CMS Higgs overview

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

CMS Compact Muon Solenoid

More than a decade and counting for H(125)

Higgs boson portray:

data corresponding to production of several-times larger number of Higgs bosons since discovery

has allowed

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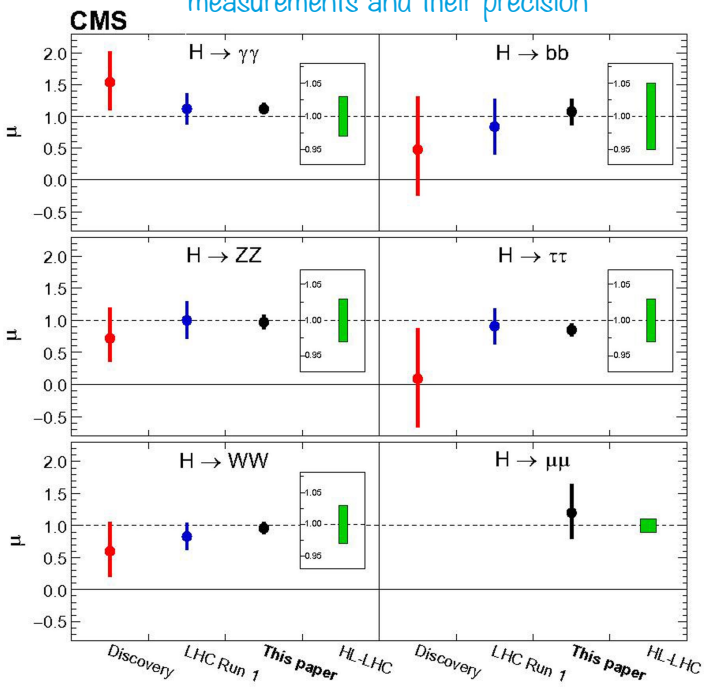
- to determine its mass
- measure its production cross-section in various modes
- observe numerous (all currently accessible) of its fermionic and bosonic decay channels
- establish its spin–parity quantum numbers

> transition from discovery to precision measurement era

Time evolution of signal-strength measurements and their precision



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Overview

> Review of new Standard Model (SM) Higgs boson measurements [*]:

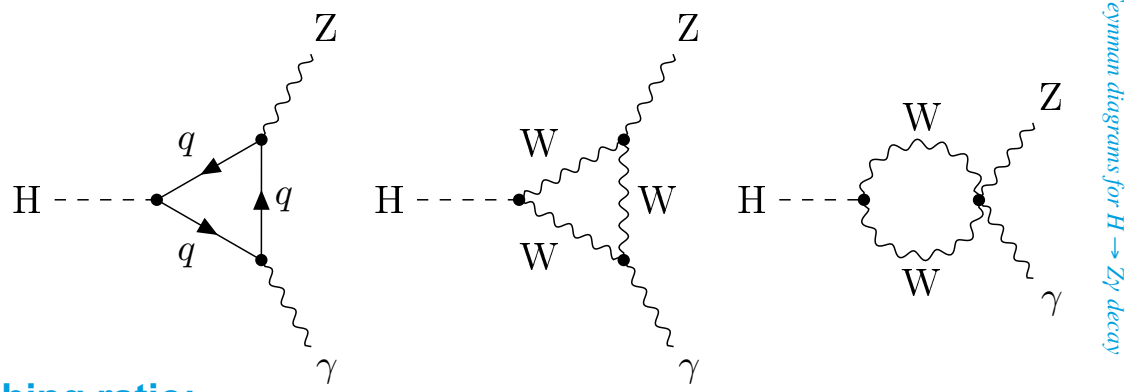
- Start with first evidence of Higgs boson decay to Z boson and photon
- One discovery channel: comprehensive characterisation and going differential
- A few words on di-Higgs searches and Higgs self-coupling
- A sample of new Beyond Standard Model (BSM) searches for:
  - Exotic decays of H(125)
  - Additional Higgs bosons
  - Lepton-flavor violating decays

[*] during the year 2023

Evidence for Higgs boson decay

to Z boson and photon, $H \rightarrow Z\gamma$

$Z \rightarrow l^+l^-$, $l = e$ or μ



Feynman diagrams for $H \rightarrow Z\gamma$ decay

> SM Branching ratio:

$\mathcal{B}(H \rightarrow Z\gamma) = (1.57 \pm 0.09)$ X 10^{-3} for 125.38 GeV

sensitive to potential anomalous trilinear Higgs self-coupling

- $\mathcal{B}(H \rightarrow Z\gamma)$ / $\mathcal{B}(H \rightarrow \gamma\gamma)$ -> sensitive observable to BSM physics

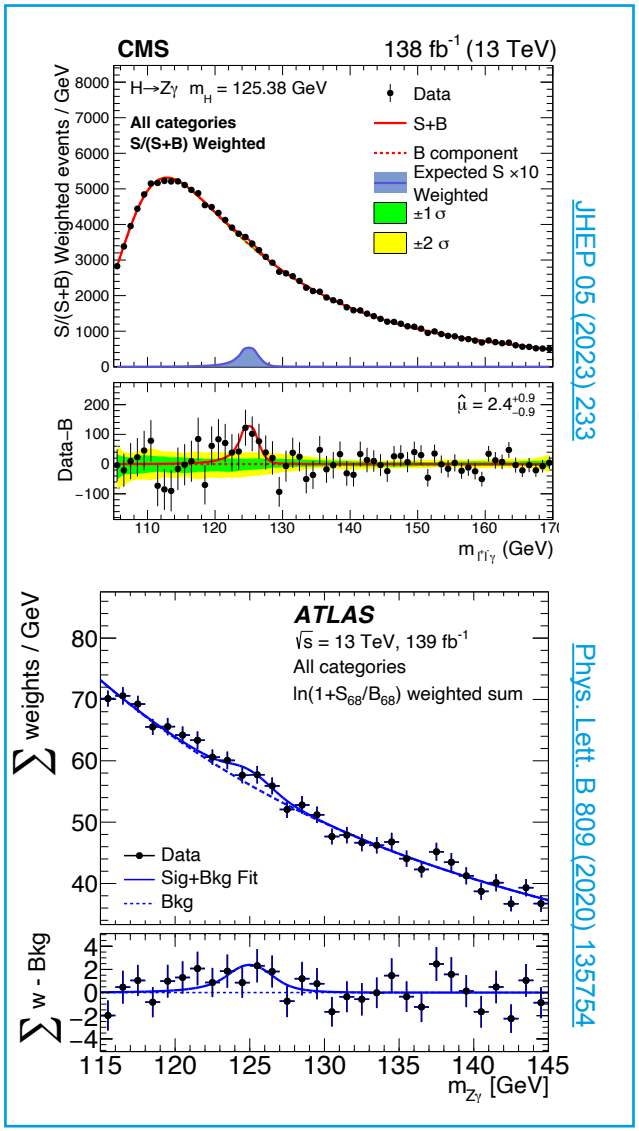
> Main backgrounds: SM $Z\gamma$, Z + jets

> Final discriminant: $l^+l^-\gamma$ invariant mass ($m_{l^+l^-\gamma}$),

simultaneous maximum likelihood fit to $m_{l^+l^-\gamma}$ covering all analysis categories

Evidence for Higgs boson decay

$H \to Z\gamma$

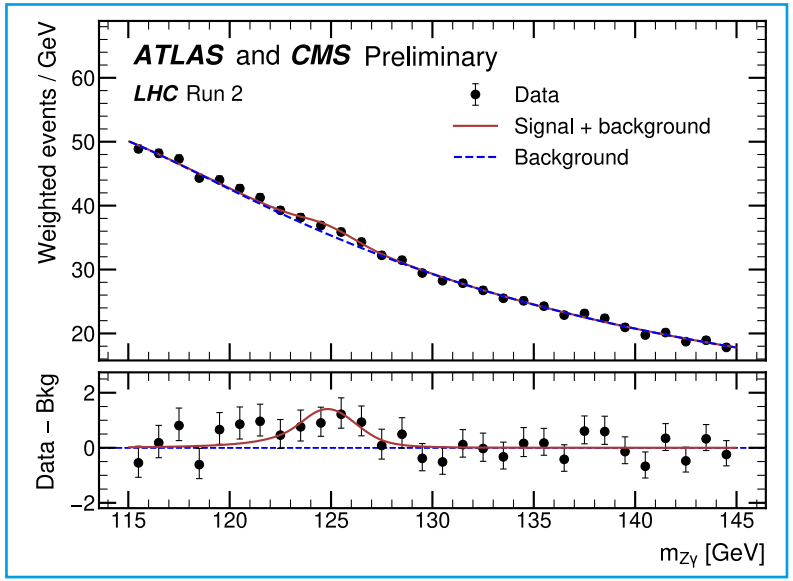


JHEP 05 (2023) 233

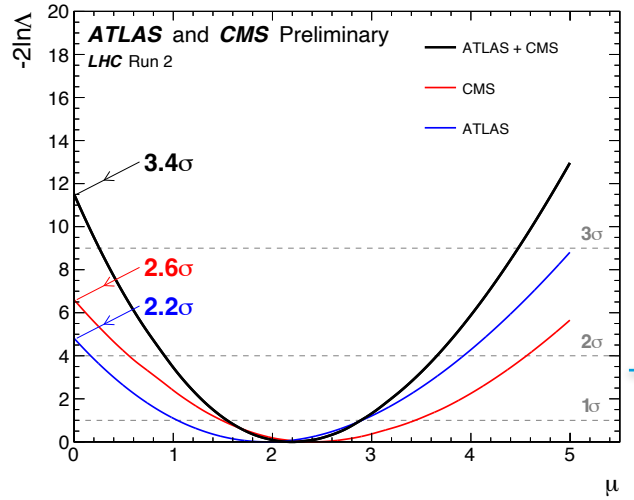
Phys. Lett. B 809 (2020) 135754

> First time CMS and ATLAS results combined to get an evidence!

measured signal rate relative to SM prediction: 2.2 ± 0.7



CMS-PAS-HIG-23-002



CMS-PAS-HIG-23-002

Observed evidence for a signal with 3.4σ significance (expected 1.6σ)

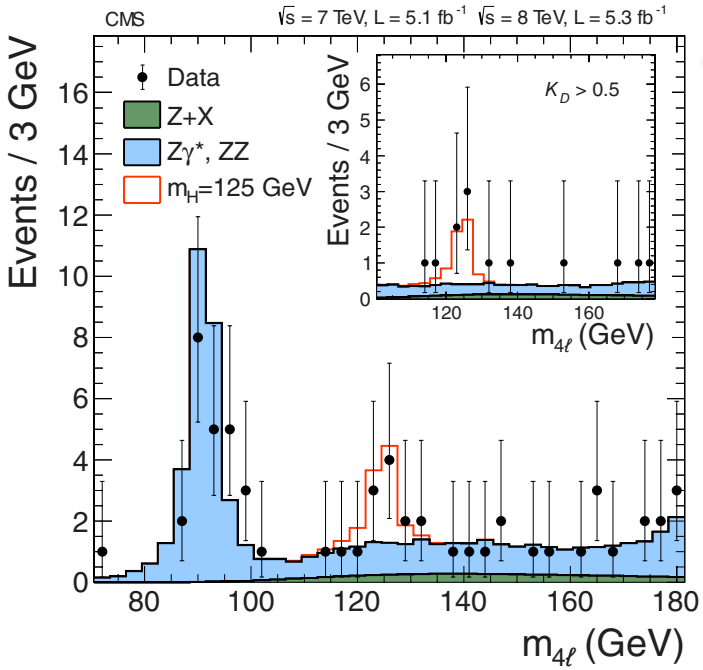
Discovery channels

$H \to Z \to 4l$, inclusive cross-section measurements

- $(l = e, \mu)$, fully reconstructible final state
- large signal-to-background ratio
- pillar for characterisation of H(125) since its discovery

-> several properties measured in this decay channel

2012



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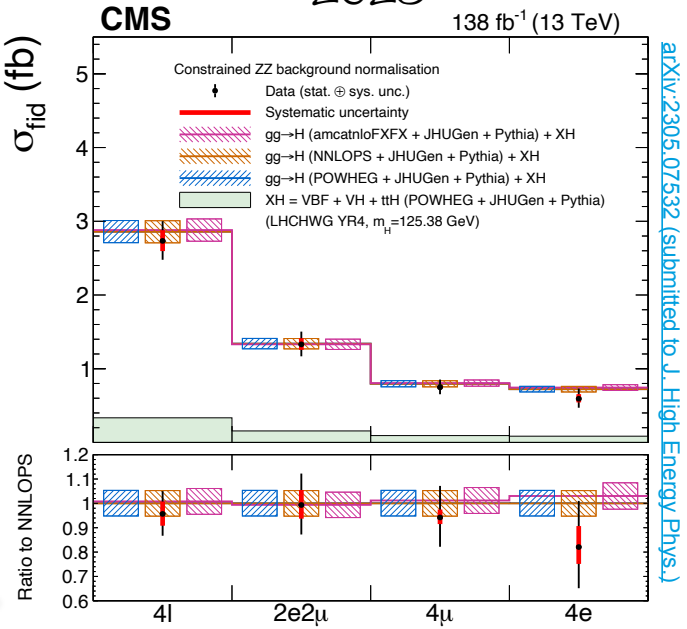
inclusive fiducial cross-section for the various final states of decay channel

2023



arXiv:2305.07532 (submitted to J. High Energy Phys.)

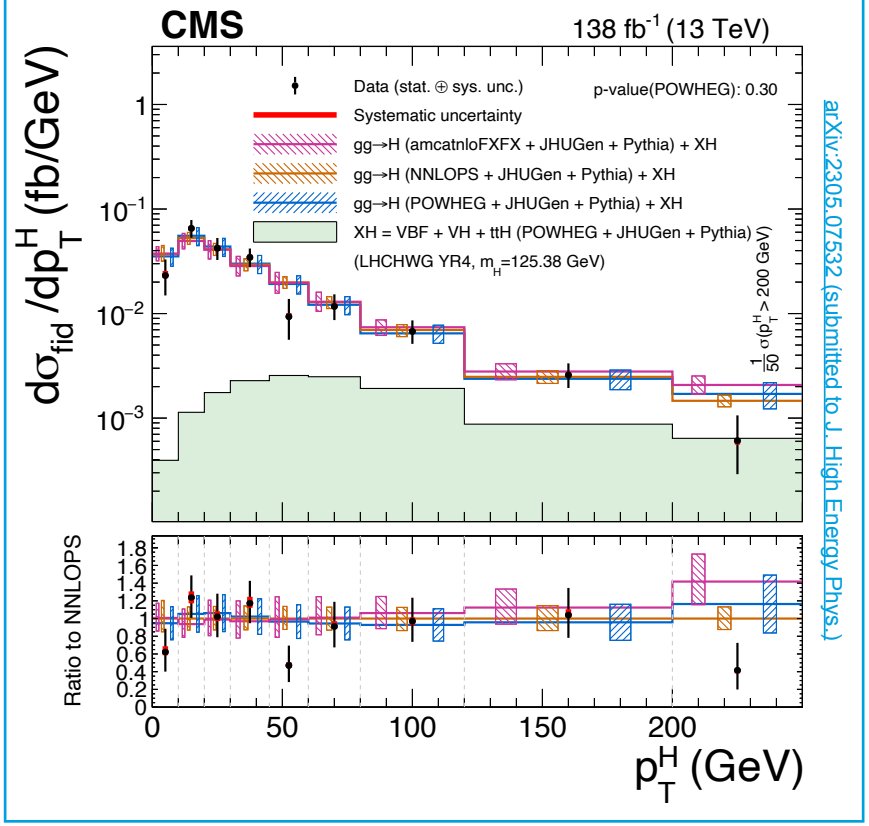
Discovery channels

$H \to Z \to 4l$, going differential

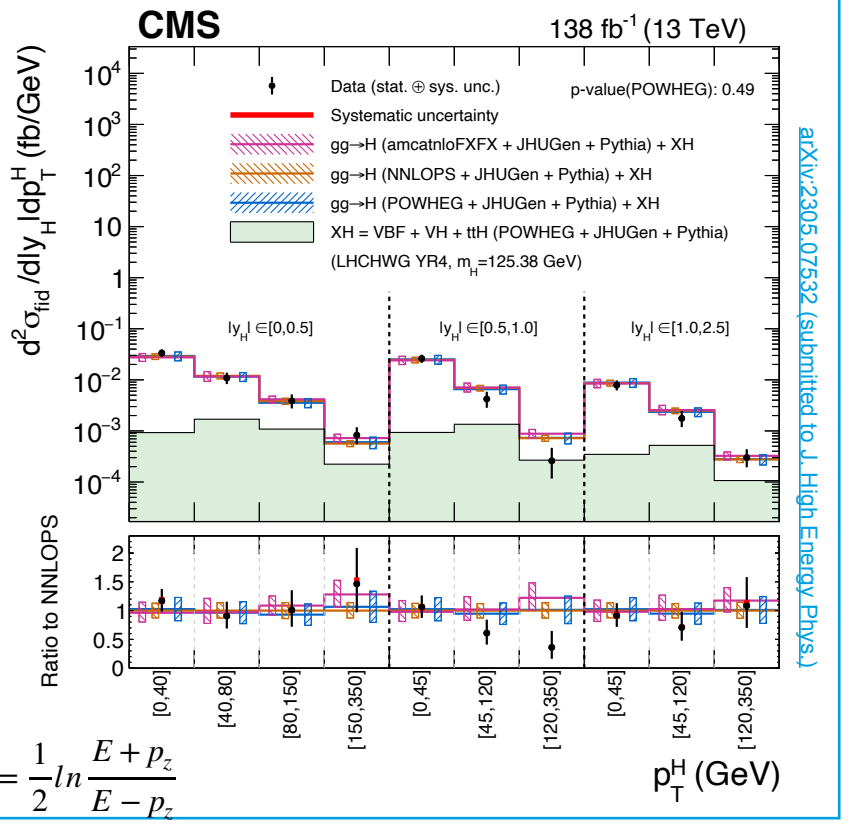
reduction of ~40% for leading systematic uncertainty in lepton reconstruction and selection efficiencies

> Comprehensive characterisation of four leptons final state via

Differential cross-section measurements



Double-differential cross-section measurements



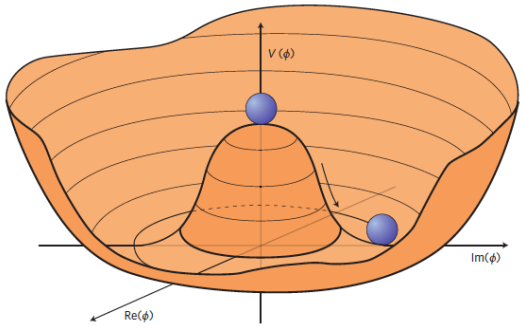
> All results consistent with SM predictions for $H \to Z \to 4l$ decay channel in considered fiducial phase space

$-5.4\ (-7.6) < \kappa_\lambda < 14.9\ (17.7)$ $\quad \kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH,SM}}$ $\quad -1.1\ (-1.3) < \kappa_b < 1.1\ (1.2)$ $\quad -1.1\ (-1.3) < \kappa_c < 1.1\ (1.2)$

Search for HH production

> Direct access to trilinear self-coupling and quartic VVHH coupling

> Probe shape of Higgs field potential



CERN-PH-TH-2015-098

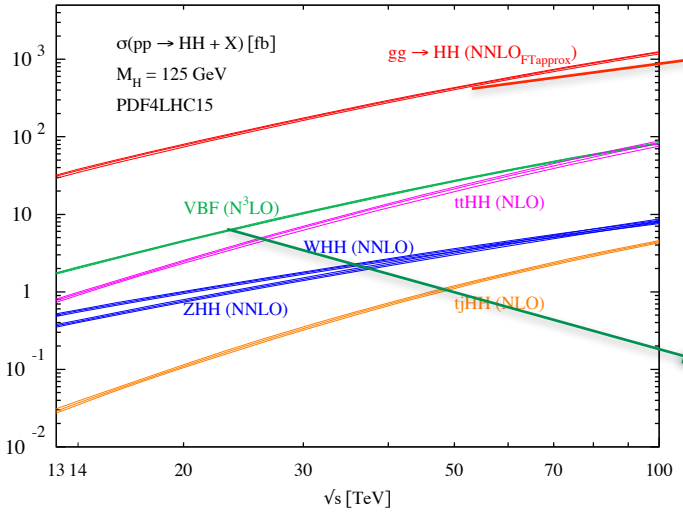
$$V = \mu^2 H^2 + \frac{\mu^2}{v} H^3 + \frac{\mu^2}{4v^2} H^4 = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v} H^3 + \frac{m_H^2}{8v^2} H^4$$

mass term

λ_3, trilinear self-coupling

λ_4, quartic self-coupling

Production cross-section



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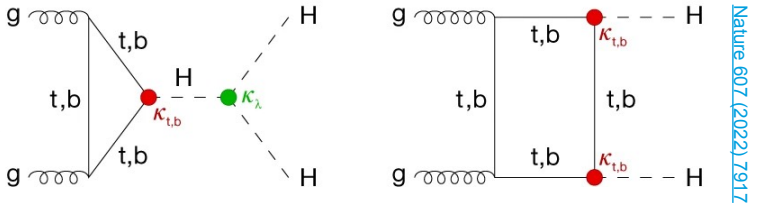
ggF: dominant, larger initial state radiation from gluons



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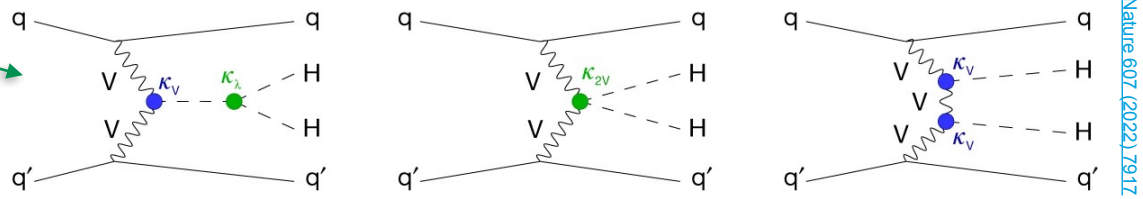
$\sigma = \sigma(\kappa_\lambda, \kappa_t)$ = 31.05 fb (SM, 13 TeV)

VBF: two forward jets with high mass and large rapidity gap



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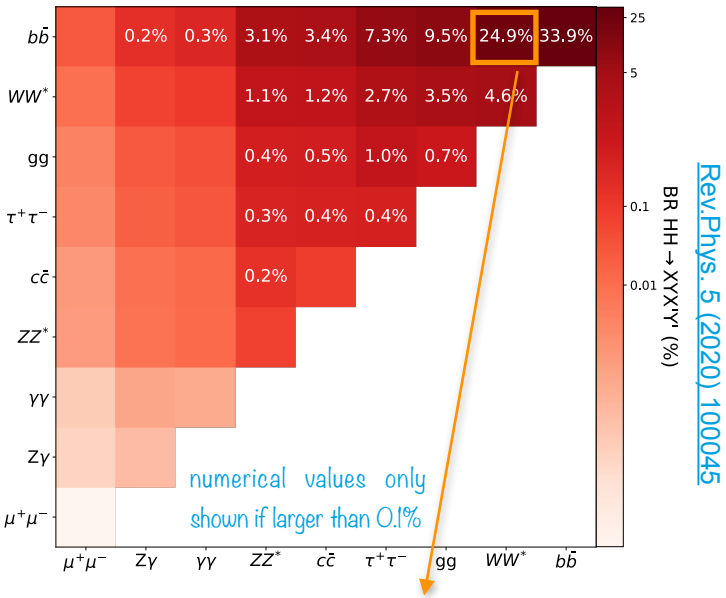
$\sigma = \sigma(\kappa_\lambda, \kappa_v, \kappa_{2v})$ = 1.73 fb (SM, 13 TeV)

Search for HH production

$HH \rightarrow bbWW$

Decay branching fractions



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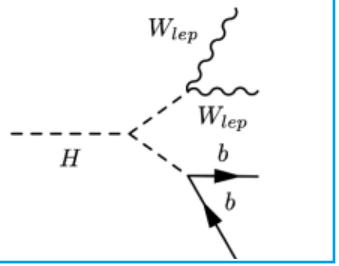
> second largest HH channel

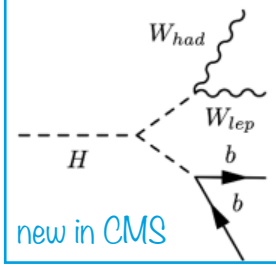
> **Production modes:** ggF and VBF

> **Decay modes:**

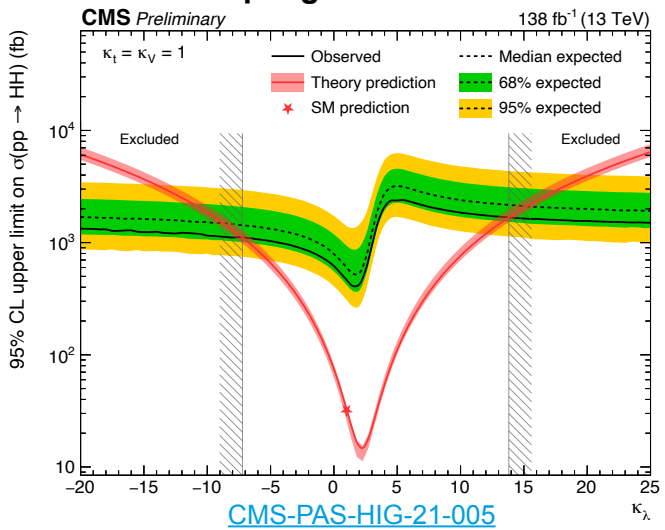
DL: $W_{lep}W_{lep}$ (~6%)



SL: $W_{lep}W_{had}$ (~38%)



Coupling scan

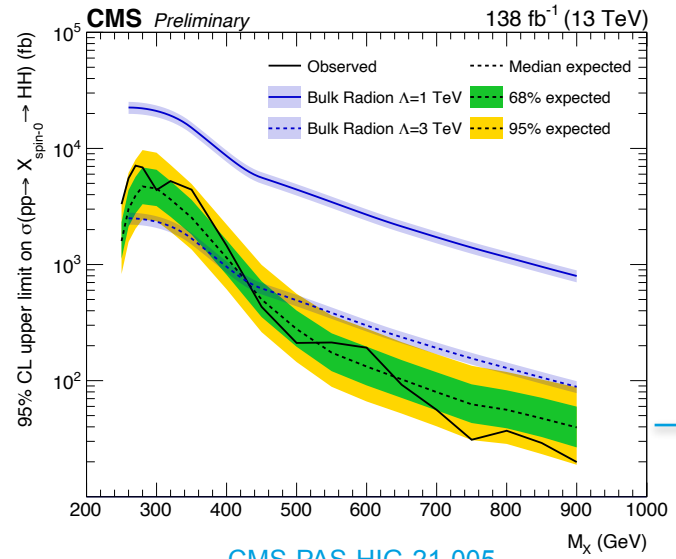


CMS-PAS-HIG-21-005

Non-resonant search

Looking for:

- anomalous (modified w.r.t. SM values) couplings of the Higgs boson
- additional couplings in Effective Field Theory



CMS-PAS-HIG-21-005

Resonant search

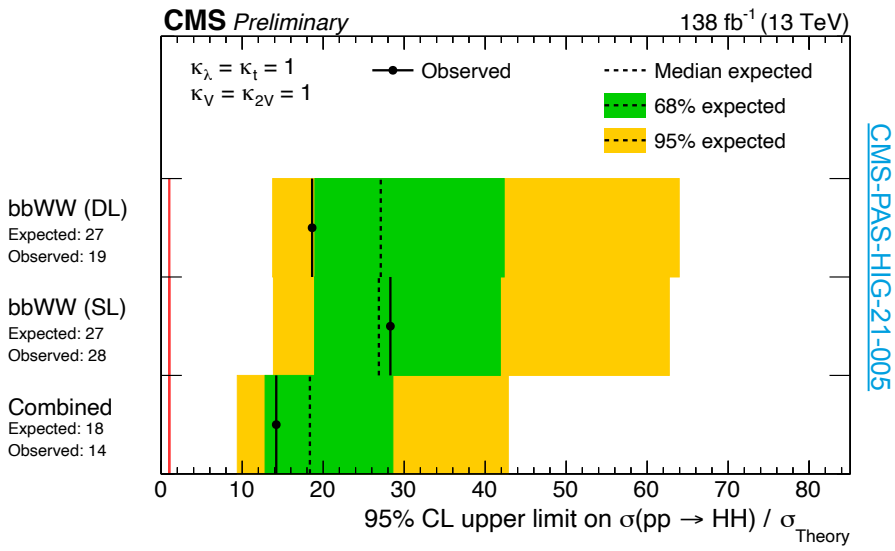
Looking for:

- new particles that decay to a Higgs pair
- production of particles X of spin 0 and mass m_X

Search for HH production

HH → bbWW

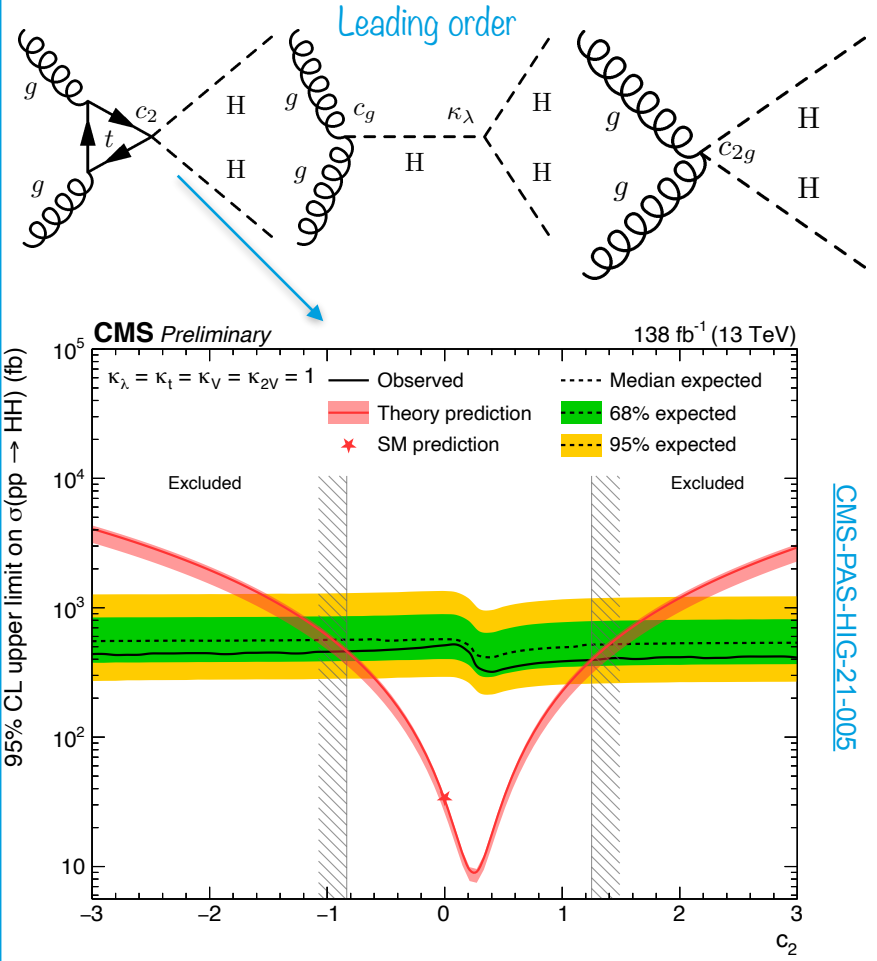
ggF + VBF production



Observed: 14 x SM

Expected: 18 x SM

- Feynman diagrams for non-resonant production via gluon fusion with anomalous Higgs couplings



Search for HH production

associated production with vector boson, $ZHH/WHH \rightarrow bbbb$

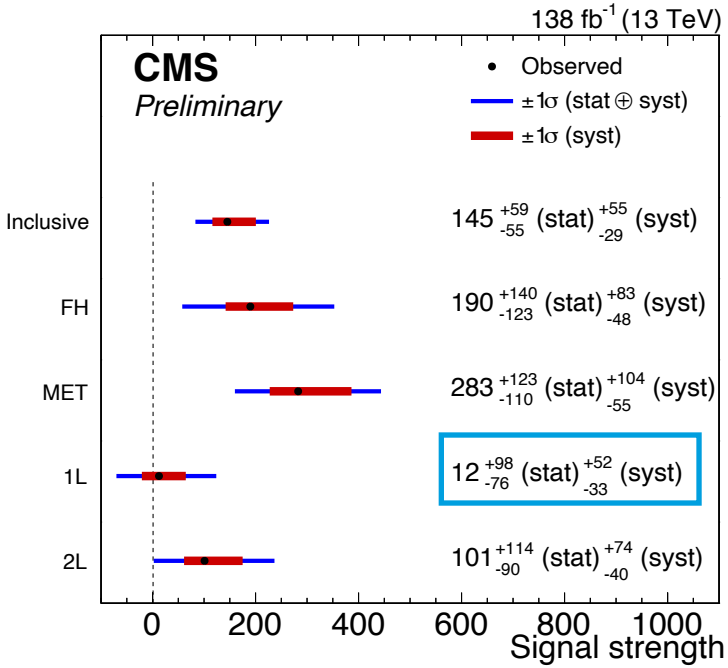
> Focus on HH → 4b final states (largest HH channel) with both leptonic and hadronic decays of V boson

> Construct HH from 4 jets with highest b-tag scores

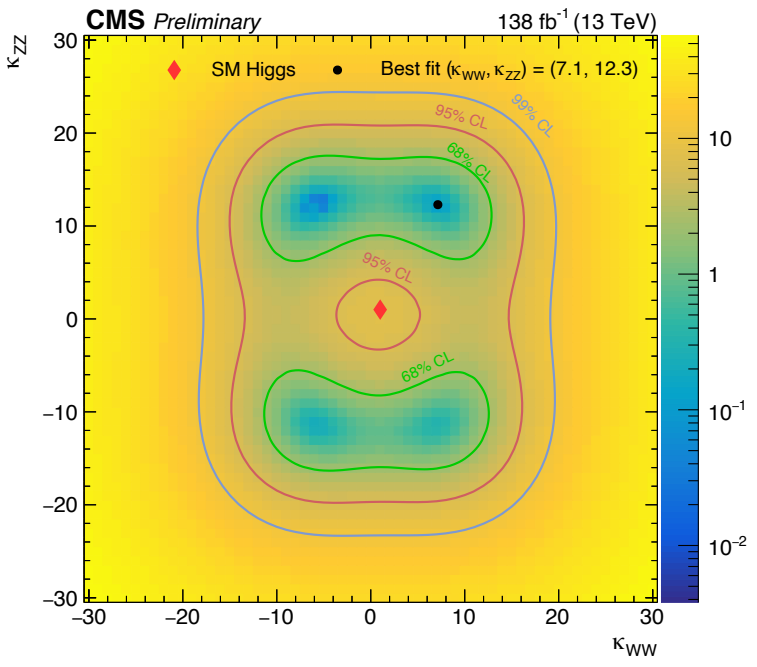
first analysis to include fully hadronic channel in non-resonant VHH → bbbb

> V = W/Z channels (resolved and boosted categories)

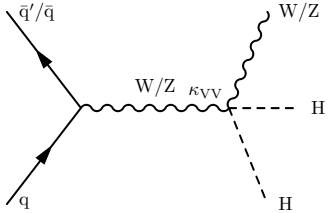
- 1L: $W \rightarrow l\nu$
- 2L: $Z \rightarrow ll$
- MET: $Z \rightarrow \nu\nu$
- FH: $W/Z \rightarrow qq$



CMS-PAS-HIG-22-006



CMS-PAS-HIG-22-006



> Unique feature to decompose κ_{WW} and κ_{ZZ} couplings separately

Search for exotic decay of Higgs boson

into Z boson and light pseudoscalar, $H \rightarrow Za$

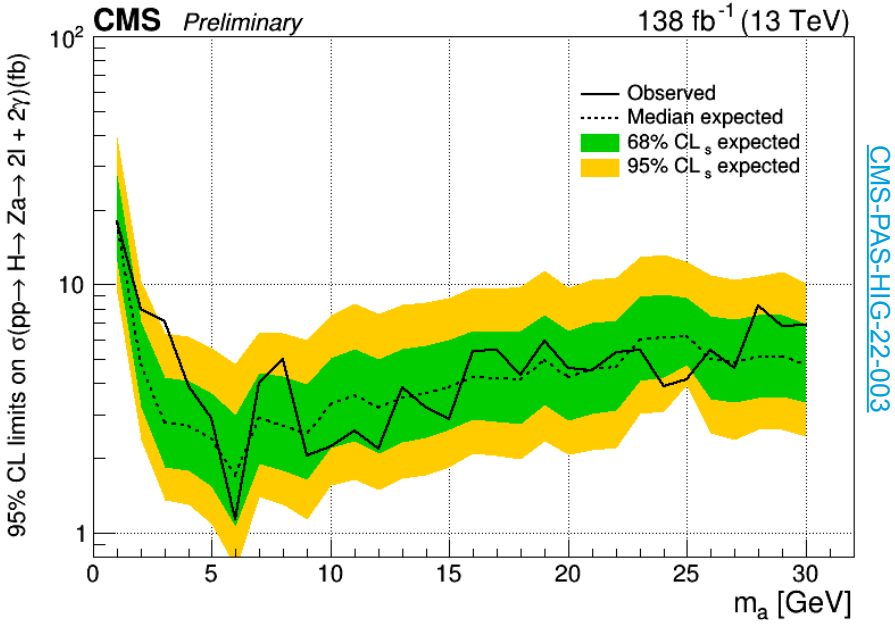
first search of this type at the LHC

> Higgs boson decaying to axion-like particle (ALP) and Z boson

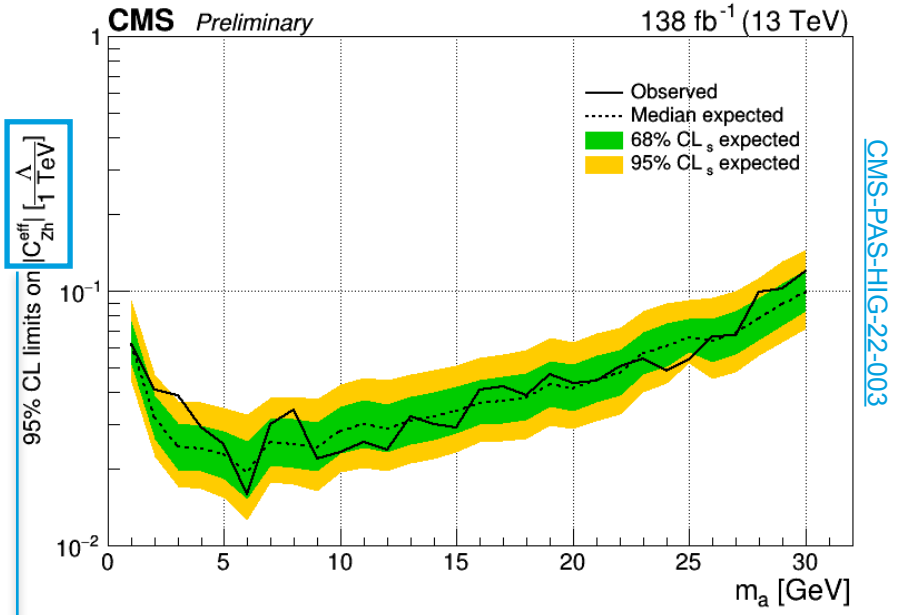
- ALP decaying to pair of photons
- Z boson decaying leptonically to electrons or muons

> $1 < m_a < 30$ GeV leading to two pairs of well-isolated leptons and photons

> BDTs using event kinematics, mass hypothesis, and photon quantities for background rejection



- observed (expected) limits ranging from 17.8 (17.9) fb for m_a = 1 GeV to 4.7 (6.9) fb for m_a = 30 GeV



- ALP assumed to decay promptly with $\mathcal{B}(a \rightarrow \gamma\gamma)$ = 100%

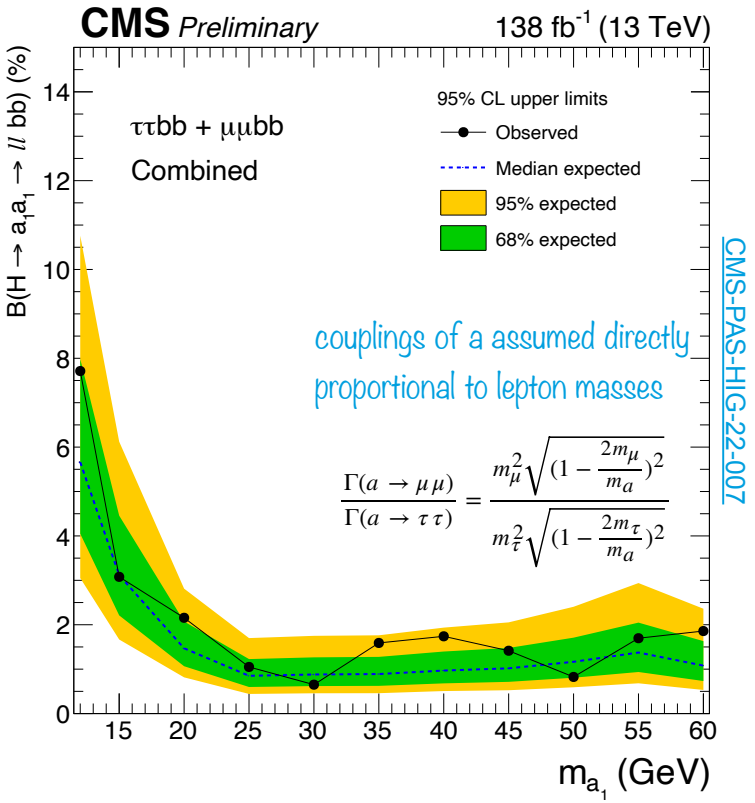
effective coupling parameter of Higgs boson, Z boson, and ALP, Λ new physics scale

Search for exotic decay of Higgs boson

into pair of light pseudoscalars, $H \rightarrow aa$

> one pseudoscalar decays to two b quarks, the other to two τ leptons or muons

$\mu\mu bb$ channel	$\tau\tau bb$ channel
Event selection:	
• at least 2 b jets and 2 opposite sign muons	• Three different $\tau\tau$ final states: eμ, eτ_h, and $\mu\tau_h$, with at least one b-tagged jet
m_{a_1} region probed:	
• 15 GeV < m_{a_1} < 62.5 GeV	• 12 GeV < m_{a_1} < 60 GeV
Background:	
• DY and $t\bar{t}$. Modelled with a set of analytical functions, using the discrete profiling method	• $t\bar{t}$ and $Z \rightarrow \tau\tau$ production
Final discriminant:	
• unbinned maximum-likelihood fit to $m_{\mu\mu}$ invariant mass distribution	• binned maximum likelihood fit to $m_{\tau\tau}$ distribution



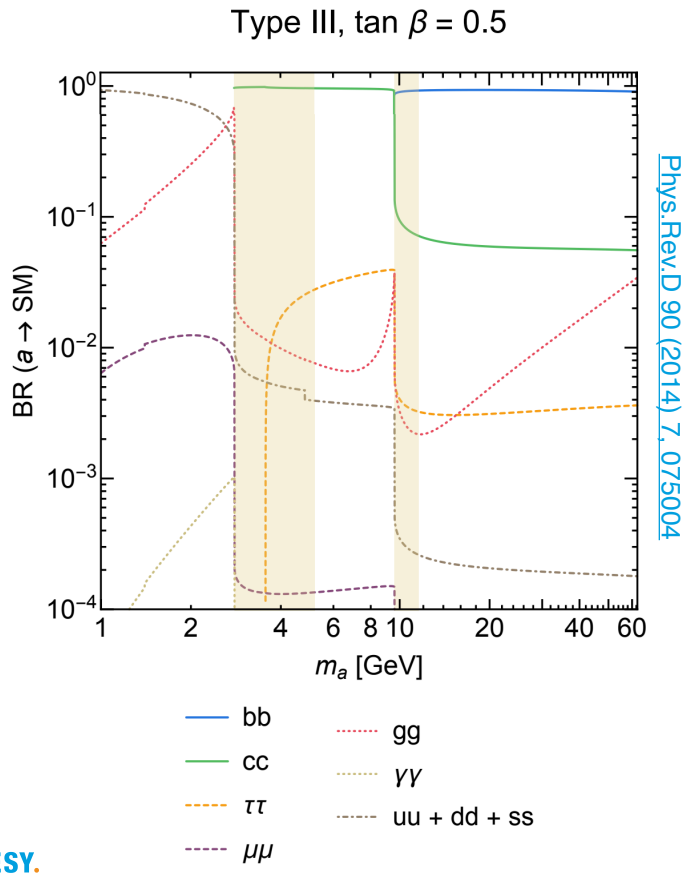
> exclusion limits for $\mathcal{B}(a_1 a_1 \rightarrow llbb)$ at 95% confidence level (CL) obtained by combining $\mu\mu bb$ and $\tau\tau bb$ final states

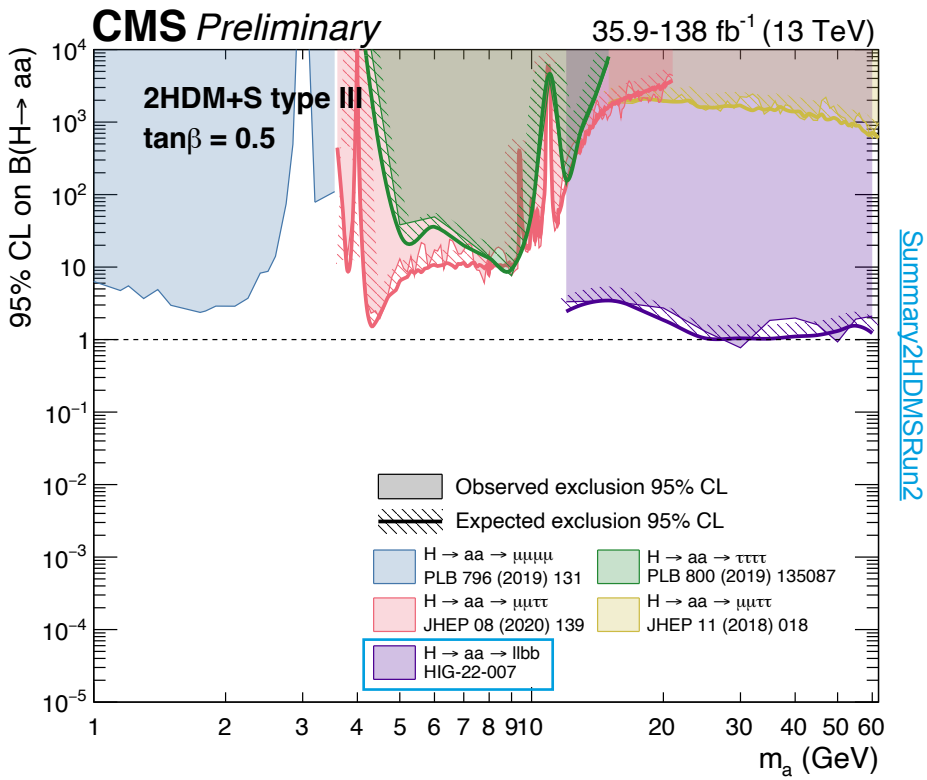
$H \to aa$ searches: Summary

The four standard types of fermion couplings in 2HDMs without FCNC

2HDM	up-type quarks	down-type quarks	charged leptons
Type-I	H_2	H_2	H_2
Type-II (MSSM-like)	H_2	H_1	H_1
Type-III (lepton-specific)	H_2	H_2	H_1
Type-IV (flipped)	H_2	H_1	H_2

$$(\sigma/\sigma_{SM}\mathcal{B}(h \to aa))_{up} = \frac{\mu_{up}(m_a)}{\mathcal{B}(a \to x\bar{x}; m_a, tan\beta)\mathcal{B}(a \to y\bar{y}; m_a, tan\beta)}$$

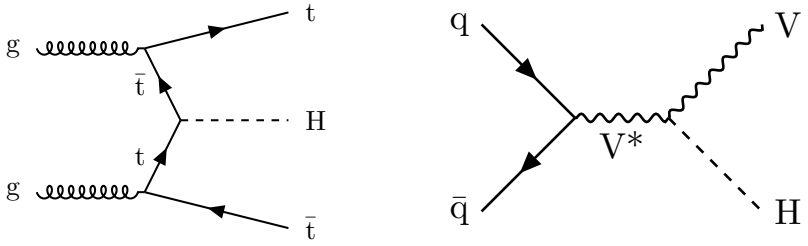




Search for decay of Higgs boson

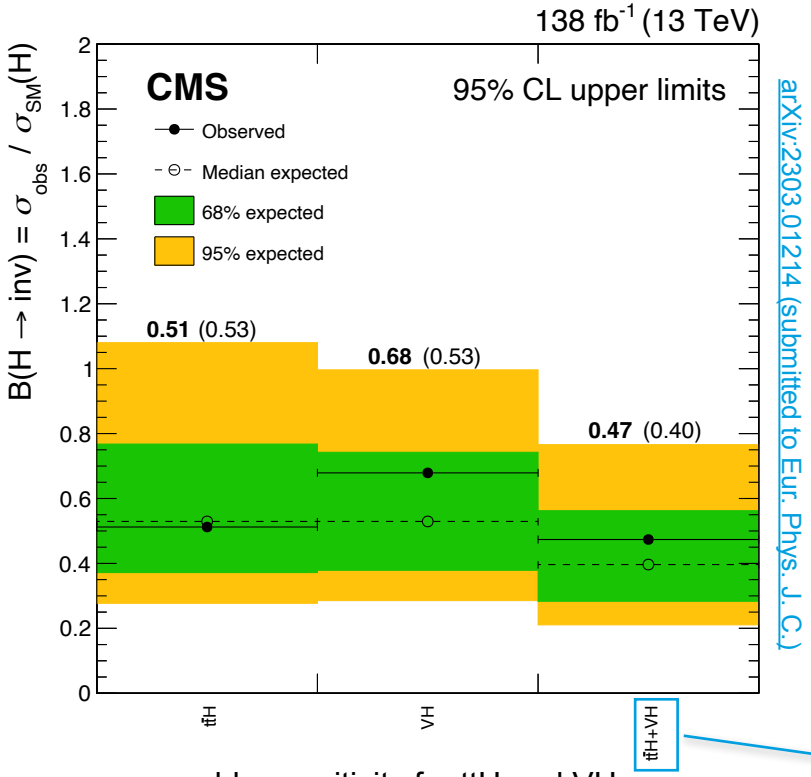
into invisible particles in events with top-antitop quark pair or vector boson

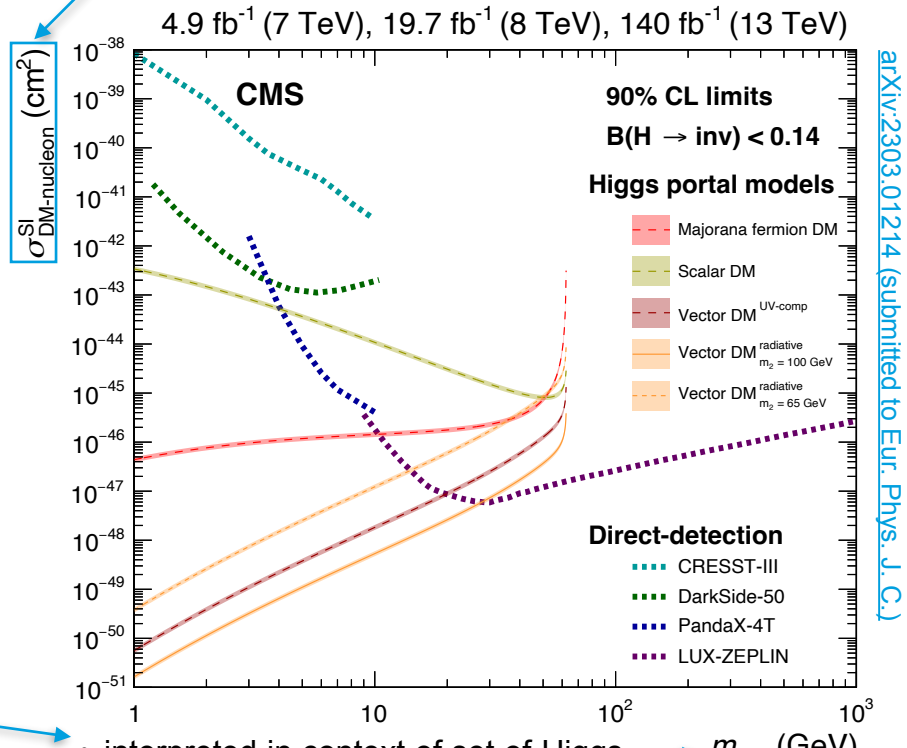
invisible decays to BSM particles that escape detection in the experimental apparatus



- fully hadronic final states
- interaction of weakly interacting massive particle with atomic nucleus via exchange of a Higgs boson

from resulting nuclear recoil -> upper bound on spin independent DM-nucleon scattering cross-section





- comparable sensitivity for ttH and VH
- interpreted in context of set of Higgs portal models of DM interactions → m_{DM} (GeV)

Search for additional Higgs bosons

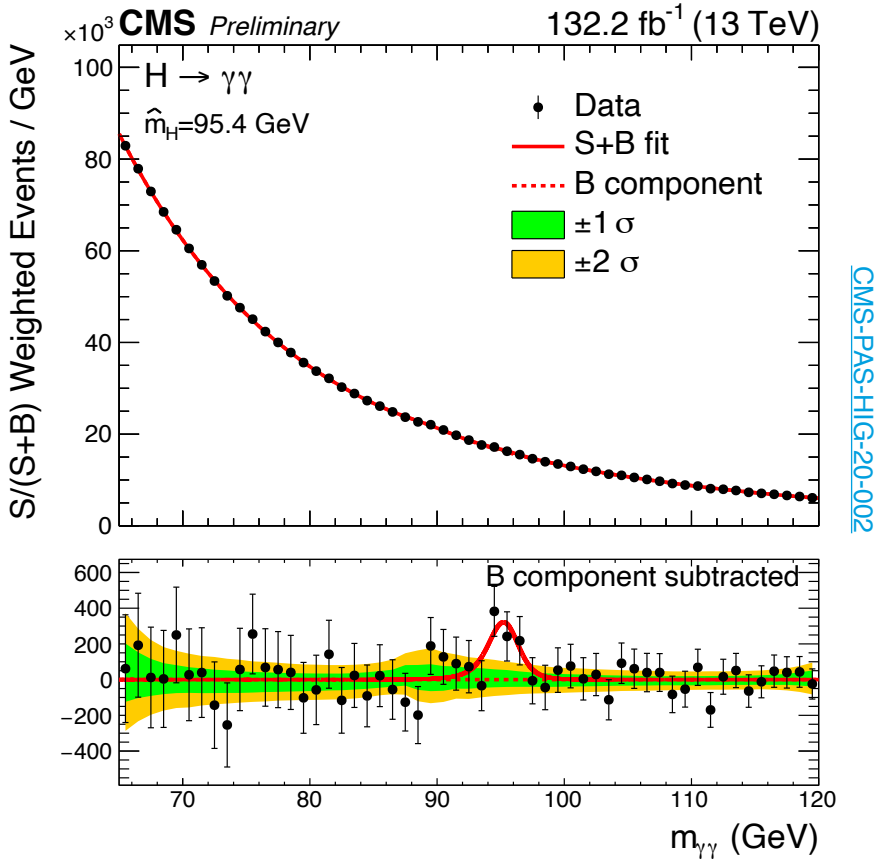
into pair of photons, $H \to \gamma\gamma$

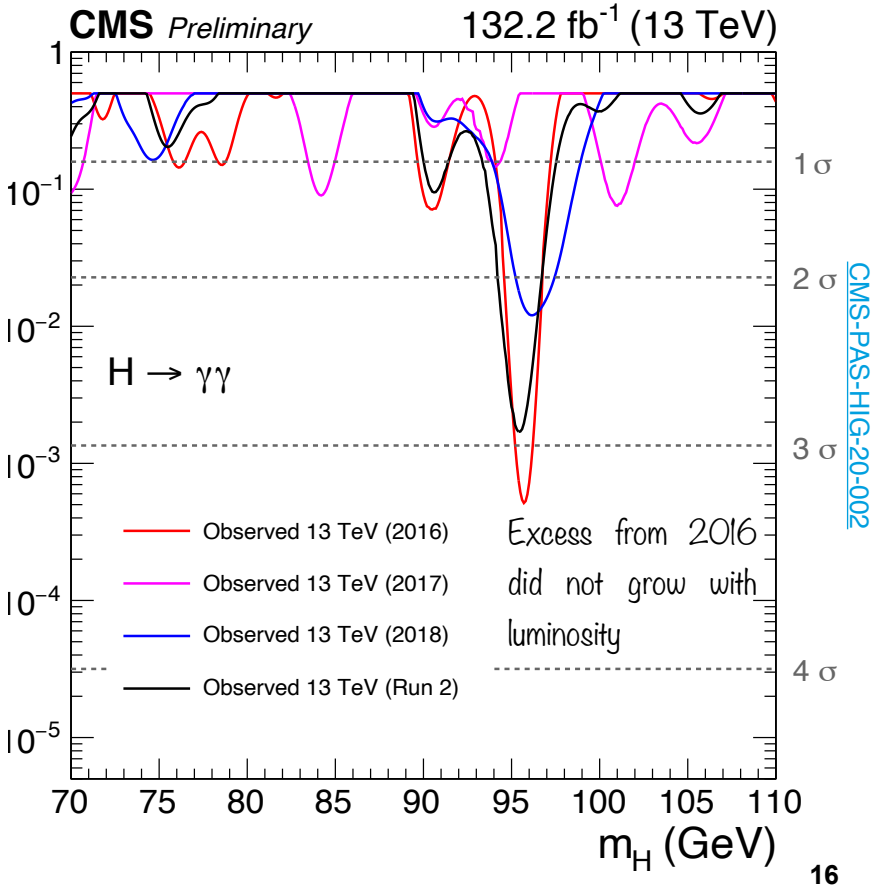
> Clean final-state topology

- Higgs boson mass reconstructed with high precision in search range

> Search follows-up on ~1.3σ (global) excess at $m_{\gamma\gamma} \approx 95$ GeV in 2012+2016 data

> Dedicated BDTs for photon identification, primary vertex selection, and signal events selection



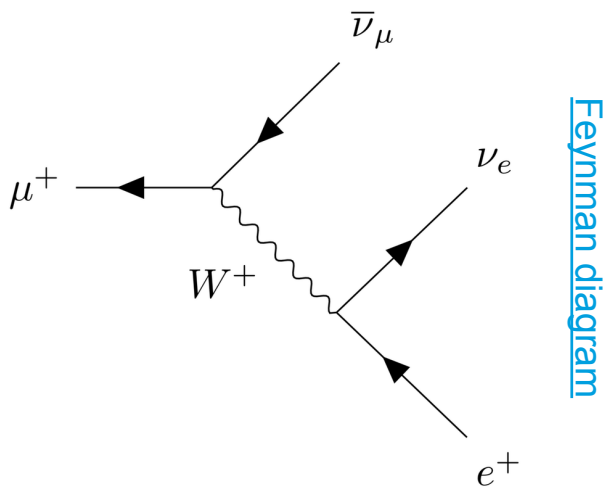


Lepton flavor violation decay (LFV)

> Transition among leptons of different flavour that does not conserve lepton family number

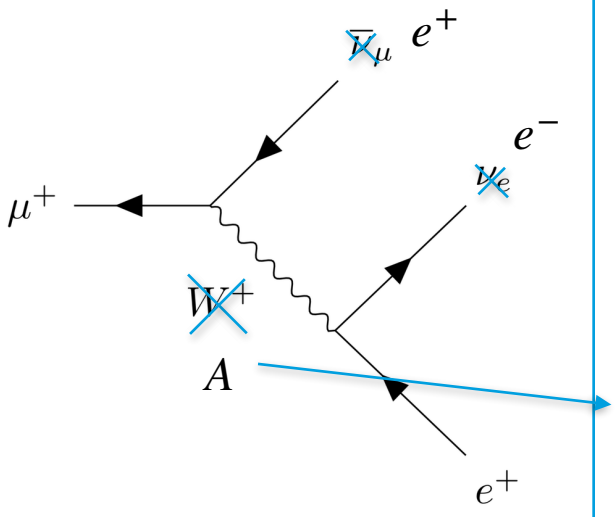
- $\mu \to 3e$ or $\mu \to e\gamma$
- $\tau \to 3\mu$
- $Z/H \to e\mu$

Muon decay in SM:



Feynman diagram

Muon LFV decay:



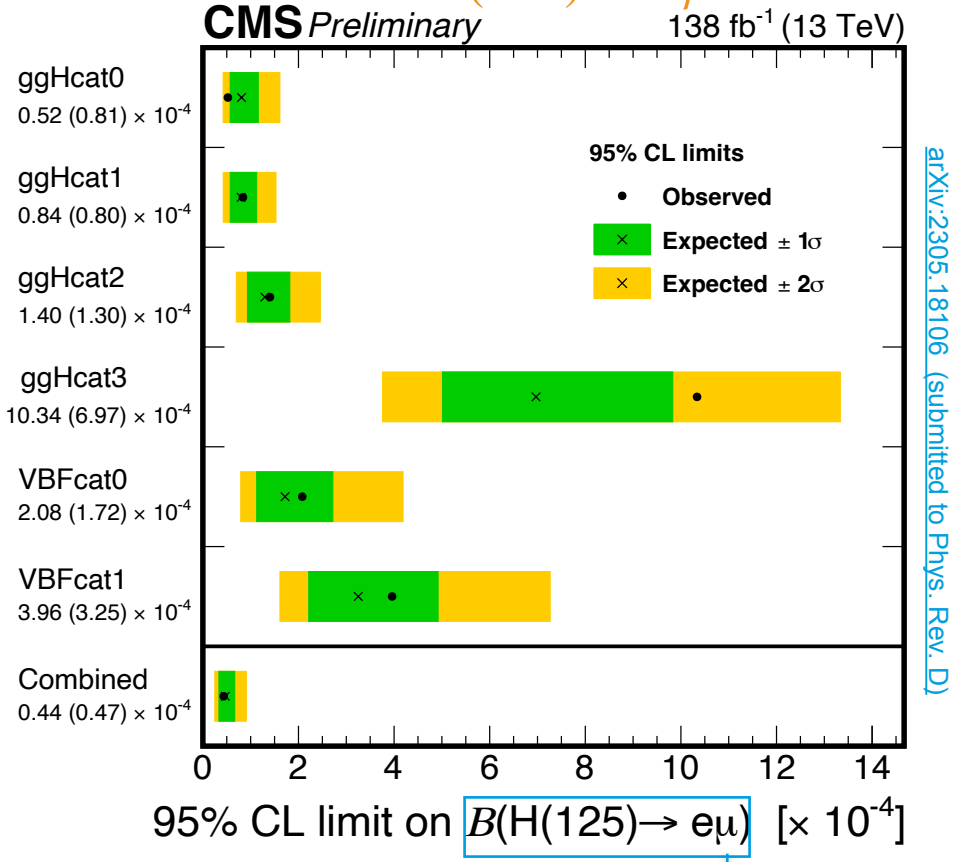
e.g. ALPs

LFV observation -> evidence of BSM Physics

Lepton flavor violation decay

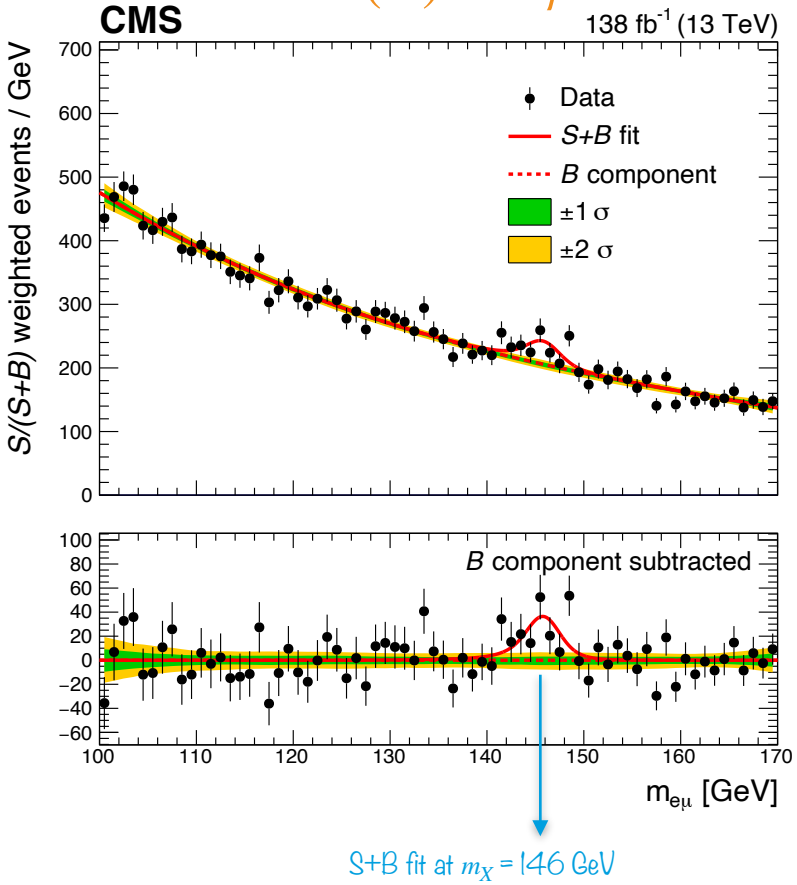
search for Higgs boson decaying to electron and muon

$H(125) \rightarrow e\mu$



arXiv:2305.18106 (submitted to Phys. Rev. D)

$H(X) \rightarrow e\mu$



arXiv:2305.18106 (submitted to Phys. Rev. D)

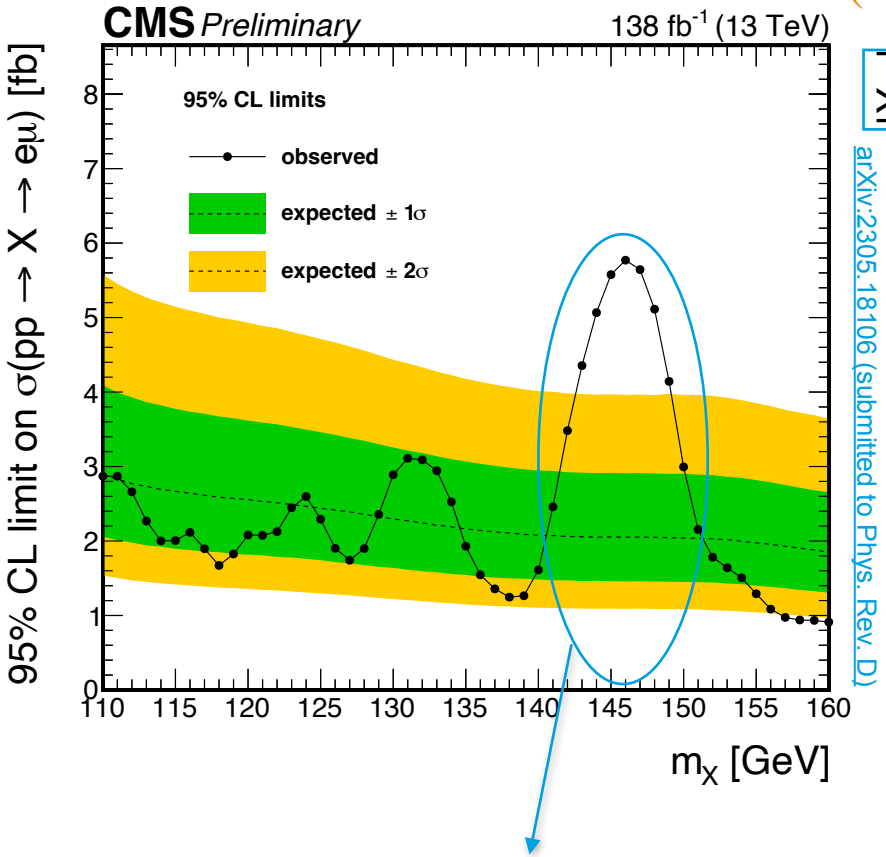
- **LFV decay** -> arises at tree level from $Y_{e\mu}$
- interpreted as constraint on BSM Yukawa couplings $Y_{e\mu}$

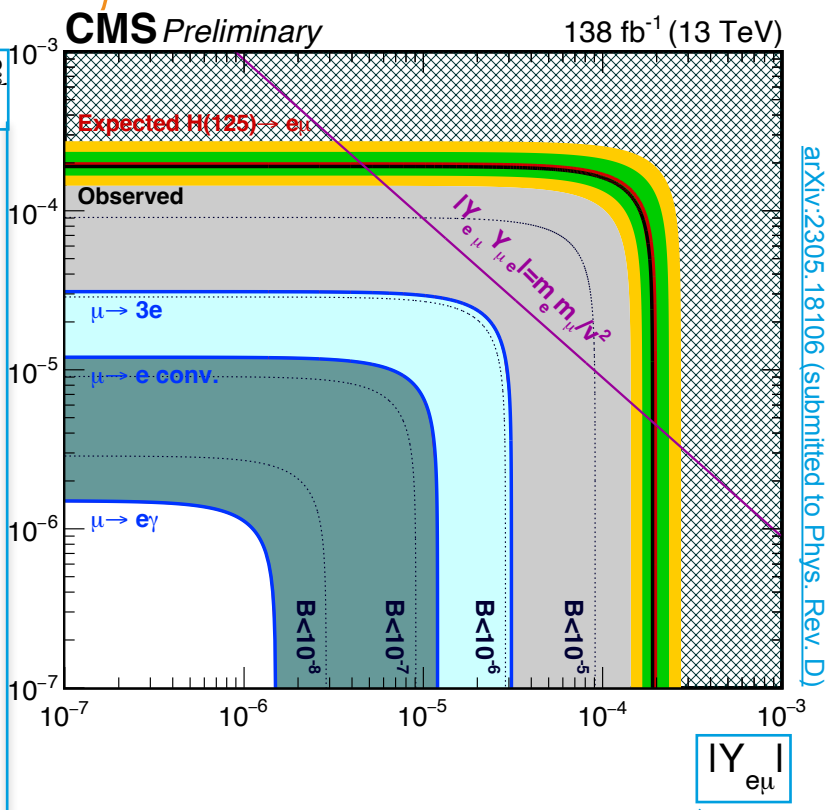
- **Background:** Bernstein polynomials
- **Signal:** sum of Gaussian distributions for each production mode, category, and Higgs boson mass

Lepton flavor violation decay

search for Higgs boson decaying to electron and muon

$$H(X) \rightarrow e\mu$$





arXiv:2305.18106 (submitted to Phys. Rev. D)

- ~146 GeV observed (expected) excess of events
- **2.8 (3.8) σ global (local) significance**

- Lepton flavor-violating Yukawa couplings

$$|Y_{l\tau}^2| + |Y_{\tau l}^2| = 8\pi \frac{\Gamma_H^{SM}}{m_H} \cdot \frac{\mathcal{B}(H \rightarrow l\tau)}{1 - \mathcal{B}(H \rightarrow l\tau)}$$

SM total width of Higgs boson

Summary

- Rare Higgs decay observed in first CMS and ATLAS combination for an evidence
- Progress in Higgs self-coupling measurement ahead from earlier expectations
- Many results on BSM searches (innovative approaches to target challenging signatures)
- Differential measurements as function of BSM sensible kinematic observables

The path ahead

An order of magnitude larger number of Higgs bosons, expected to be examined over next 15 years

- precise measurements of Higgs boson properties and its self-coupling
- search for BSM physics
- selected precision SM measurements

Translation of these physics goals into experimental design goals ongoing with detector upgrade program

Thank you!

Contact

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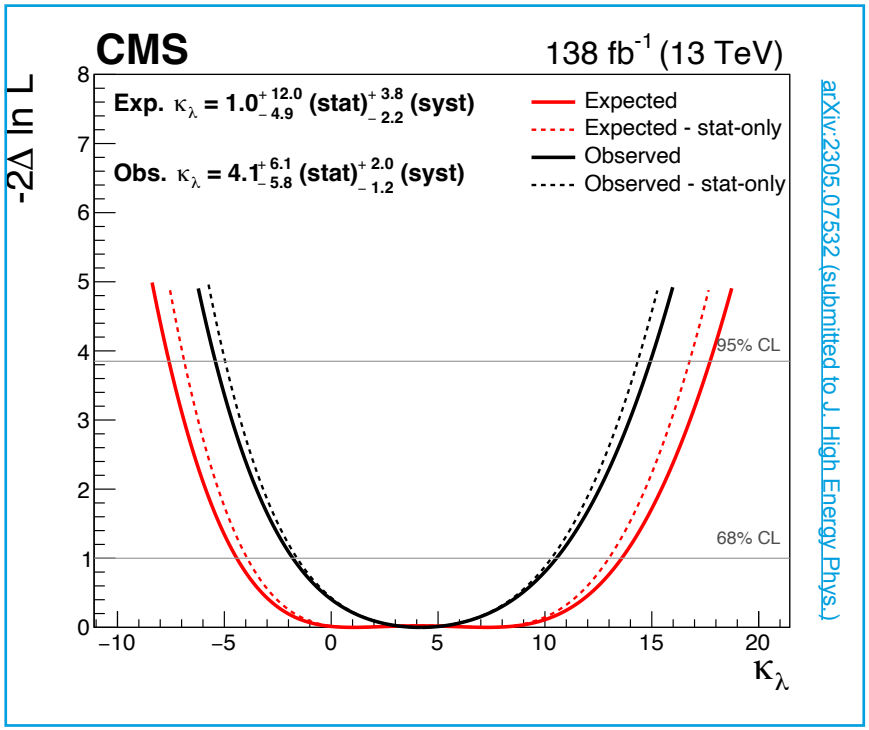
Backup

> Additional material

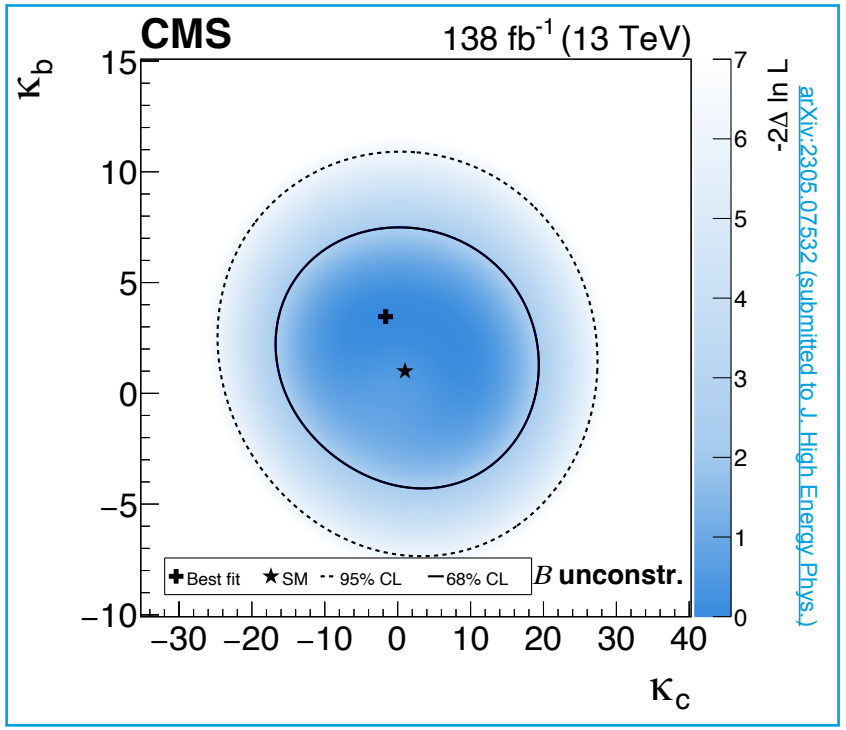
Discovery channels

$H \to Z \to 4l$, setting constraints

Higgs boson trilinear coupling



Bottom and charm quark coupling modifiers



observed (expected) excluded range at 95% CL:

$-5.4\ (-7.6) < k_\lambda < 14.9\ (17.7)$

$-5.6\ (5.5) < k_b < 8.9\ (7.4)$

$-20\ (19) < k_c < 23\ (20)$

> All results consistent with theoretical predictions from SM

Search for exotic decay of Higgs boson

into pair of light pseudoscalars, $H \rightarrow aa$

Model dependent interpretations (2HDM+S Models):

- three CP-even ($h_{1,2,3}$), two CP-odd ($a_{1,2}$), and two charged Higgs states (H^+, H^-)

Branching fraction:

$\mu\mu bb$

- 1.7 X 10^{-3} in Type-III 2HDM+S models with tanβ = 2, m_{a_1} = 30 GeV

$\tau\tau bb$

- above 10% in Type-II 2HDM+S models and tanβ > 1
- up to about 50% in Type-IV with tanβ ≈ 2