CMS Overview

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on behalf of the CMS Collaboration

Outline

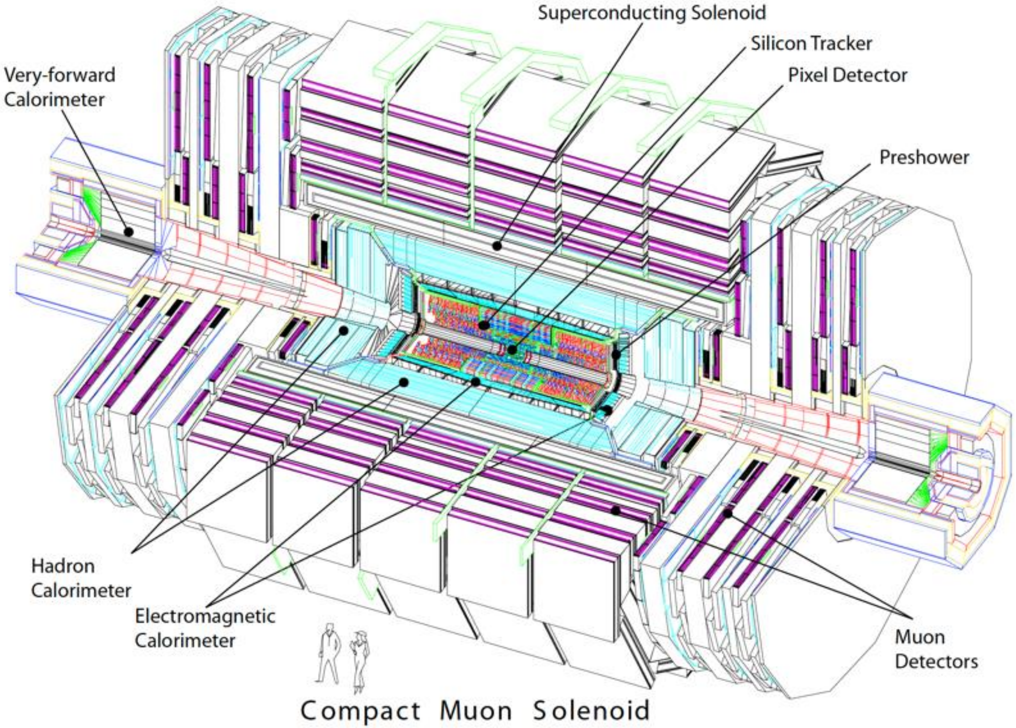
CMS 101

- Detector
- Going beyond the ”nominal mandate”
- Upgrades for HL-LHC
- Luminosity: past, present, future

Hand-picked recent physics results

- Part I: Higgs boson
- Part II: beyond Higgs boson

CMS at glance



Solenoid: 3.8 T

Pixel Detector: $\sigma_{\mathrm{IP}} \sim 10\ \mu m$

Silicon Strip Tracker: $\delta p_T / p_T \sim 1\%$

EM calorimeter: $\delta E_T / E_T \sim 0.5\%$

Hadron calorimeter: jet $\delta E_T / E_T \sim 10\%$

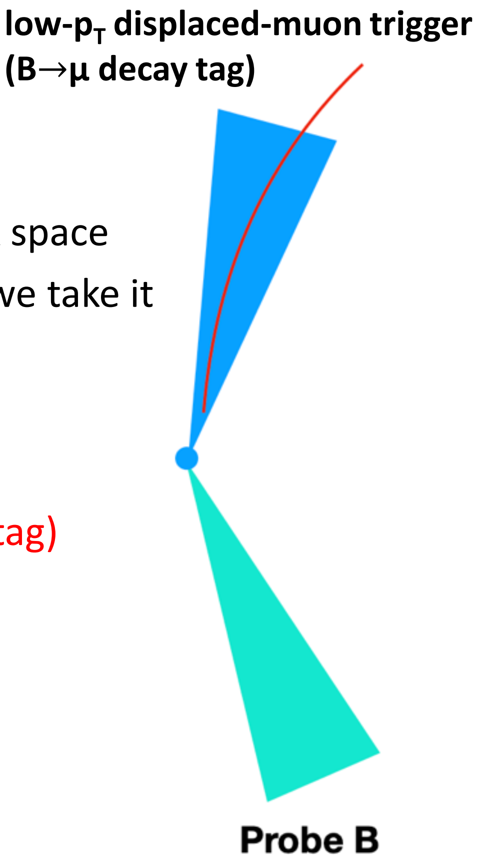
Muon System: standalone $\delta p_T / p_T \sim 10\%$

Trigger:

- Level 1 (calo+muon only): 100 kHz
- High-Level Trigger: 1 kHz

30 years since inception (Letter of Intent)

CMS: going beyond the “nominal mandate” (1)



Parked data

HLT rate:

- **original design goal: 100 Hz**, limited by anticipated DAQ bandwidth and disk space
- **current rate: 1 kHz**, limited by the computing power to reconstruct data as we take it

CMS can take data at higher rates, **2-4 kHz, with low trigger thresholds** and “park” extra data for reconstruction during long shutdowns

In 2018, parked data was taken with low-p_T displaced-muon triggers (B→μ decay tag)
Recorded >10^{10} events with unbiased B’s (20 times the entire BaBar B dataset)

Example of analysis: $R(K^*) = \frac{\mathcal{B}(B \to K^*\mu\mu)}{\mathcal{B}(B \to K^*ee)}$ (in progress, stay tuned)

CMS: going beyond the “nominal mandate” (2)

Scouting trigger datasets

Another way to take events **with low-threshold triggers** without breaking the DAQ bandwidth is to record events with limited amount of information

- discard all raw data information
- retain HLT-reconstructed objects and only those of interest
- event size ~1 kB (vs ~1 MB for a full event record)
- can have a few triggers running at > 1kHz
  while taking only a tiny fraction of the DAQ bandwidth

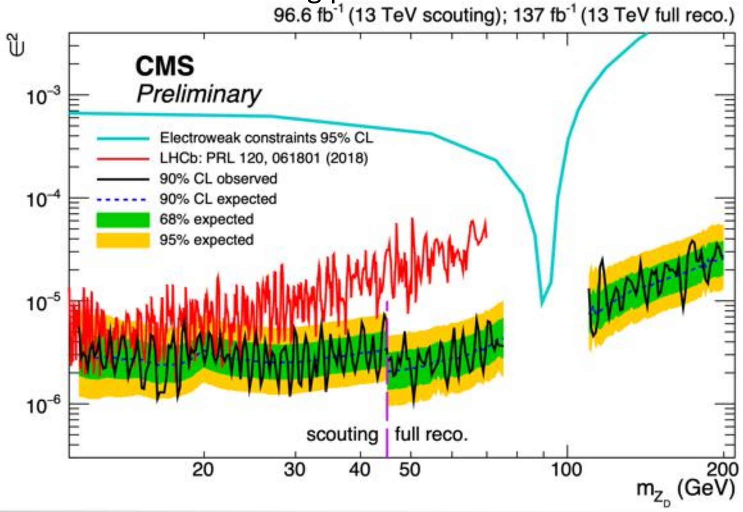
Scouting triggers in Run 2

- H_T>250 GeV (vs 900 for the nominal path)
- Dimuons with muon p_T>3 GeV (vs 17/8 for nominal path)

Examples of analyses:

- Search for $X \to jj$ in 0.6-1.6 TeV range [JHEP08(2018)130
- Search for $X \to \mu\mu$ with masses
  10-45 GeV [PRL 124 (2020) 131802]
  1-10 GeV (in progress, stay tuned)

Dark photon ($Z_d \to \mu\mu$):
limits on the mixing parameter ϵ



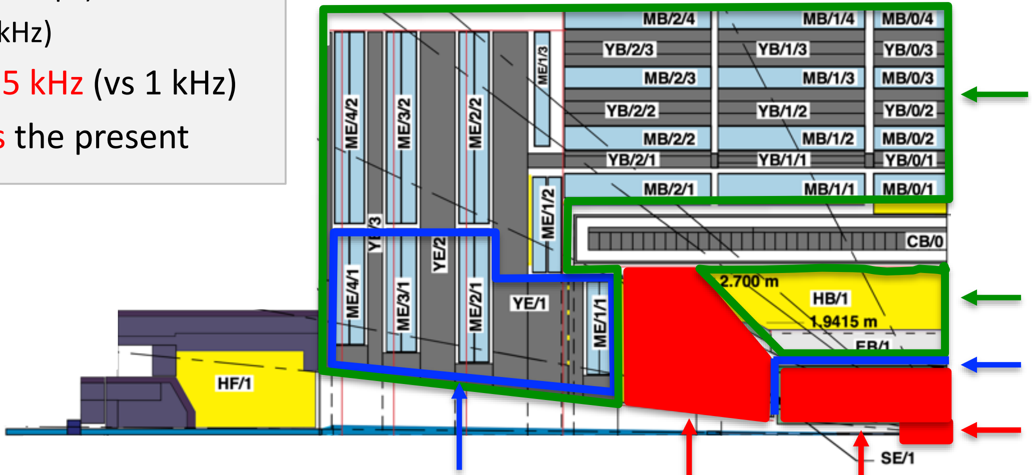
CMS: upgrades for HL-LHC

L1 Trigger:

- add **L1 track trigger** (presently none)
- latency of 12.5 µs (vs 3.6 µs)
- rate 750 kHz (vs 100 kHz)

High-Level Trigger: rate 7.5 kHz (vs 1 kHz)

DAQ bandwidth: 10 times the present



new trigger/DAQ for all muon detectors

new trigger/DAQ for barrel calorimeters

add new mip timing detector

replace pixel detector

add new muon detectors

replace Si tracker

replace endcap calorimeters

All upgraded subsystems will have enhanced capabilities

Luminosity reminders

Run 1

- 7 TeV (2011): **~5 fb^{-1}**
- 8 TeV (2012): **~20 fb^{-1}**

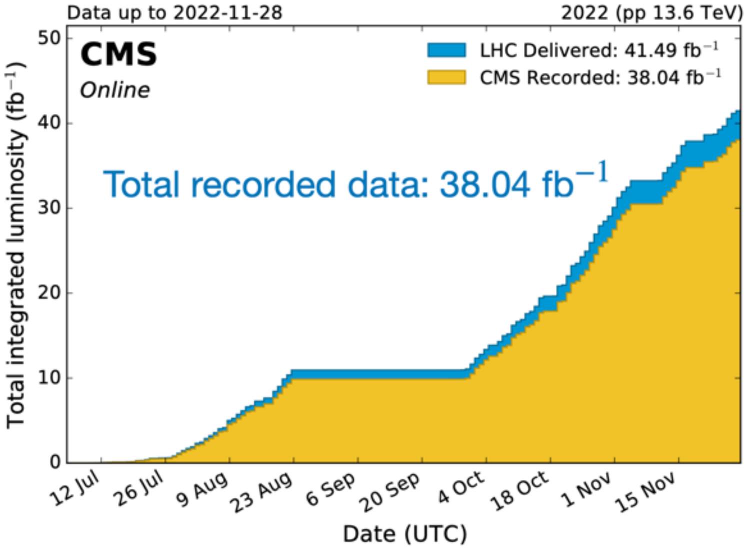
Run 2 (2015-2018): 13 TeV **~140 fb^{-1}**

Run 3 (2022-2025): 13.6 TeV **~300 fb^{-1}** **triple statistics** (from 140 to 440 fb^{-1})

HL-LHC (2029-2041): 14 TeV **~ 3000 fb^{-1}** **× 20 statistics** (from 140 to 3000+ fb^{-1})

+ trigger/detector upgrades

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

Hand-picked recent physics results

Part I: Higgs boson

H(125) as a portal to BSM

The discovered Higgs boson:

- In SM, the Higgs boson's mass is the only free parameter in the Higgs sector – **must be measured**

However:

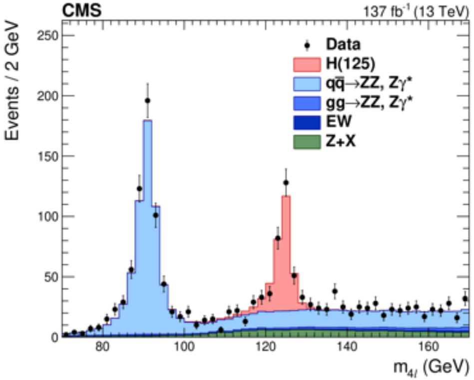
- being a theoretically-problematic oddity (scalar)
- and given its profound role in the SM,
- **Higgs boson just may turn out to be a unique portal to BSM unlike any other SM particle**

CMS has a broad program of searches for BSM associated with the discovered H_{125} :

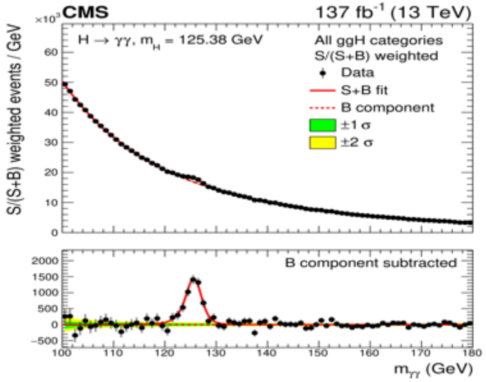
- are there small deviations in H_{125} couplings to the SM particles?
- is it 100% pure CP-even scalar? is it truly point-like?
- are there BSM production modes? ($t \to q\mathrm{H}, X \to \mathrm{HH}$, abnormal non-resonant HH)
- are there BSM decay modes? (H width, H → invisible, H → $\ell\ell'$(CLFV), H → BSM particles)
- And, of course, are there more BSM spin-0 particles? (another scalar, pseudoscalar, $H^{\pm}$, $H^{\pm\pm}$)

Higgs boson: 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*

HL-LHC: Expected precision ~20 MeV CMS PAS FTR-21/007 and 21/008

Decay modes

Nature 607 (2022) 60-68
Jul 4, 2022

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

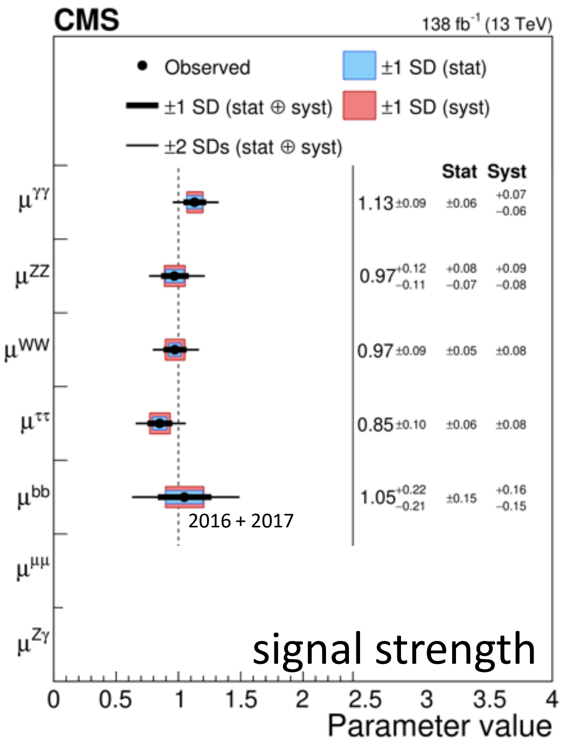
In green: five well-established decay modes (>5σ)

- 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 uncertainness. 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…



2016 + 2017

signal strength

Search for $H \to \mu\mu$

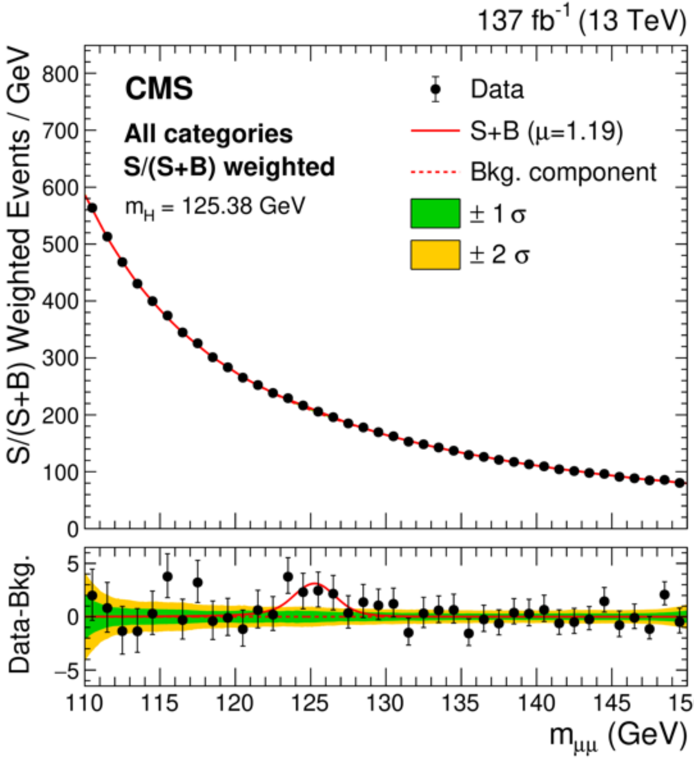
JHEP 01 (2021) 148
Jan 25, 2021
[Run 2]

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 blip in the dimuon invariant mass at $m_{\mu\mu} \sim 125$ GeV



Significance: 3.0 (evidence)

Signal strength: μ = 1.2 ± 0.4 (consistent with SM)

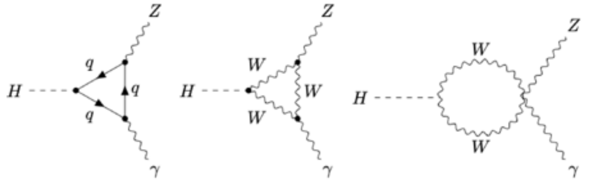
Assuming SM H, we need ~4 times more data to establish this decay mode with 5σ

Search for $H \to Z\gamma$

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

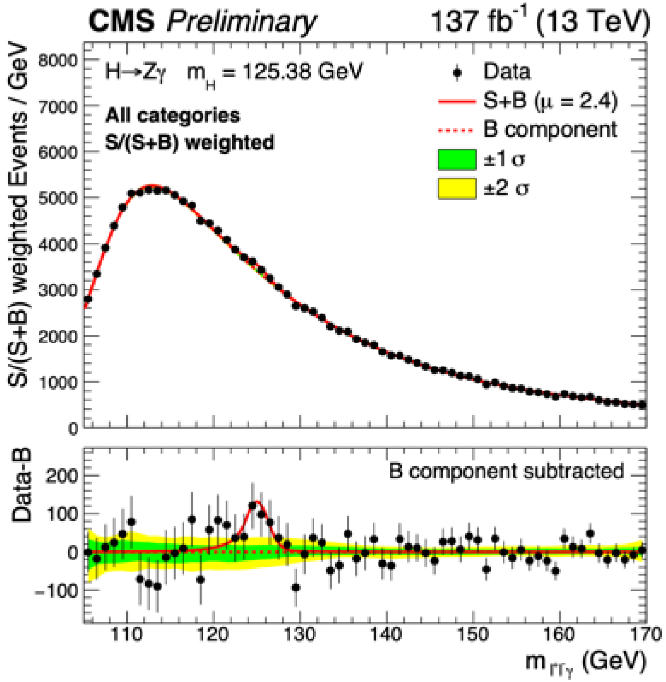
SM: $B(H \to Z\gamma)B(Z \to ee/\mu\mu) \approx 0.01\%$

loop-induced rare decay -> potentially 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 blip in the dimuon invariant mass at $m_{\ell\ell} \sim 125$ GeV



Significance: 2.7

Signal strength: μ = 2.4 ± 0.9

(an excess, but still well consistent with SM)

Assuming SM H, we need ~20 times more data to establish this decay mode with 5σ

Search for $H \to cc$

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

SM: $B(H \to cc) \approx \quad 3\%$

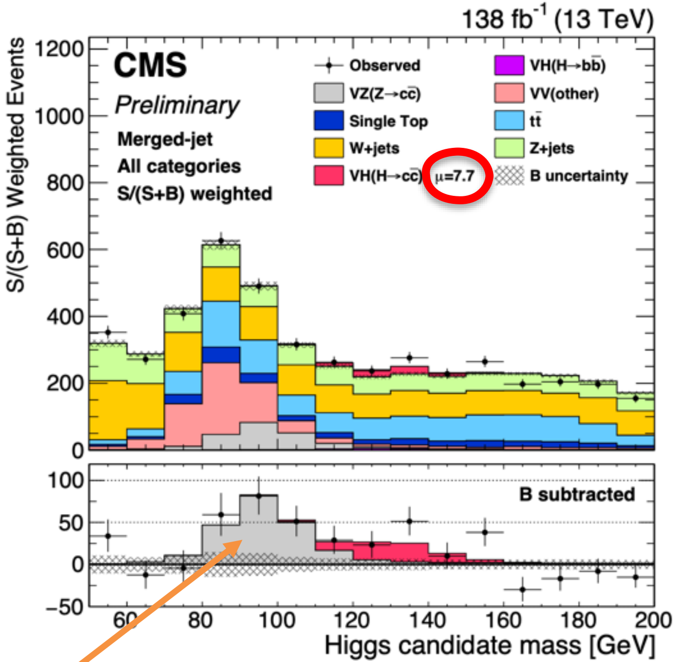
probing Higgs coupling to the second-generation fermions

Search mode:

- **V+H(cc),** including high-p_T 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**
- Advanced ML/AI techniques are now being employed and provide significant improvements in such discrimination



95% CL limit: μ < 14 (7.6 expected)

Signal strength: μ = 7.7 ± 3.7

Naively, one would need >100 times more data to see an evidence for this SM H decay with 3σ

"*standard candle*" $VZ, Z \to cc$

μ = 1.0 ± 0.2

significance 5.7

Just out: search for high-p_T H(cc)
CMS-HIG-21-012 (Nov 25, 2012)
95%CL limit: μ<47 (39 expected)

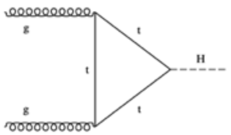
Established production modes

Nature 607 (2022) 60-68
Jul 4, 2022

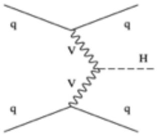
	gg	VBF	WH	ZH	ttH	tH	bbH
SM Higgs (σ=55.7 pb at 13 TeV)	**87.2%**	**6.8%**	**2.5%**	**1.6%**	**0.9%**	**0.2%**	**0.9%**

In green are five well stablished production modes $(> 5\sigma)$

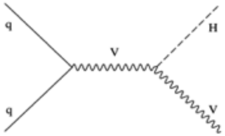
All event rates are compatible with the SM predictions



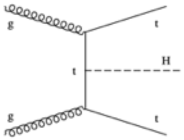
gg-fusion



VBF

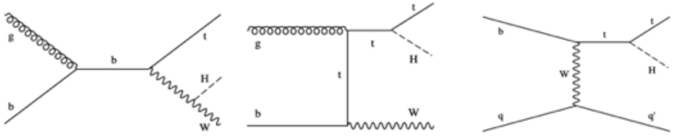


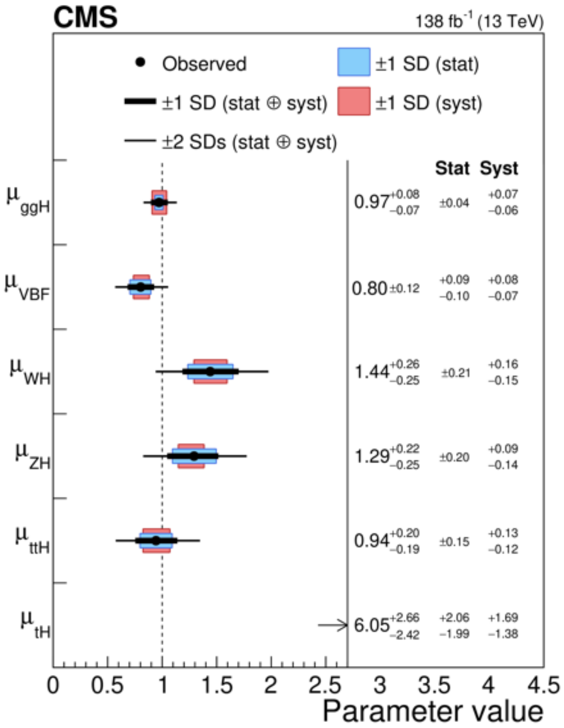
WH, ZH



ttH, bbH

tH



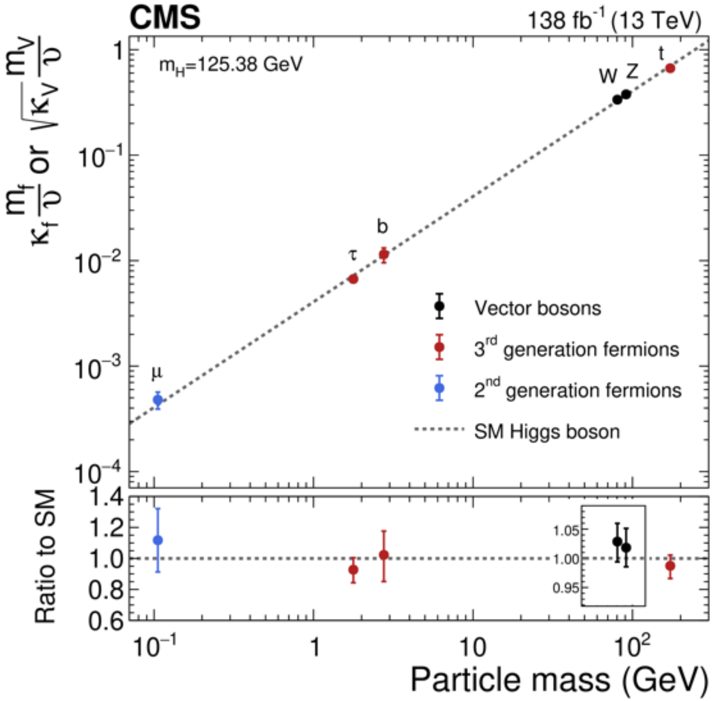


Fit for couplings modifiers

Nature 607 (2022) 60-68
Jul 4, 2022

Event rate for $ii \rightarrow H \rightarrow ff$: $\sigma_i \mathcal{B}^f = \dfrac{\sigma_i(\vec{\kappa})\Gamma^f(\vec{\kappa})}{\Gamma_{\mathrm{H}}(\vec{\kappa})}$

Fit for six Higgs coupling modifiers: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$



Assuming:

- 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** of couplings

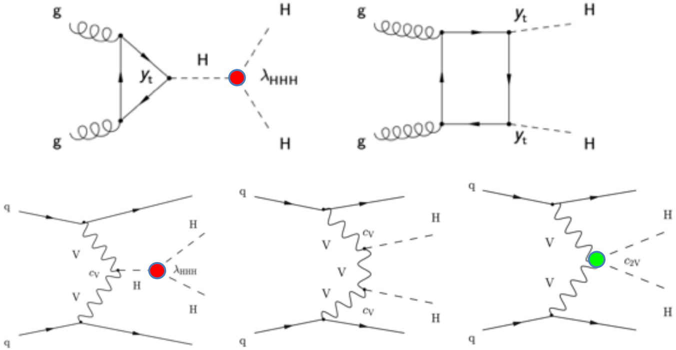
Search for HH production

Nature 607 (2022) 60-68
Jul 4, 2022
[Run 2]

In SM, $\sigma(HH) : \sigma(H) \sim 1:1000$

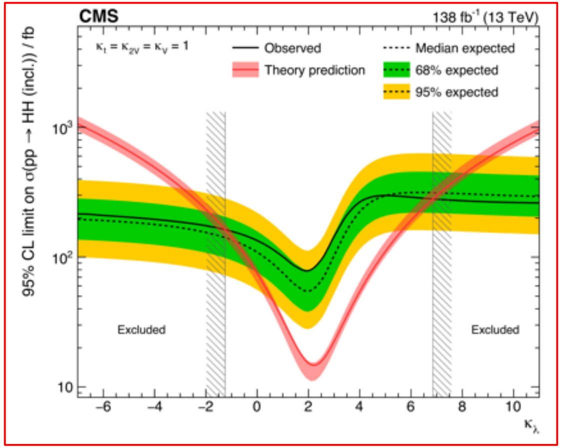
Three most sensitive decay modes:

- HH→ $(bb)(bb)$
- HH→ $(bb)(\tau\tau)$
- HH→ $(bb)(\gamma\gamma)$



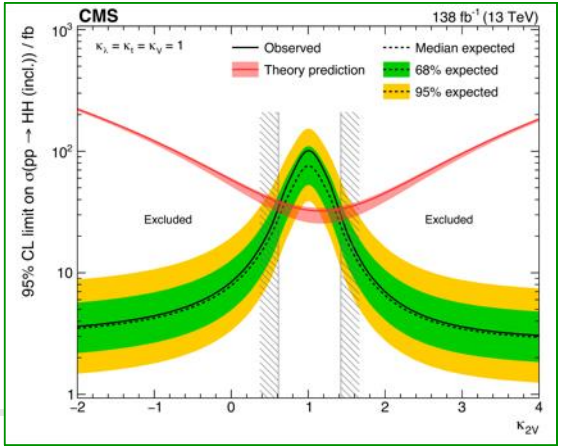
Production modes tags:

- 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 $0.7 < \kappa_{2V} < 1.4$ (0 excluded with 6.6σ!)



Hand-picked recent physics results

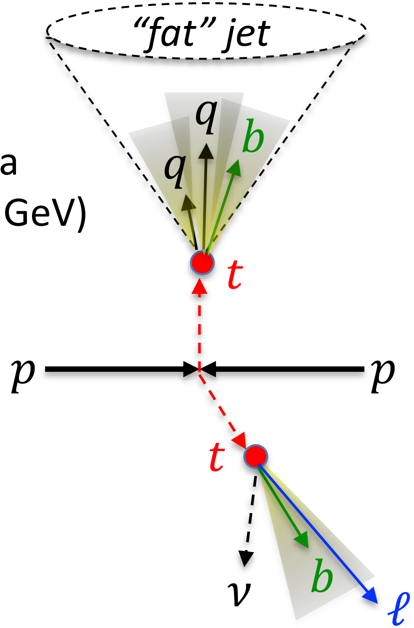
Part II: Beyond Higgs boson

SM: Top quark mass (boosted top)

CMS PAS TOP-21-012
(Nov 1, 2022)
[Run 2]

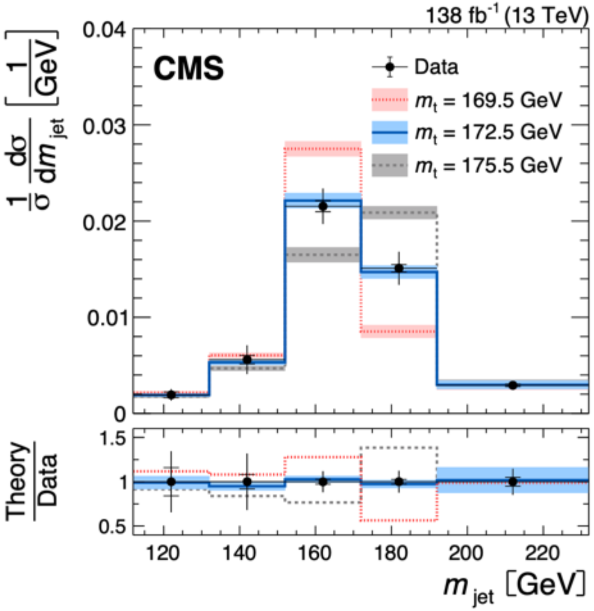
Signature: $tt \rightarrow (bjj) + b\ell\nu$

- target events with top p_T>400 GeV
- one top decays hadronically and forms a "fat" jet with sub-structure (jet p_T>400 GeV)
- another top decays leptonically (due to boost, the lepton may not be isolated)



Final observable: "fat" jet mass (m_{jet})

Significant effort on reducing uncertainties on jet mass scale and jet energy scale – dominant experimental syst. uncertainties



$$m_t = 172.76 \pm 0.81 \text{ GeV}$$
$$= 172.76 \pm 0.22(stat) \pm 0.57(exp) \pm 0.48(model) \pm 0.24(theo)\text{GeV}$$

First top quark mass measurement with the full Run 2 dataset
(precision is improved by a factor of 3 w.r.t. the 2016 dataset analysis)

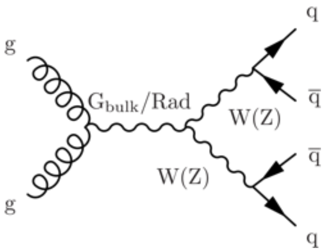
Measurements with the 2016 dataset:
dilepton: 172.33±0.73 GeV
single lepton: 172.25±0.63 GeV
all jets: 172.34±0.73 GeV
from abs. x-section: 172.33±0.70 GeV
from diff. x-sections: 170.5±0.8 GeV

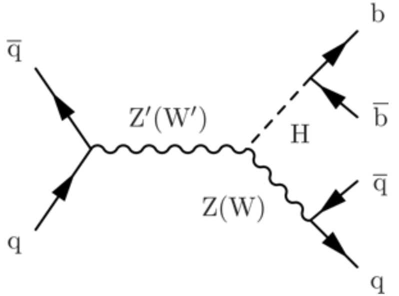
BSM: $X \to VV, VH \to (jj)(jj)$

CMS PAS B2G-20-009
(Sep 30, 2022)
[Run 2]

Motivation examples:

- Graviton (J=2), W'/Z' (J=1), radion, heavy H (J=0)





Signature:

- SM bosons (W, Z, H) decay to qq pairs
- for $m_X > 1.3$ GeV, expect two "fat" jets (R=0.8)
- assume $\Gamma_X \ll m_{JJ}$
- VBF production is also explored

Final discriminating observable:

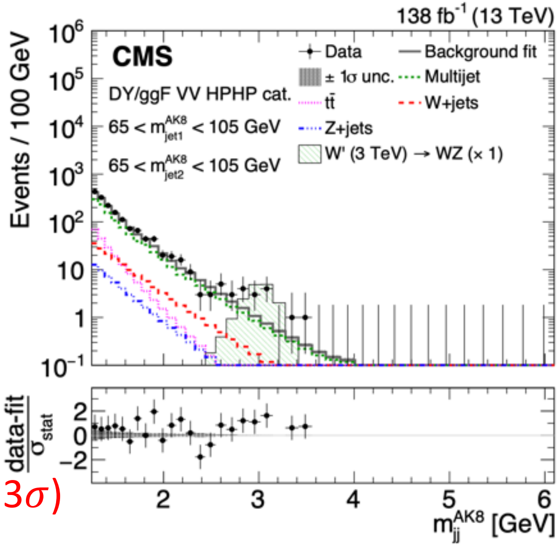
3D(m_{JJ}, m_{J1}, m_{J2})

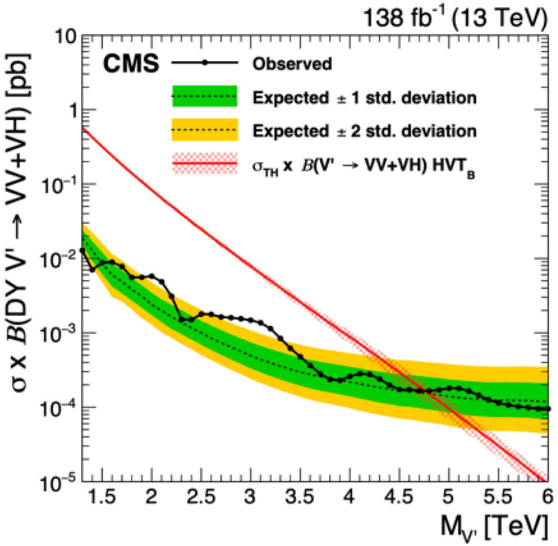
V' → VV+VH: $m_{V'} > 4.8$ TeV

Radion → VV: $m_{V'} > 2.7$ TeV

Graviton → VV: $m_{V'} > 1.4$ TeV

Max. excess at 2.9 TeV (local 3.6 σ, global 2.3σ)





BSM: τ + MET

CMS PAS EXO-21-009
(Dec 22, 2022)

Motivation examples:

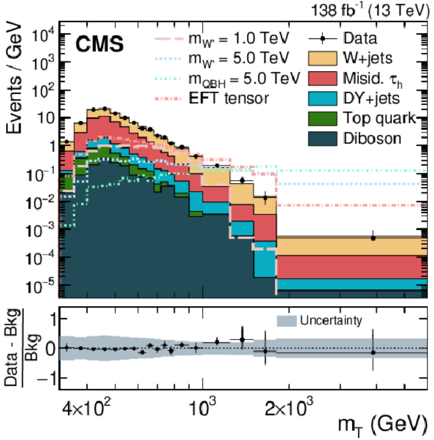
- new heavy gauge bosons (W')
- leptoquarks (LQ)
- with dominant coupling to third generation fermions

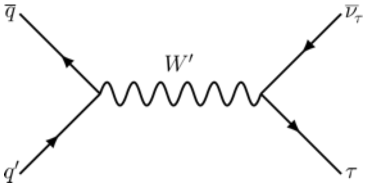
Signature: **Hadronically decaying tau + MET**

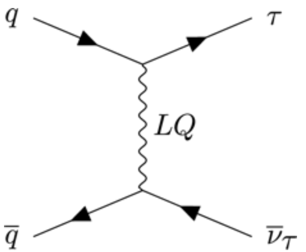
Final discriminating observable:

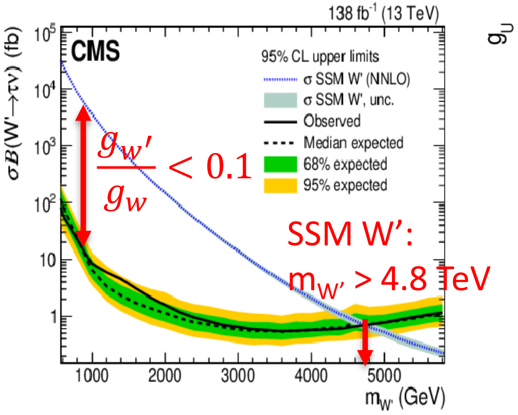
transverse mass m_T

$$m_T = \sqrt{2 p_T^{\tau_h} p_T^{\text{miss}} [1 - \cos \Delta\phi(\vec{p}_T^{\tau_h}, \vec{p}_T^{\text{miss}})]}$$







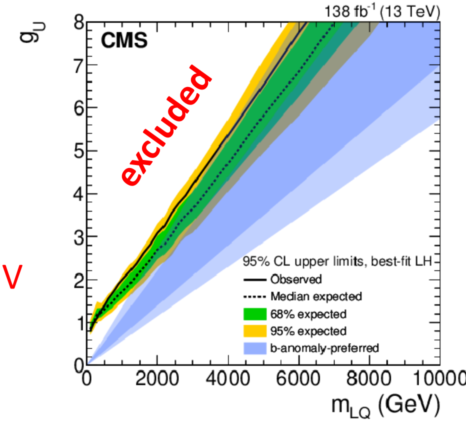


$\frac{g_{W'}}{g_W} < 0.1$

SSM W':
$m_{W'}$ > 4.8 TeV

Compare:

e+MET: $m_{W'}$ > 5.4 TeV
μ+MET: $m_{W'}$ > 5.6 TeV
[JHEP 07 (2022) 067]



Limits in the context left-handed LQ model:
Search sensitivity is just next to the blue best-fit region to explain "B decay anomalies"

BSM: SUSY $\tilde{\tau}\tilde{\tau} \rightarrow \tau\tau + p_{\mathrm{T}}^{\mathrm{miss}}$

CMS PAS SUS-21-001
(Jul 4, 2022)

Motivation examples:

- SUSY resolves the hierarchy problem, gives a dark matter candidate
- and often favors 3rd generation sfermions to be the lightest

Signature:

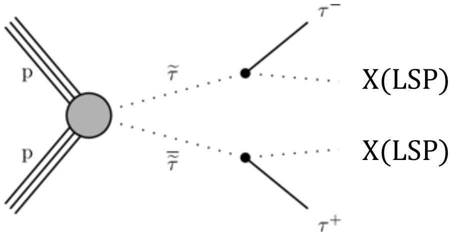
- two hadronically decaying tau leptons + MET
- non-prompt (long-lived) $\tilde{\tau}'$s are also explored

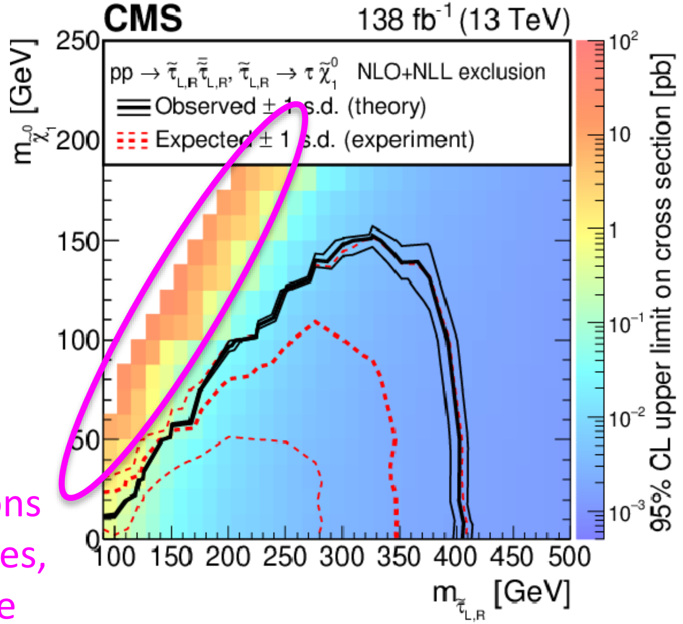
Final discriminating observables:

- sum of transverse masses: $\Sigma m_{\mathrm{T}} = m_{\mathrm{T}}(\tau_{\mathrm{h}}^{(1)}) + m_{\mathrm{T}}(\tau_{\mathrm{h}}^{(2)})$
- "stransverse mass": $m_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T}}^{\mathrm{X}(1)} + \vec{p}_{\mathrm{T}}^{\mathrm{X}(2)} = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}} \left[\max \left(m_{\mathrm{T}}^{(1)}, m_{\mathrm{T}}^{(2)} \right) \right]$
- $\mathrm{p_T}(\tau_1)$
- number of jets

31 signal region bins:

no significant excesses





Notoriously difficult regions with small mass differences, where SUSY/BSM can hide

SM and BSM: $B \to \mu\mu$

CMS PAS BPH-21-006
(Dec 20, 2022)
[Run 2]

Motivations:

- B→ μμ is highly suppressed in SM, which can make BSM-induced decays more visible

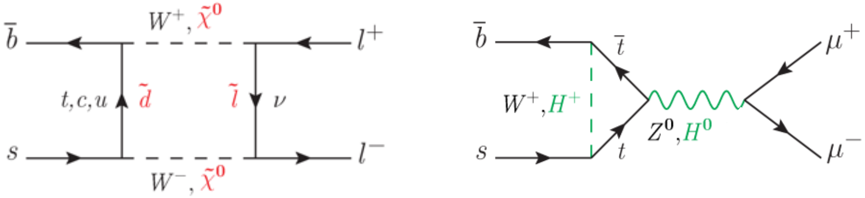
Analysis:

- Two muons, forming a common displaced vertex
- MVA to suppress backgrounds. Main bkgs:
  - muons from different heavy-flavor mesons
  - muons from B-meson cascade decays
  - $B \to K\pi, B_s \to KK$ (mis-id)

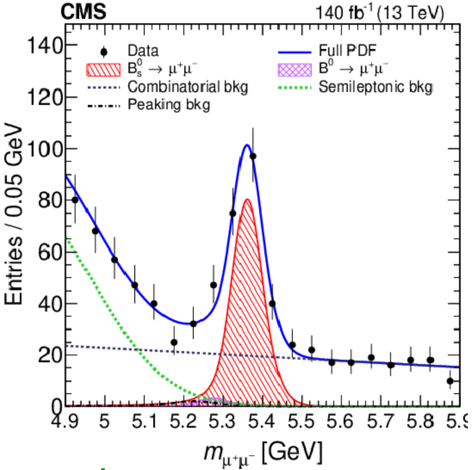
Results:

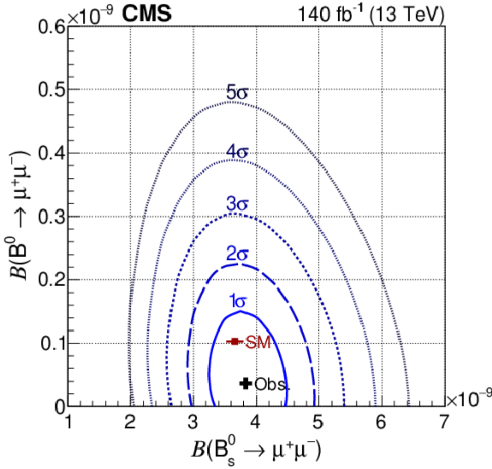
$$\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = \left[4.02^{+0.40}_{-0.38}\,(\mathrm{stat})\,^{+0.28}_{-0.23}\,(\mathrm{syst})\,^{+0.18}_{-0.15}\,(\mathcal{B})\right] \times 10^{-9}$$

$$\mathcal{B}(\mathrm{B^0} \to \mu^+\mu^-) < 1.5 \times 10^{-10} \text{ at } 90\% \text{ CL}$$



Examples of Feynman diagrams: black – SM particles
red/green - BSM





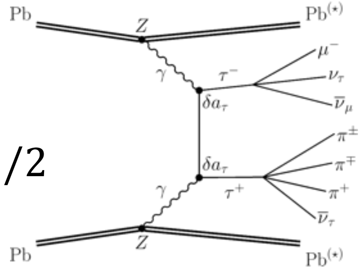
Both agree with the SM and are the most precise to date

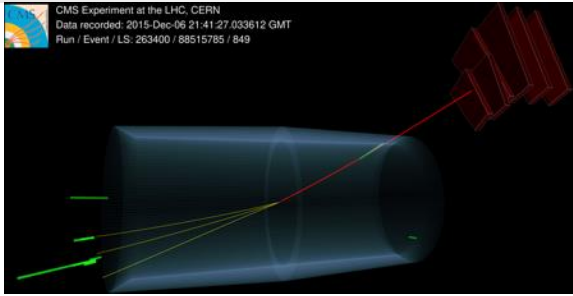
Heavy Ions with a twist: $\gamma\gamma \to \tau\tau$

CMS HIN-21-009
(Jun 10, 2022)
[2015 dataset]

Motivations:

- measure cross section $\sigma(\gamma\gamma \to \tau\tau)$ and probe tau-leptons gyromagnetic ratio, $a_\tau = (g_\tau - 2)/2$
- note: $\sigma_{\mathrm{NN}}(\gamma\gamma \to \tau\tau) \sim \boldsymbol{Z}^4 \times \sigma_{\mathrm{pp}}(\gamma\gamma \to \tau\tau)$





Analysis:

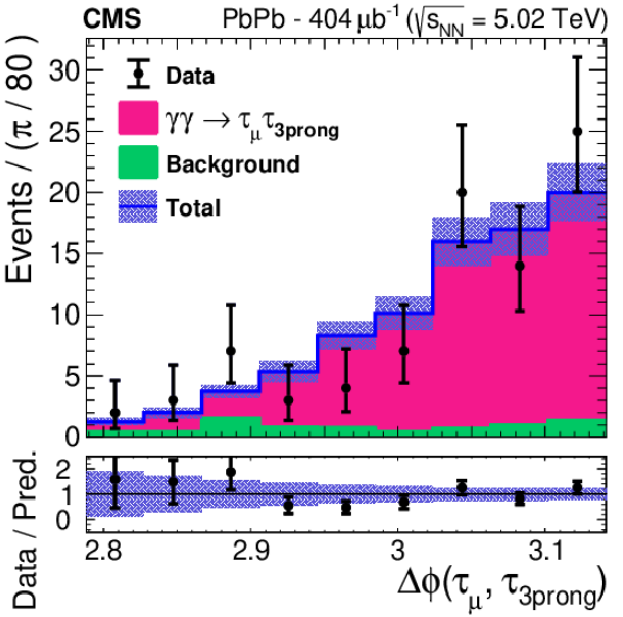
- 2015 dataset: Pb-Pb (Z=94), $\sqrt{\sigma_{NN}} = 5.02$ TeV, $L = 0.40\ \mathrm{nb}^{-1}$
- ultraperipheral scattering (little activity in the CMS detector)
- τ_μ (muon) and τ_h (3-prong)

$\sigma(\gamma\gamma \to \tau\tau) = 4.8 \pm 0.6(stat) \pm 0.5(syst)\ \mu\mathrm{b}$, in agreement with SM

From this value: $a_\tau = 0.001^{+0.055}_{-0.089}$

SM prediction: $a_\tau = 0.00117721\ (5)$

The best measurement so far (DELPHI): $a_\tau = -0.018 \pm 0.017$

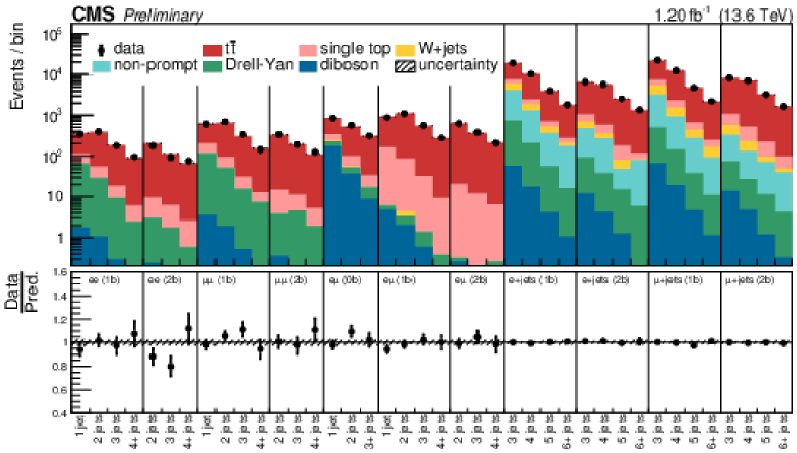


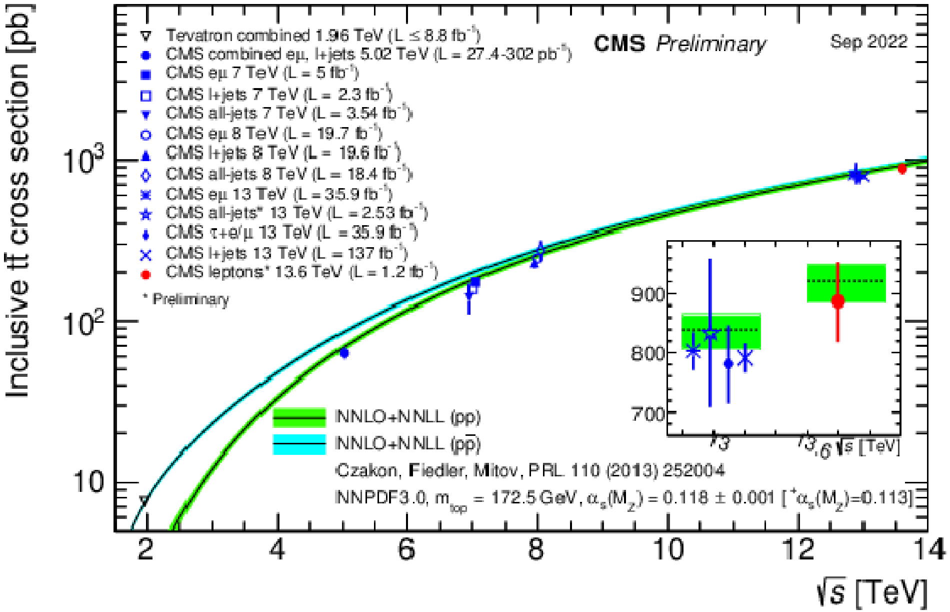
SM: $t\bar{t}$ production at 13.6 TeV

CMS PAS TOP-22-012
(Sep 22, 2022)
[Run 3, 2022: 1.2 fb^{-1}]

Signal signature and analysis:

- Two OS leptons or one (ee, μμ, eμ, e, μ)
- Varying number of jets with 0/1/2 b-tags
- 40 signal region bins
- signal >> background in all bins
- main backgrounds are constraint from data





$$\sigma = 887 \pm 42\ (stat + syst)\ \pm\ 53\ (lumi)\ \mathrm{pb}$$

in agreement with the SM

Summary

Exquisite measurements and BSM search results obtained with the Run 2 data keep coming

- I presented just a few hand-picked recently released results
- There are lots more out there, and many more to come – https://cms-results-search.web.cern.ch

Run 3 has stated (13.6 TeV) and CMS takes data with high efficiency

- In 2022, collected data corresponds to 38 fb^{-1} – first results are already coming out
- Three more years to run – with the goal to get 300 fb^{-1} worth of data
- By then, statistical power of measurements/searches will be three times of what we show now

CMS upgrades are well underway for HL-LHC operation to start in six years

- A giant leap in the CMS data-taking capabilities
- And 3000 fb^{-1} worth of data by 2041 (CMS will be half-century old by then)

Backup

Search for H125 → invisible

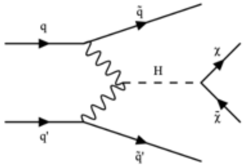
Phys. Rev. D 105 (2022) 092007
Jan 27, 2022
[Run 2]

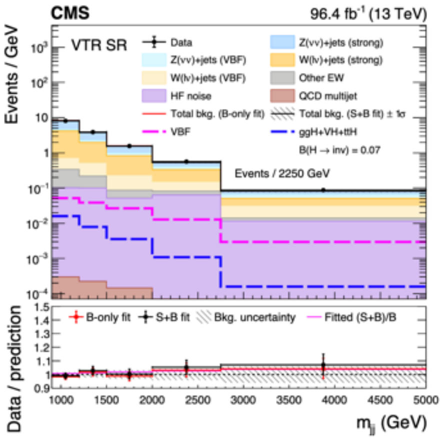
Motivation:

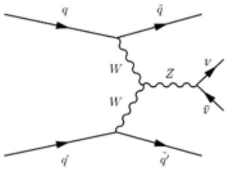
- BSM (Higgs as a portal to dark sector)
- in SM, $B(H \rightarrow ZZ \rightarrow 4\nu) \sim 0.001$

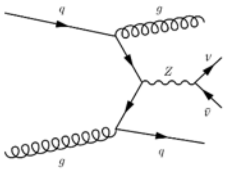
Analysis:

- Signature: MET + VBF-like jets
- Main backgrounds: Z($\nu\nu$)+jets, W($\ell\nu$)+jets





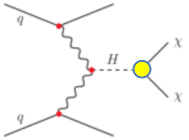




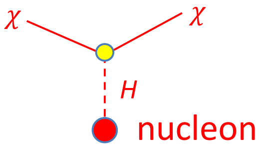
B(H→inv) < 0.18 at 95% CL
(0.10 expected)

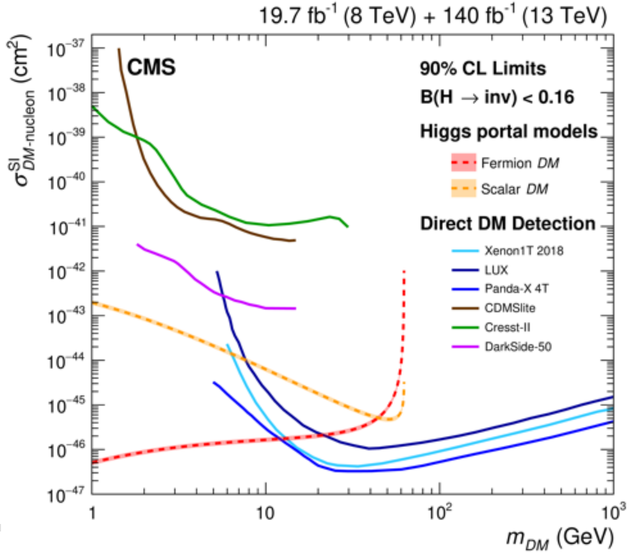
REINTEPRETATION

$B(H \rightarrow \chi\chi)$ ⇒ χN scattering cross section



⇒



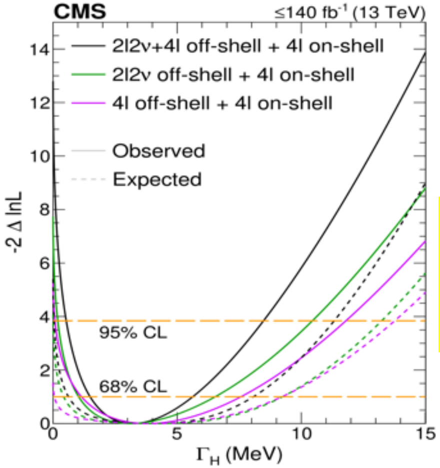


Higgs boson’s natural width

From the ratio of off-shell to on-shell rates using $H \to ZZ \to 2\ell 2\nu$ [Run 2] and $H \to ZZ \to 4\ell$ [2016+2017]

And assuming:

- SM-like amplitude structure for $H \to ZZ$ decays
- No significant BSM physics in $gg \to H$ up to $m_{H*} \sim 1$ TeV *(fair, as otherwise we would probably already see it explicitly)*



Nat. Phys. 18 (2022) 1329
Feb 14, 2022

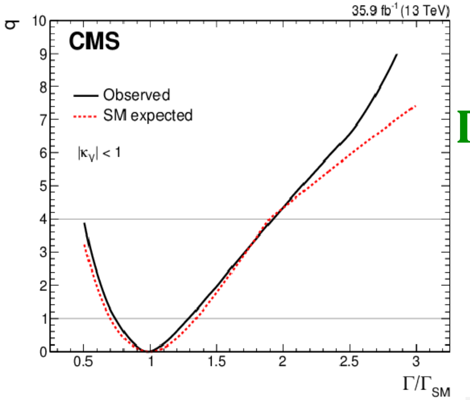
$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV}$$

First evidence for Higgs off-shell production with 3.6σ significance

From the combination of all on-shell decays

And assuming:

- SM-like amplitude structure for all Higgs coupling
- $|\kappa_W|, |\kappa_Z| \leq 1$ *(fair, as it is hard to build a self-consistent theory violating these conditions)*
- Ad’l unknown partial width, making the total width a free par

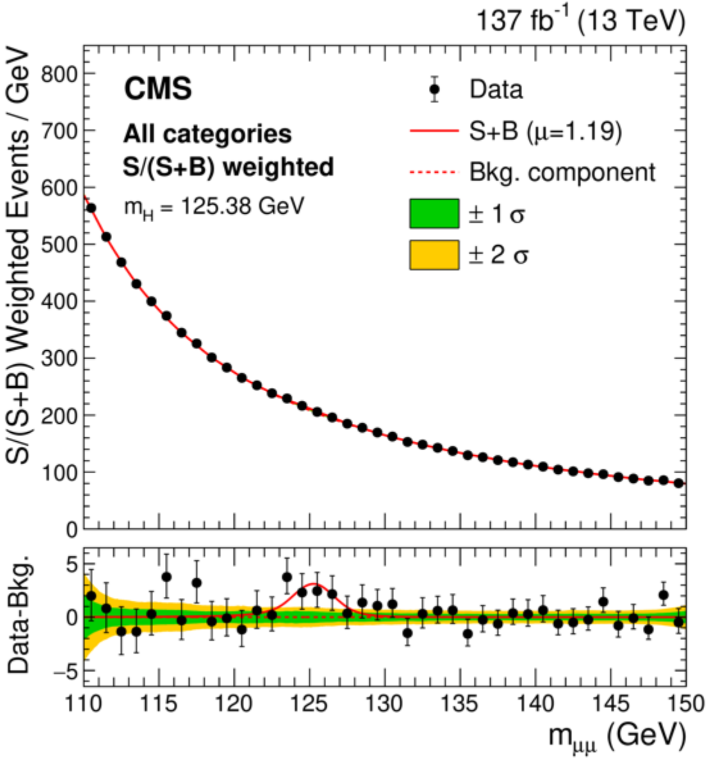


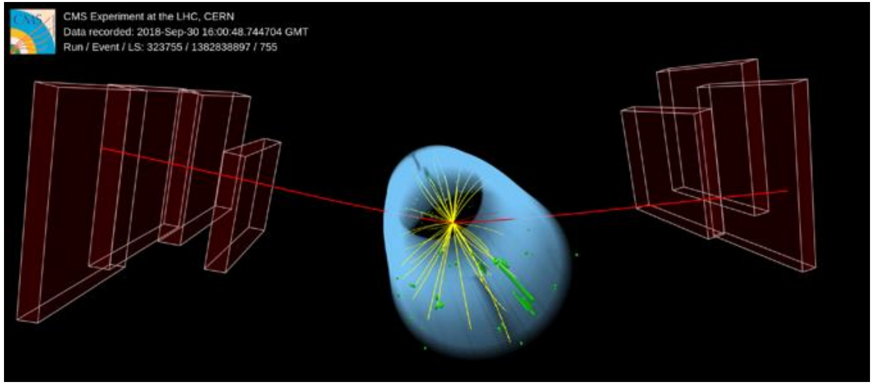
Eur. Phys. J. C 79 (2019) 421
[2016 dataset]

$$\Gamma_H = 4.0\ ^{+1.3}_{-1.0}\ \text{MeV}$$

Search for $H \rightarrow \mu\mu$

SM: $B(H \rightarrow \mu\mu) \approx 0.02\%$





	CMS [Run 2] JHEP 01 (2021) 148	**ATLAS [Run 2]** PLB 812 (2021) 135980
Significance	3.0	2.0
Signal strength (μ)	1.2 ± 0.4	1.2 ± 0.6

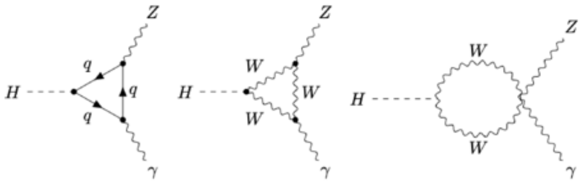
Evidence for the Higgs boson's coupling to the second generation fermions!

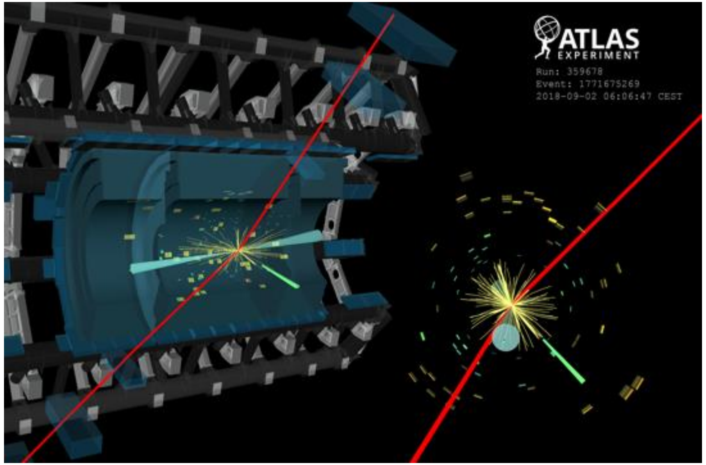
Need ~4 times more data to establish this SM H decay with 5σ

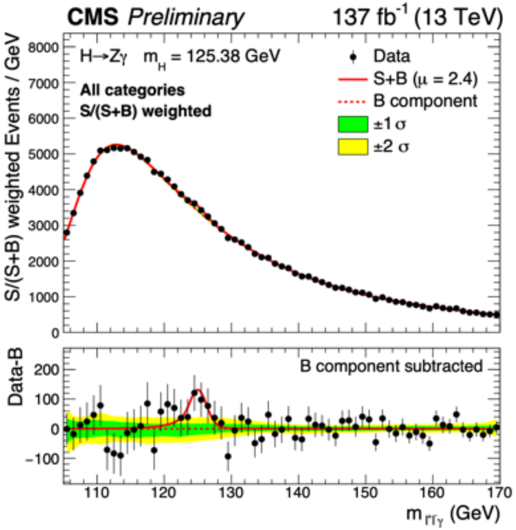
Search for $H\to Z\gamma$

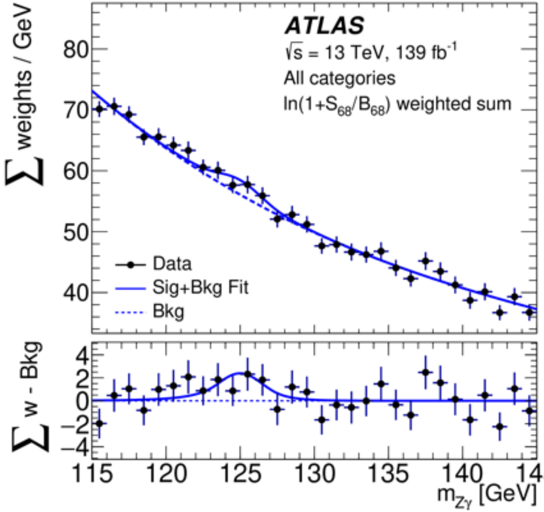
Loop-induced decay in SM

SM: $B(H\to Z\gamma)B(Z\to ee/\mu\mu)\approx 0.01\%$





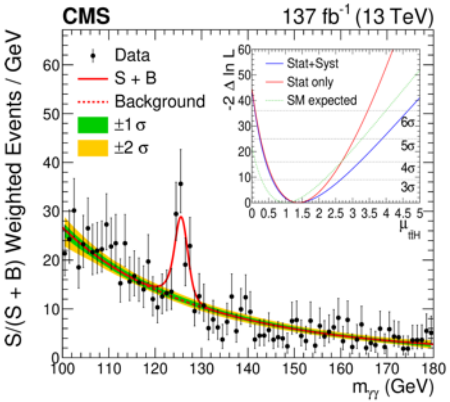


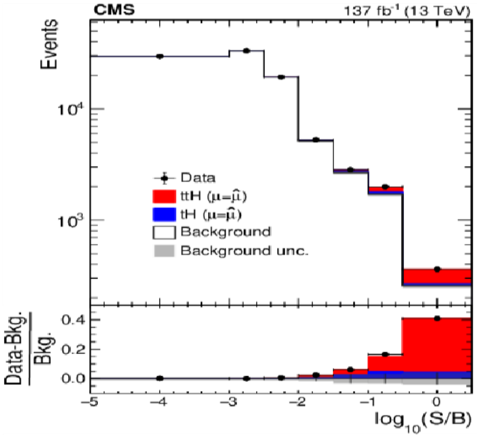


	CMS [Run 2] PAS HIG-19-014	**ATLAS [Run 2]** PLB 809 (2020) 135754
Significance	2.7	2.2
Signal strength (μ)	2.4 ± 0.9	2.0 ± 1.0

Need ~20 times more data to establish this SM H decay with 5σ

ttH – production mode established most recently





$ttH, H \rightarrow \gamma\gamma$

	CMS [Run 2] PRL 125 (2020) 061801	**ATLAS [Run 2]** PRL 125 (2020) 061802
Significance	6.6	5.2
Signal strength (μ)	1.38 ± 0.33	1.43 ± 0.37

$ttH, (H \rightarrow WW/ZZ/\tau\tau) \rightarrow leptons$

	CMS [Run 2] EPJC 81 (2021) 378	**ATLAS [2016+2017]** ATLAS-CONF-2019-045
Significance	4.7	1.8
Signal strength (μ)	0.92 ± 0.24	0.58 ± 0.26

Are H125's quantum J^{CP} numbers 0^{++}, as predicted by the SM ?

INTRO: Higgs bosonic (V) coupling structure

General Lagrangian for HVV interactions up to dim-5 operators:

$$L = \boxed{-\frac{a_1}{2v} m_V^2 H V_\mu V^\mu} \boxed{-\frac{a_2}{2v} H F_{\mu\nu} F^{\mu\nu} - \frac{a_3}{2v} H F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{a_4}{2v} H V_\mu \Box V^\mu + \frac{a_5}{2v} \Box H\, V_\mu V^\mu}$$

SM dim-3 operator

In SM: $a_1 = 2$ for ZZ, WW

The term vanishes for $\gamma\gamma$

dim-5 operators: loop-induced (very small in SM) or, otherwise, non-renormalizable

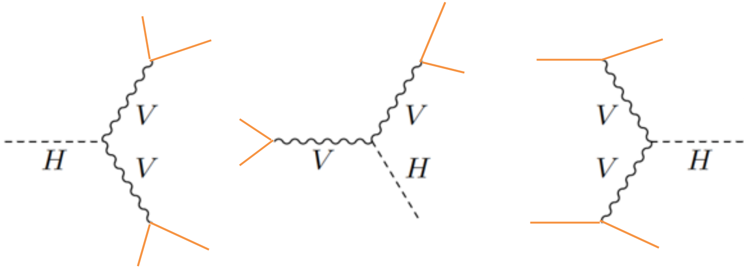
red factors with a_i/v are one of a conventions; they could've been written just as $1/\Lambda_i$

The $\boldsymbol{a_2}$ term is CP-even. In SM, $\boldsymbol{a_2} \sim \mathrm{O}(10^{-2})$ [it is actually the lowest-order term for $H \to \gamma\gamma$]

The $\boldsymbol{a_3}$ term is **the CP-odd term**. In SM, $\boldsymbol{a_3} \sim \mathrm{O}(10^{-11})$ [arises from CP-violation in the quark sector]

The $\boldsymbol{a_4}$ term is is yet another CP-even distinct operator. In SM, $\sim \mathrm{O}(10^{-2})$

The $\boldsymbol{a_5}$ term is experimentally indistinguishable from SM in on-shell studies (important for off-shell)



HVV couplings can be probed in **H→VV** decays and **VH** and **VBF** production modes: four-fermion kinematics is sensitive to the HVV coupling structure.

This technique was used to establish π^0 parity in 1962: $\pi^0 \to \gamma^*\gamma^* \to (ee)(ee)$

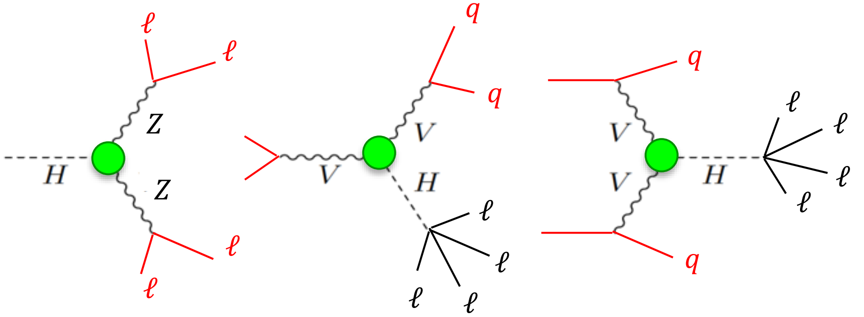
When combining, HZZ and HWW processes,
one has to assume how a_i^{ZZ} and a_i^{WW} are related to each other

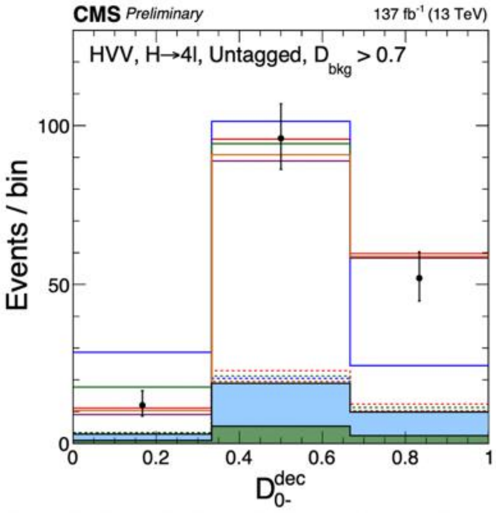
Higgs bosonic (V) coupling structure

CMS: PRD 104 (2021) 052004 [Run 2]

H→ZZ→4l

- On-shell analysis only
- WW and ZZ couplings a_i^{WW} and a_i^{ZZ} are related via custodial and SU(2)xSU(1) symmetries:
  - $a_1^{WW} = a_1^{ZZ}$
  - $a_2^{WW} = \cos^2\theta_W \, a_2^{ZZ} + \cdots \ (negligible)$
  - $a_3^{WW} = \cos^2\theta_W \, a_3^{ZZ} + \cdots \ (negligible)$
  - …
- Production modes: VBF tag, VH tag, untagged
- ME-based discriminants





gg-fusion selection
– red line: SM 0^+
– blued line: 0^-

68% CL: $a_3^{ZZ} / a_1^{ZZ} = 0.018^{+0.066}_{-0.034}$ (CP-odd admix)

$a_2^{ZZ} / a_1^{ZZ} = -0.004^{+0.045}_{-0.058}$

Coupling ratios are extracted from ratios f_{a3} and f_{a2} (Approach 2), given in the paper

INTRO: Higgs fermionic (f) coupling structure

General lowest-dim Lagrangian for Higgs-fermion interactions:

$$L = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + i\tilde{k}_f\gamma_5\right)\psi_f H$$

κ_f term is CP-even

$\tilde{k}_f$ term is CP-odd

both are tree-level (**unlike HVV**)

Define mixing angle ϕ, where $\tan\alpha = \frac{\tilde{k}_f}{\kappa_f}$

- pure CP-even state: $\alpha = 0°$
- pure CP-odd state: $\alpha = 90°$

SM: $\boldsymbol{\kappa_f = 1,\ \tilde{k}_f = 0;}$ **hence,** $\alpha = \mathbf{0}$

MSSM: $\alpha \approx 0$

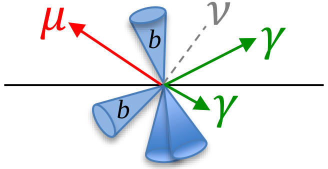
nMSSM: α can be large

Higgs CP-odd admixture: ttH

Final states used:

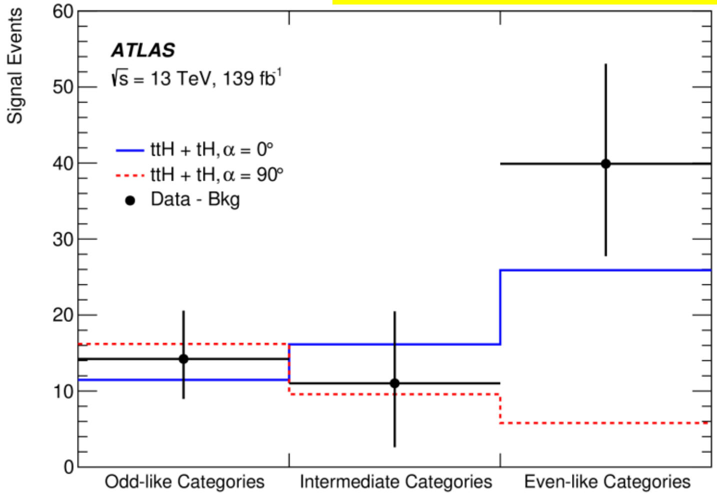
$pp \to ttH \to (jjb)(jjb)(\gamma\gamma)$ [all-hadronic]

$pp \to ttH \to (l\nu b)(jjb)(\gamma\gamma)$ [semi-leptonic]



Building an analytic ME-based discriminant that would account for jet mis-measurements (plus missing neutrino in semi-leptonic channe is challenging…

Instead, a BDT-based discriminant is built using CP-even and CP-odd MC models



background is subtracted

	CMS [Run 2] PRL 125 (2020) 061801 ($\gamma\gamma$) CMS PAS HIG-21-006 (Mar 2022): $\gamma\gamma$+ZZ+multileptons	**ATLAS [Run 2]** PRL 125 (2020) 061802 ($\gamma\gamma$)
Purely CP-odd Htt coupling is disfavored at	**3.7σ**	**3.9σ**
95% CL limit on α	$\lvert\alpha\rvert < 60°$	$\lvert\alpha\rvert < 43°$

Higgs CP-odd admixture: $H\tau\tau$

CMS: arXiv:2110.04836 [Run 2]

Final states used: $\tau_\mu\tau_h$ and $\tau_h\tau_h$

$\tau_\mu \rightarrow \mu^\pm\nu\nu(17\%)$

$\tau_h \rightarrow \pi^\pm\nu\ (12\%)$

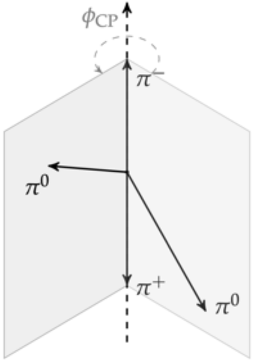
$\rightarrow \rho^\pm\nu \rightarrow \pi^\pm\pi^0\nu\ (26\%)$

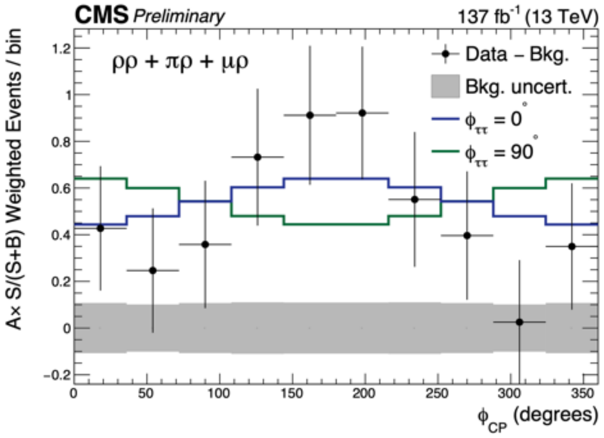
$\rightarrow a_1^\pm\nu \rightarrow \pi^\pm\pi^0\pi^0\nu\ (10\%)$

$\rightarrow a_1^\pm\nu \rightarrow \pi^\pm\pi^\pm\pi^\mp\nu\ (10\%)$

ϕ_{CP} angle for

$H \rightarrow \tau_h\tau_h \rightarrow (\rho^+\nu)(\rho^-\nu) \rightarrow \pi^+\pi^0\pi^-\pi^0\nu\ \nu$





Signal (H) vs Bkg BDT enhances the signal VBF contribution with two forward-backward jets

Building a ME-based discriminants that would account for jet mis-measurements and missing neutrinos is possible, but challenging…

Distributions of angles between planes set by observable particles from decaying tau leptons (ϕ_{CP}) are sensitive to CP-admixture phase α

Pure CP-odd $H\tau\tau$ coupling is disfavored at **3.2σ**

95% CL limit on α: $|\alpha| < 36°$

Looking for explicitly abnormal decay/production modes of the H125 boson

Search for CLFV decays: $H \rightarrow \mu\tau$

CMS: PRD 104 (2021) 032013 [Run 2]

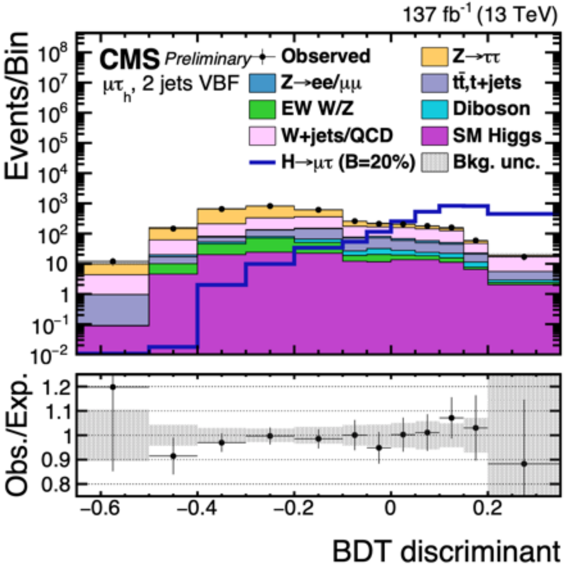
Channels used: $\mu\tau_h$, $\mu\tau_e$

Very similar to the "nominal" $H \rightarrow \tau\tau$ analysis, except that ***muons***

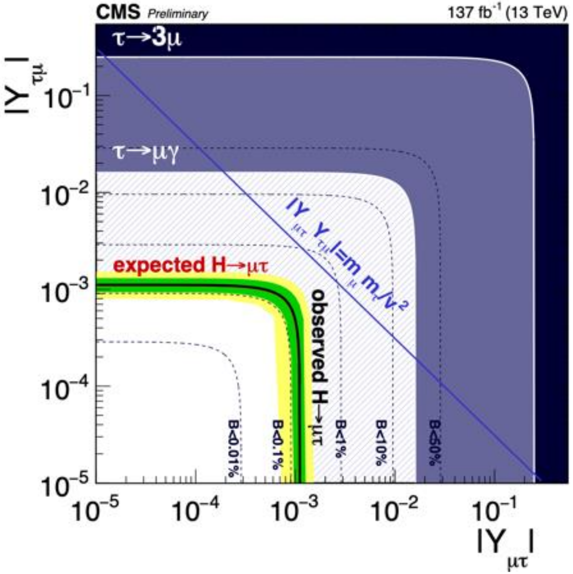
- *are prompt*
- *tend to have larger momenta*

BDT is used to separate signal from non-Higgs bkg and $H \rightarrow \tau\tau$

$B(H \rightarrow \mu\tau) < 0.15\%$



most sensitive final state in $H \rightarrow \mu\tau$ search: $\mu\tau_h$ + 2-jet VBF tag

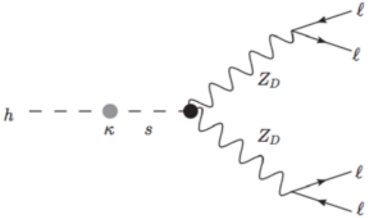


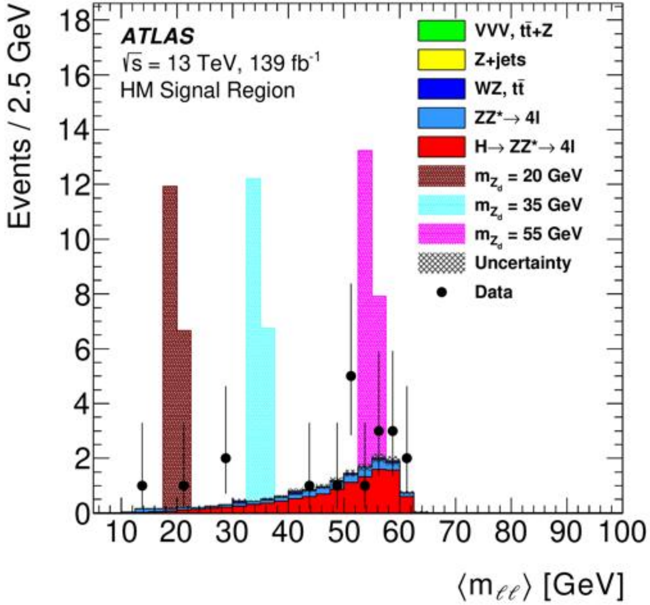
Limits on off-diagonal Yukawa couplings $Y_{\mu\tau}$

Search for H125 $\rightarrow XX \rightarrow (\ell\ell)(\ell\ell)$

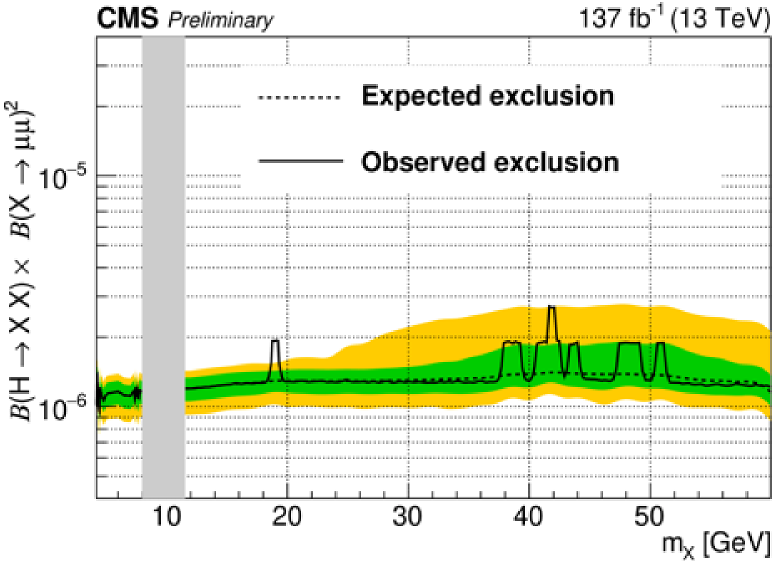
CMS: arXiv:2111.01299 [Run 2]
ATLAS: arXiv:2110.13673 {Run 2]

Search for low-mass dilepton resonances in H125 decays





model independent limits on $\sigma \times \mathcal{B}$



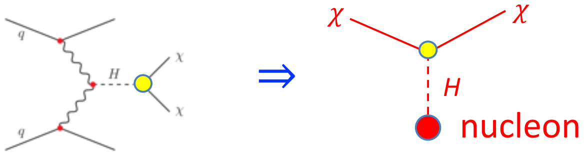
Search for H125 → invisible

ATALS: arxiv2202.07953 [Run 2]
CMS: arxiv2201.11585 [Run 2]

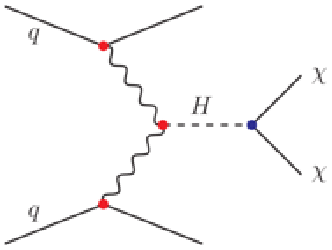
In SM: $B(H \to ZZ \to 4\nu) \sim 0.001$

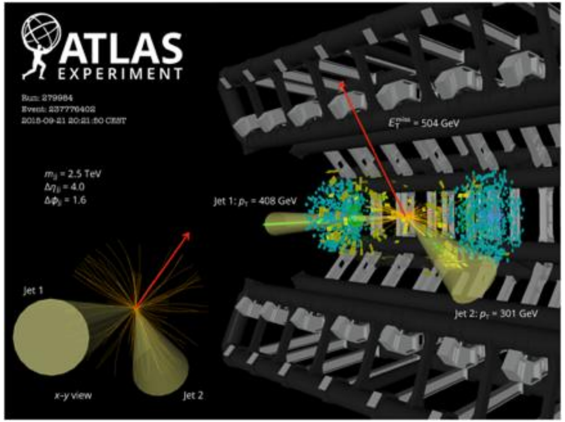
reinterpretation

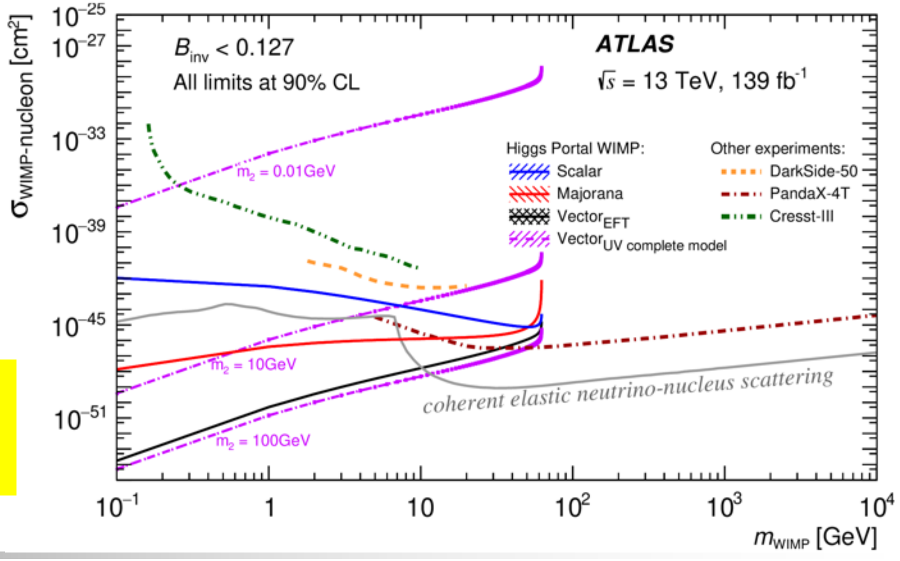
B(H → $\chi\chi$) ⇒ χ-nucleon σ



VBF jets + MET







ATLAS: B(H→inv) < 0.15 at 95% CL (expected 0.10)
CMS: B(H→inv) < 0.18 at 95% CL (expected 0.10)

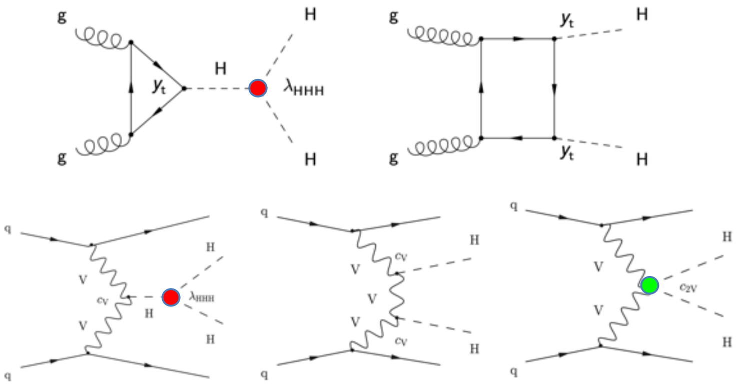
Search for HH production (non-resonant)

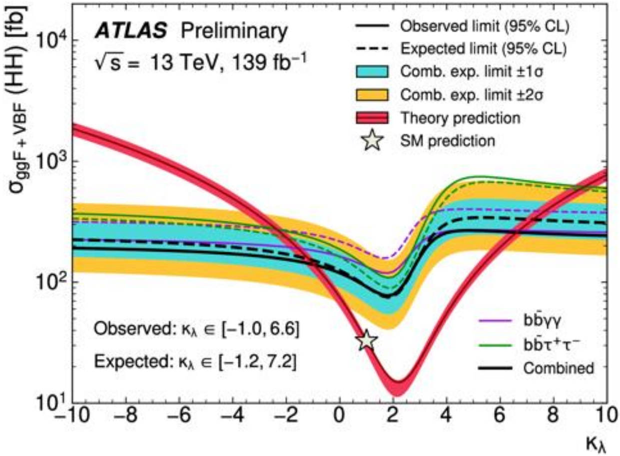
Decay modes:

- HH→ $(bb)(bb)$
- HH→ $(bb)(\gamma\gamma)$
- HH→ $(bb)(\tau\tau)$

Production modes tags:

- VBF
- untagged (ggF)





	CMS arXiv:2202.09617 [Run 2] JHEP 03 (2021) 257[Run 2]	**ATLAS** arXiv:2112.11876 [Run 2] JHEP 07 (2020) 108 [Run 2] ATLAS-CONF-2021-052 [Run 2]
HH production signal strength (excluded at 95% CL)	3.9	3.1
Higgs self-coupling (allowed range at 95% CL)	$-2.3 < \kappa_\lambda < 9.4$	$-1.0 < \kappa_\lambda < 6.6$
VVHH quartic coupling (allowed range at 95% CL)	$-0.1 < \kappa_{2V} < 2.2$	$-0.4 < \kappa_{2V} < 2.6$