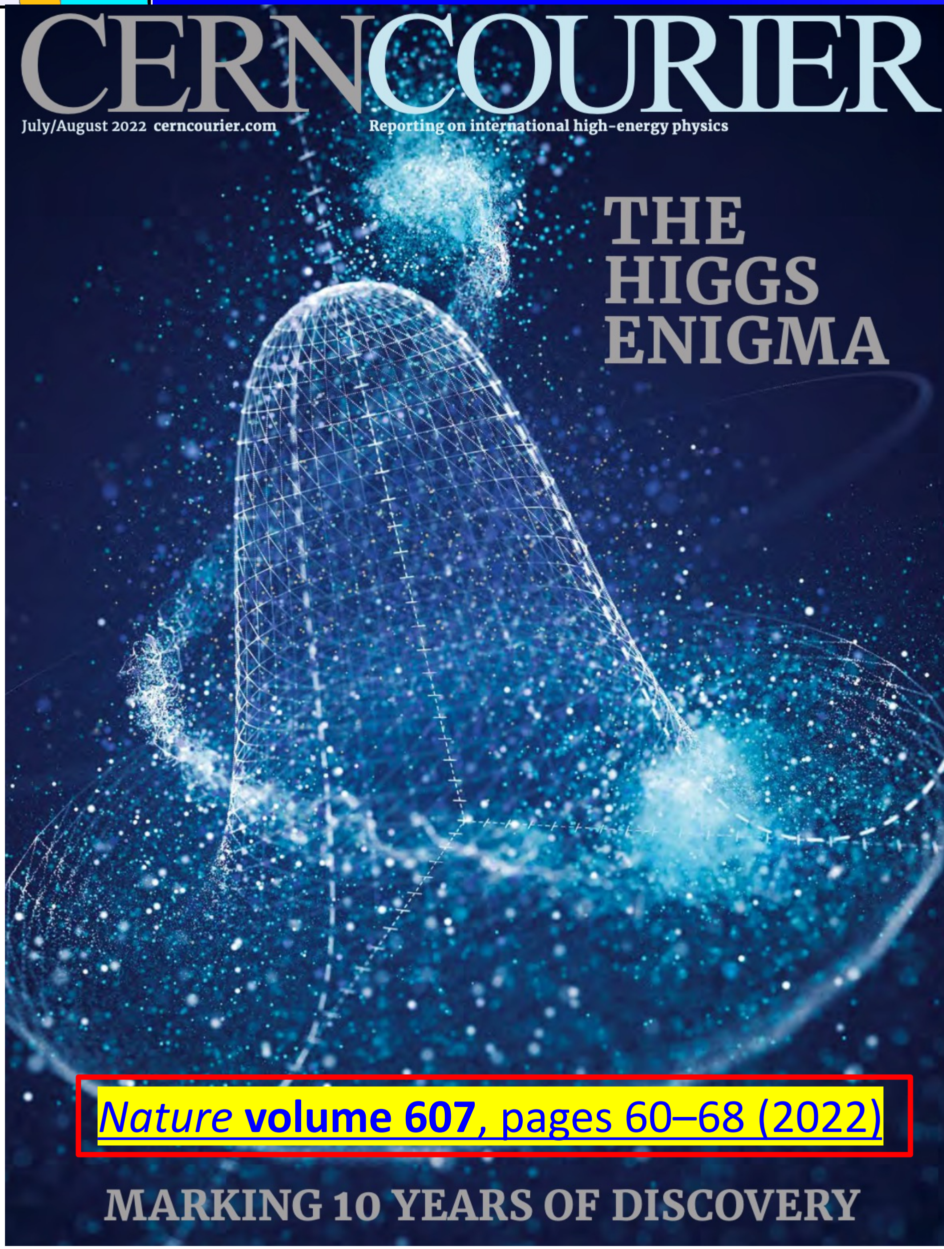
H^0

$J = 0$

2023

H DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$W W^*$		(25.7 ± 2.5) %		–
$Z Z^*$		(2.80 ± 0.30) %		–
$\gamma\gamma$		$(2.50 \pm 0.20) \times 10^{-3}$		62625
$b\bar{b}$		(53 ± 8) %		–
e^+e^-		$< 3.6 \times 10^{-4}$	95%	62625
$\mu^+\mu^-$		$(2.6 \pm 1.3) \times 10^{-4}$		62625
$\tau^+\tau^-$		$(6.0\ ^{+0.8}_{-0.7})$ %		62600
$Z\gamma$		$(3.2 \pm 1.5) \times 10^{-3}$		29431
$Z\rho(770)$		< 1.21 %	95%	29423
$Z\phi(1020)$		$< 3.6 \times 10^{-3}$	95%	29417
$J/\psi\gamma$		$< 3.5 \times 10^{-4}$	95%	62587
$J/\psi J/\psi$		$< 1.8 \times 10^{-3}$	95%	62548
$\psi(2S)\gamma$		$< 2.0 \times 10^{-3}$	95%	62571
$\Upsilon(1S)\gamma$		$< 4.9 \times 10^{-4}$	95%	62268
$\Upsilon(2S)\gamma$		$< 5.9 \times 10^{-4}$	95%	62224
$\Upsilon(3S)\gamma$		$< 5.7 \times 10^{-4}$	95%	62197
$\Upsilon(\mathrm{nS})\Upsilon(\mathrm{mS})$		$< 1.4 \times 10^{-3}$	95%	–
$\rho(770)\gamma$		$< 8.8 \times 10^{-4}$	95%	62623
$\phi(1020)\gamma$		$< 4.8 \times 10^{-4}$	95%	62621
$e\mu$	LF	$< 6.1 \times 10^{-5}$	95%	62625
$e\tau$	LF	$< 2.2 \times 10^{-3}$	95%	62612
$\mu\tau$	LF	$< 1.5 \times 10^{-3}$	95%	62612
invisible		< 13 %	95%	–
γinvisible		< 2.9 %	95%	–

Higgs Program

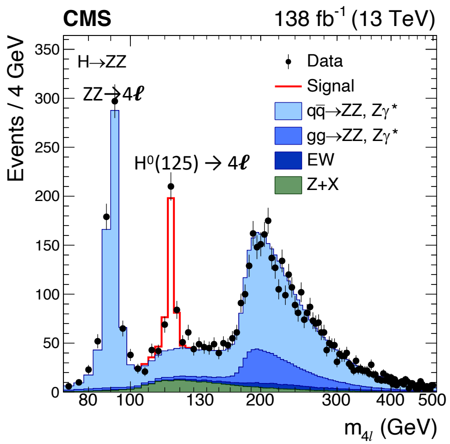


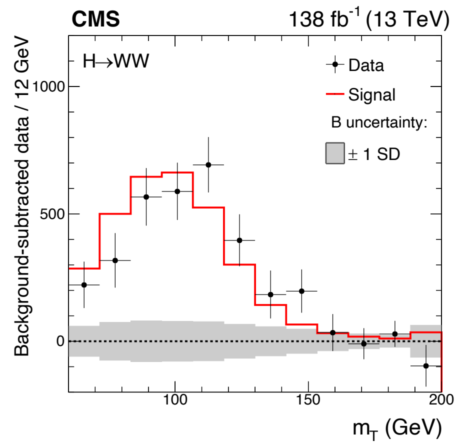
Nature **volume 607**, pages 60–68 (2022)

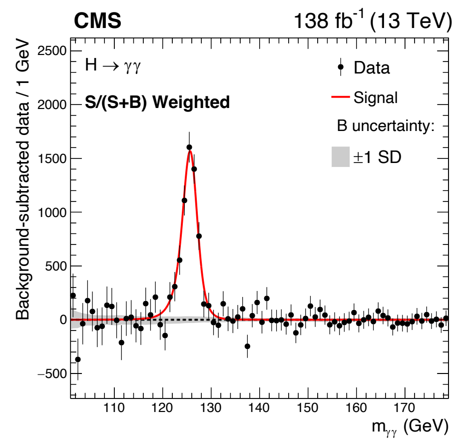
- Many **precision** Higgs measurements enabled with large Run 2 & 3 data sets already collected
  - Mass and couplings
  - Couplings to vector bosons, quarks and leptons and ttH (H→bb/$\tau\tau$/$\gamma\gamma$)
  - Differential cross sections
  - Rare decays H→Zγ or not allowed in SM: LFV H→τe/μe/$\tau\mu$
  - HH resonance studies (bb + bb/$\gamma\gamma$/$\tau\tau$)
  - Decays to non-SM particles: H→*invisible* or light pseudo- or scalar-particles
- Experimental precision confirms Higgs role in the SSB in the SM

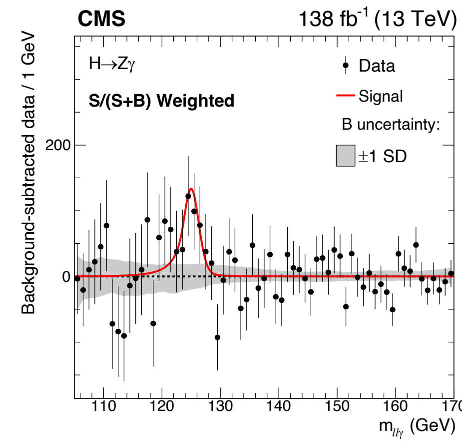
Higgs Mass Peaks in Run 2

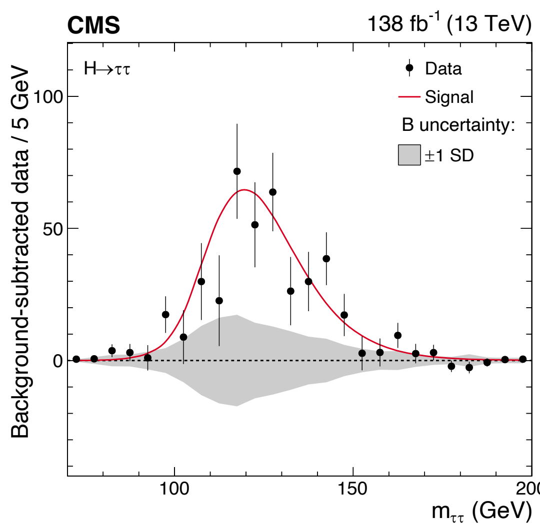
Nature607(2022)60-68

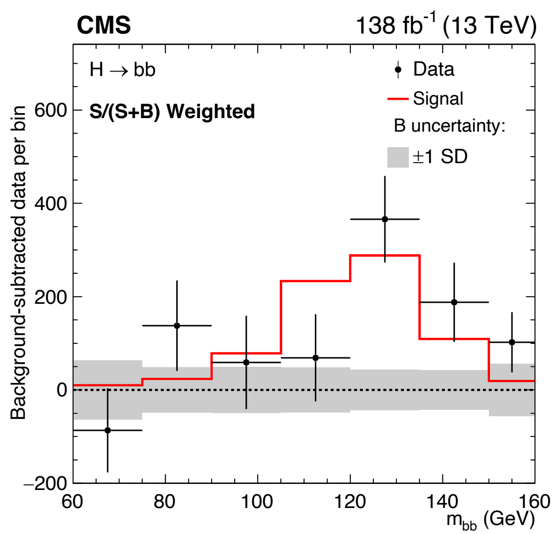


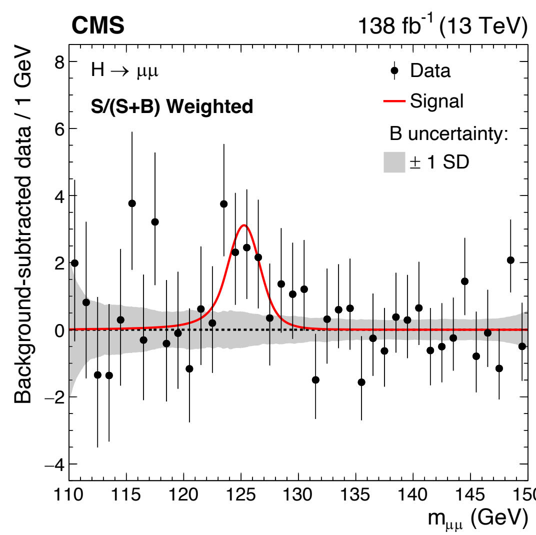








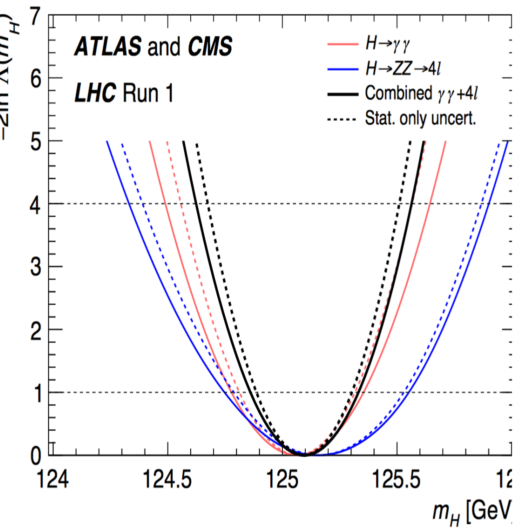


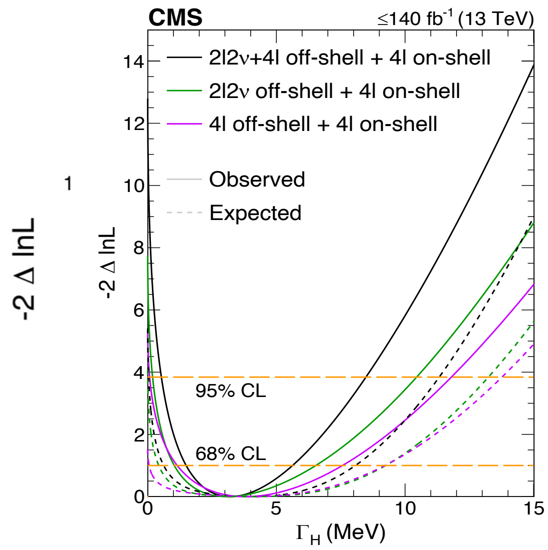


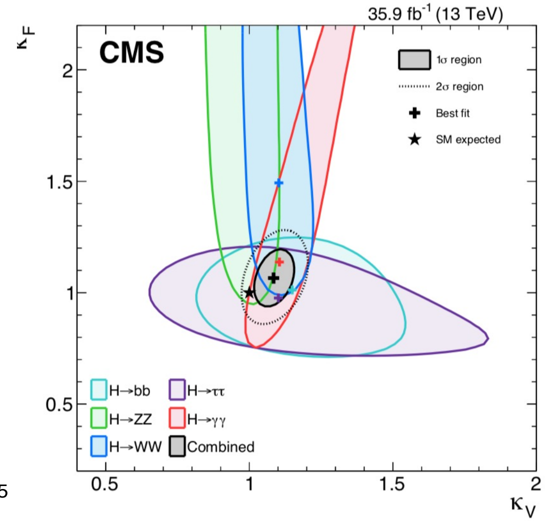
CMS HIG-22-001

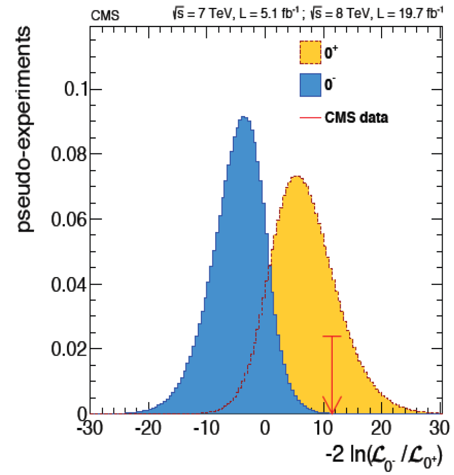
Higgs Measurements from Run 2

Nature607(2022)60-68









Mass = CMS+ATLAS
125.09 ±0.21(stat) ±0.11(syst) GeV

Width
3.2 +2.4/-1.7 MeV (95%CL)

Couplings
within ~15-20% of the SM values

Spin
$0^{+(+)}$ preferred over 0^{-},1,2

CMS HIG-22-001

Higgs Mass Measurement H→ZZ→4l

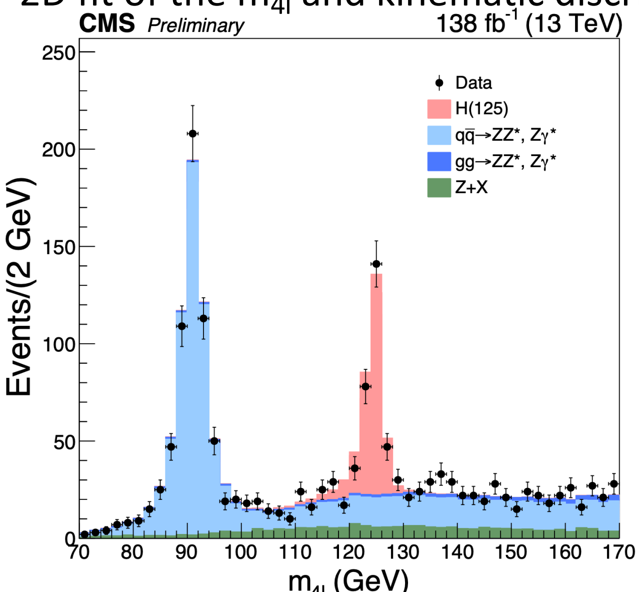
CMS PAS HIG-21-019

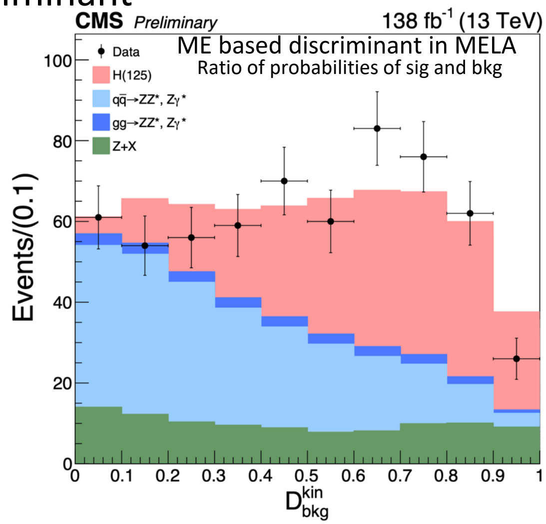
New tracker alignment and muon reconstruction with beam spot constraint

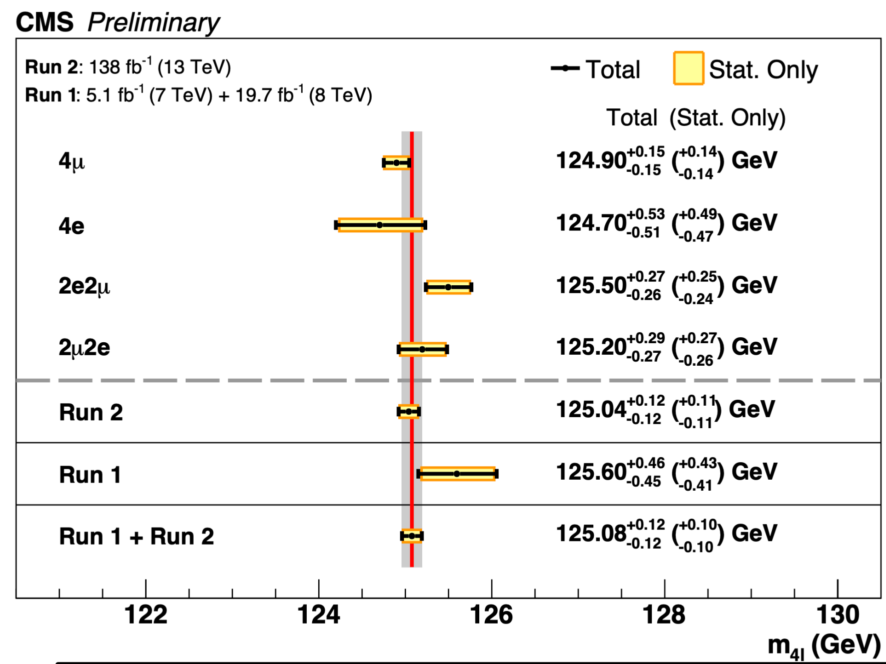
Event categories based on 4l mass uncertainty

2D fit of the m_{4l} and kinematic discriminant

New !
Only shown yesterday at HH







Mass:
125.04 ±0.11(stat)±0.05(syst) GeV

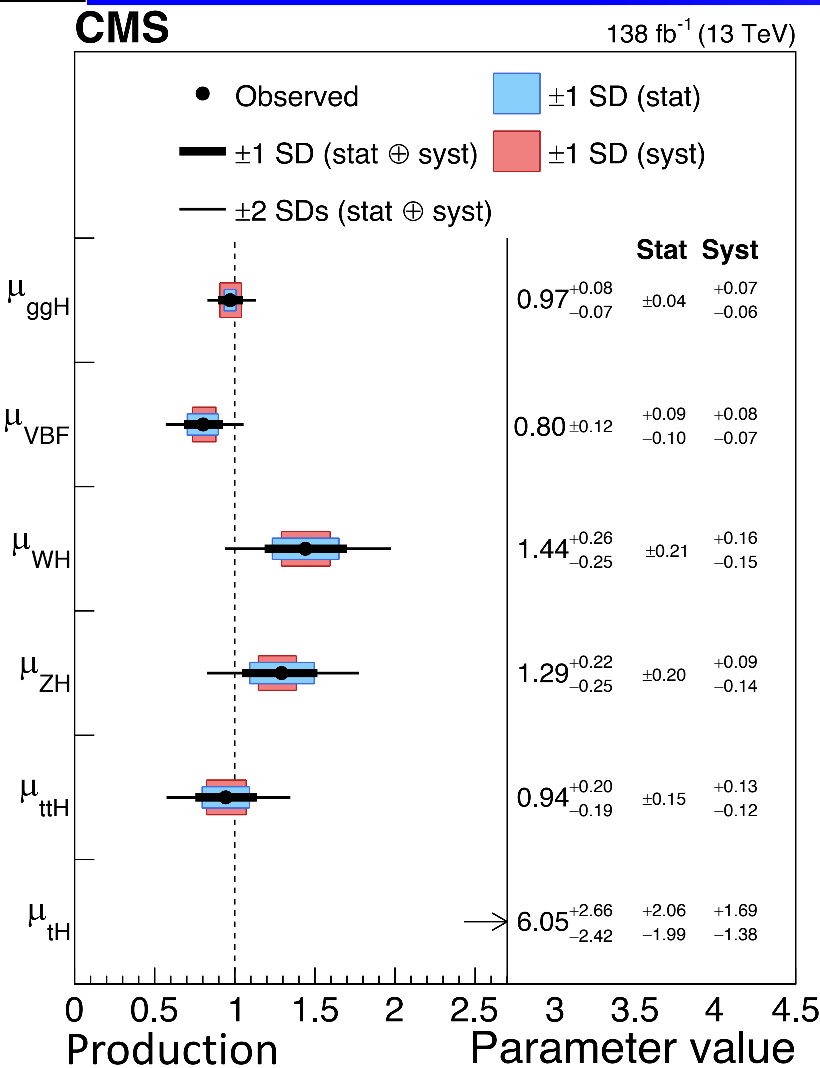
Width: Γ_H < 0.06 GeV at 68% CL
On-/off-shell combination fit:
2.9 +2.3/-1.7 MeV (95% CL)

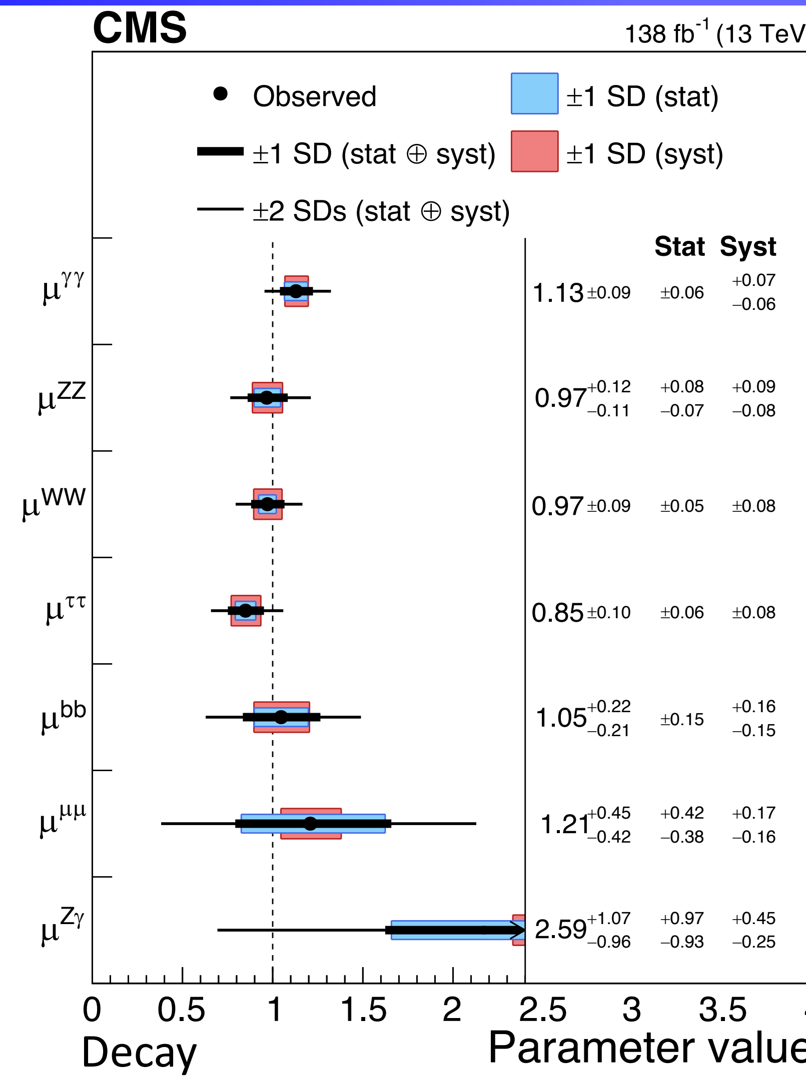
Run 1 and 2 Combination Mass:
125.08 ±0.10(stat)±0.05(syst) GeV

Most precise single measurement of H mass

Higgs Measurements from Run 2

[Nature 607 (2022) 60-68]

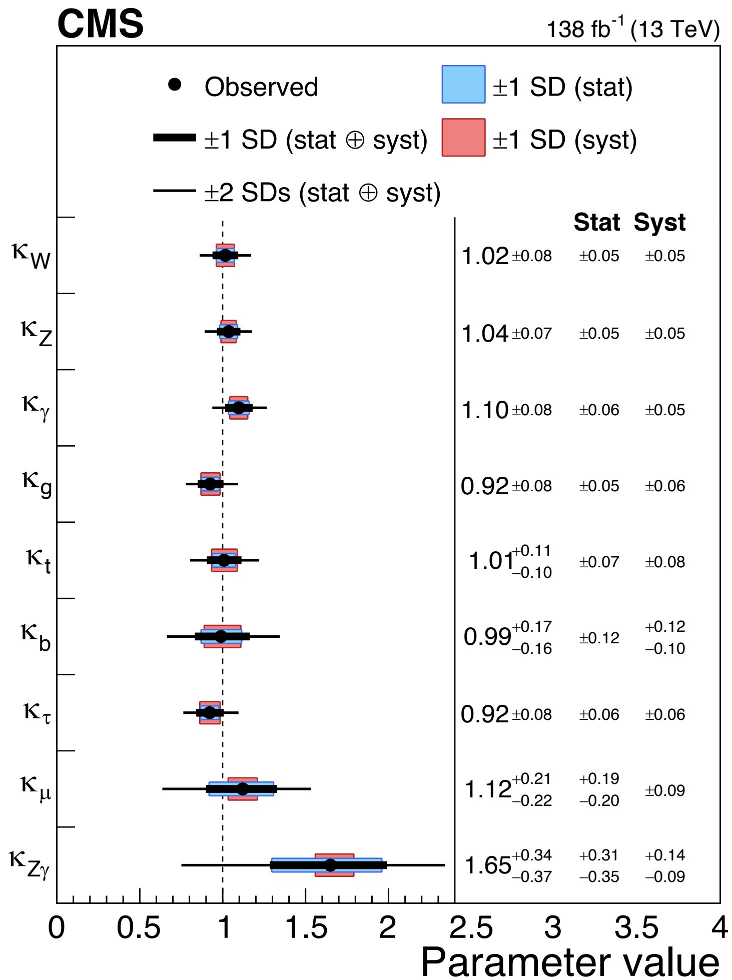




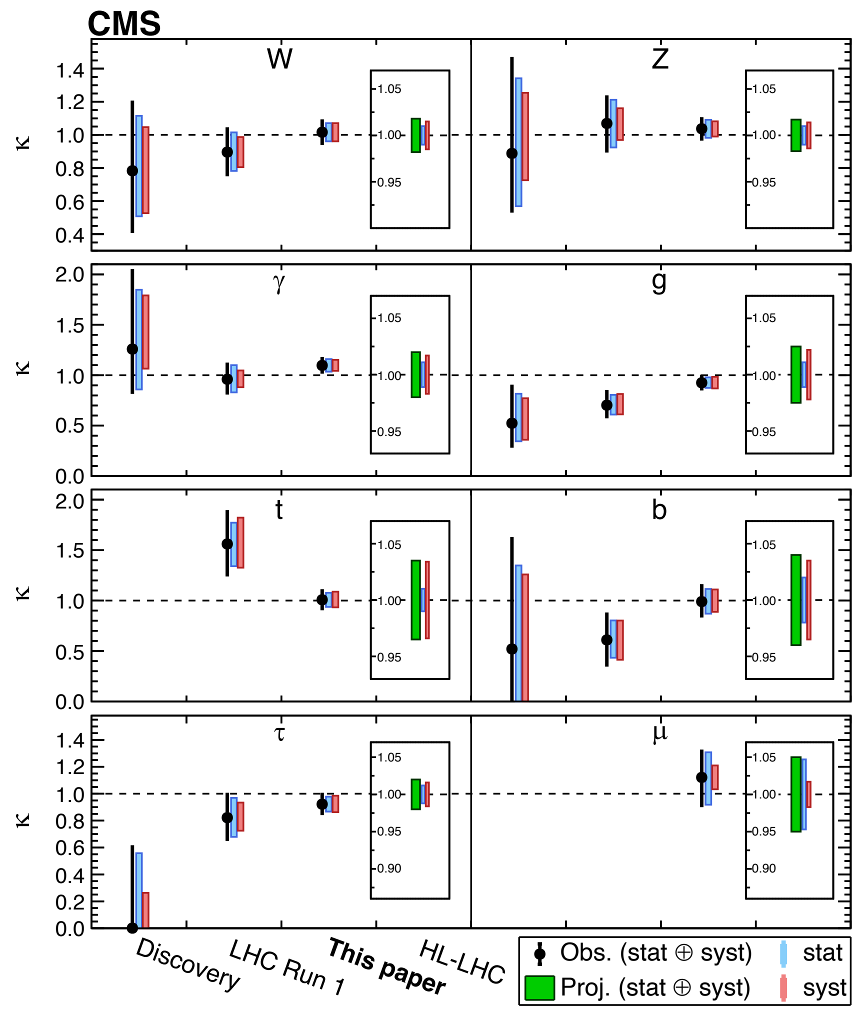
Signal Strength μ in good agreement with the SM **production** modes and **decays** channels

Higgs Couplings Run 2 and Beyond

Nature 607 (2022) 60-68



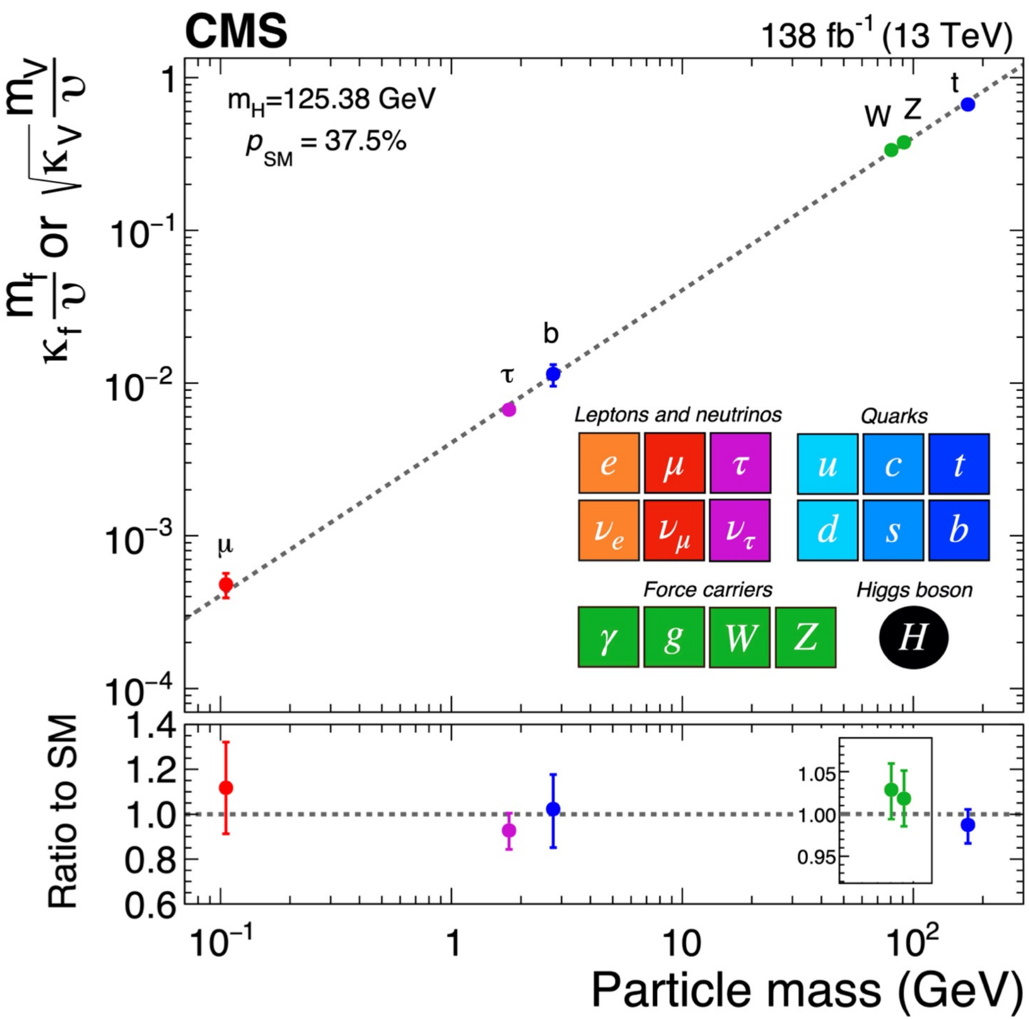
Run1 JHEP 08 (2016) 045

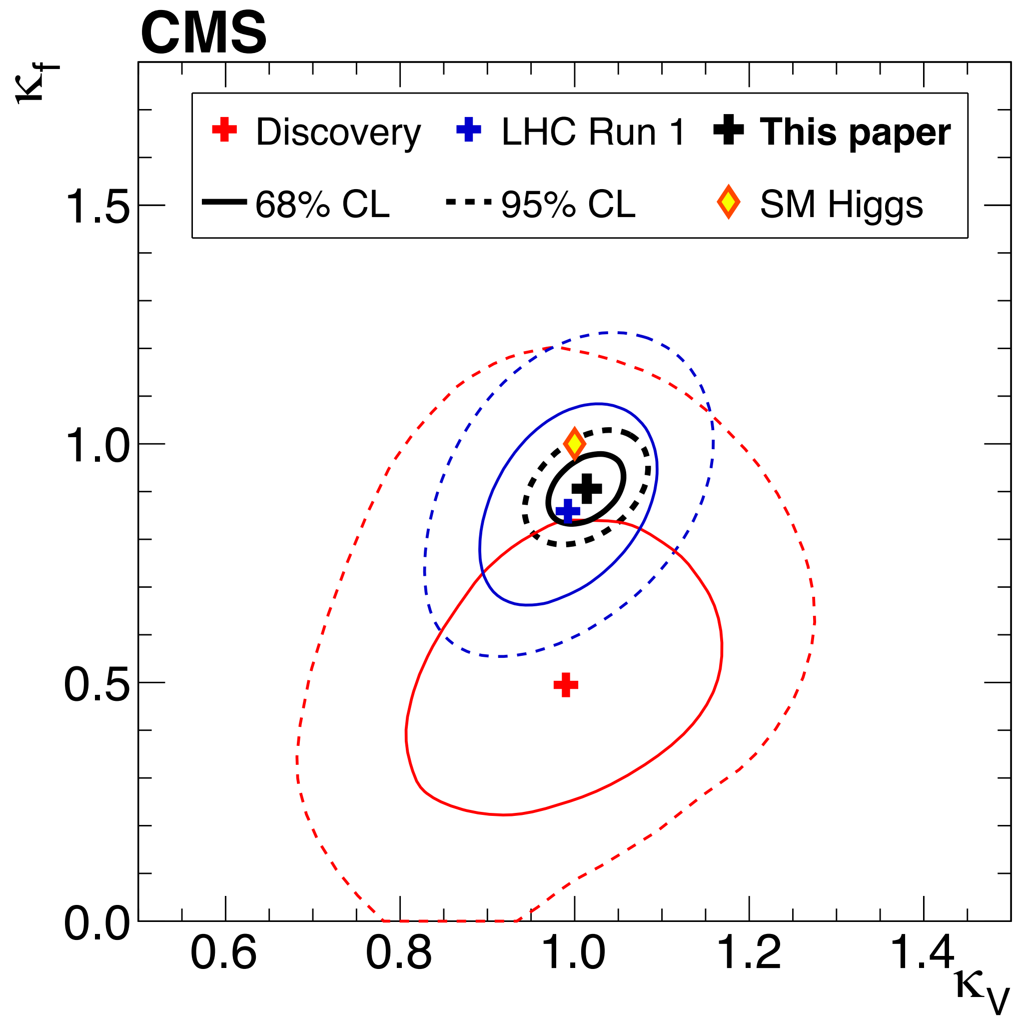


Production and decay measurements used
to determine the Higgs couplings
to fermions and bosons

Higgs Couplings Run 2 Results

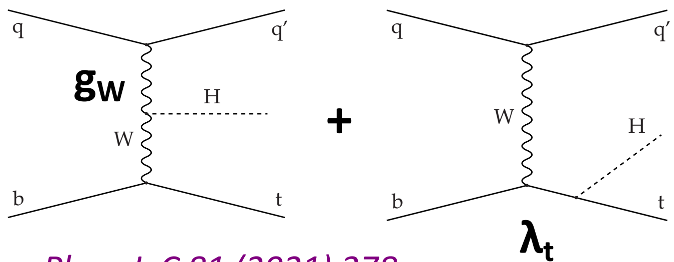
Nature 607 (2022) 60-68





Higgs Coupling to Top Quarks

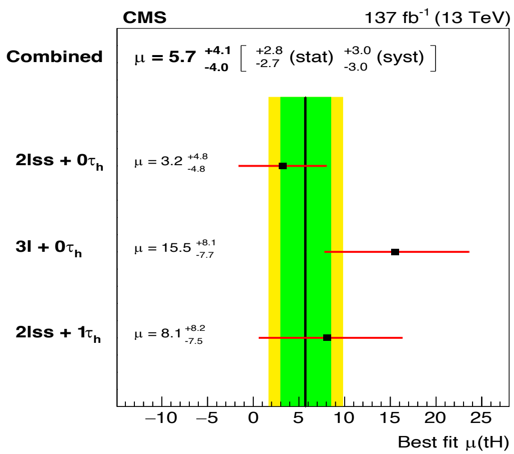
ttH - a direct probe to Top Yukawa $\boldsymbol{\lambda_t}$ cplg while **tH** - a unique channel to study the relative sign of couplings while

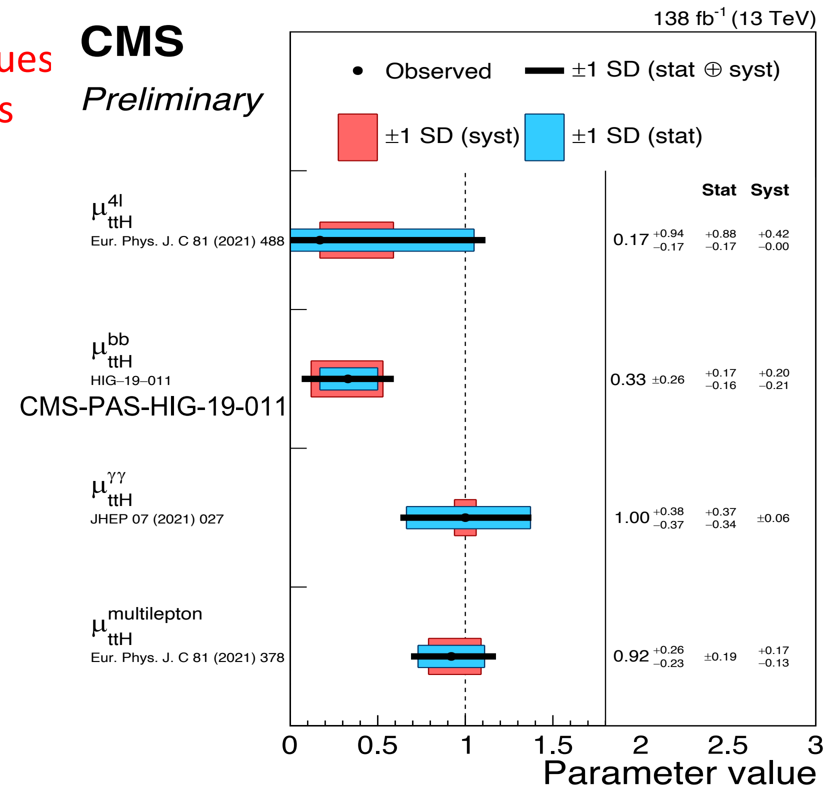


Constructive interference when $\boldsymbol{\lambda_t}$ and $\boldsymbol{g_W}$ have opposite sign → large increase in x-section

- tHV + tHq + ttH with tt decays to multi-ℓ or all-jet final states
- H→WW*,ZZ*,ττ, bb – channels in 10 signatures depending on lepton multiplicity
- MVA, ML and ME techniques to separate ttV and tt+jets backgrounds from signals

Eur. Phys. J. C 81 (2021) 378





Significance for **tH** with M_h=125 GeV:
Observed: **1.4** σ Expected: **0.3** σ

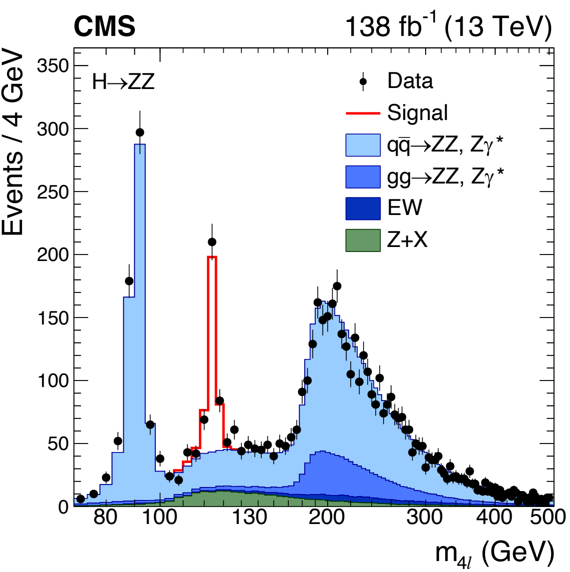
Significance for ttH with M_h=125 GeV:
Observed: **4.7** σ Expected: 5.2 σ

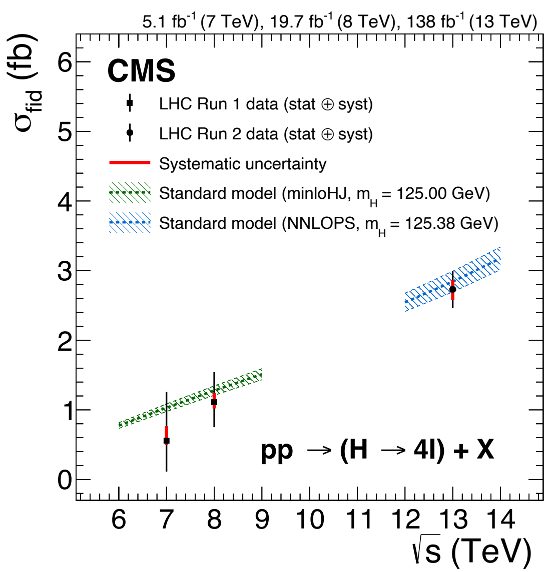
Higgs Cross Sections

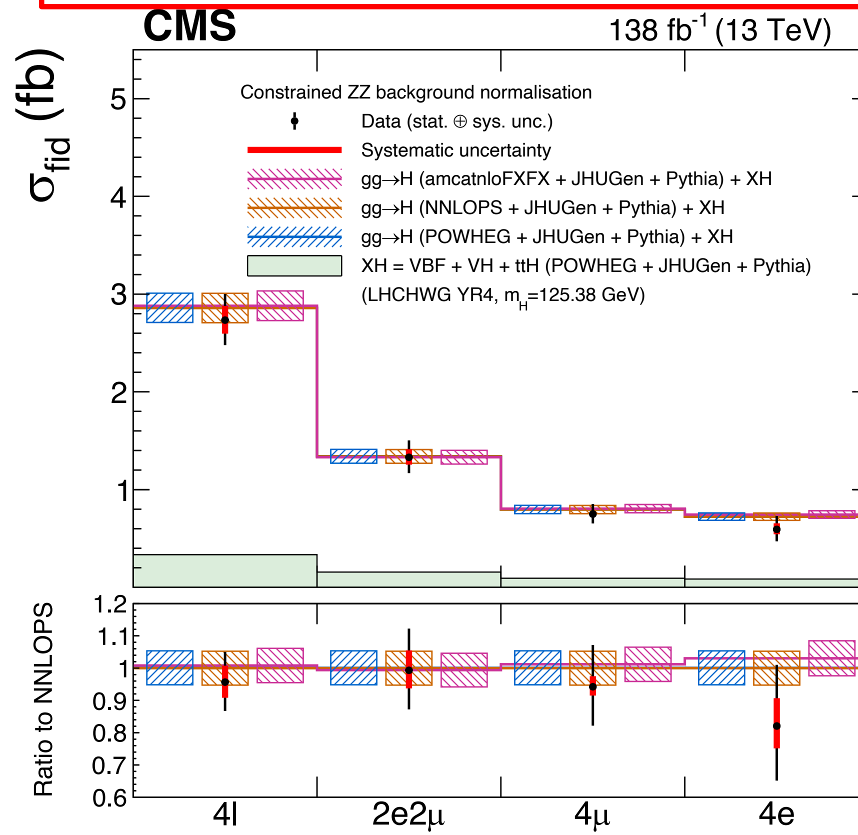
JHEP08(2023)040

Differential x-section in H→ 4ℓ, ℓ=e,μ
Very clean signature with excellent resolution

Fiducial differential x-section measured in various decay channels



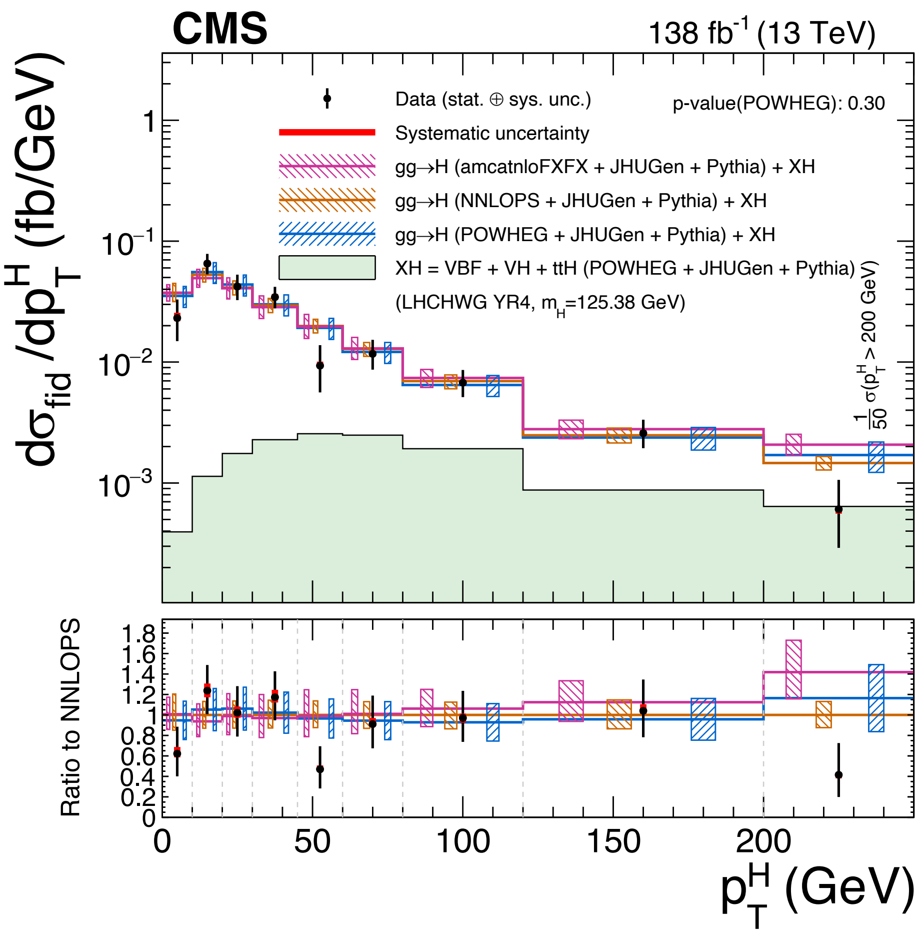


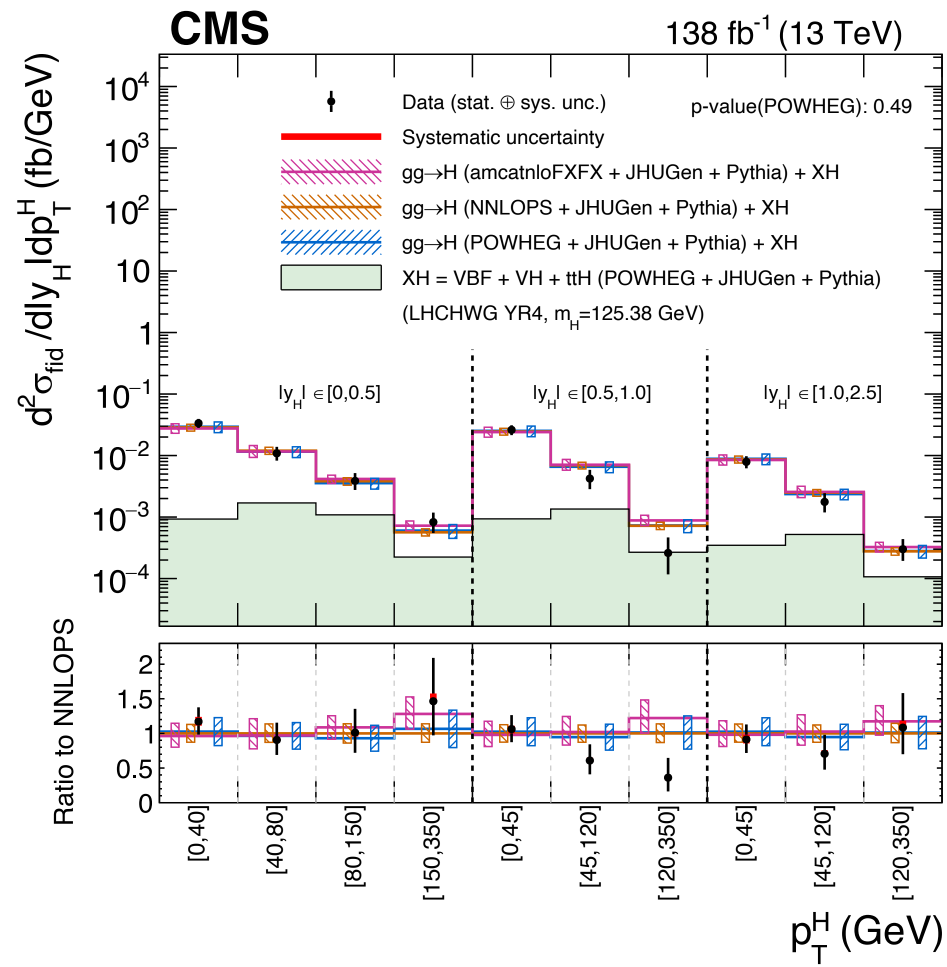


Excellent agreement with the SM

Higgs Differential Cross Sections

JHEP08(2023)040

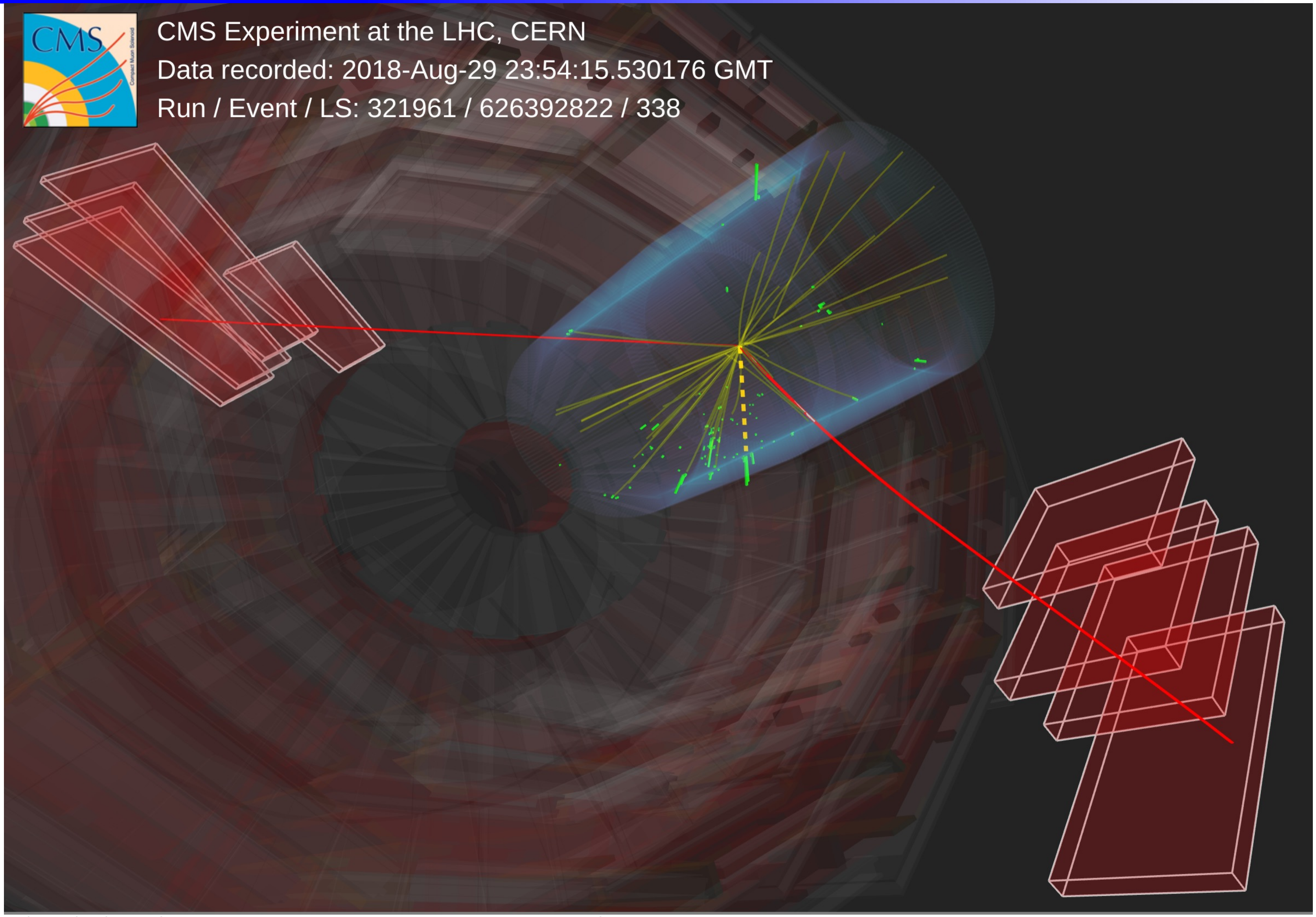




Opportunities to study :
Dynamics of H production models, constrains of couplings, additional jet structure

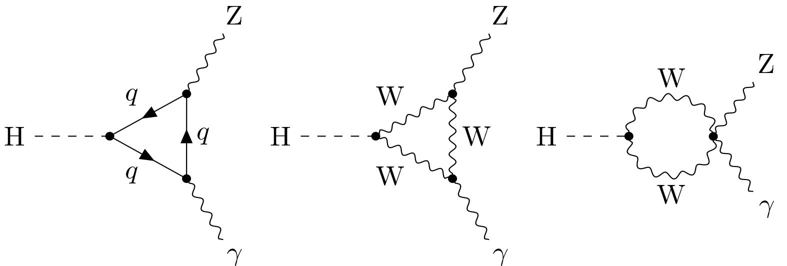
Higgs Decay H → Zγ

JHEP05(2023)233



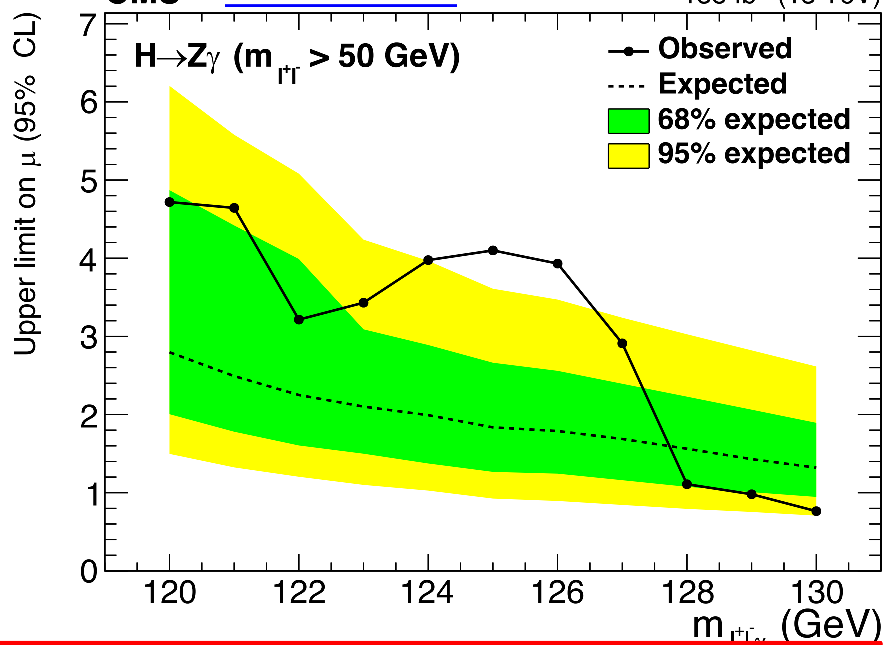
Higgs Decay H → Zγ

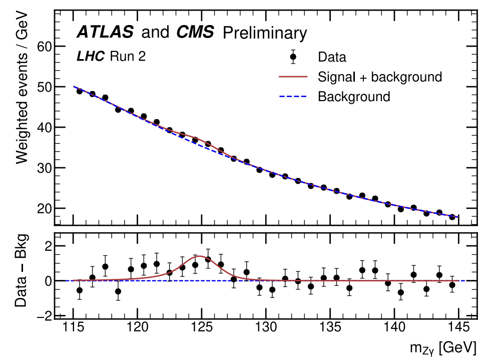
JHEP05(2023)233

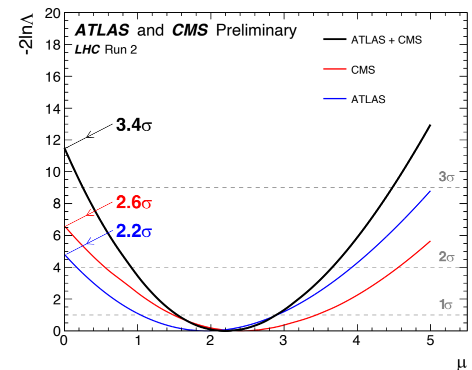


- Similar to H→ γγ already reconstructed but rate reduction in Z→ ℓ ℓ channel
- Sensitivity to BSM effects at the decay
- First example of combined ATLAS and CMS evidence of H →Zγ from previously published results

2204.12945







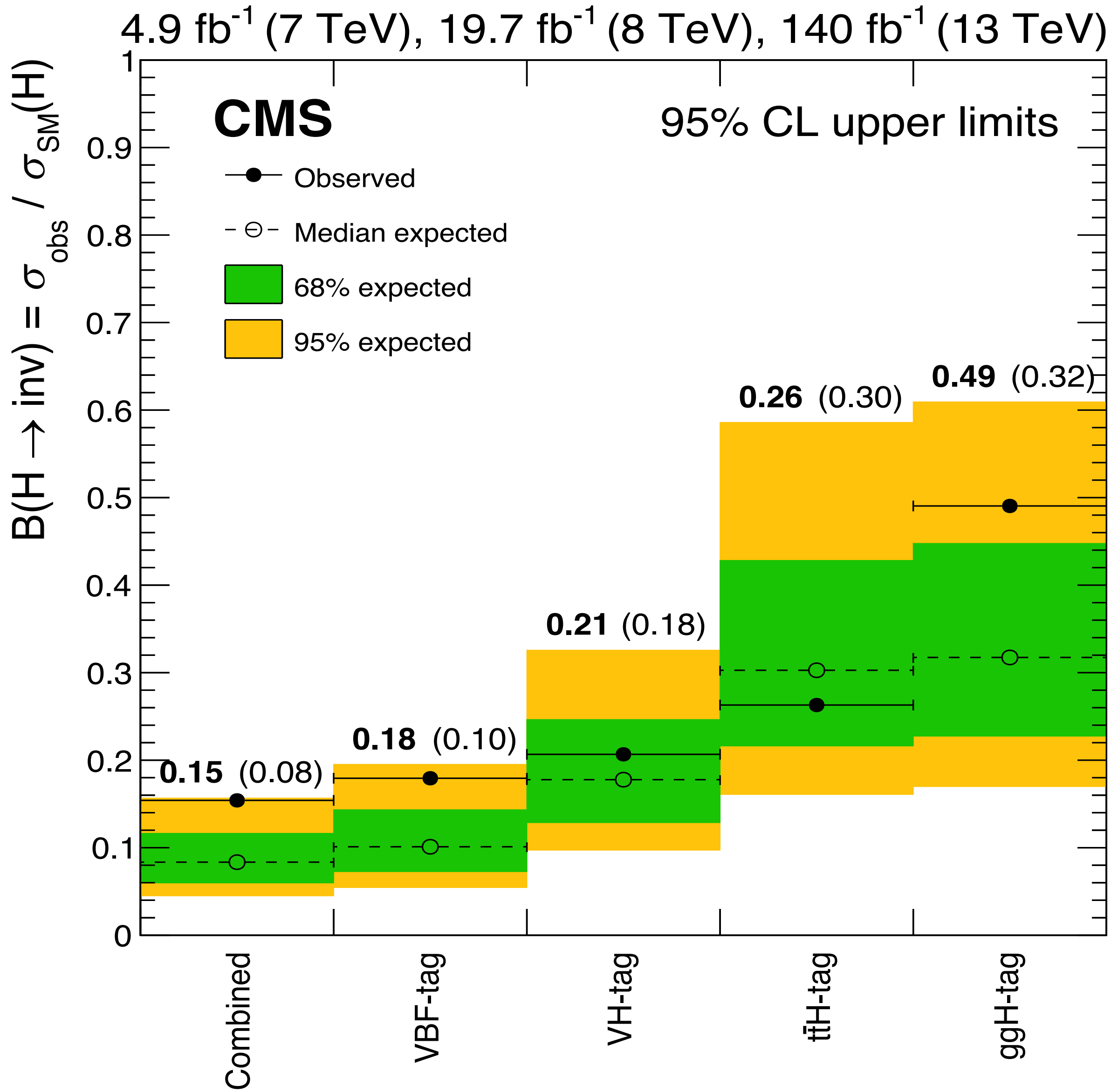
Signal strength μ for M_h=125.38 GeV: μ=2.4 ±0.9
Observed significance: **2.7** σ
Upper limit on μ: 4.1 Observed 1.8 Expected

Combined CMS and ATLAS first evidence for H → Zγ decay with observed significance: **3.4** σ (expected **1.6** σ)

Signal strength: μ=2.2 ±0.7
1.9 σ compatibility with the SM prediction

Higgs Width to Invisible Run 2

CMS-HIG-21-007
acc. Eur. Phys.J.C.
March 2023



Run 1 & 2 combination
Multiple channels:
VBF, ggH, VH, ttH
Boosted and resolved V

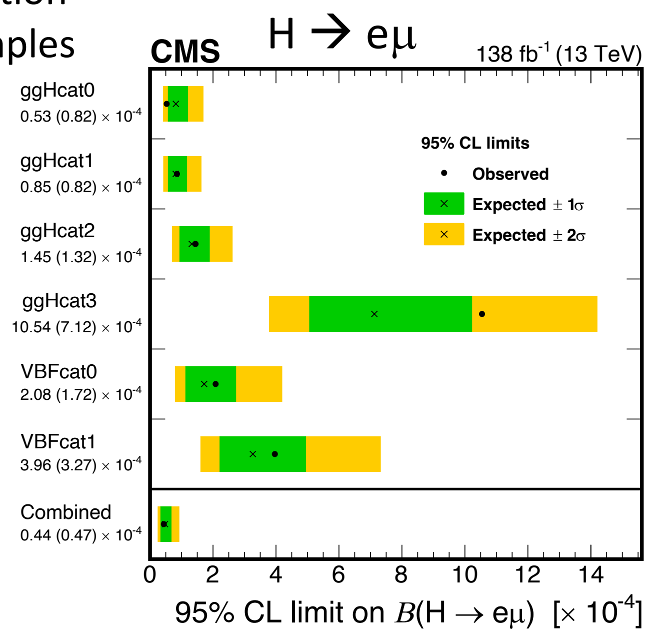
No significant excess
of events above the SM

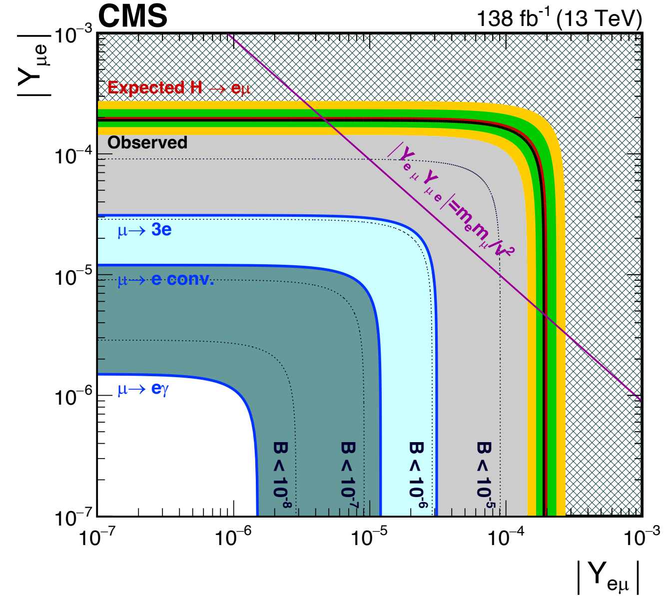
LFV Higgs Decays Run 2

arxiv:2305.18106
HIG-22-002

Production of X in the mass range 110-160GeV

Select one eμ OS pair
b-jet veto
VBF and ggF production
Divided into subsamples





@M_H=125GeV: Observed(expected) Upper Limit on BF of H→ eμ:
4.4(4.7) x 10^{-5} @95% CL
Yukawa Coupling: $\sqrt{(|Y_{\mu\varepsilon}|^2 + |Y_{e\mu}|^2)} <$ 1.9(2.0) x 10^{-4} @95% CL

arxiv:2305.18106

HIG-22-002

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Select one eμ OS pair

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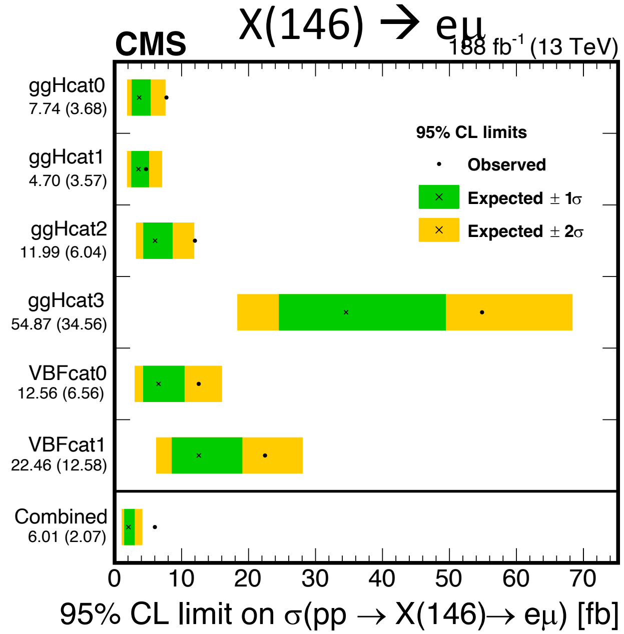
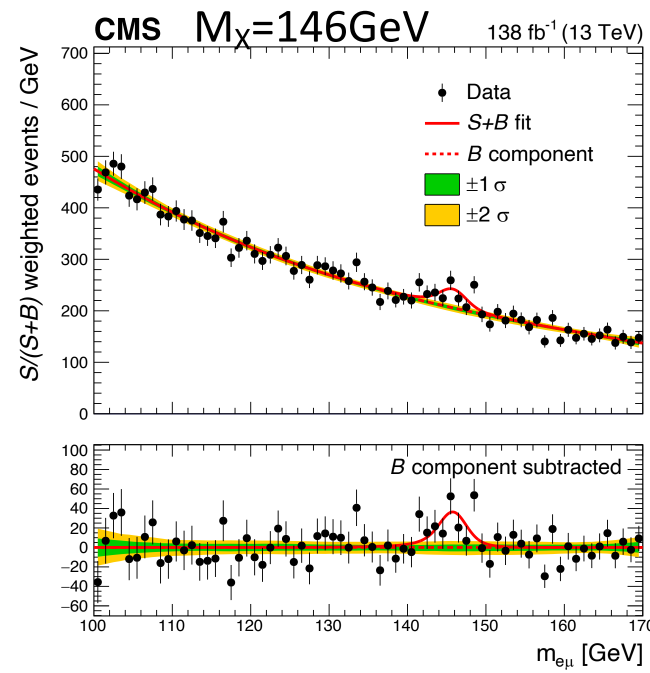
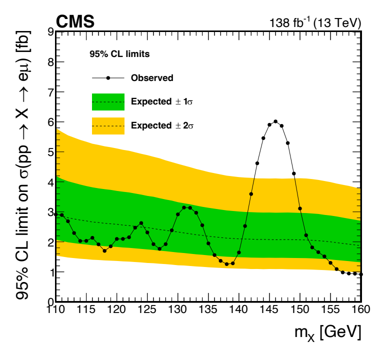
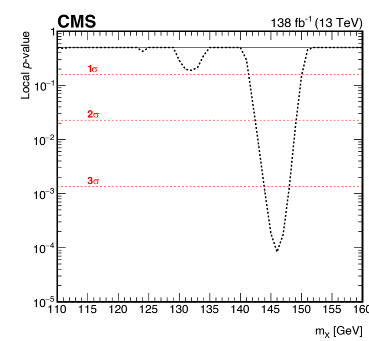
Divided into subsamples









@M_H=146GeV:

Observed(expected) Upper Limit on x-sec of X→ eμ:

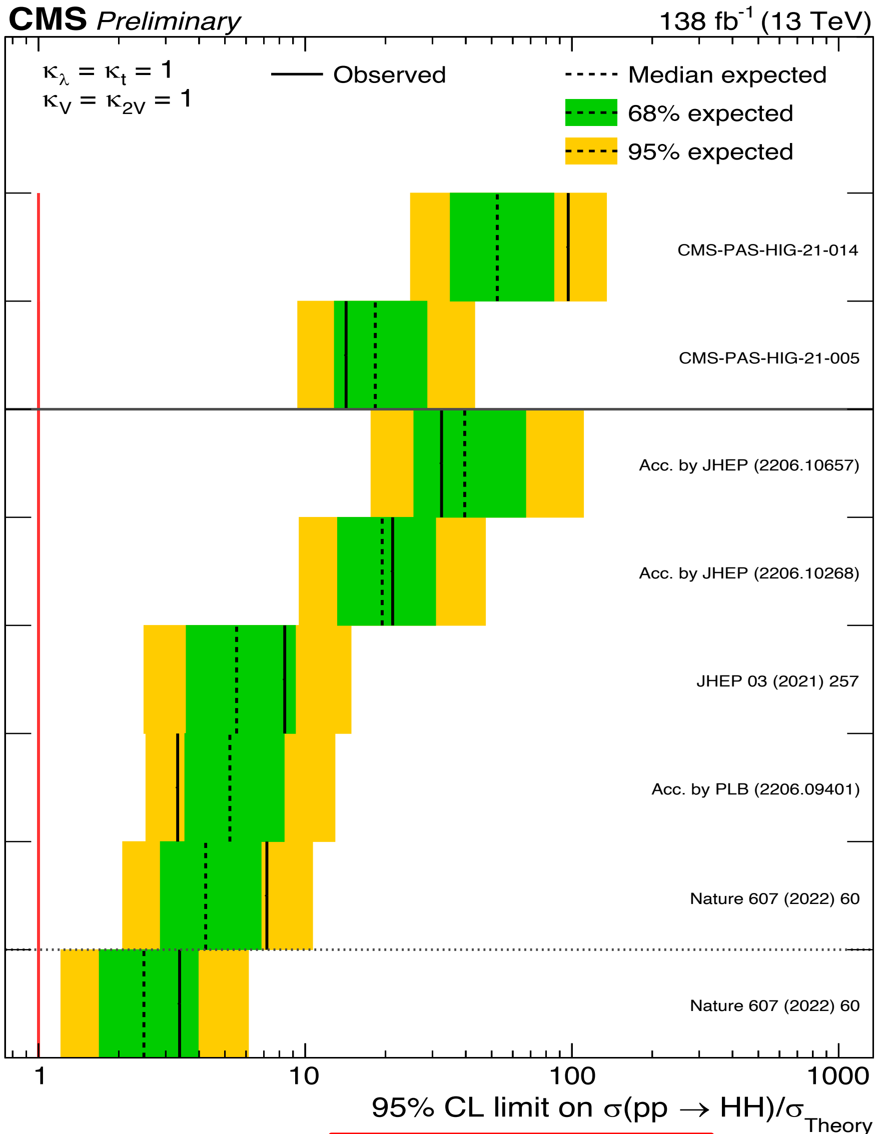
6.0(2.1) fb^{-1} @95% CL

Excess observed: **Global (local)significance: 2.8(3.8)σ**

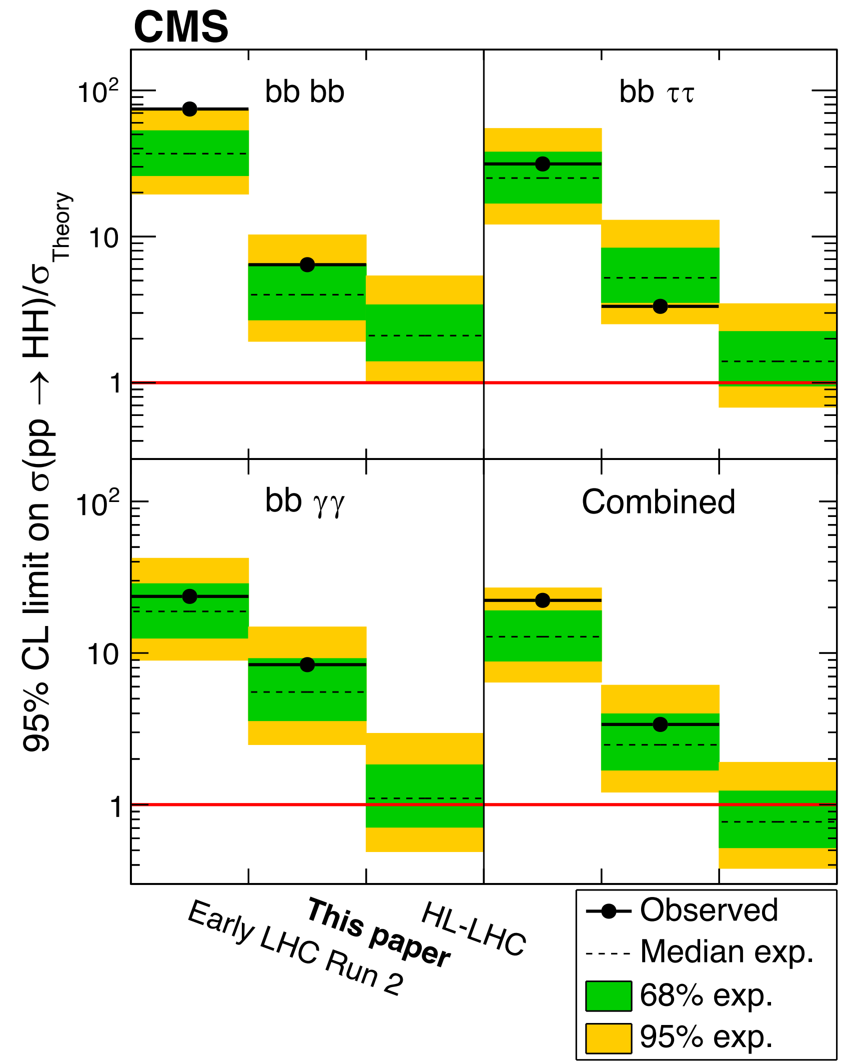
HH Production Limits

[Nature 607 (2022) 60-68]

March 2023



σ = 3.4 times σ_{SM}



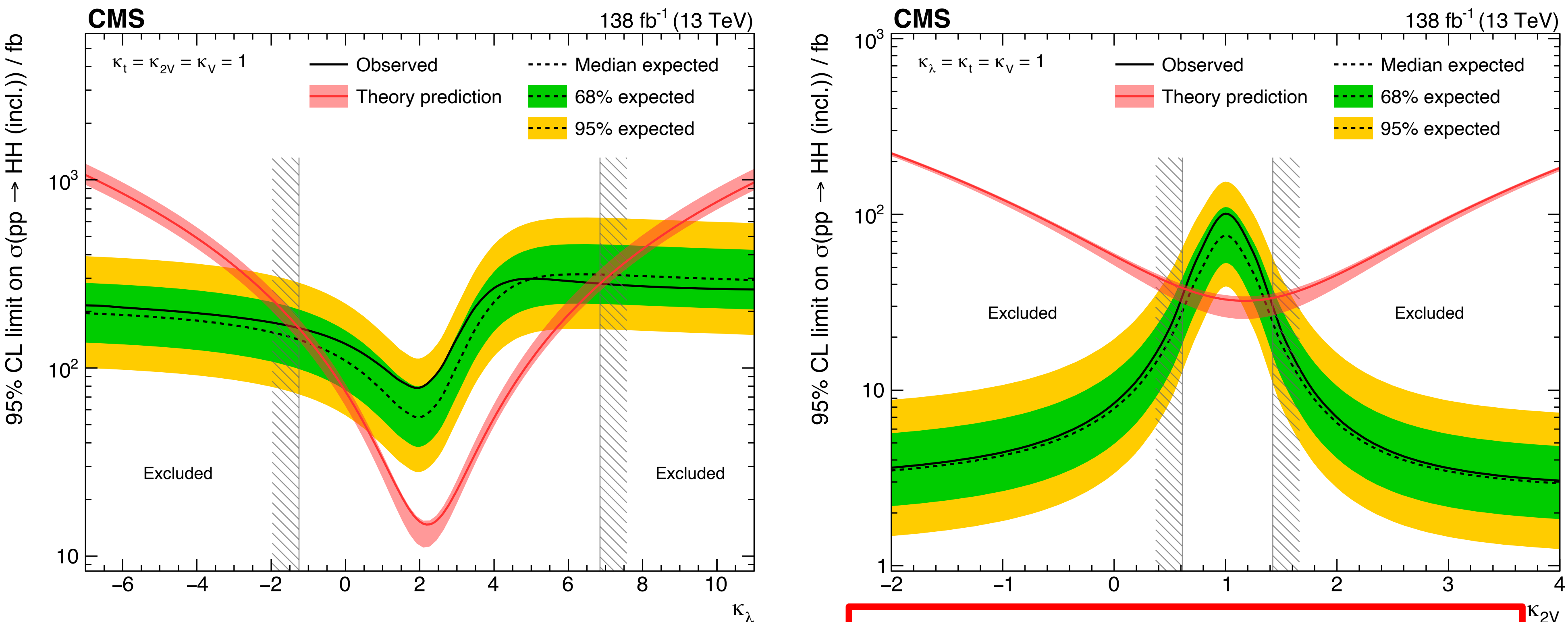
HH Discovery expected at the HL-LHC

HH Production Limits Run 2

Nature 607 (2022) 60-68

Limits on Higgs boson self-interaction κ_λ and quartic coupling κ_{2V} (VVHH)

SM values assumed for H modifier couplings to t and V



Constrain on Higgs self coupling modifier κ_λ

$-1.24 < \kappa_\lambda < 6.49$

Constrain on Higgs coupling modifier κ_{2V}

$-0.67 < \kappa_{2V} < 1.38$

K_{2V}=0 excluded with 6.6σ significance

Summary of Higgs Measurements

- Results in agreement with the SM
- Strong limits, below **1**%, on LVF of H→μe, $\mu\tau$, τe
- Higgs may play a role as a portal to new physics theories ; H→invisible observed (expected) limit of **0.15(0.08)** @95% CL
- HH measurements @HL-LHC

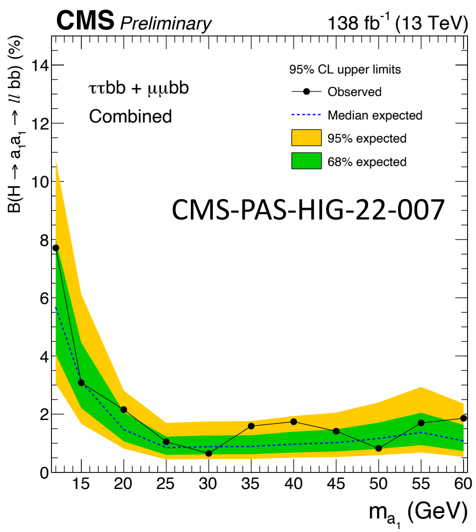
Part 2

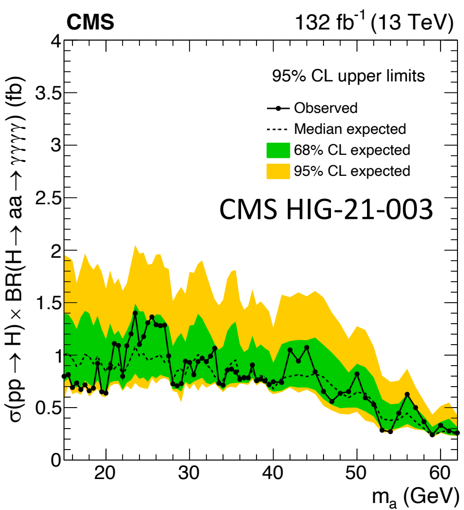
- Searches for BSM decays of the H
  - The exotic decay channels may include the Higgs boson decaying to a pair of light pseudoscalar particles, subsequently decaying to pairs of SM particles.

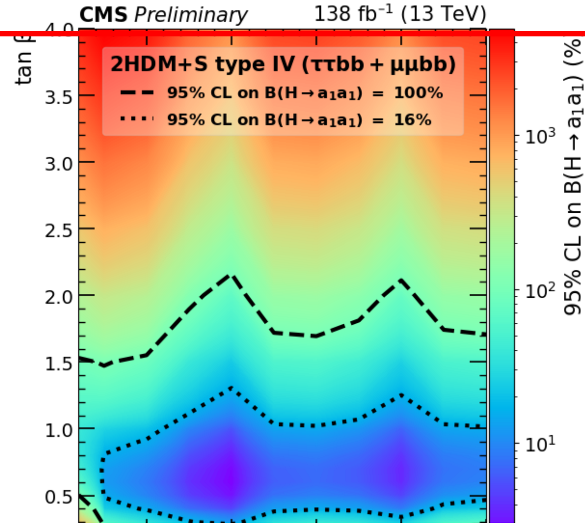
Search for H → aa →bb ττ(μμ), γγ γγ

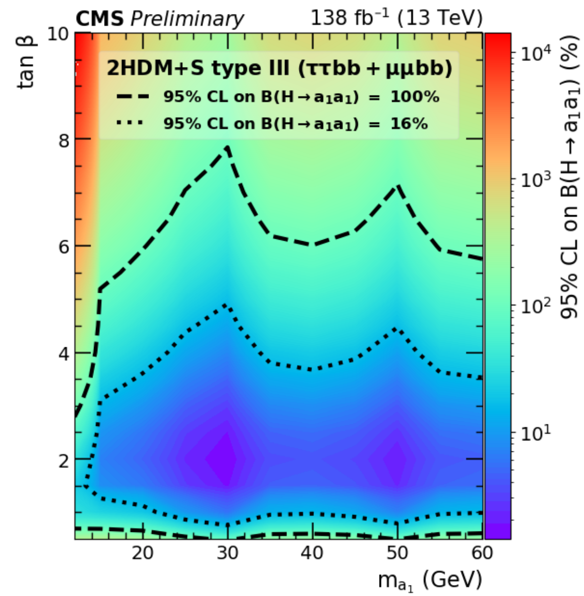
CMS HIG-21-003 CMS-PAS-HIG-22-007

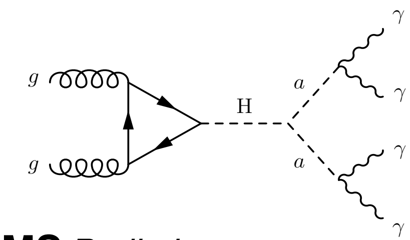
Interpretation in 2HDM+S (4 types cplgs to avoid FCNC@LO
Mass range: 15-60 GeV

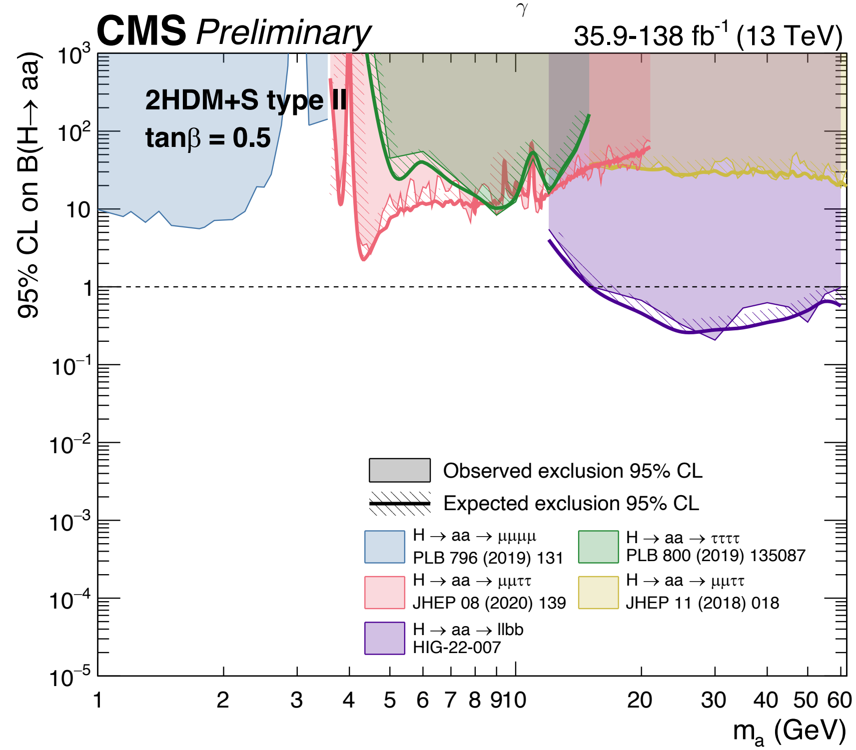












CMSPublic/Summary2HDMSRun2

Most stringent limits on Br(H→aa) in the mass range 15 – 60 GeV
Values above 23% excluded for Type II

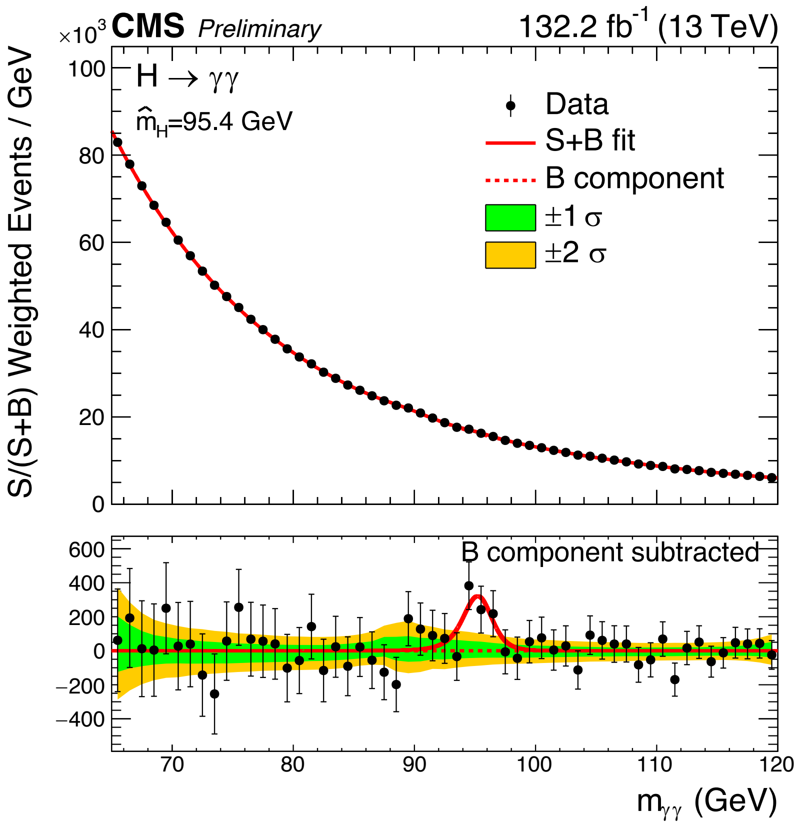
Part 3

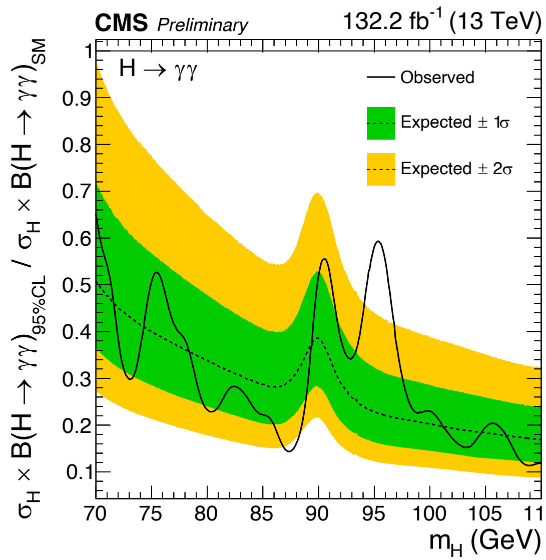
- Searches for other spin-0 particles

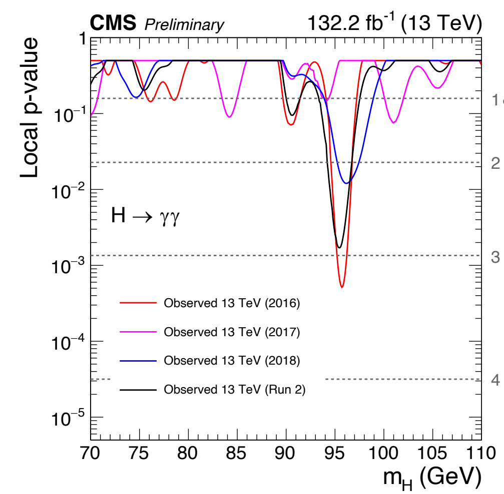
Search for Light H → γγ

CMS-PAS-HIG-020-002

Search for additional light H → γγ decays below H(125)





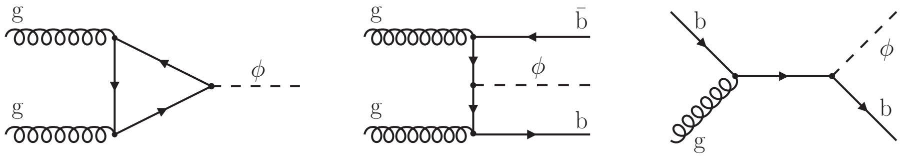


Data compatible with background-only-hypothesis
Observed Upper Limit on σ x BF : from 73 to 15 fb-1
Largest deviation M=**94.5** GeV w/ Local (Global) **2.9**(**1.3**)σ

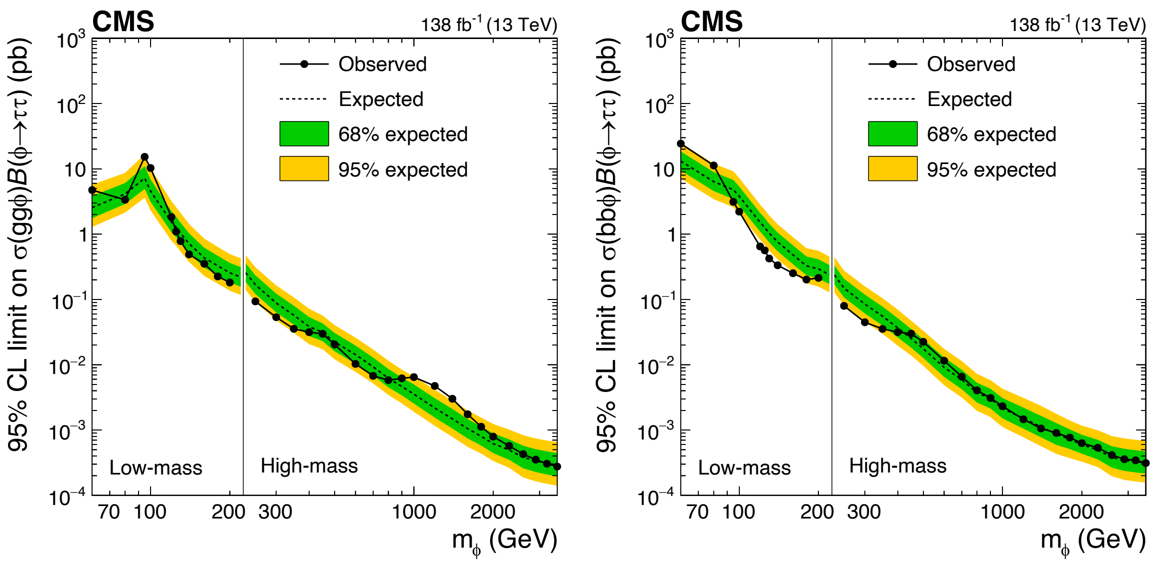
Search for neutral higgs ϕ

JHEP07(2023)073

Neutral higgs ϕ in ggF or in association with b-quark(s)



$\phi \rightarrow \tau\tau$ in lepton or hadron decays



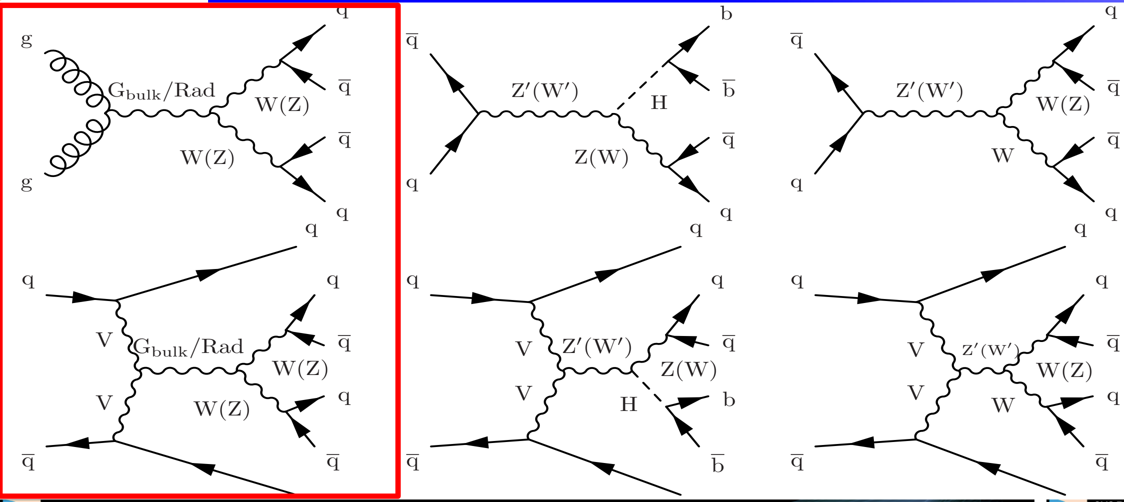
Limits set [60 - 3500 GeV] ranging from 10pb to 0.3fb
e.g. two excesses in ggϕ at 0.1 and 1.2 TeV with ~3σ

In MSSM scenarios M_h^{125} & $M_{h,\,EFT}^{125}$ additional Higgs bosons with masses below 350 GeV excluded

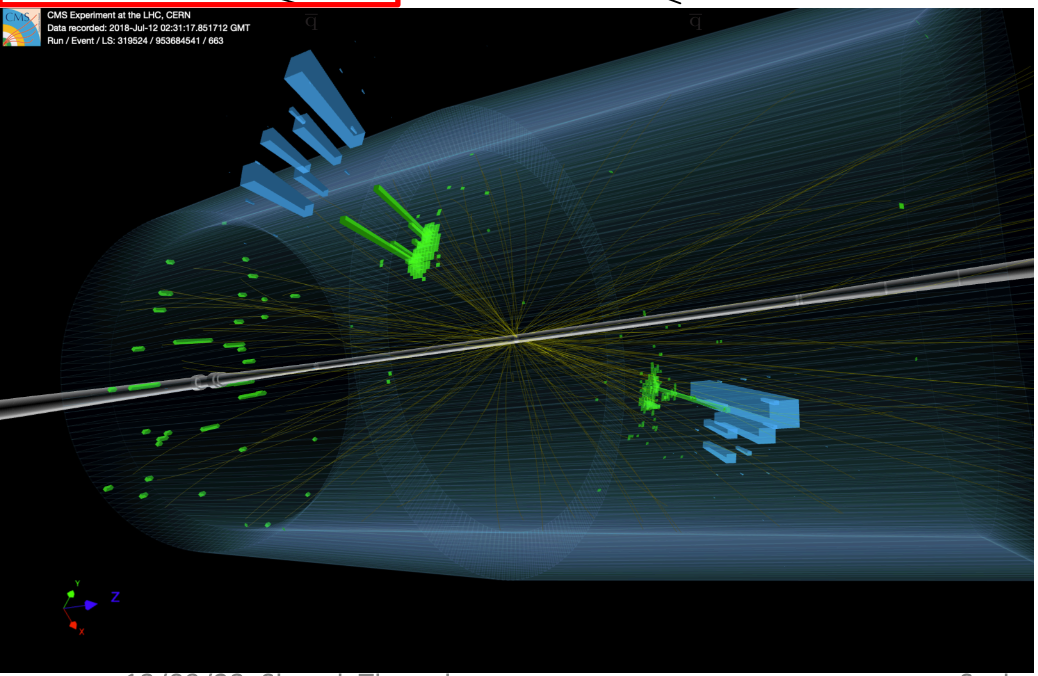
Search for VV,VH All-Hadronic Resonance

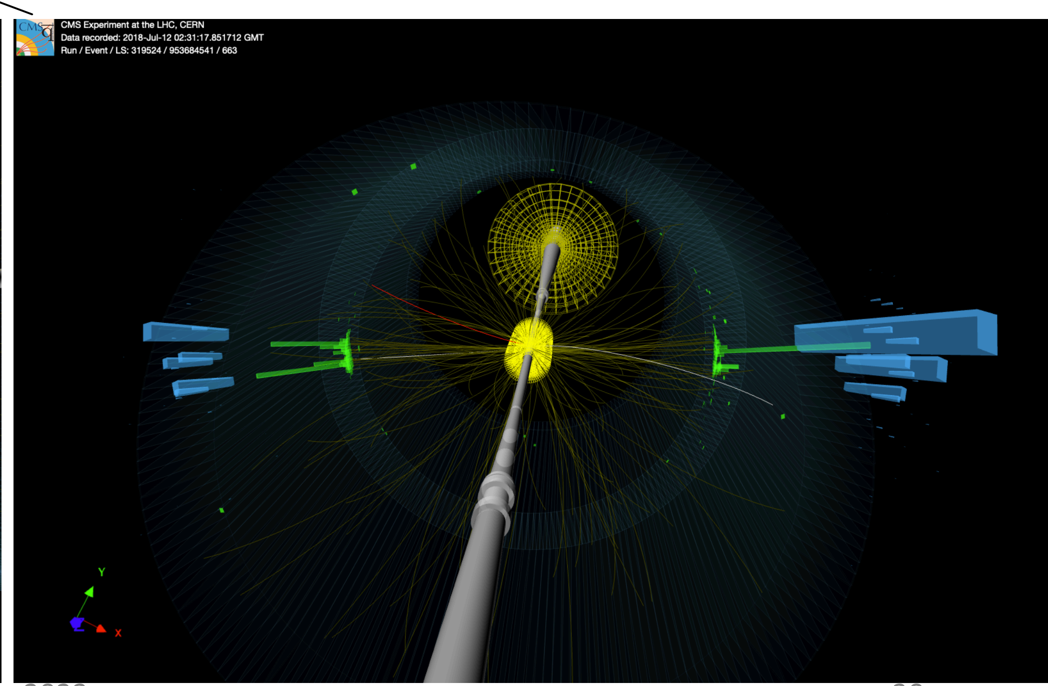
CMS PAS B2G-20-009

[Phys. Let. B 844 (2023) 137813]



Bosons highly boosted reconstructed as 1 super-jet with new ML algorithm



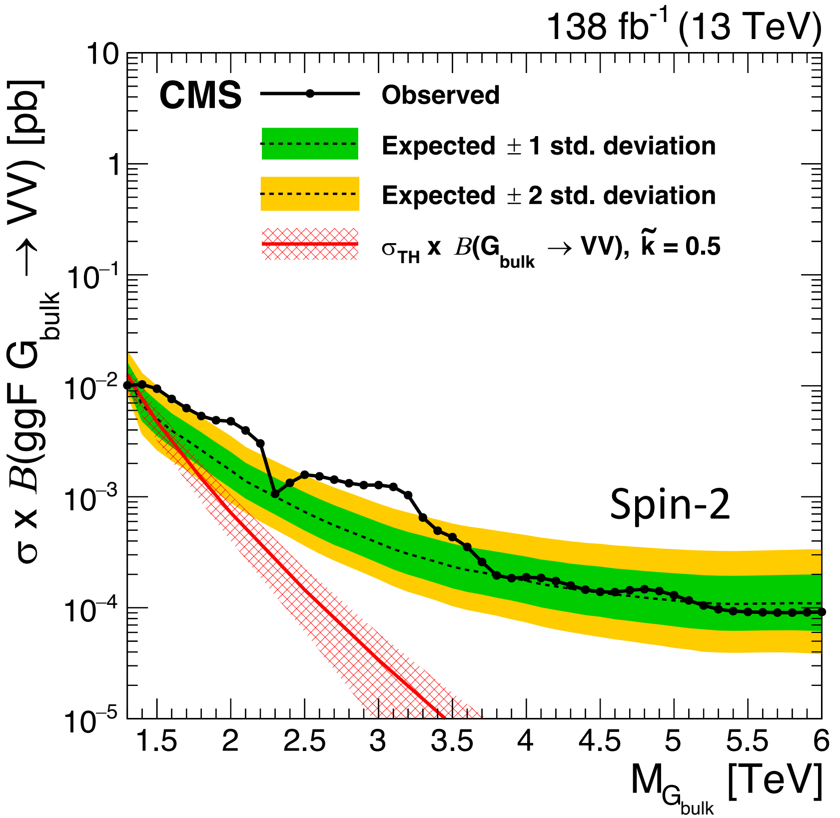


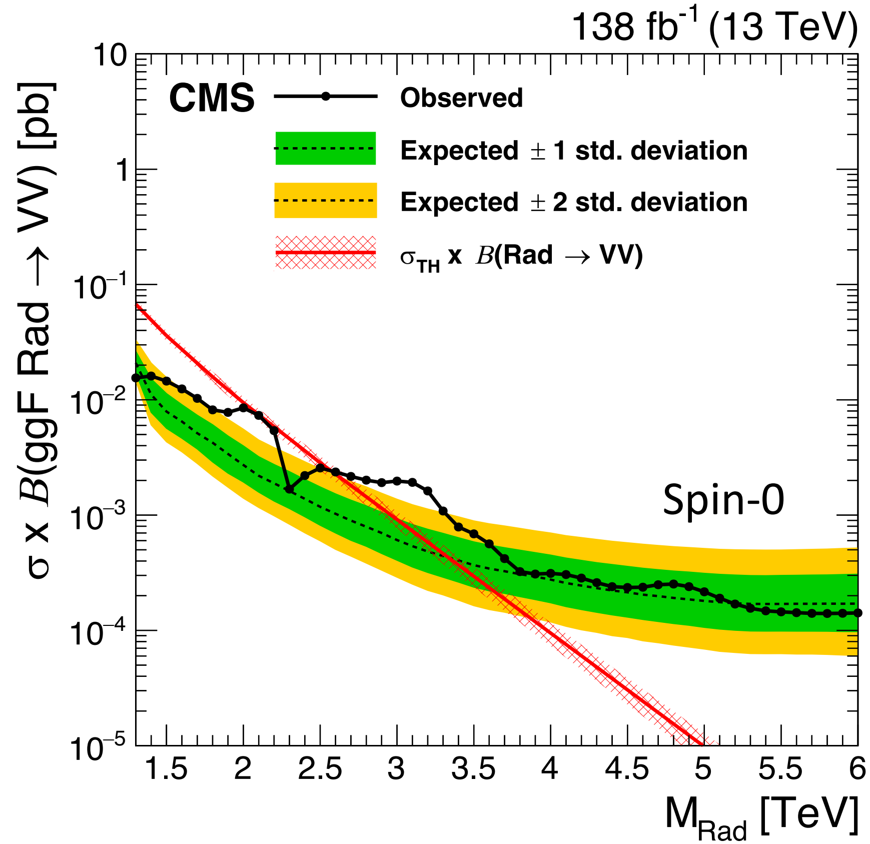
Search for VV,VH All-Hadronic Resonance

CMS PAS B2G-20-009

Phys. Let. B 844 (2023) 137813

Models: spin-2 Gravitons, and spin-0 radions





Limit on G_{bulk} mass
G_{bulk} 1.4 TeV at 95%CL

Mild excesses observed @**2.1**&**2.9**TeV with **3.6σ(2.3σ)** local (global) significance

Limits on Radion mass:
Rad: 2.7 TeV at 95%CL

Search for charged Higgs

CMS HIG-20-017

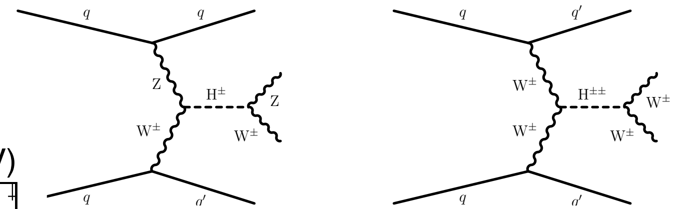
[Eur. Phys. J. C 81 (2021) 723]

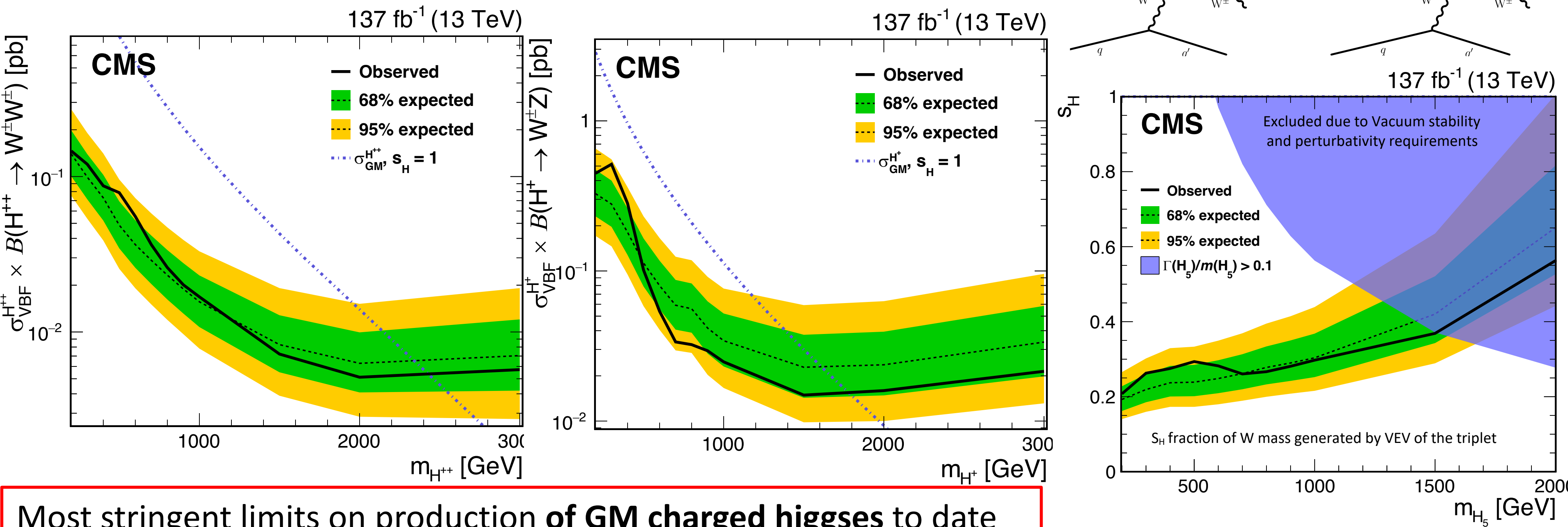
Leptonic decays of VV and VBF selection

Interpretation using **Georgi-Machacek** model with additional triplets

e.g. one SU(2) isotriplet allows charged higgses to couple at LO to V-bosons

VBF production of charged Higgs: $H_5(H^+, H^{++})$ – degenerated in mass@LO





Most stringent limits on production of GM charged higgses to date

GM particles as a resolution of tensions in EWK fits with new CDF m_W e.g.Ellis et al. arXiv:2204.05260 - list tree-level single field extensions that include EFT dim-6 operators providing a better fit than SM alone among them 2.9TeV Ξ– triplet

Exclusion of model parameter S_H for masses 200-1500GeV: 0.2-0.35@95%CL

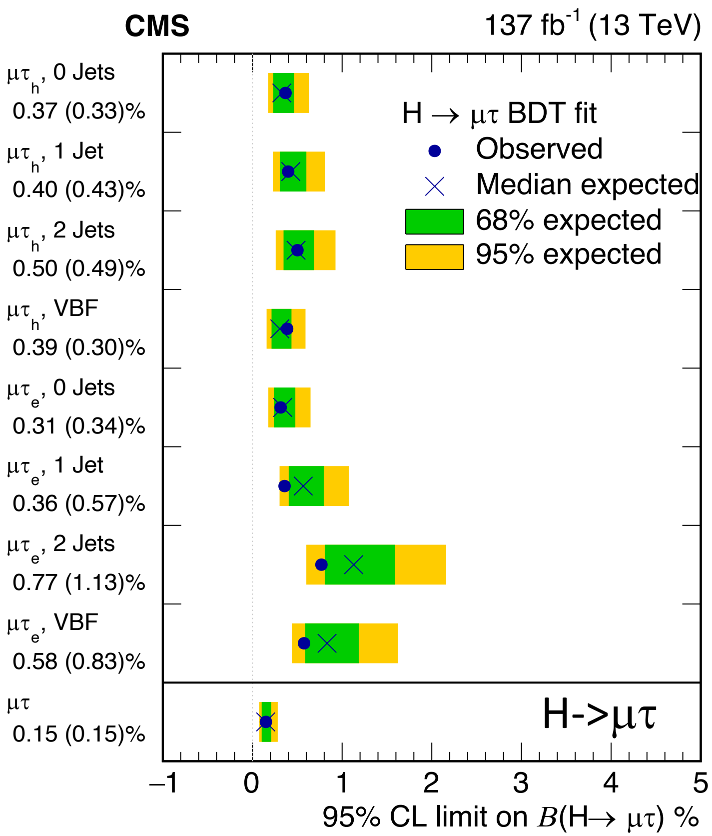
SUMMARY

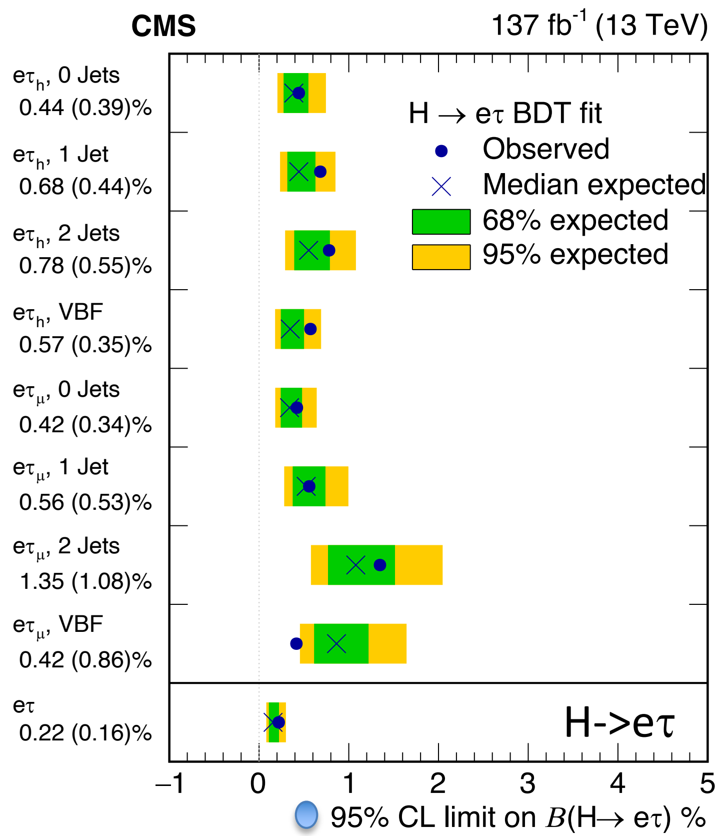
- Crucial precision and fundamental Higgs measurements available
  - Exciting info about properties, exotic decay modes
  - Agreement with the SM expectations and EWSB
- No hints of additional spin-0 particles so far
- Additional results soon to come with Run2&3 datasets
  - Clarification of the mild excesses observed in the data
  - Improved precision with increased impact on the Higgs boson physics

Additional Slides

LFV Higgs Decays Run 2

Phys. Rev. D 104 (2021) 032013





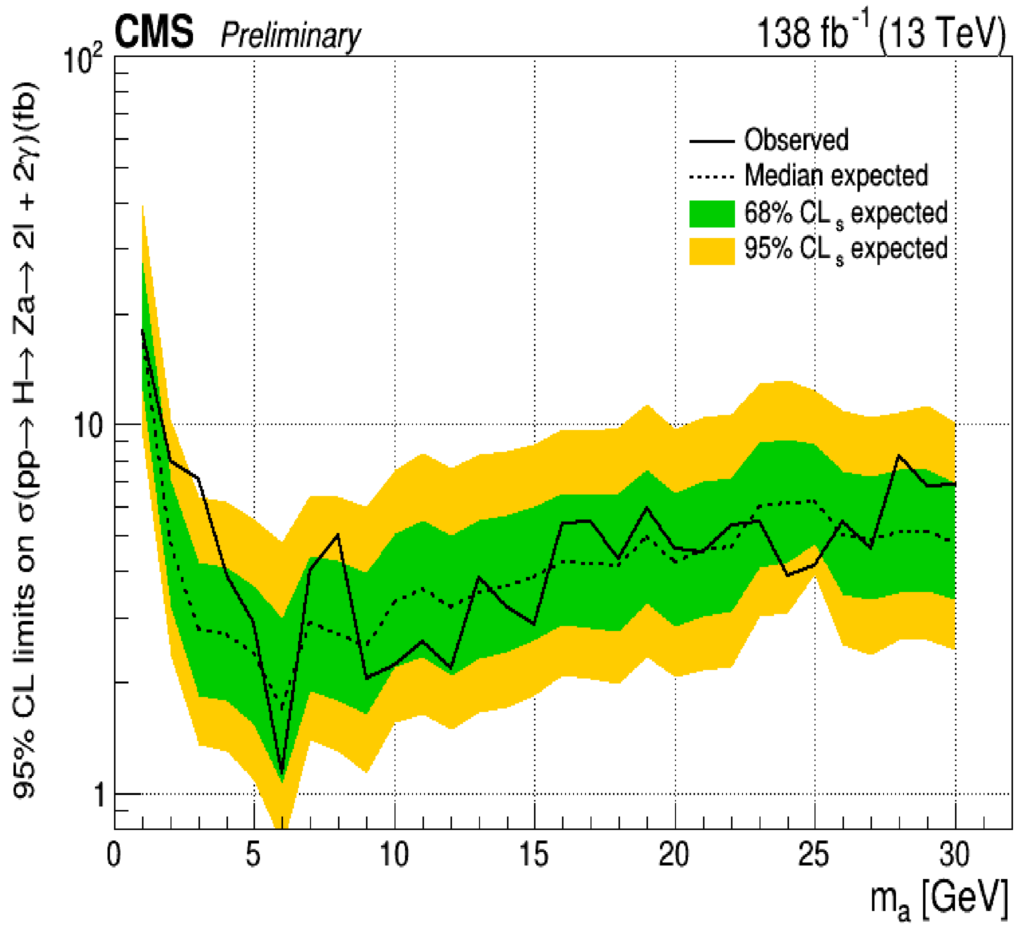
	Observed (expected) upper limits (%)	Best fit branching fractions (%)	Yukawa coupling constraints
$\mathrm{H} \to \mu\tau$	<0.15 (0.15)	0.00 ± 0.07	$< 1.11\,(1.10) \times 10^{-3}$
$\mathrm{H} \to e\tau$	<0.22 (0.16)	0.08 ± 0.08	$< 1.35\,(1.14) \times 10^{-3}$

No excess observed in Run 2 data

Search for H → Za → $\ell\ell\gamma\gamma$

CMS-PAS-HIG-22-003

1<m(a)<30 GeV mass range considered with resolved $\gamma\gamma$
Data driven methods to estimate Backgrounds
BDT classifier optimized to discriminate signal



Data compatible with background-only-hypothesis

Limits set on σ(H) x Br(H→ Za→ $\ell\ell\gamma\gamma$)

Limits set on the Axion-Like-Particle coupling parameter to H,Z, ALP

Search for Heavy Higgs to WW decays

CMS-PAS-HIG-020-016

ggF and VBF production considered
Fully leptonic final states (ee, μμ, eμ)

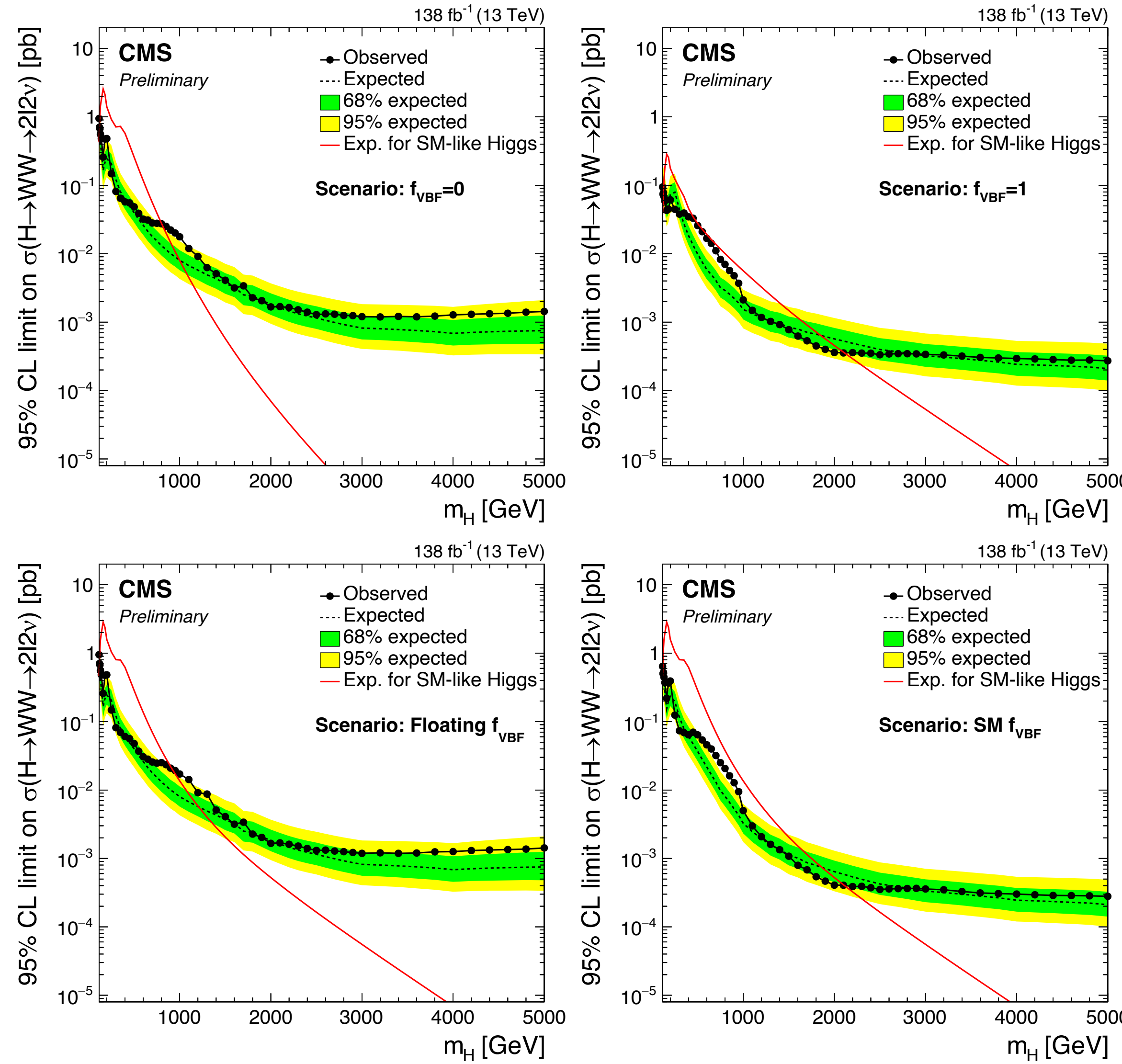
New analysis techniques implemented
Various width hypothesis considered

Heavy higgs excluded up to 2100TeV @95% CL depending on the production model

Upward fluctuation observed in data over the expected background

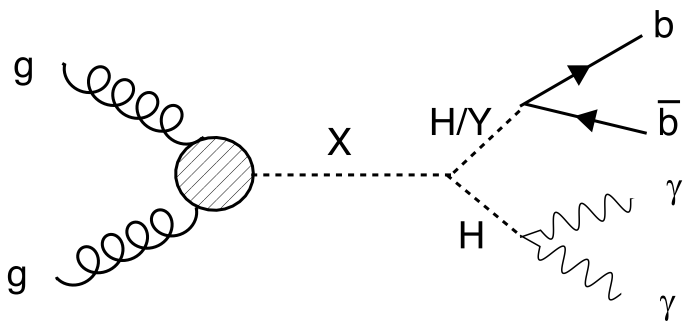
Signal hypothesis at mass of **650** GeV with highest global significance of **2.6σ** for VBF production only

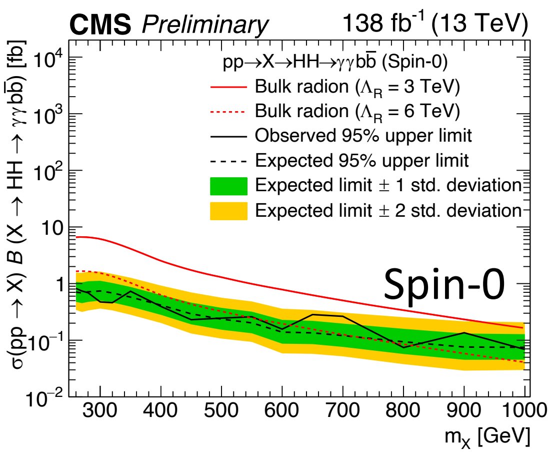
Additional exclusion limits obtained on MSSM and 2HDM scenarios

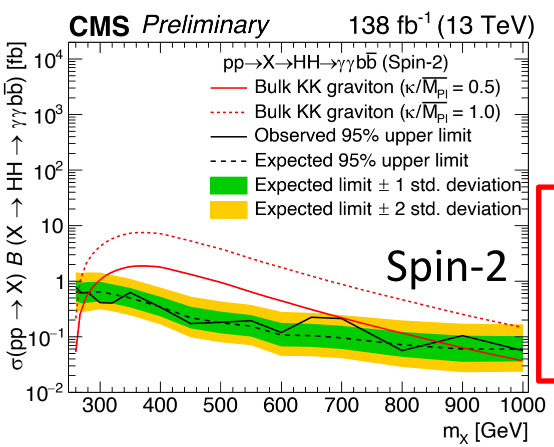


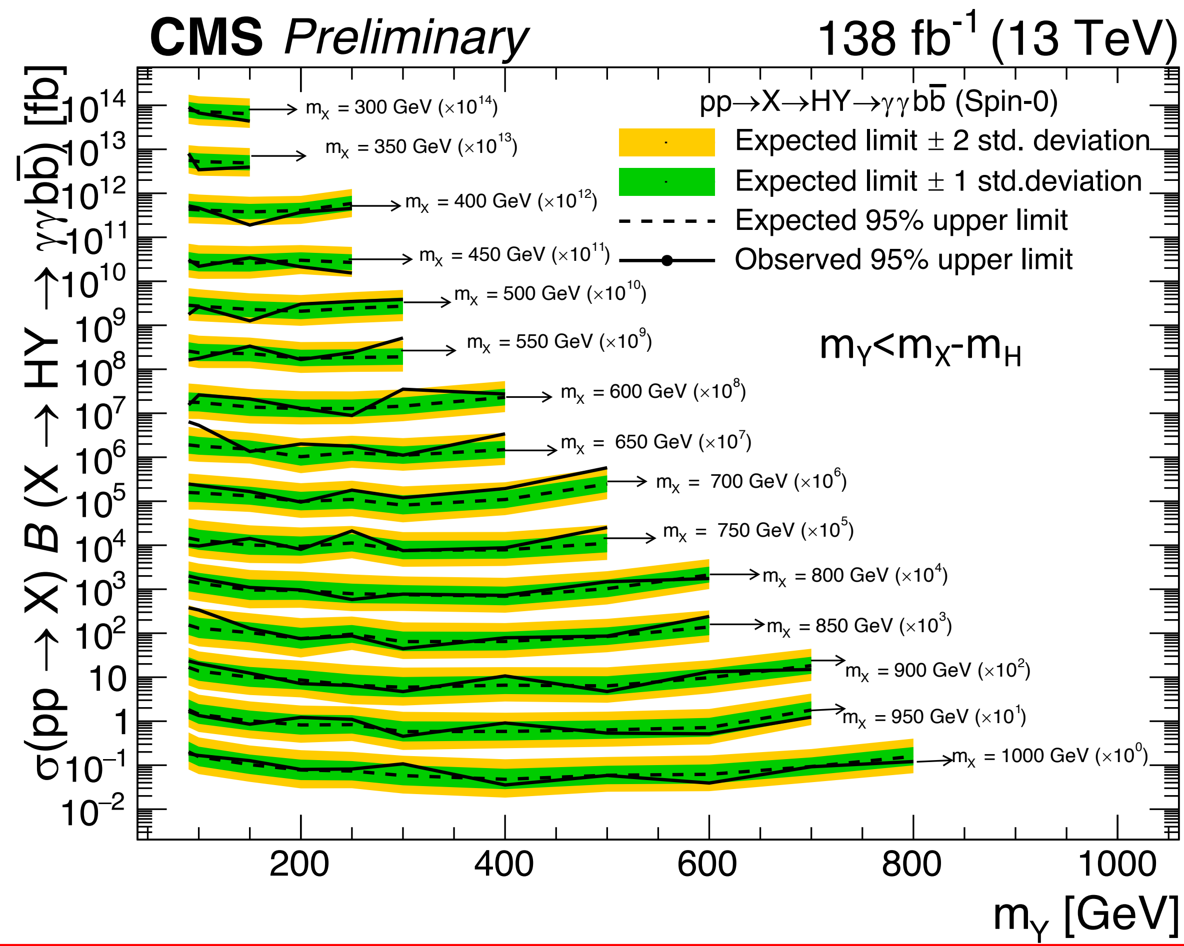
Search for X → H/Y(bb)H(γγ)

CMS-PAS-HIG-021-011









Overall agreement with the SM

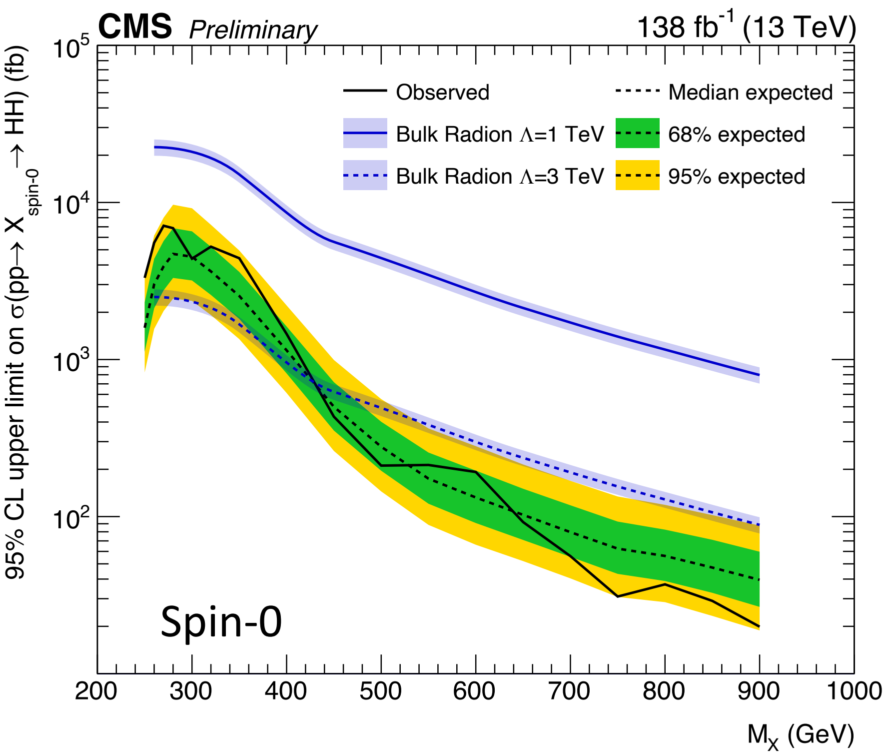
Data compatible with background-only-hypothesis

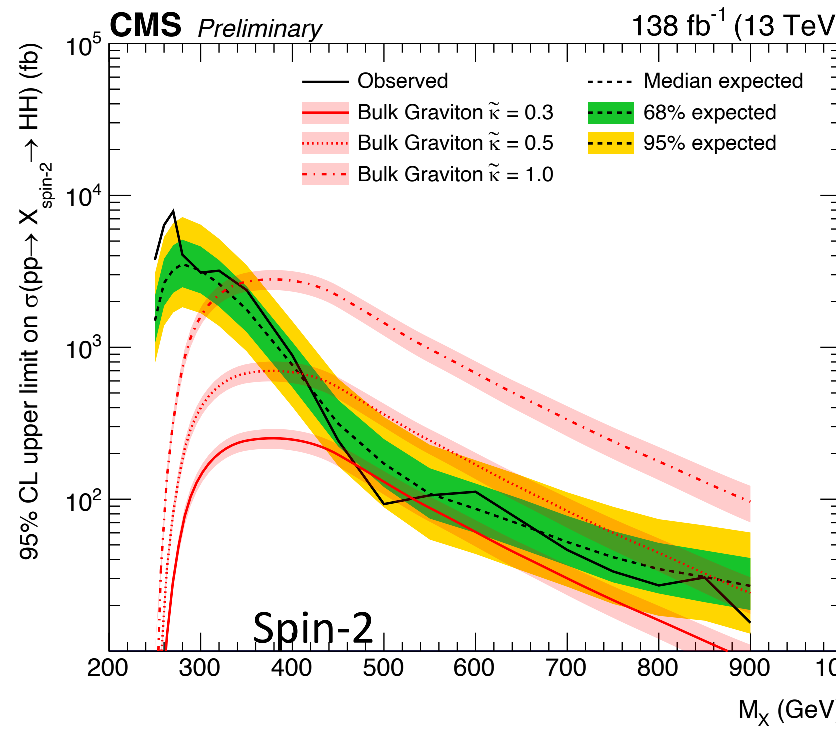
Largest deviation M_X=650GeV and M_Y=90GeV w/ Local (Global)3.8σ(2.8σ)

Search for X→H(WW)H(bb)

CMS-PAS-HIG-021-005

Resonant X→HH → WWbb in leptonic and hadronic decays
Motivated by the Extended Higgs and Warped ED models
DNN to classify events according to categories





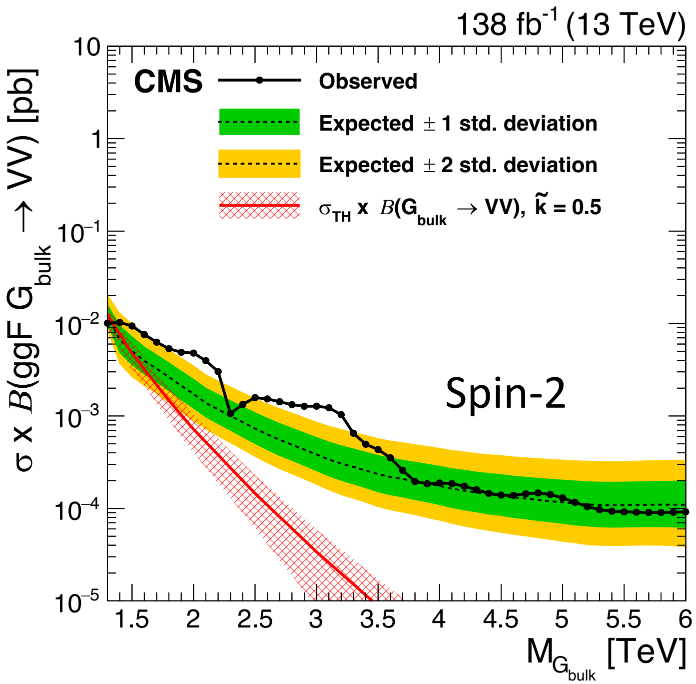
Limits set on HH production for spin-0 (**Radion**) and spin-2 (**Graviton**) in the mass range 250-900 GeV
Compared to warped Extra Dimension Models with warp parameters Λ and κ
Data compatible with background-only-hypothesis

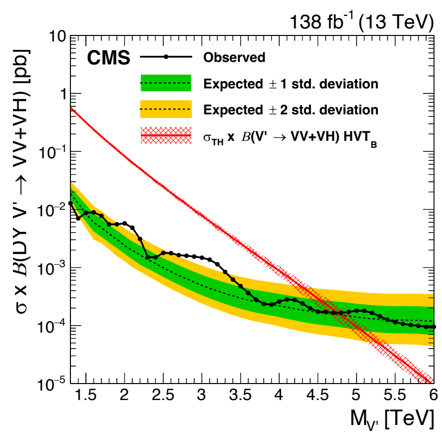
Search for VV,VH All-Hadronic Resonance

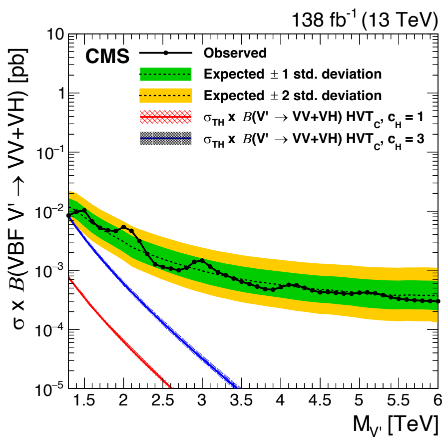
CMS PAS B2G-20-009

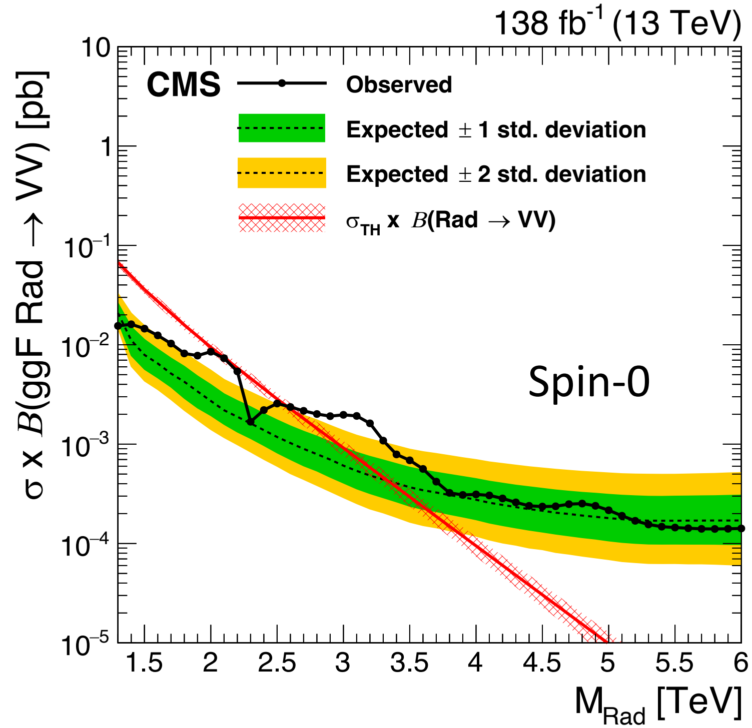
Phys. Let. B 844 (2023) 137813

Models: Gravitons, heavy spin-1 bosons (W', Z') and spin-0 radions









Limit on G_{bulk} mass
G_{bulk} 1.4 TeV at 95%CL

Mild excesses observed @**2.1**&**2.9**TeV with **3.6σ(2.3σ)** local (global) significance

Limits on Radion mass:
Rad: 2.7 TeV at 95%CL

Limits on the Heavy Vector Triplet "B"-type model: V': 4.8 TeV at 95%CL
HVT C-type: Upper Limit on
x-section and branching ratio at 0.1fb