The Higgs boson:

standard model like or not?

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Preface

Why study the Higgs boson?

SM without Higgs boson

Matter: fermions

- 3 generations
- each generation comprises a doublet of leptons and a doublet of quarks

Forces, carried by vector bosons, arise from requiring local gauge symmetries

- SU(1): single field **B**
- SU(2): triplet of fields $\mathbf{W^+}$ $\mathbf{W^0}$ $\mathbf{W^-}$
- SU(3): octet of **gluons**

B and $\mathbf{W^0}$ are then mixed to give **photon** and **Z**

SU(2) – troublemaker (twice!)

- *forces introduced via gauge symmetry are* ***renormalizable***; however, the gauge symmetry implies that the corresponding force carriers are massless. But **W and Z bosons are massive**
- *weak force violates parity:* with the gauge symmetry, this requires fermions to be massless. But **fermions are massive**

Brout-Engler-Higgs (BEH) and Weinberg solve both mass problems

Brout + Engler; Higgs (1964):

(1) introduce a **doublet of pseudoscalars**, Φ:

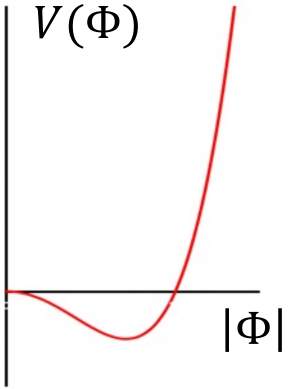
(four degrees of freedom, so to speak)

$$\Phi = \begin{pmatrix} \varphi_1 + i\varphi_2 \\ \varphi_3 + i\varphi_4 \end{pmatrix}$$

(2) give the doublet a **potential in a very unusual form**:

$$V(\Phi) = -\frac{1}{2}\mu^2|\Phi|^2 + \frac{1}{4}\lambda|\Phi|^4$$

(minimum energy is not when there is no field)



(3) require the **doublet to be SU(2) invariant**

(just as for fermion doublets)

- this makes new scalars interact with SU(2) fields: $g^2|\Phi|^2W^2$

Weinberg (1967):

(4) require Φ to be a force for fermions (ψ_i) with non-universal ad hoc couplings λ_i: $\lambda_i\psi_i\Phi\bar{\psi}_i$

(direct analogy to Yukawa's theory in which a scalar field was responsible for a strong force between nucleons)

Hocus pocus

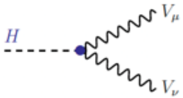
The minimum of energy is when field is non-zero: vacuum expectation value (vev) is $v = \frac{\mu}{\sqrt{\lambda}}$

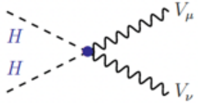
Hence, consider field fluctuations around its vacuum state: $\Phi(x) = v + h(x)$

Re-write everything for the expanded field near V$_{\text{min}}$ and **observe the magic!**

- Terms with SU(2) gauge bosons: $g^2|\Phi|^2 W^2 \rightarrow (g^2 v^2)W^2 + (2g^2 v)hW^2 + (g^2)h^2W^2$

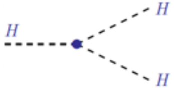
mass term! hWW interaction hhWW interaction





- Higgs field potential itself: $\mathrm{V}(\Phi) = \mathrm{V}(v+h) = \mathrm{const} + (\lambda v^2)h^2 + (\lambda v)h^3 + \frac{\lambda}{4}h^4$

mass term! trilinear self-interaction interaction quartic self-interaction interaction



- Terms with fermions: $\lambda_i \psi_i \Phi \bar{\psi}_i \rightarrow (\lambda_i v)\psi_i\bar{\psi}_i + \lambda_i \psi_i h \bar{\psi}_i$

mass term! hff interaction

The Higgs boson conundrum (1)

The entire BEH mechanism is very much ad hoc.

It works, but still an odd construct…

Is it just as Ptolemaic planetary system construct?

It worked extremely well (for centuries!), but was very odd too…

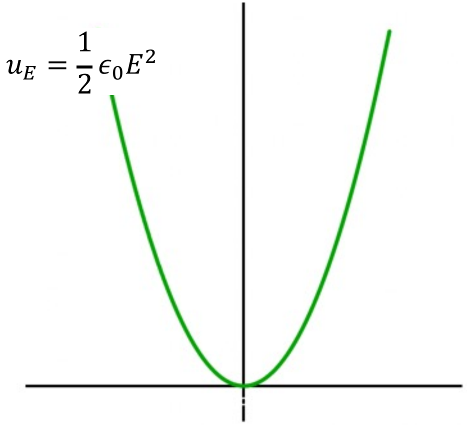
The Higgs boson conundrum (2)

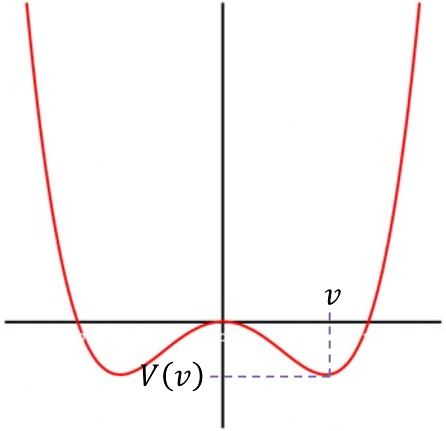
Higgs potential: $V(\Phi) = -\frac{1}{2}\mu^2|\Phi|^2 + \frac{1}{4}\lambda|\Phi|^4$

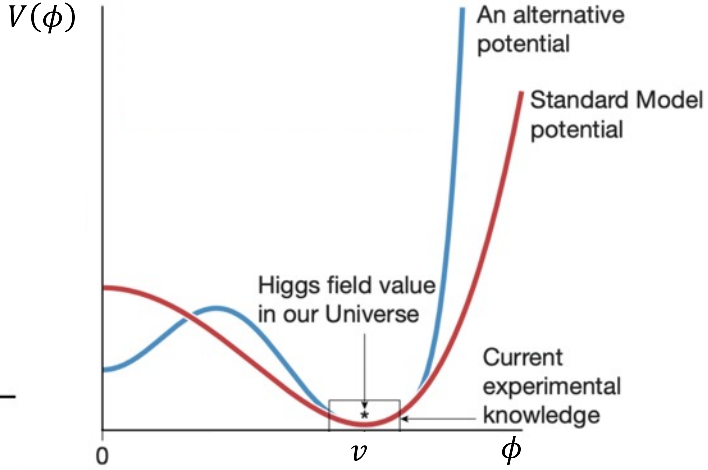
- Unlike for any other field, the minimum of energy is not when there is no field…
- The energy density associated with vev is enormous, –O(10^{28}) kg/m^3.

  To bring it to zero of just above zero not to overclose the Universe, one needs to add a const to $V(\Phi)$ that must be fine-tuned at the level of O(10^{-56})
- Can we know more about $V(\Phi)$?

  For the BEH mechanism, any potential with an off-zero local minimum would do (it should be renormalizable though)







The Higgs boson conundrum (3)

Higgs boson is a scalar:

- Radiative corrections to its mass (m^2) diverge quadratically with momentum scale of particles in the loop. What keeps its mass from running away to Plank's scale? (aka the hierarchy problem: why $m_H <<< m_{Plank}$?)
- SUSY would solve this elegantly – but where is SUSY? If not SUSY, then what?
- Is the Higgs boson a fundamental particle or is it just a composite state, like a pion?

Higgs boson is the only scalar in SM:

- We see many fermions and many vector bosons…
- Are there more scalars out there as well?

End of preface

The Higgs boson:

- **was indeed discovered** by ATLAS and CMS in 2012
- **has saved the standard model** from crumbling down in front of our eyes…

However:

- **It is unlike any other particle** in SM (and the entire BEH mechanism is very ad hoc)
- It brings new **puzzling conundrums**…

Hence, the Higgs boson may very well be that brightest lamp post around which BSM physics may reveal itself first – which brings me to the substance of my talk

Outline

Higgs boson mass – in SM, it is the last free parameter

Part 0: **measure it as accurately as possible**

just as we measure all other SM parameters (couplings, masses, mixing angles/phases)

Searches for BSM in the Higgs sector:

Part 1: search for **deviations** in the Higgs boson properties from the SM predictions

Part 2: search for explicitly **abnormal production/decay modes**

Part 3: search for **additional scalars**

Dataset reminders

Run 1 (2010-2012): 7-8 TeV **~25 fb^{-1}**

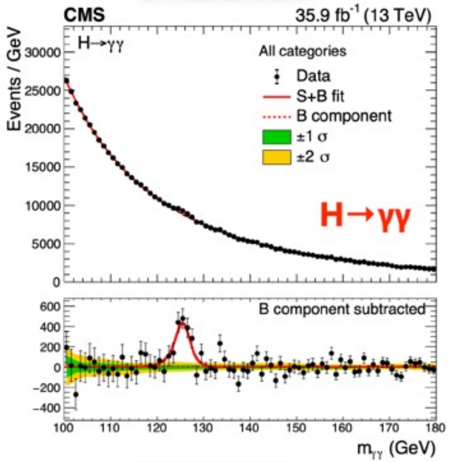
Run 2 (2015-2018): 13 TeV **~140 fb^{-1}** **the current dataset**

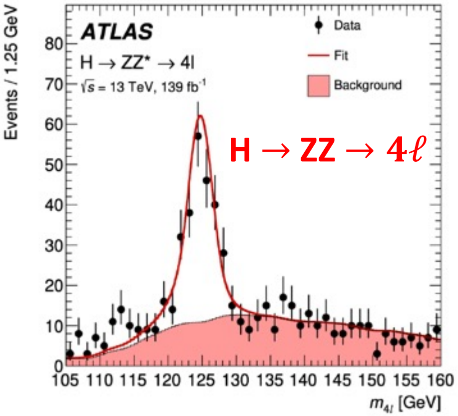
Run 2 vs Run 1: Higgs boson production cross sections are >2 times larger; integrated luminosity is ~6 times larger

Run 3 (2022-2025): 13.6 TeV ~**300 fb^{-1}** (40 fb^{-1} in 2022) **triple the current dataset**

HL-LHC (2029-2041): 14 TeV **~3000 fb^{-1}** **×20 + detector upgrades**

Part 0: Higgs boson mass measurement





$H \to ZZ \to 4\ell$ and $H \to \gamma\gamma$ are two workhorse channels

CMS best so far: 125.38 ± 0.14 GeV ($4\ell + \gamma\gamma$; 2016 + Run 1)

ATLAS best so far: 124.94 ± 0.17 GeV (4ℓ; full Run 2 + Run 1)

CMS (2016 + Run 1):

- **$H \to ZZ \to 4\ell$:** 125.26 ± 0.20(stat) ± 0.08(syst) GeV
- **$H \to \gamma\gamma$:** 125.78 ± 0.18(stat) ± 0.18(syst) GeV

Statistical powers of the two channels are similar

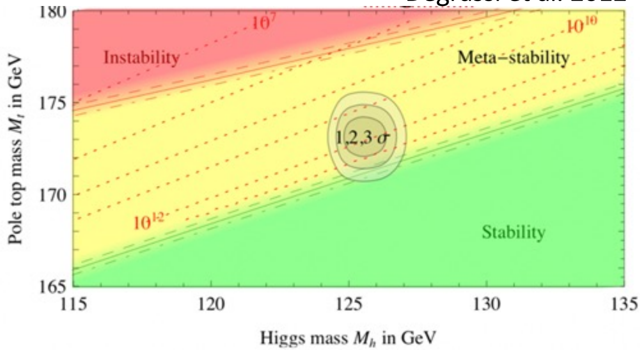
Emerging challenge in $H \to \gamma\gamma$: syst. uncertainties become a limiting factor

Full Run 2: *expected precision <100 MeV (better than 1 per mil)*

HL-LHC: *expected precision ~20 MeV*

Higgs boson mass: is it just a number?

- **The future of the Universe may depend on it!**
  - With no BSM up to the Plunk scale (really?), the top quark and Higgs boson masses seem to imply we may be leaving in a metastable universe…
  - *If you about to panic, don't:* $\tau_{\text{transition}} \sim 10^{600}\, T_{\text{Universe}}$



Degrassi et al. 2012

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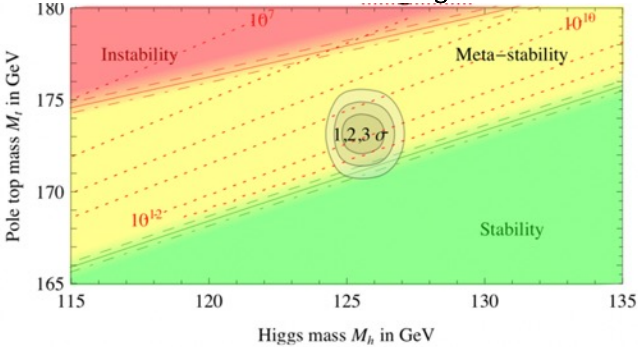
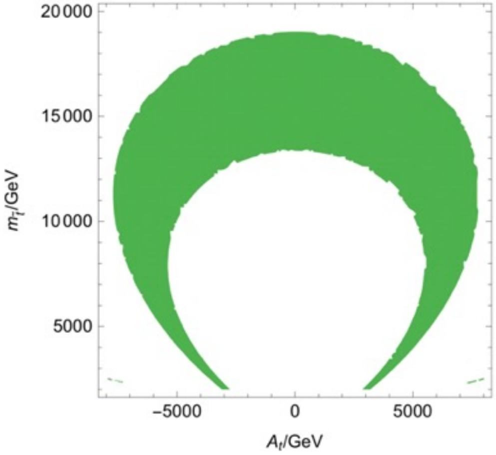


- **Constraints on MSSM**
  - In MSSM, at tree level, Higgs mass $m_H < m_{Z.} = 91$ GeV
  - It can be higher, up to ~130 GeV, via loop corrections
  - Mass m_H=125 is fairly large and sets interesting constraints on the average mass of two stop quarks – *no wonder squarks/gluinos are not yet discovered…*

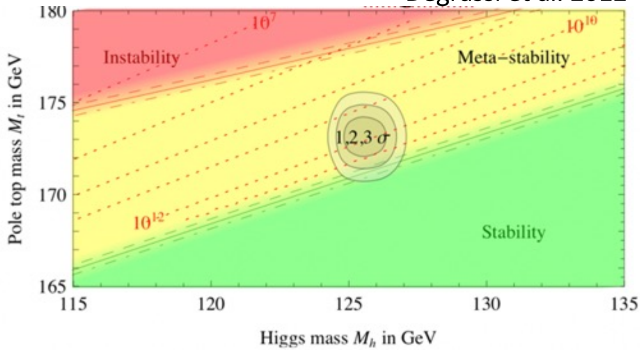
Hieu et al. 2017



Higgs boson mass: is it just a number?

- **The future of the Universe may depend on it!**
  - With no BSM up to the Plunk scale (really?), the top quark and Higgs boson masses seem to imply we may be leaving in a metastable universe…
  - *If you about to get scared, you can relax:* $\tau_{\text{transition}} \sim 10^{600}\, T_{\text{Universe}}$

Degrassi et al. 2012



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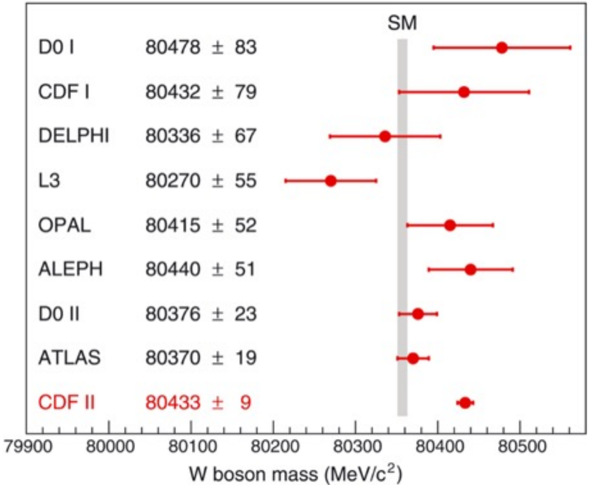

- **SM mass triangulation self-consistency:** $m_W - m_t - m_H$
  - The recent CDF result (m_W) makes *everyone hold their breath!*

Part 1: Search for deviations from SM-like properties

- **Rates in different production and decay modes:** test of couplings' strengths with respect to the SM predictions
- **Non-SM like structures in production and decay amplitudes:** spin-parity, mixed states, compositeness
- **Natural width:** can provide an indirect sign for presence of abnormal decay modes

Decay modes

	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)

In gray: three decay modes being searched for…

Decay modes

	bb	WW	ττ	cc	ZZ	γγ	Zγ	μμ	“hopeless”: gg, qq, ee
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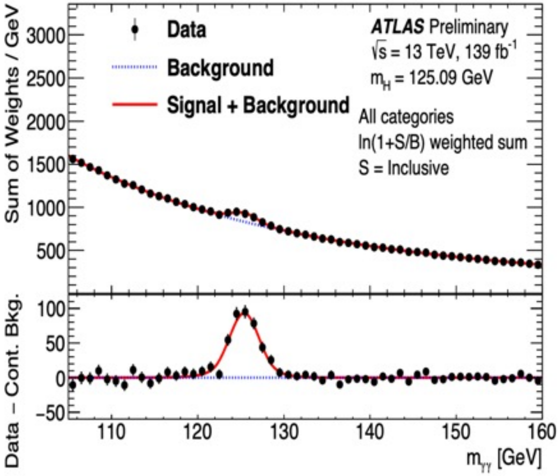
In green: five well-established decay modes (>5σ)

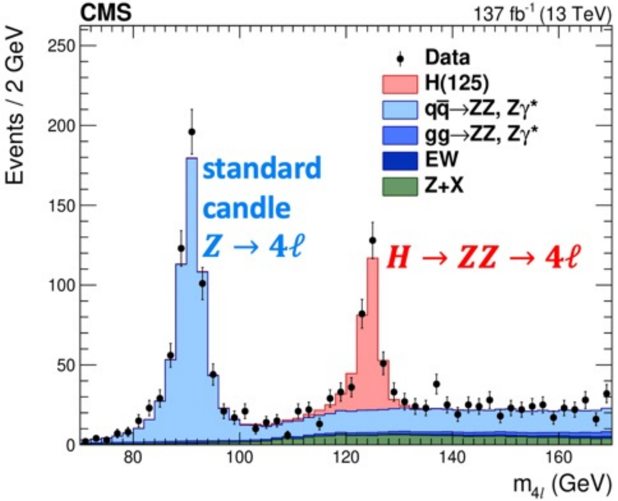
$H \rightarrow \gamma\gamma$

ATLAS: 1.04 ± 0.11
CMS: 1.12 ± 0.09



$H \rightarrow ZZ \rightarrow 4\ell$

ATLAS: 1.01 ± 0.11
CMS: 0.94 ± 0.11



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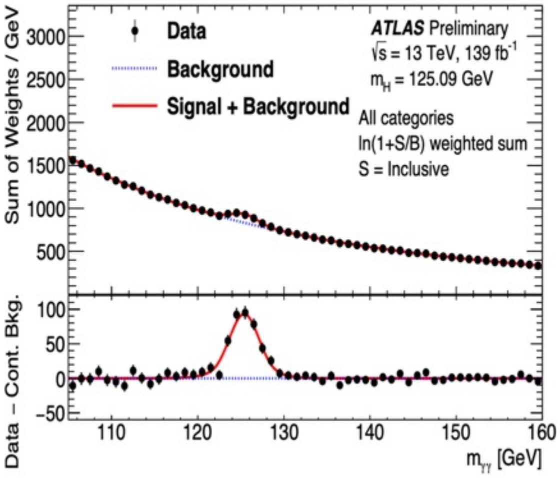
Emerging challenge:
Experimental uncertainties are getting close to uncertainties in in theoretical calc.

$H \to \gamma\gamma$:

$$\mu = 1.12^{+0.09}_{-0.09} = 1.12^{+0.06}_{-0.06}\,(\text{theo})^{+0.03}_{-0.03}\,(\text{syst})^{+0.07}_{-0.06}\,(\text{stat})$$

$H \to \gamma\gamma$ ATLAS: 1.04 ± 0.11 CMS: 1.12 ± 0.09



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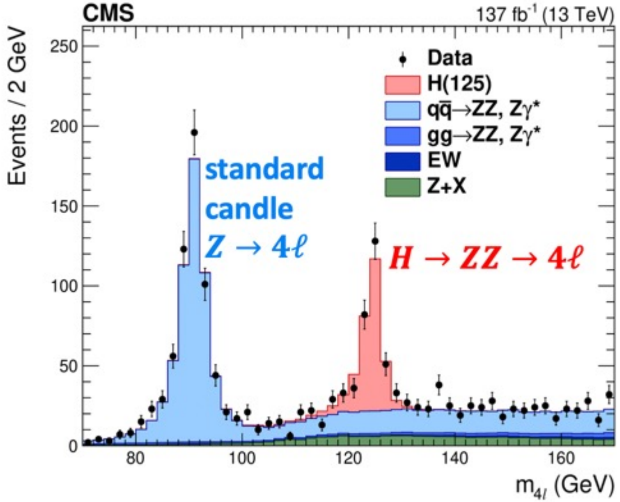

Decay modes

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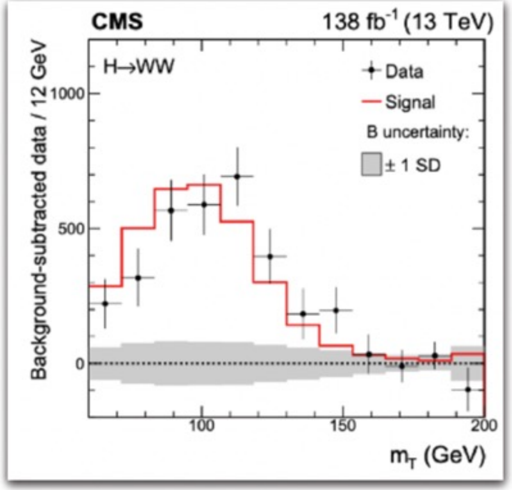
SM Higgs	58%	21%	6.3%	2.9%	2.6%	0.23%	0.15%	0.022%	9%

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

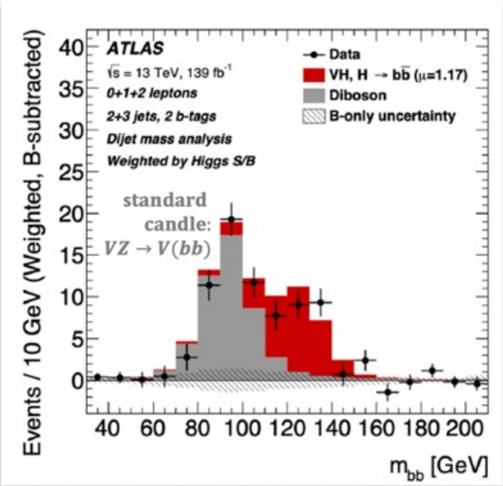
$H \to WW$

ATLAS: $\mathbf{1.09 \pm 0.11}$
CMS: $\mathbf{1.05 \pm 0.12}$



$H \to bb$

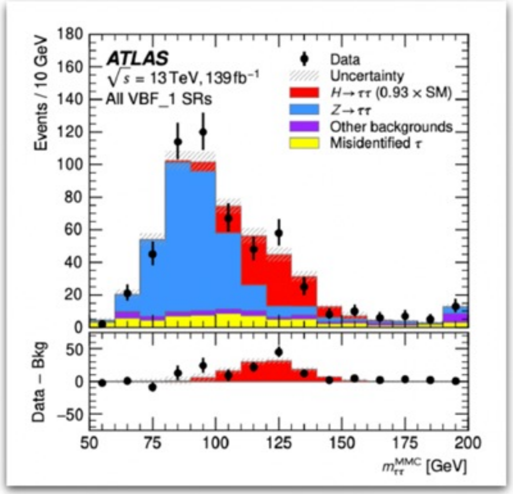
ATLAS: $\mathbf{1.02 \pm 0.18}$
CMS: $\mathbf{1.04 \pm 0.20}$



standard candle: $VZ \to V(bb)$

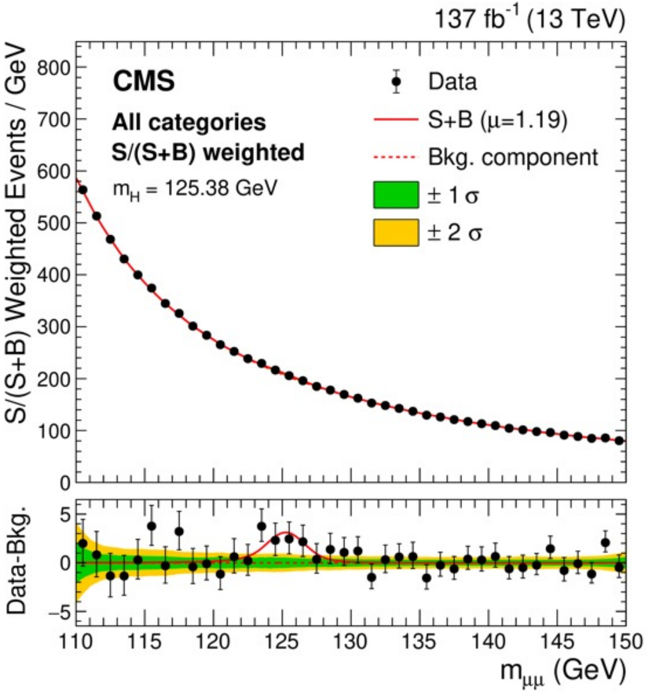
$H \to \tau\tau$

ATLAS: $\mathbf{0.93 \pm 0.13}$
CMS: $\mathbf{0.85 \pm 0.12}$



Search for $H \rightarrow \mu\mu$

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



Analysis:

- Two prompt muons
- ggF, VBF, and VH categories
- Look for a small blip, effectively O(1%), in the dimuon invariant mass at $m_{\mu\mu} \sim 125$ GeV

	CMS [Run 2]	ATLAS [Run 2]
Significance	**3.0**	2.0
Signal strength (μ)	1.2 ± 0.4	1.2 ± 0.6

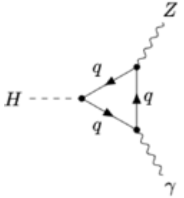
Evidence for the Higgs boson's coupling to the second generation fermions!

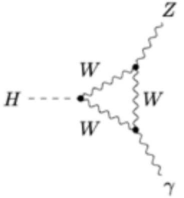
Naively, need ~4 times more data to establish this decay (assuming SM) **with 5σ: maybe, already in Run 3**

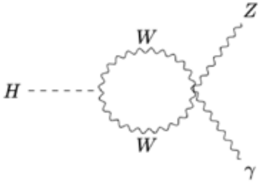
Search for $H\to Z\gamma$

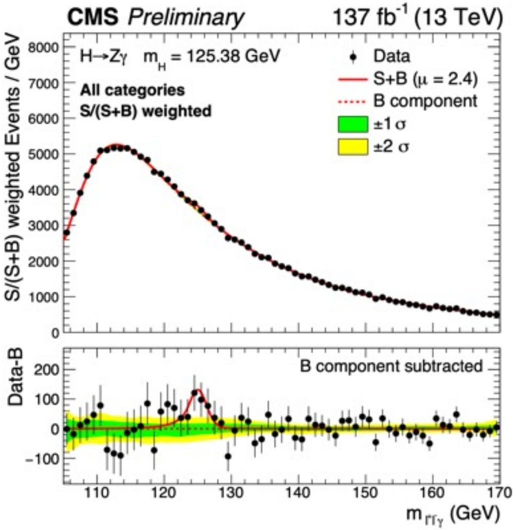
Loop-induced decay in SM

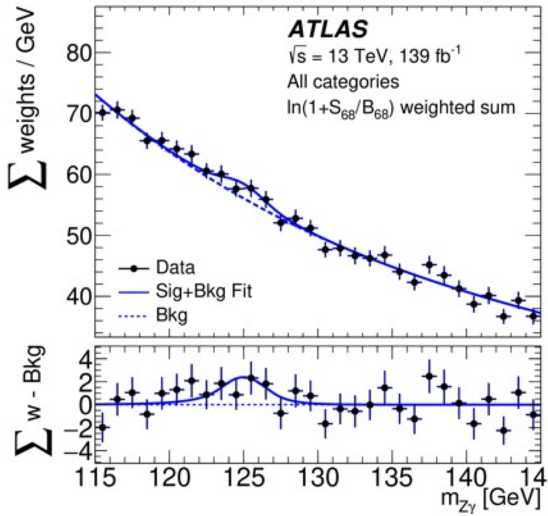
SM: $B(H\to Z\gamma)B(Z\to ee/\mu\mu)\approx \mathbf{0.01\%}$











Analysis:

- Two prompt leptons with $m_{\ell\ell}\sim m_Z$
- VBF, VH, and ttH categories + ggF with kinematic discriminant $D_{kin}(\ell\ell\gamma)$
- Look for a small blip, effectively O(1%), in dimuon invariant mass at $m_{\ell\ell}\sim m_H$

	CMS [Run 2]	ATLAS [Run 2]
Significance	2.7	2.2
Signal strength (μ)	2.4 ± 0.9	2.0 ± 1.0

Naively, need ~20 times more data to establish this decay (assuming SM) **with 5σ:** **HL-LHC**

Search for VH, $H \to cc$ (1)

SM: $B(H \to cc) \approx 3\%$
$B(H \to \boldsymbol{bb}) \approx \mathbf{60\%}$

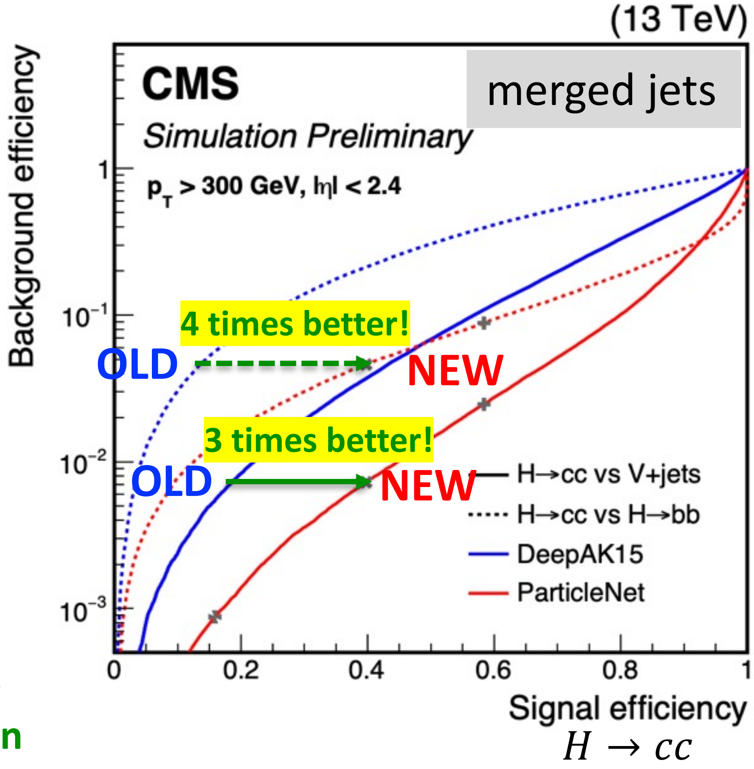
Signal signature: VH, with $H \to cc$

Need to fight:

- **V+jets**: huge cross section
- **VH, H→bb:** 20 times the H→cc rate!

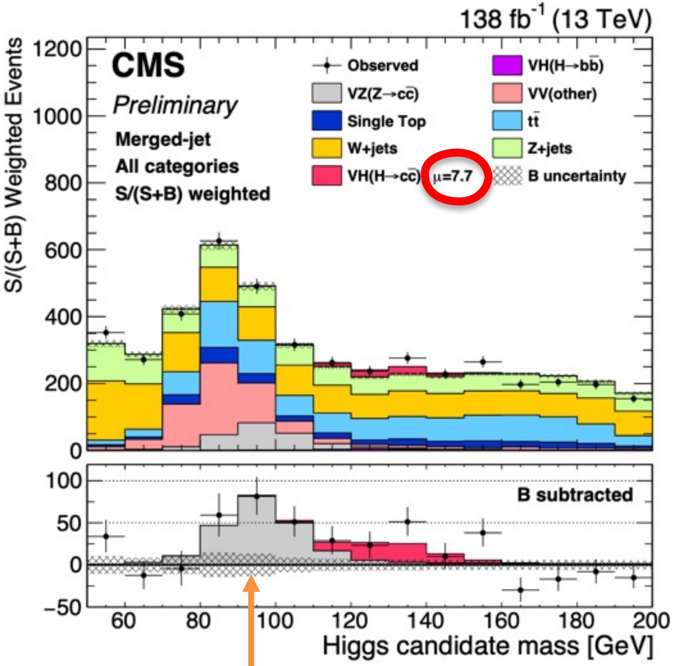
Need a two-sided discriminant: **q/g-jet** vs **c-jet** vs **b-jet**

Advanced ML/AI techniques are now being employed and are proved deliver significant improvements in such discrimination



Search for VH, $H \to$ cc (2)

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



“*standard candle*” $VZ, Z \to cc$
μ = 1.0 ± 0.2 (5.7σ)

$VH, H \to cc$	CMS [Run 2]	ATLAS [Run 2]
Obs (exp, no H $\to cc$) 95% CL limit on μ	14 (7.6)	26 (31)
Signal strength (μ)	7.7 ± 3.7	-9 ± 16

Validation process (”standard candle”): $VZ, Z \to cc$		
Significance	**5.7**	2.6
Signal strength (μ)	1.0 ± 0.2	1.2 ± 0.5

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

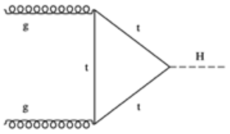
To see its evidence at HL-LHC, can we get 5 times smarter?

Established production modes

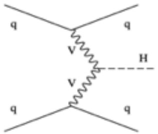
	gg	VBF	WH	ZH	ttH	bbH	tH
SM Higgs (σ=55.7 pb at 13 TeV)	87.2%	6.8%	2.5%	1.6%	0.9%	0.9%	0.2%

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

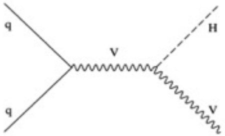
All event rates are compatible with the SM predictions



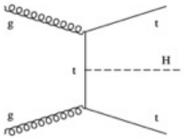
gg-fusion



VBF

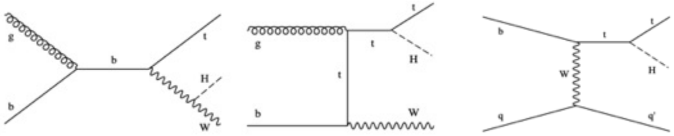


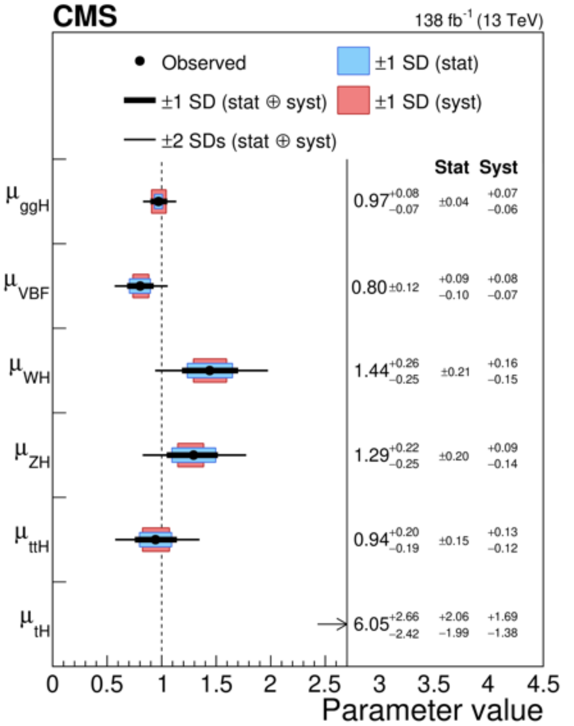
WH, ZH



ttH, bbH

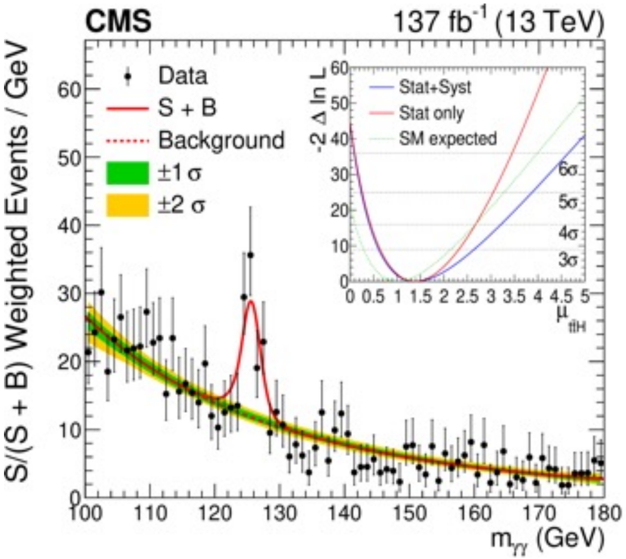
tH





ttH – production mode established most recently (2020)

$\boldsymbol{ttH, H \rightarrow \gamma\gamma}$ (1% of total cross section)



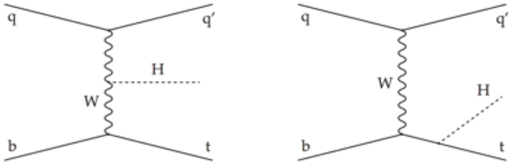
Analysis:

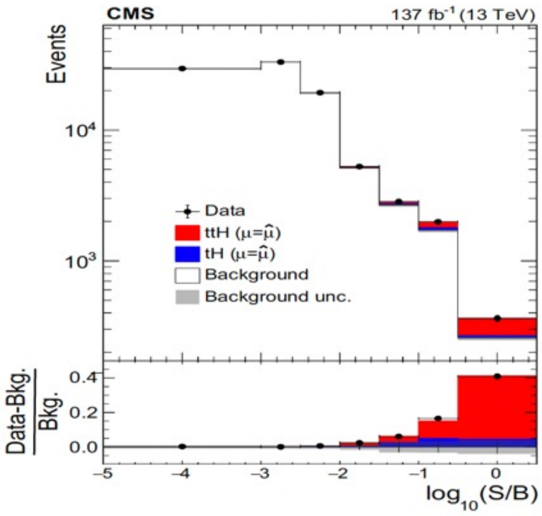
- tt
- two isolated photons
- make sure that other Higgs production mechanisms are suppressed (tt selections) – 99% of Higgs events are BKG!
- look for a peak in the diphoton mass distribution

	CMS [Run 2]	ATLAS [Run 2]
Significance	6.6	5.2
Signal strength (μ)	1.38 ± 0.33	1.43 ± 0.37

Search for rare tH production

main diagrams





Very challenging search

- two diagrams nearly cancel out (0.2% of the total H production cross section)
- **ttH** is a serious background (5 times larger, very similar experimental signature) – it is measured in the same analysis flow: $\mu = 0.92 \pm 0.24$

Analysis: considered events with *electrons, muons, taus, and jets*

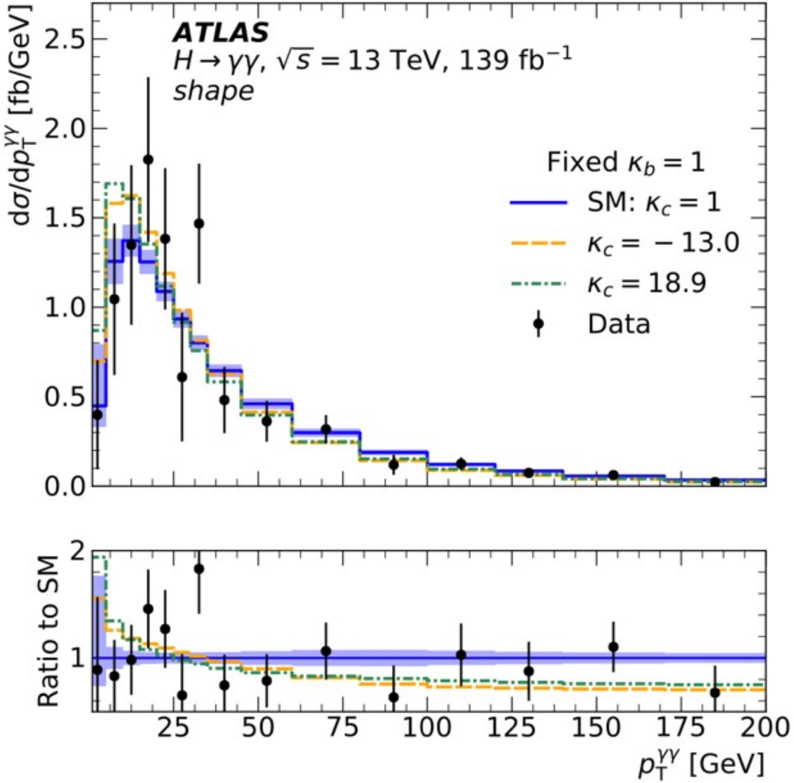
- H→ ZZ, WW, ττ
- t → Wb → (jj)b or (lν)b

Should one flip relative sign of Higgs-top and Higgs-W couplings, cross section would become 15 x SM. But B(H-> γγ) would increase just as dramatically, which is not…

Observed tH signal strength: $\mu = 5.7 \pm 2.7$ (stat) ± 3.0 (syst)

Hard to project forward as the uncertainty is systematics-limited
Naively, to decrease stat uncertainty to 0.2, one needs ~200 times more data

Differential cross sections: Higgs p_T is one of many



Possible BSM information:

- **Larger couplings of Higgs to b/c-quarks** make the Higgs boson p_T distribution becomes softer
- **BSM particles in the gg->H loop** make the Higgs boson p_T distribution becomes softer

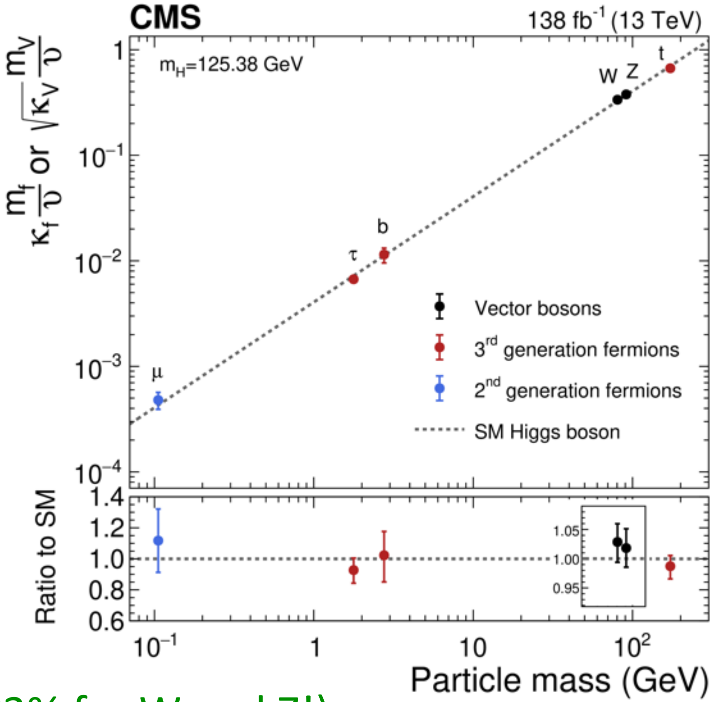
From the Higgs p_T spectrum: $-13 < \kappa_c < 19$

With added info on observed event rates in all production/decay modes: $-2.7 < \kappa_c < 2.6$
(better than from direct searches for H->cc)

Fit for couplings modifiers

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: $\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, \kappa_{\mathrm{t}}, \kappa_{\mathrm{b}}, \kappa_{\tau}, \kappa_{\mu}$



Assuming:

- no "new physics" in loop-driven couplings ($H \rightarrow \gamma\gamma$, gg→ 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 precision and agreement with SM (~3% for W and Z!) over **three orders of magnitude** of couplings

Search for HH: why?

Higgs potential: $\mathrm{V}(\Phi) = \mathrm{V}(v + h) = \mathrm{const} + (\lambda v^2)h^2 + (\lambda v)h^3 + \frac{\lambda}{4}h^4$

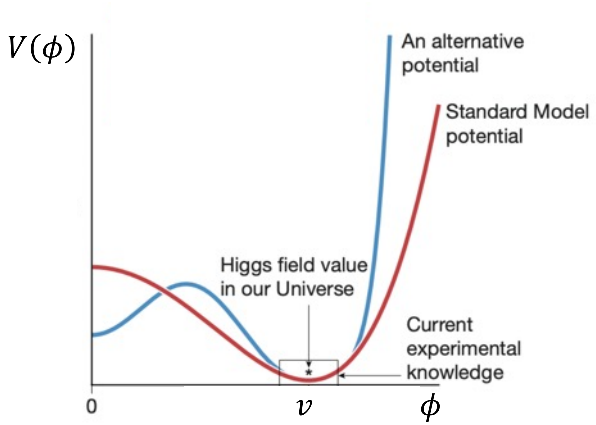
non-zero curvature defines Higgs mass

non-zero 3rd derivative implies trilinear self-interaction

non-zero 4th derivative implies quartic self-interaction

Observing trilinear (and quartic) self-interactions would be a direct experimental evidence for the weirdness of the underlying Higgs boson potential

Deviations from the SM Higgs boson prediction would imply a more complex potential form



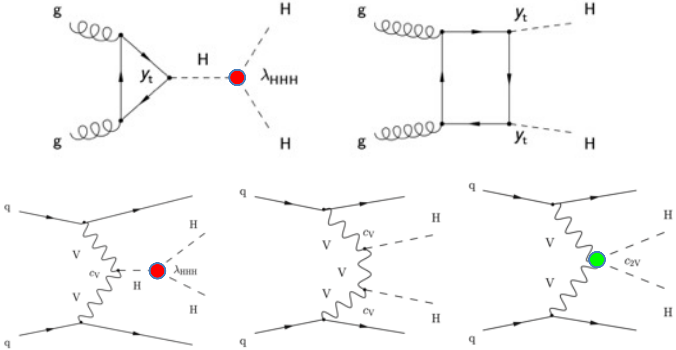
NB: for BEH mechanism to work, all one needs is a potential that takes minimum at non-zero field

Search for HH production

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

Three most sensitive decay modes:

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

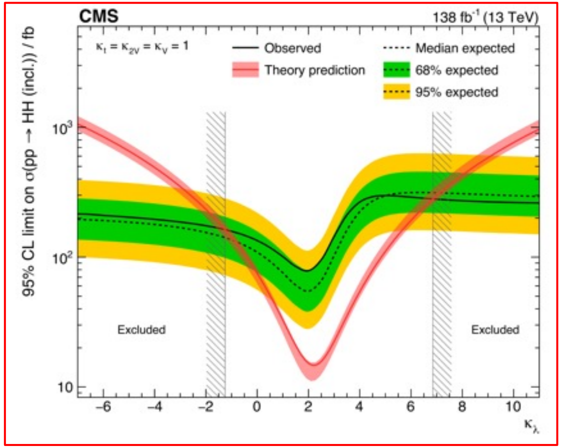


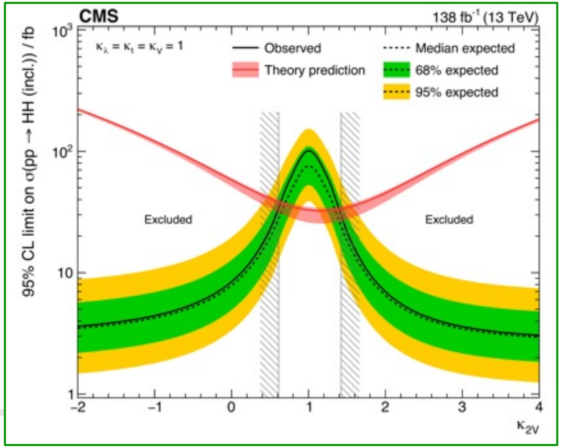
Production modes tags:

- VBF
- untagged (ggF)

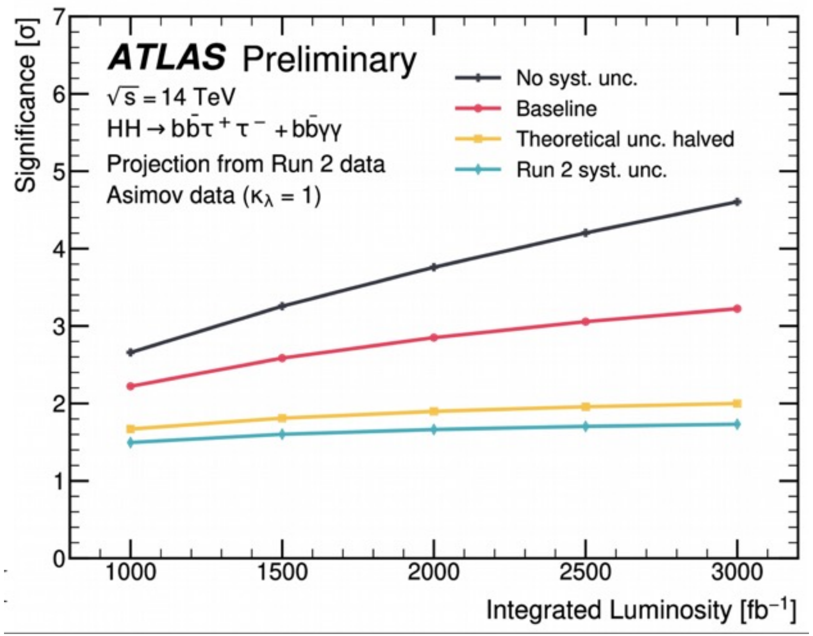
Results (95% CL limits)

- HH production signal strength **μ < 3.4**
- **HHH** coupling **$-1.2 < \kappa_\lambda < 6.5$**
- **VVHH** quartic coupling **$0.7 < \kappa_{2V} < 1.4$** (0 excluded with ~7σ!)

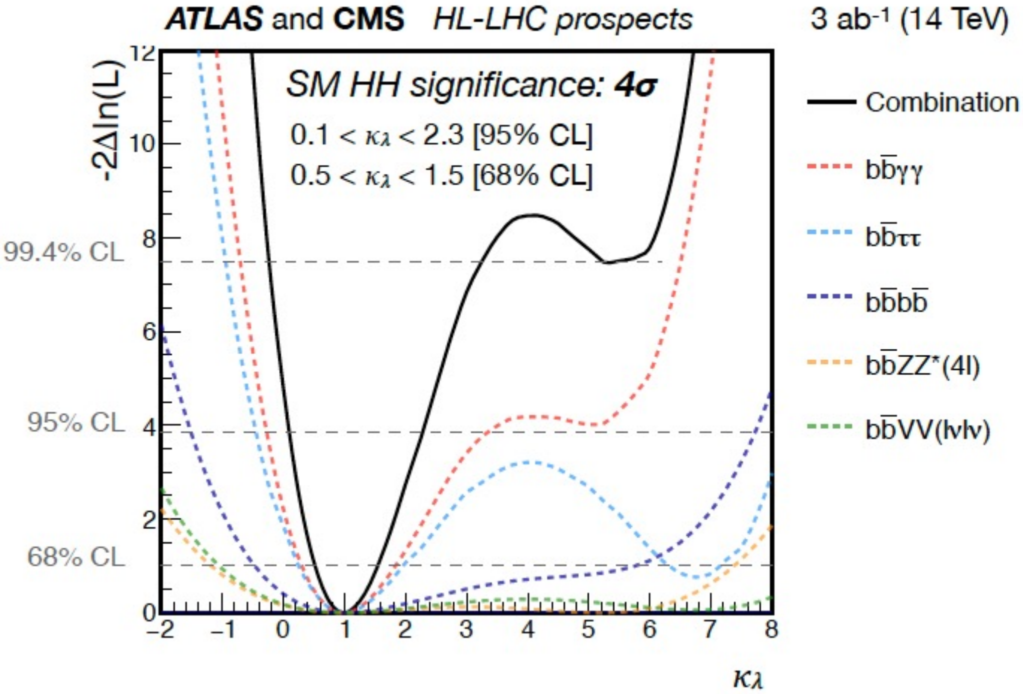




Search for HH: prospects (HL-LHC)



ATLAS + CMS: 4σ at HL-LHC



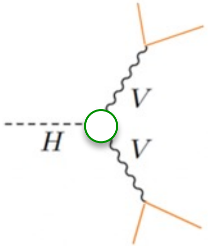
$$0.52 \le \kappa_\lambda < 1.5$$

at 95% CL

Part 1: Search for deviations from SM-like properties

- **Rates in different production and decay modes:** test of couplings to SM particles
- **Non-SM like structures in production and decay amplitudes:** spin-parity, mixed states, compositeness
- **Natural width:** can provide an indirect sign for presence of abnormal decay modes

INTRO: Higgs bosonic (V) coupling structure



Four-body decay kinematics is sensitive to the HVV coupling structure.

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

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

This term vanishes for $\gamma\gamma$

dim-5 operators: must be 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, $\boldsymbol{a_2} \sim O(10^{-2})$ [it is actually the lowest-order term for $H \rightarrow \gamma\gamma$]

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

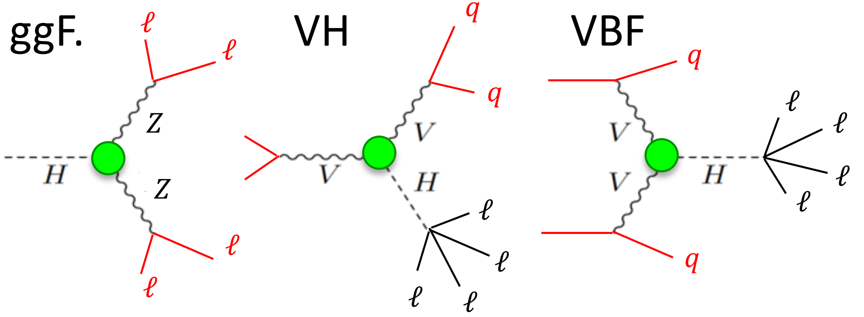
The $\boldsymbol{a_4}$ term is is yet another CP-even distinct operator. In SM, $\sim O(10^{-2})$

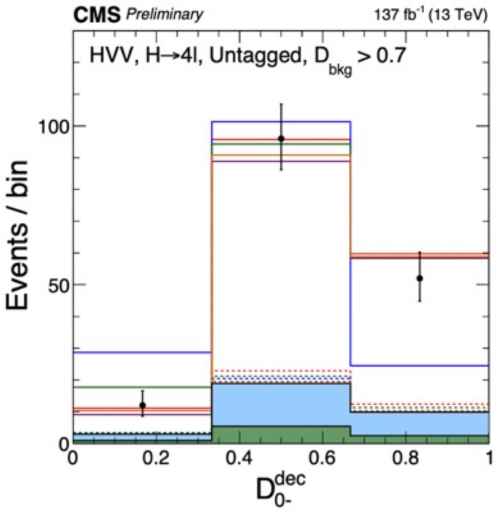
The $\boldsymbol{a_5}$ term is experimentally indistinguishable from SM in on-shell studies (important for off-shell)

Higgs bosonic (V) coupling structure

Analysis:

- decay channel: H→ZZ→4l
- target the **three main production modes**
- W and ZZ couplings a_i^{WW} and a_i^{ZZ} are related via custodial and SU(2)xSU(1) symmetries:
  - $a_1^{WW} = a_1^{ZZ}$
  - $a_2^{WW} = \cos^2\theta_W\, a_2^{ZZ} + \cdots\ (negligible)$
  - $a_3^{WW} = \cos^2\theta_W\, a_3^{ZZ} + \cdots\ (negligible)$
  - …
- 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: $\alpha = 0$

MSSM: $\alpha \approx 0$

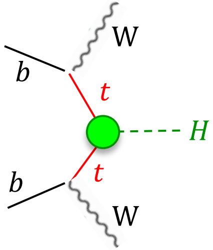
nMSSM: α can be large

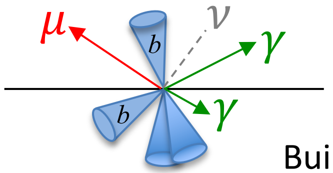
Higgs CP-odd admixture: ttH

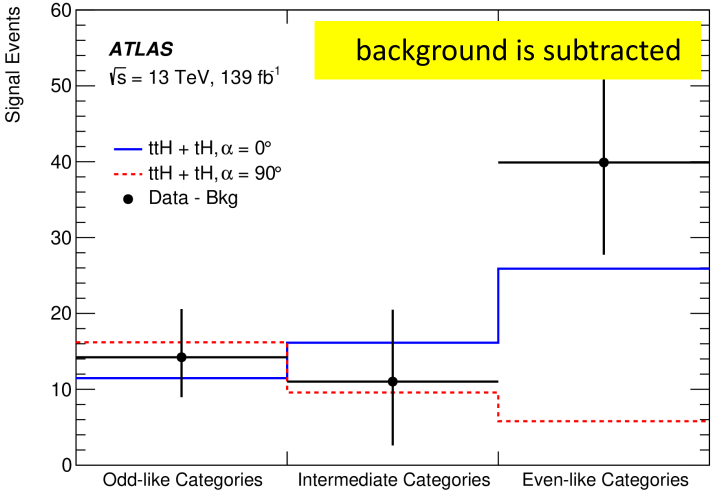
Final states used:

$pp \to tt\boldsymbol{H} \to (jjb)(jjb)(\boldsymbol{\gamma\gamma})$ [all-hadronic]

$pp \to tt\boldsymbol{H} \to (l\nu b)(jjb)(\boldsymbol{\gamma\gamma})$ [semi-leptonic]







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

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

	CMS [Run 2]	ATLAS [Run 2]
Purely CP-odd ttH coupling is disfavored at	**3.7σ**	**3.9σ**
limit on α	$\lvert\alpha\rvert < 60°$	$\lvert\alpha\rvert < 43°$

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

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

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

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

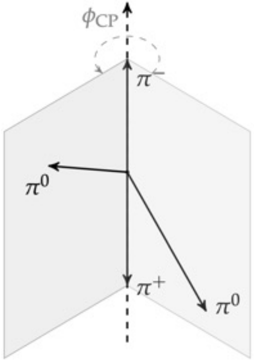
$\rightarrow \rho^\pm \nu \rightarrow \pi^\pm \pi^0 \nu\ (26\%)$

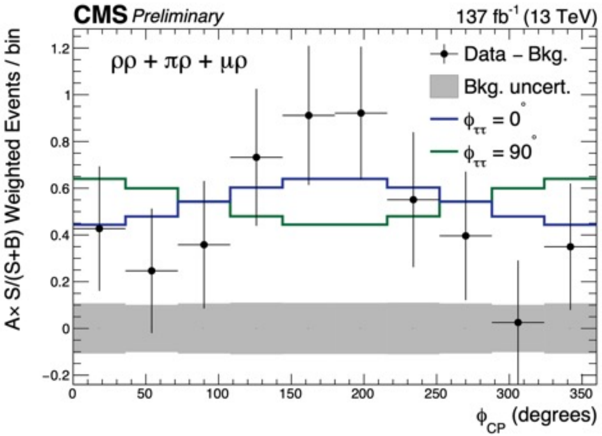
$\rightarrow a_1^\pm \nu \rightarrow \pi^\pm \pi^0 \pi^0 \nu\ (10\%)$

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

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**

Limit on α: $|\alpha| < 36°$

Part 1: Searches for deviations from SM-like properties

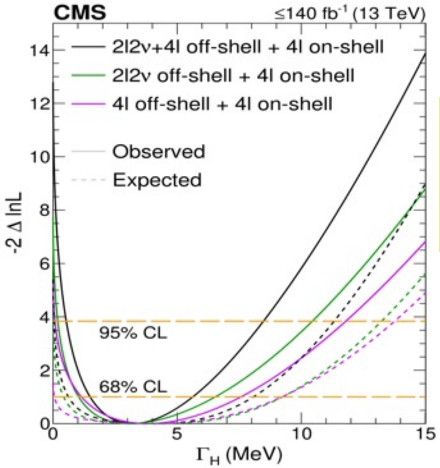
- **Rates in different production and decay modes:** test of couplings to SM particles
- **Non-SM like structures in production and decay amplitudes:** spin-parity, mixed states, compositeness
- **Natural width:** can provide an indirect sign for presence of abnormal decay modes

Natural width

From the ratio of off-shell to on-shell rates using $H \to ZZ \to 2\ell 2\nu$ and $H \to ZZ \to 4\ell$

And assuming:

- SM-like amplitude structure for $H \to ZZ$
- 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)*



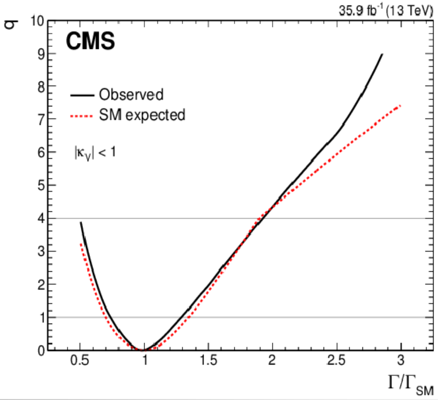
$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV}$$

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 Higgs couplings
- $|\kappa_W|, |\kappa_Z| \leq 1$ *(fair, as it is hard to build a self-consistent theory violating these conditions)*



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

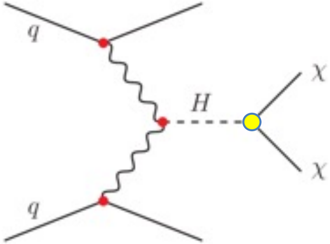
Part 2: abnormal decay/production modes

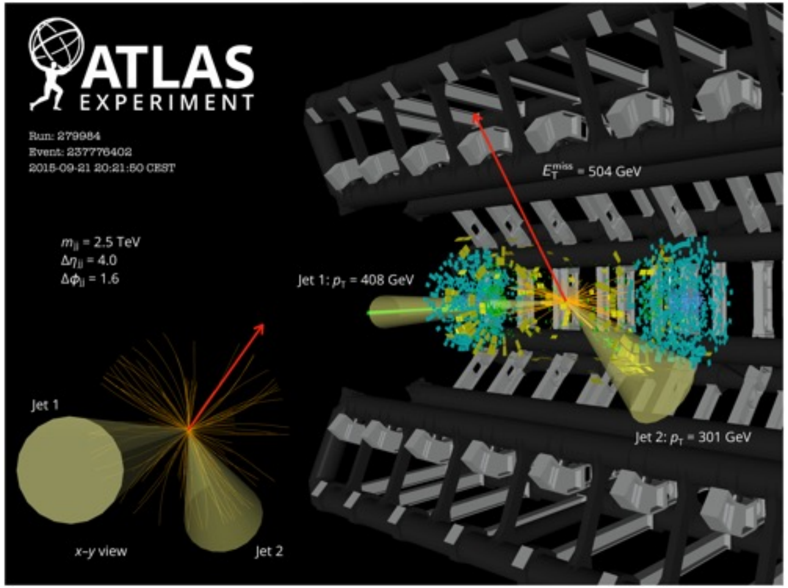
Search for H → invisible

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

Signature:

- VBF jets
- MET

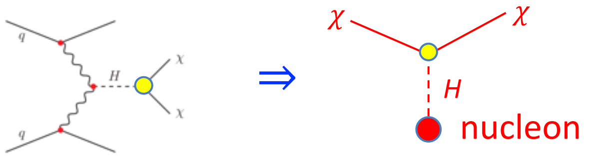




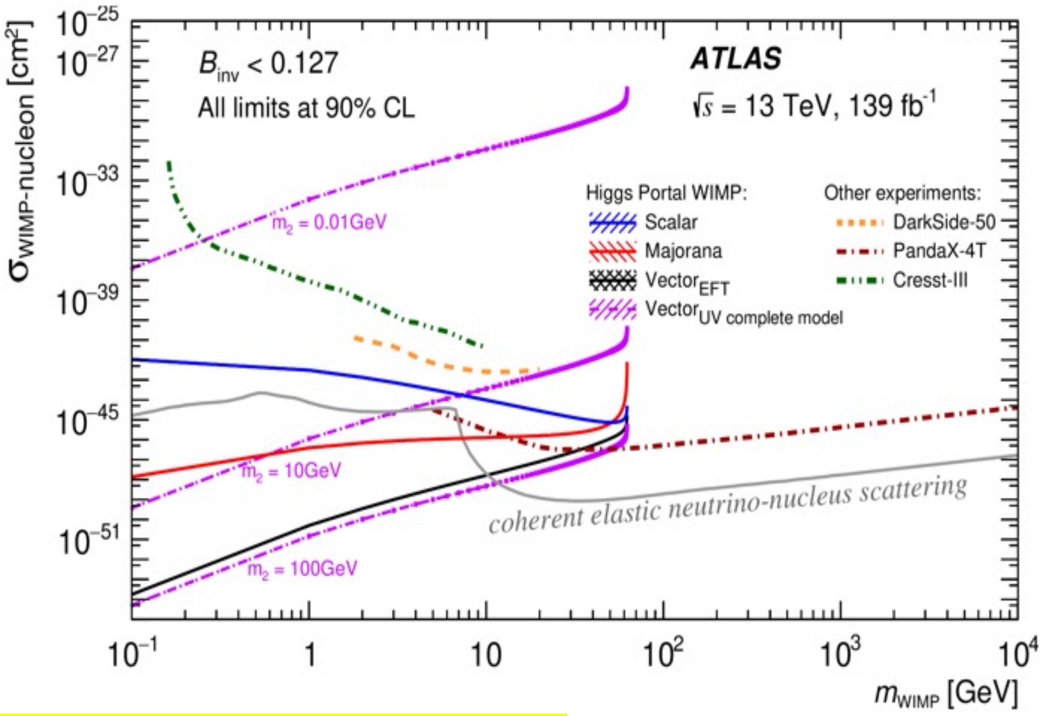
ATLAS: B(H→inv) < 0.15 at 95% CL (expected 0.10)
CMS: B(H→inv) < 0.18 at 95% CL (expected 0.10)

Search for H → invisible

Reinterpretation



$B(H \to \chi\chi)$ ⇒ χ-nucleon σ



If DM is due to WIMPs that are lighter than $m_H/2$ and couple to Higgs boson, LHC provides stronger limits on DM than non-accelerator DM searches

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

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

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

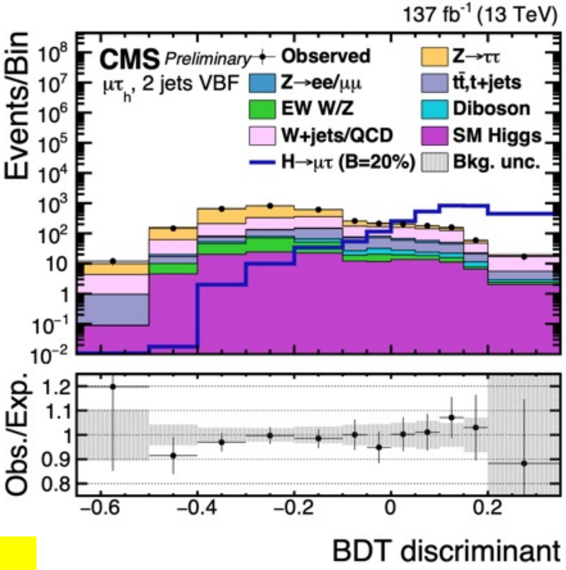
Very similar to the "nominal" $H \to \tau\tau$ analysis, except that ***muons***

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

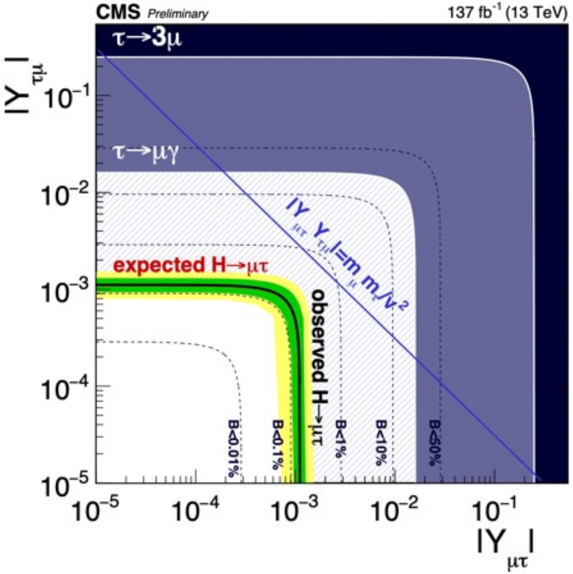
BDT is used to separate signal from non-Higgs bkg and $H \to \tau\tau$

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

If searched-for CLF violating decays $\tau \to 3\mu/\mu\gamma$ are mediated via Higgs boson, LHC gives the most stringent limits



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

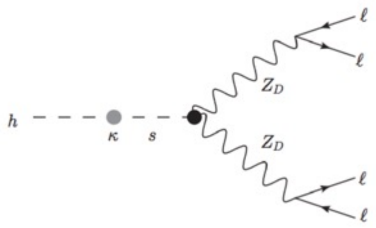


Limits on off-diagonal Yukawa couplings $Y_{\mu\tau}$

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

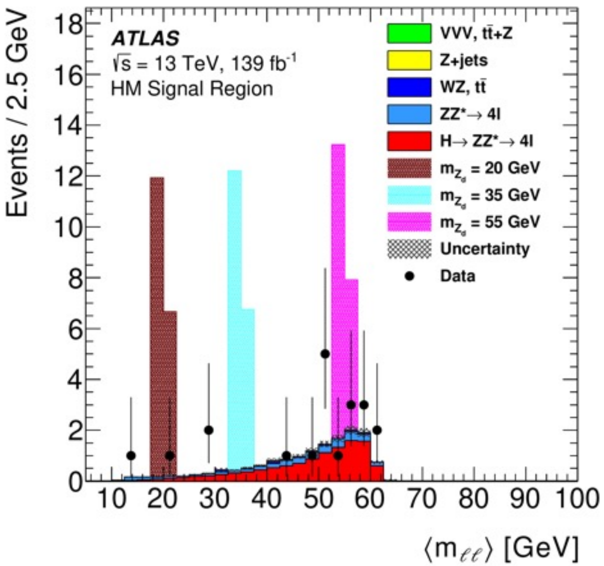
Search for low-mass dilepton resonances in H125 decays

(e.g., a pair of dark photons (Z_d), each of which decays pairs of leptons)

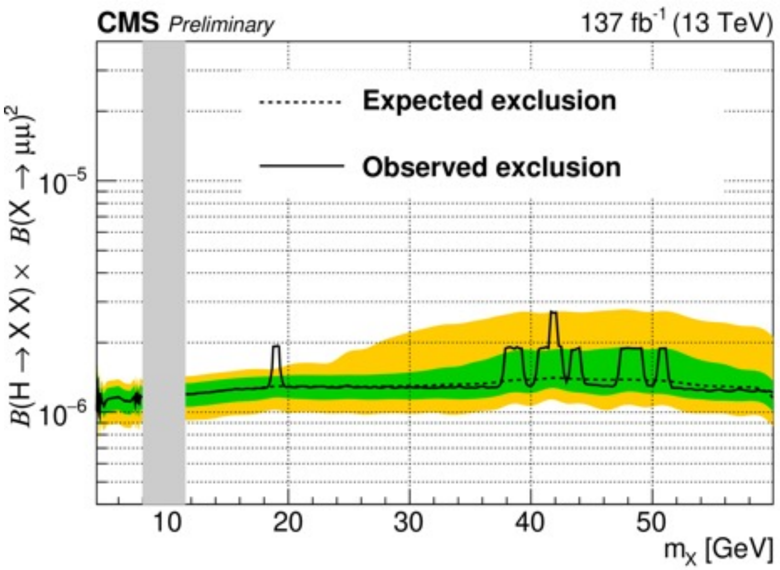


Analysis:

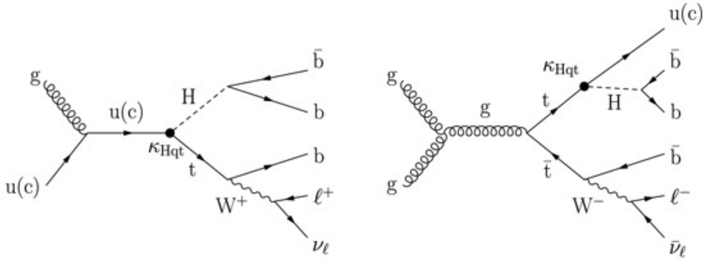
- Two pairs of prompt isolated leptons
- $m_{12} \sim m_{34}$
- $m_{4l} \sim m_H$

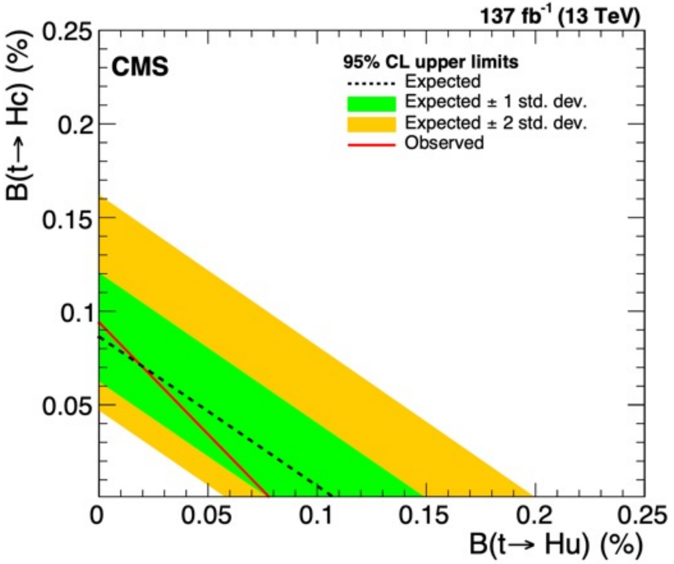


model independent limits on $\sigma \times \mathcal{B}$



Search for FCNC tqH coupling (e.g., t→qH)





Search:

- consider **ttH** and **tH** production
- *H → bb*
- *t →* b(*lv)*

Since top is very heavy, this coupling is not much constraint by studies if FCNC decays in light meson systems

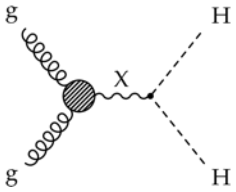
ttH: some weak distinction between t->Hu and t->Hc

tH: no experimental distinction between tuH and tcH couplings

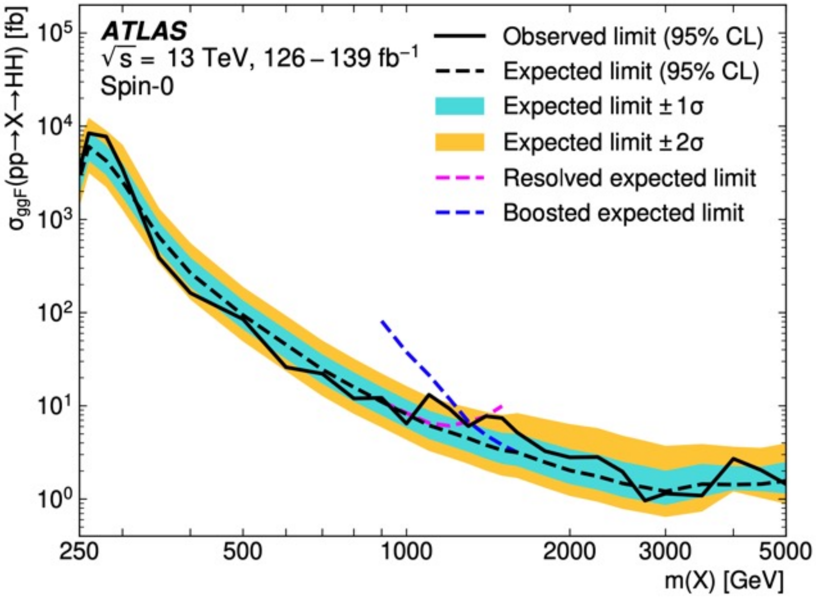
$$B(t \rightarrow qH) < 0.1\%$$

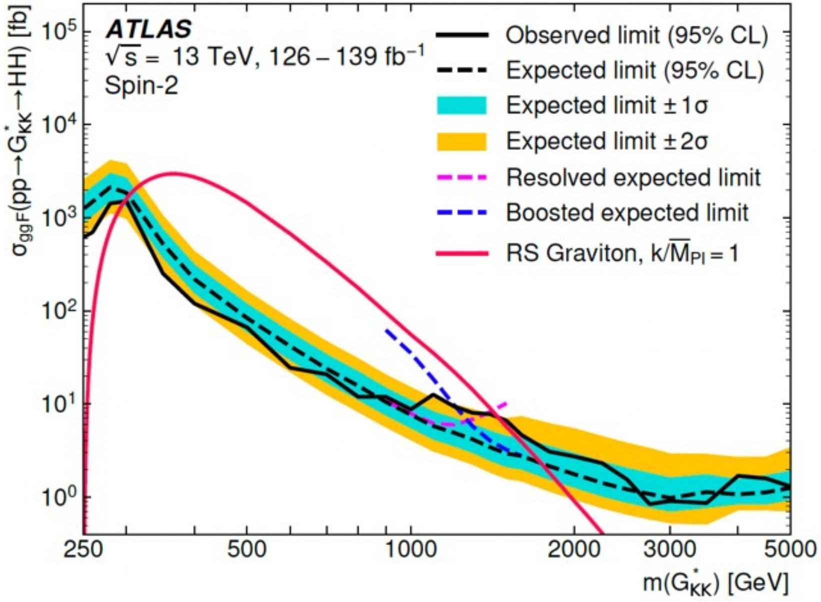
Most sensitive result thus far

Search for $X \to HH$



$\mathbf{X \to HH \to (}\boldsymbol{bb}\mathbf{)(}\boldsymbol{bb}\mathbf{)}$: Best results for m(X)>400 GeV





Part 3: Searches for other scalars – why not?

And there are plenty of theoretical motivations!

Model	What is it good for?	Higgs bosons
SM (one doublet of complex scalar fields)	3 d.o.f. give mass to $W^\pm$ and Z bosons Yukawa couplings generate fermion masses	h
SM + real singlet	attractive in the context of DM, EWK baryogenesis, …	h, H
SM + 2nd doublet (2HDM) e.g., MSSM	prerequisite for SUSY natural in Grand Unifying Theories additional source of CP violation DM originating directly from 2HDM	h, H, A, $H^\pm$
2HDM + complex singlet e.g., nMSSM	resolves the μ-problem in MSSM h(125) is unnaturally heavy in MSSM – not in nMSSM	h_1, h_2, h_3, a_1, a_2, $H^\pm$
SM + triplet	gives a natural explanation for small neutrino masses	h, H, A, $H^\pm$, $H^{\pm\pm}$

Searches for other scalars…

Lots of them at LHC (and elsewhere!)

To cover this domain would require a whole other seminar

In brief, all searches have come back with null results
(indeed, otherwise, you would certainly already know!)

We will keep digging and sifting…

Summary

Run 2: current status

- The discovered Higgs boson
  - **mass = 125.38 ± 0.14 GeV** (best measurement thus far; not yet final from Run 2)
  - **deviations from SM Higgs boson properties – null results**
    - **must keep looking**: the discovery of CP-violation in the Kaon system is a lesson!
    - **emerging challenge:** experimental uncertainties in some measurements approach the accuracy of theoretical predictions
- Searches for **explicitly abnormal decay/production** modes – **null results**
- Searches for **additional scalars** – **null results**

Run 2: more results are still to come: in particular, ATLAS+CMS combinations

Run 3 (2022-2024):

- expect to triple statistics of the current dataset
- and ATLAS and CMS are even more capable detectors in Run 3 than before!