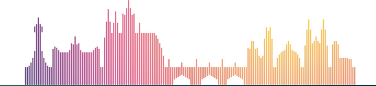
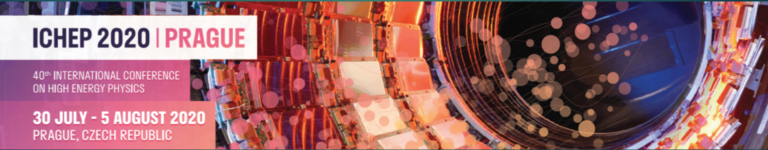


LHC Higgs Boson Experimental Overview

CHRISTOPHER PALMER (HE, HIM, HIS) (PRINCETON UNIVERSITY/FNAL, CMS)

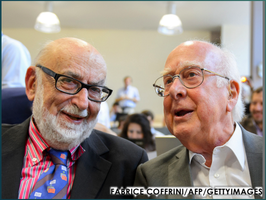
ON BEHALF OF THE CMS AND ATLAS COLLABORATIONS

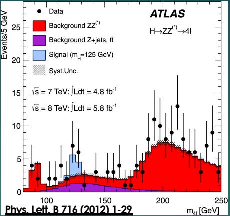
AUGUST 3RD, 2020

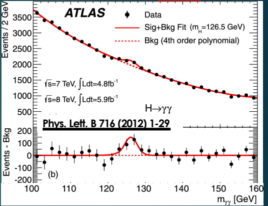


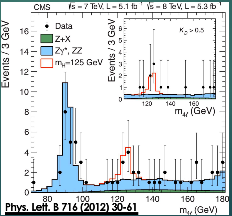
8 years ago…

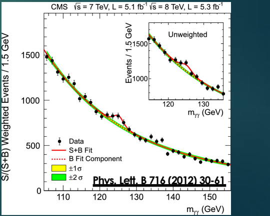
- ATLAS and CMS both first observed the Higgs boson.
  - Theorized in summer of 1964
  - Francois Englert and Peter Higgs were awarded the 2013 Nobel Prize in physics for this prediction.





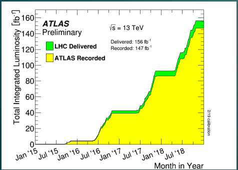


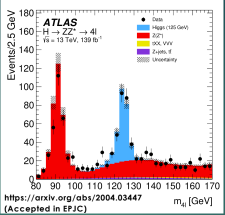


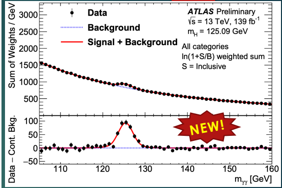


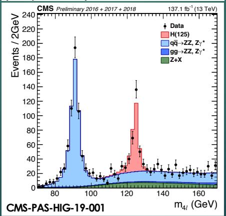
Full LHC Run 2

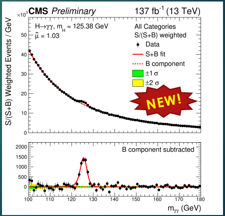
- With LHC's exceptional performance from 2015-2018 each experiment has ~140/fb of proton-proton collision data at 13 TeV, from which to harvest Higgs bosons!
  - LHC operated at twice design (!) luminosity in 2018!
  - Very impressive! Thank you LHC!





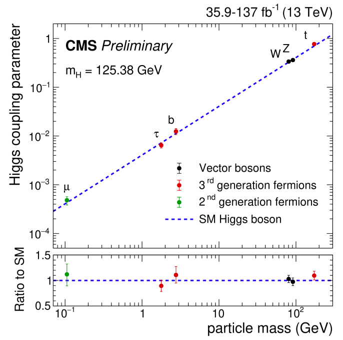






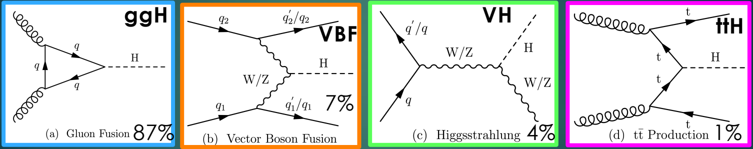
Overview

- Review of the new SM Higgs boson measurements shown at ICHEP 2020
  - Start at the largest coupling
  - End with the first evidence of second generation coupling (H→μμ in CMS)
- A few words on HH and self-coupling
- Sample of new BSM searches



Simplified Template Cross Section (STXS)

- ATLAS, CMS and the theory community have been working together in the LHC Higgs Working Group to setup a common framework for Higgs boson measurements in Run 2.
  - Reduce theory uncertainty and model dependence on measured bins
  - Each Higgs boson production mode is split into numerous templates by kinematic features that are highly correlated with reconstruction-level objects.



p_T (H)	Njets	p_T (V)	p_T (H)
Njets	Mjj, p_T(H+jj) (if Njets>1)	Njets	
Mjj, p_T(H+jj) (if Njets>1, VBF-like)	p_T (H)		

H→γγ Analysis Strategies

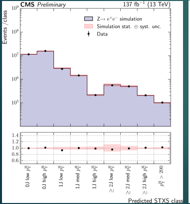
DOUBLE NEW!

- The di-photon signal is very well reconstructed and triggerable because of the precision of the CMS and ATLAS electromagnetic calorimeters.
  - Pre-select events with two isolated photon candidates
- Since this Higgs decay signature directly anchors the trigger and reconstruction, both experiments can probe all four of the production channels (and single top+Higgs production too!).
  - Identify isolated electrons and muons as well as jets with minimally sufficient p_T.

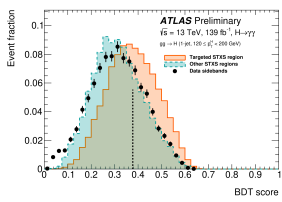
ATLAS-CONF-2020-026

CMS-PAS-HIG-19-015

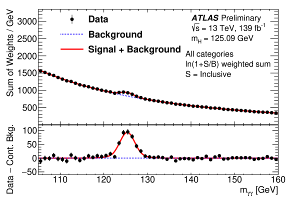
Classify



Optimize categories per class



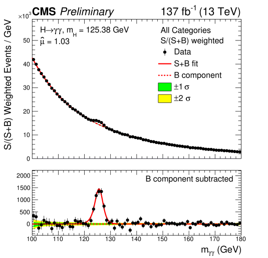
Fit the data per category



H→γγ Overall Results

DOUBLE NEW!

- Assuming SM coupling and excluding theory uncertainties both experiments achieve about 8% uncertainty on the signal strength of H→γγ production.



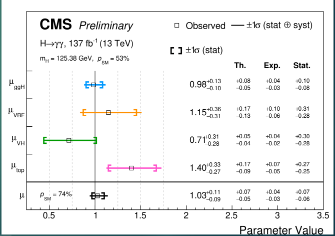
ATLAS

$$(\sigma \times B_{\gamma\gamma})_{\text{obs}} = 127 \pm 10\,\text{fb} = 127 \pm 7\,(\text{stat.}) \pm 7\,(\text{syst.})\,\text{fb}$$

$$(\sigma \times B_{\gamma\gamma})_{\text{exp}} = 116 \pm 5\,\text{fb}$$

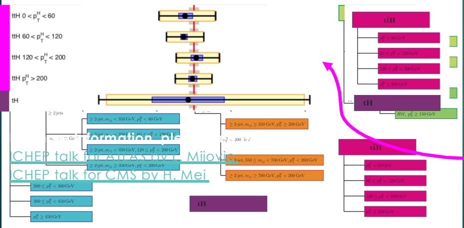
CMS

$$\mu = 1.03^{+0.11}_{-0.09} = 1.03^{+0.07}_{-0.05}\,(\text{theo})^{+0.04}_{-0.03}\,(\text{syst})^{+0.07}_{-0.06}\,(\text{stat})$$



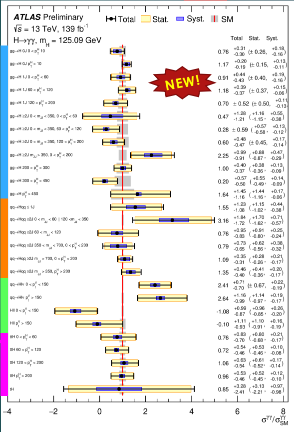
ATLAS H→γγ STXS Results

- With such large datasets and signal yields, we are measuring the Higgs boson's kinematics differentially.
- From 44 target bins, 27 merged bins are measured.
- CMS has similar results.
- Compatibility with SM p-value 60%.



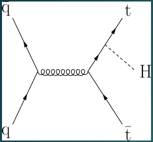
[ICHEP talk for ATLAS by L. Mijovic](#)

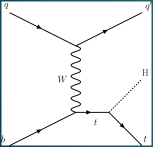
[ICHEP talk for CMS by H. Mei](#)



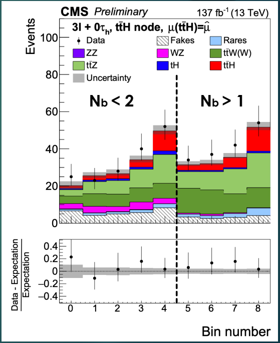
ttH MultiLepton, CMS

NEW!





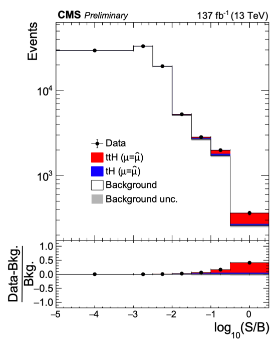
- Higgs decays of H→WW, H→ZZ and H→ττ with 2-4 leptons (e, μ, τ_{Hadron}) are targeted.
  - In both ttH and tH production
- Number of jets and b-jets are used for further categorization.
- BDTs and ANNs are used to separate signal from background in these categories.



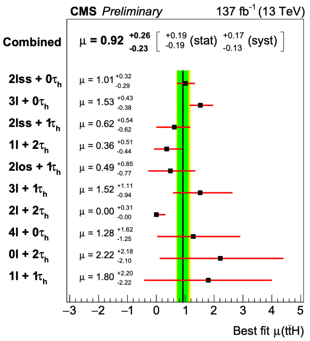
ICHEP talk by S. Sanchez Cruz   HIG-19-008

ttH MultiLepton, CMS

NEW!



- Key backgrounds are freely-floated in the full fit.
  - All are quite in agreement with simulation expectations
- Results for ttH are also very much in agreement with the SM expectations.



VBF, H→WW, ATLAS

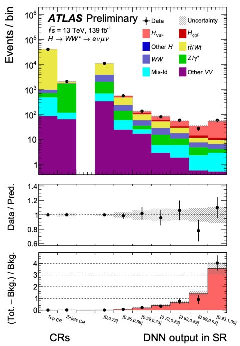
- This analysis is anchored in an electron-muon pair arriving from the leptonic decays of 2Ws.
- VBF topology is ensured by requiring that there are at least two jets and that the di-jet mass is greater than 120 GeV.
- Controls regions employed/fit to constrain normalization
  - Z+jets
  - Top quark
- A DNN is utilized to isolate VBF signal process
  - This is a major improvement to the analysis

Observed (exp) significance **7.0σ** (6.2σ)

$$\mu_{\mathrm{VBF}} = 1.04 \,^{+0.24}_{-0.20}$$

$$^{+0.13}_{-0.12}\ (\text{stat.})\ ^{+0.09}_{-0.08}\ (\text{exp syst.})\ ^{+0.17}_{-0.12}\ (\text{sig. theo.})\ ^{+0.08}_{-0.07}\ (\text{bkg. theo.}).$$

ICHEP talk by L. Mijovic ATLAS-CONF-2020-045

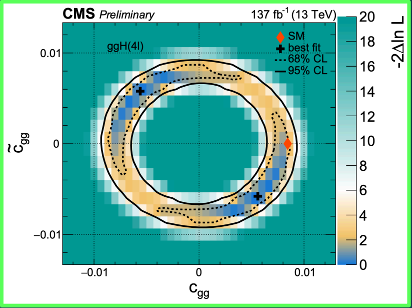


H→ZZ→4l Anomalous Couplings, CMS

NEW!

- New results from CMS take advantage of:
  - Full Higgs decay information in ZZ4l (angular distributions)
  - Full Run 2 dataset
- Results interpreted as both
  - Anomalous amplitude couplings
  - **Effective Field Theory**
- **Anomalous couplings to gluons**
  - **Compatible with SM**

$$\frac{h}{v}\tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}$$



$$\frac{h}{v}c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^a_{\mu\nu}$$

ICHEP talk by S. Kyriacou

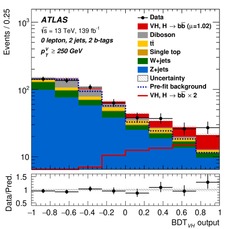
HIG-19-009

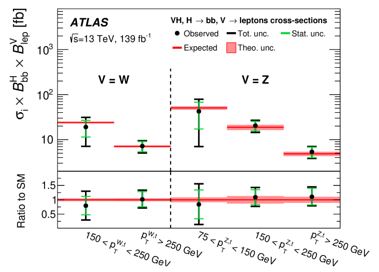
V(leptonic)H→bb, ATLAS

- Trigger and categorize on the leptonic decay products of W/Z
- Isolate signal regions requiring two b-jets and train BDTs in all signal regions.
  - Fit together with numerous control regions targeting background processes.

	Obs	Exp
WH	4.0σ	4.1σ
ZH	5.3σ	5.1σ

Total signal strength		
	Tot.	(Stat., Syst.)
1.02	$^{+0.18}_{-0.17}$	($^{+0.12}_{-0.11}$, $^{+0.14}_{-0.13}$)





ICHEP talk by M. Battaglia   HIGG-2018-51

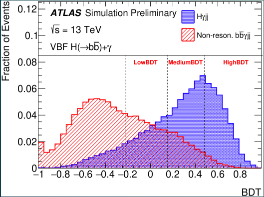
VBF+γ H→bb, ATLAS

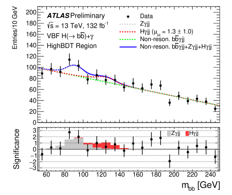
NEW!

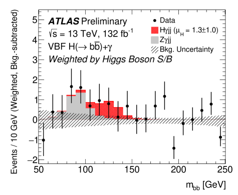
- The Hγ final state is forbidden in ggH and so it provides an opportunity to measure other production modes without contamination given enough data.
- This analysis requires a high pT photon at the level1 trigger and then 4 jets (E_T>35 GeV) at the high level trigger.
  - At least two of these jets must have large (>700 GeV) invariant di-jet mass.
- Final selection also include lepton vetoes and two b-jets.
- A BDT is used to categorize events, while background is estimated in a fit to the data.
- Uncertainty dominated by statistics (~0.8), bkg norm (~0.5) and spurious signal (~0.25).

μ_H = 1.3±1.0

Obs (exp) 1.3σ (1.0σ)





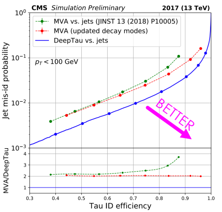


ICHEP talk by M. Battaglia

ATLAS-CONF-2020-044

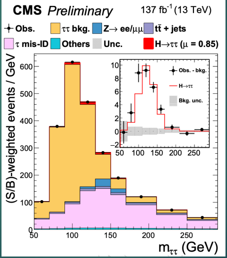
H→ττ, CMS

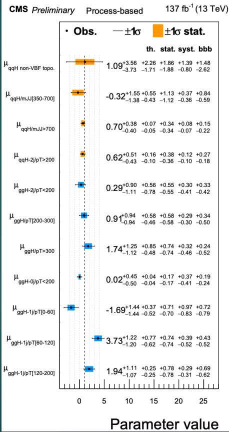
- Multiple decay channels are considered in this cut-based analysis.
  - eμ, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ in ggH and VBF
- DeepTau ID provided better efficiency and lower fake rates in the updated analysis



NEW!

- Tau embedding in Z→μμ data events critical to Z→ττ estimates
  - Replace real μ with simulated tau





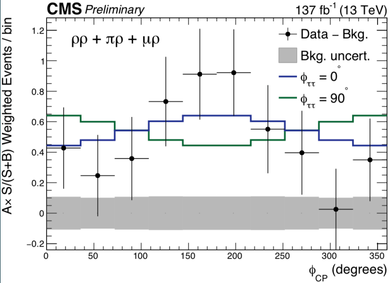
ICHEP talk by D. Winterbottom HIG-19-010 DP2019-033

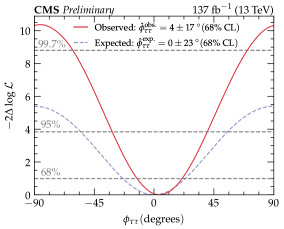
H→ττ - CP Violation Search Results

NEW!

$$\tan\phi_{\tau\tau} = \frac{\tilde{\kappa}_\tau}{\kappa_\tau} = \frac{CP\ odd}{CP\ even\ (SM)}$$

$$\phi_{\tau\tau} = (4 \pm 17\,(\text{stat}) \pm 2(\text{bin-by-bin}) \pm 1\,(\text{syst}) \pm 1(\text{theory}))^\circ$$





Pure CP-odd H→ττ are excluded at more that 3 sigma C.L

ICHEP poster by M. Hassanshahi HIG-20-006

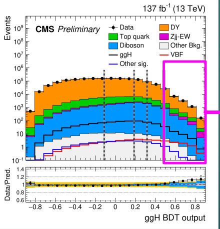
H→μμ, CMS and ATLAS

DOUBLE NEW!

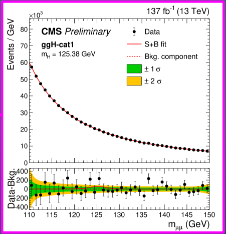
- Select events with two well-isolated opposite-signed muons.
- Classify events on the topology of the production modes.
  - ggH, VBF, VH and ttH are targeted by both collaborations.
  - VBF, VH, and ttH topologies are new features in both analyses.

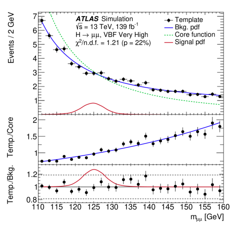
- This is the analysis strategy for all ATLAS categories and for CMS in ggH, VH, and ttH.
  - VBF in CMS has separate treatment.

Isolate signal with binary BDT or DNN output



Extract signal strength and background shape in fit to data

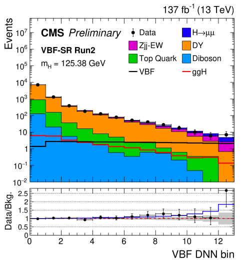




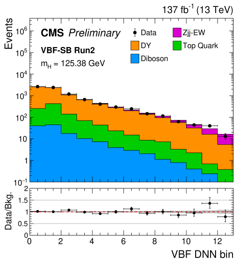
VBF H→μμ in CMS

- Unlike all other analysis regions, the uncertainty on the prediction of **background from simulation is better** than the estimate from directly fitting the data.
  - **Sensitivity increases by ~20%**
- Uncertainties on Drell-Yan (amc@NLO) and electroweak Z+di-jet (MadGraph+herwig) simulation
  - Normalization motivated by theory
    - Substantiated by CMS SM precision measurements
    - EPJC 78 (Jul. 2018) 589
  - Shape differences from:
    - Different parton showering simulations

Signal Region (SR): Mμμ in [115,135]



Sidebands (SB): Mμμ in [110,115] or (135,150]

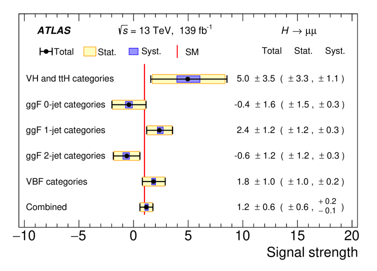


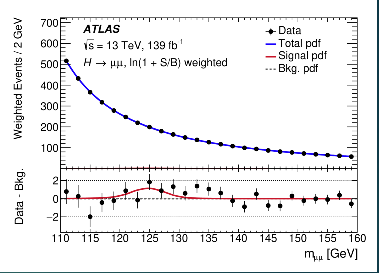
H→μμ - ATLAS Results

NEW!

μ=1.2 ± 0.6

- At mH = 125.09 GeV, ATLAS reports an observed (expected) excess with a significance of 2.0σ (1.7σ).





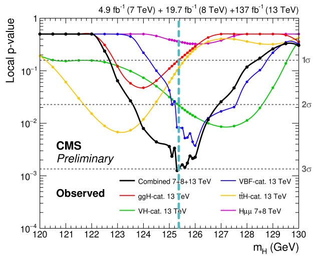
ICHEP talk by H. Borecka-Bielska ATLAS-HIGG-2019-14 https://arxiv.org/abs/2007.07830

H→μμ - CMS

First evidence of H→μμ process!

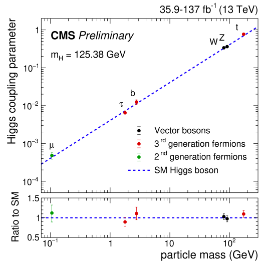
- CMS observes (expects) 3.0σ (2.5σ) at 125.38 GeV
  - Including the Run 1 analysis in the combination increased significance 1% on expected and observed.

$$\mu = 1.19^{+0.41}_{-0.39}(\text{stat})^{+0.17}_{-0.16}(\text{sys})$$



$$y_F = \kappa_F \frac{m_F}{v}$$

$$y_V = \sqrt{\kappa_V}\frac{m_V}{v}$$



Updated Combination, ATLAS

NEW!

✓ Included, will full Run 2 dataset (139 fb^{-1})
(✓) Included with 2015-2016 data only

	ZZ→4l	γγ	bb	μμ	ττ	WW	multi-lep	inv
ggF	✓	✓		✓	(✓)	(✓)		
VBF	✓	✓	(✓)	✓	(✓)	(✓)		✓
WH	✓	✓	✓	✓				
ZH	✓	✓	✓	✓				
ttH	✓	✓	(✓)	✓			(✓)	
tH		✓						

ICHEP talk by M. Klein ATLAS-CONF-2020-027

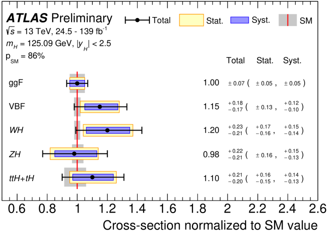
$$\mu = 1.06 \pm 0.07$$

Overall signal strength

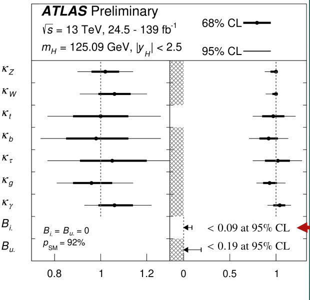
$$1.06 \pm 0.04\,(\text{stat.}) \pm 0.03\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.})$$

	Obs	Exp
WH	6.3σ	5.2σ
ZH	5.0σ	5.4σ

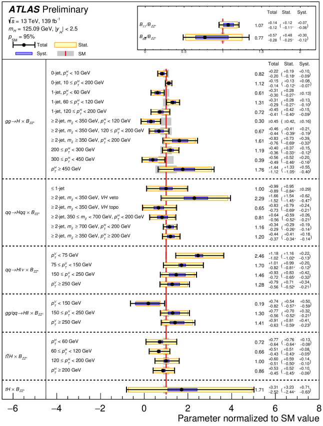
- 29 merged STXS bins
- Floating SM coupling fits (kappa-framework)
- Limits on BSM
- First observation of WH!
- Constraints of two-Higgs-doublet models in the ($\cos(\beta - \alpha)$, $\tan\beta$) plane for the



Very compatible with SM



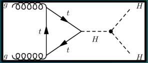
VBF+MET alone constrains BR(H→inv) < 0.13 at 95% CL

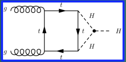


Self-coupling with HH+H (best κ_λ)

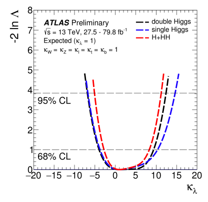
- The future of the LHC Higgs program is probing the Higgs potential.
  - That future is now!
- Right now we constrain $\kappa_\lambda = \lambda/\lambda_{SM}$ with:
  - **Double Higgs searches**
  - **Single Higgs searches**

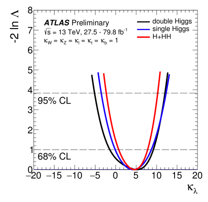
Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (excluding $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau^+\tau^-$	36.1
VH, $H \to b\bar{b}$	79.8
$t\bar{t}H$, $H \to b\bar{b}$	36.1
$t\bar{t}H$, $H \to$ multilepton	36.1
$HH \to b\bar{b}b\bar{b}$	27.5
$HH \to b\bar{b}\tau^+\tau^-$	36.1
$HH \to b\bar{b}\gamma\gamma$	36.1





Model	$\kappa_{\lambda}{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% CL]	
κ_λ-only	$4.6^{+3.2}_{-3.8}$	$[-2.3, 10.3]$	obs.
	$1.0^{+7.3}_{-3.8}$	$[-5.1, 11.2]$	exp.
Generic	$5.5^{+3.5}_{-5.2}$	$[-3.7, 11.5]$	obs.
	$1.0^{+7.6}_{-4.5}$	$[-6.2, 11.6]$	exp.

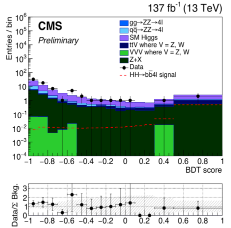


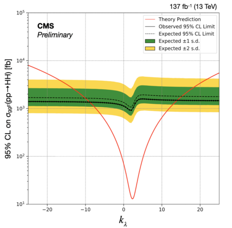


ICHEP talk by M. Swiatlowski   ATLAS-CONF-2019-049

HH→bbZZ→bb4l, CMS

- Based strongly on CMS H→ZZ→4l analysis
- Add two jets compatible with b-jets
- Cut tightly on 4l mass
- HH→bbZZ→bb4l in CMS
  - Obs at 95% CL: $-9 < k_\lambda < 14$
  - Exp at 95% CL: $-10.5 < k_\lambda < 15.5$





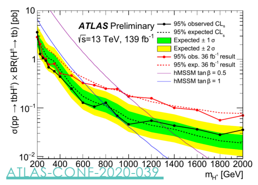
First results with this channel in the non-resonant HH search at LHC!

ICHEP talk by I. Ovtin   HIG-19-006

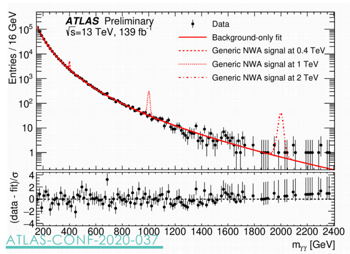
BSM Higgs

TRIPLE NEW!

- New full Run 2 ATLAS searches
  - ZZ→4l + llνν, high mass (ATLAS-CONF-2020-032)
  - γγ ,high mass (ATLAS-CONF-2020-037)
  - H^+ → tb (ATLAS-CONF-2020-039)



ATLAS-CONF-2020-039



ATLAS-CONF-2020-037

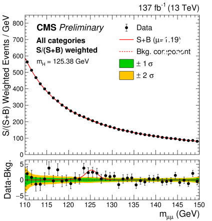
σ x BR < 3.6 pb at 95% CL (m_{H+} = 200 GeV)
σ x BR < 35 fb at 95% CL (m_{H+} = 2 TeV)

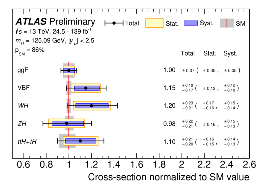
Largest deviation: 3.29σ (local) 1.3σ (global) at m_X =684 GeV
Upper limits for the narrow-width assumption: 12.5 fb (162 GeV) to 0.03 fb (3 TeV)

ICHEP talk by J. M. Lorenz

Summary

- The excellent performance of the LHC has delivered an enormous dataset, from which we are elucidating precise features of the Higgs boson.
- The lower mass particles with proportionally smaller couplings are coming into view.
  - **First evidence of H→μμ!**
  - CMS 3σ observed, ATLAS 2σ observed, μ=1.2 for both
- The global signal strength has reached a statistical precision of 4% challenging the theory error on the prediction.
- Both experiments are exploring more detailed kinematic regions sensitive to BSM effects through STXS.
- Ahead we look forward to understanding the Higgs potential itself.
  - Hoping for the unexpecting, I look forward to the future.





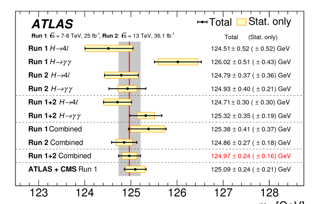
Thank you!
Be safe.
Questions?

Bibliography

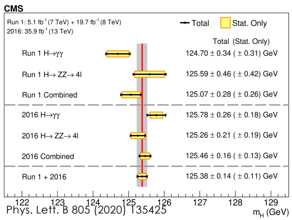
- Full Run 2 results
  - CMS, HIG-19-015, Hgg, STXS
  - ATLAS, HIGG-2018-25, Hgg, STXS
  - CMS, HIG-19-001, HZZ4l, STXS
  - ATLAS, HZZ4l, STXS
  - ATLAS, Hμμ
  - CMS, Hμμ
  - CMS, HIG-19-010, Hττ, STXS
  - CMS, HIG-20-006, Hττ, CP
  - CMS, ttH multi-lepton
  - ATLAS, VBF+γ H→bb
- HH, κλ
  - ATLAS, H+HH
- STXS
  - https://arxiv.org/abs/1906.02754 (Stage 1.1)
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGFiducialAndSTXS#Recommended_binning_Stage_1_2 (Stage 1.2)
- Higgs observation
  - **Phys. Lett. B 716 (2012) 1-29 (ATLAS)**
  - **Phys. Lett. B 716 (2012) 30-61 (CMS)**

Higgs Boson Mass Measurements

- Given the excellent resolution in the 4l and γγ channels CMS and ATLAS have both made very precise measurements of the mass.
- The Higgs mass completes the SM predictions for coupling strengths and cross sections for single Higgs boson production.



Phys. Lett. B 784 (2018) 345

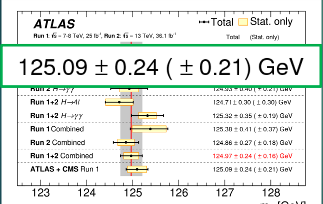


Phys. Lett. B 805 (2020) 135425

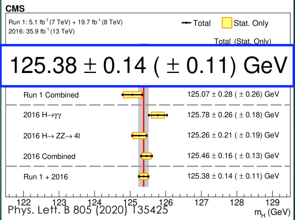
[ICHEP talk by A. Laudrain]

Standard Higgs Boson Mass Choices

- Given the excellent resolution in the 4l and γγ channels CMS and ATLAS have both made very precise measurements of the mass.
- The Higgs mass completes the SM predictions for coupling strengths and cross sections for single Higgs boson production.



Phys. Lett. B 784 (2018) 345

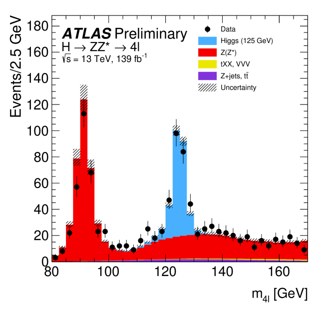


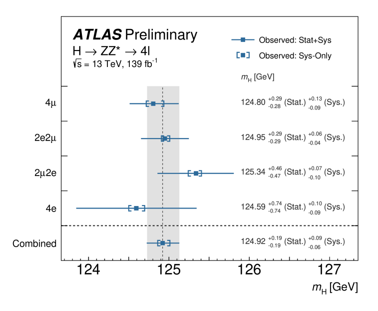
Phys. Lett. B 805 (2020) 135425

ICHEP talk by A. Laudrain

Run 2 H→ZZ→4l Mass, ATLAS

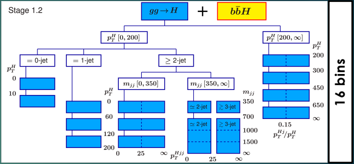
- Updated result is fully compatible with previous ATLAS results and combinations.

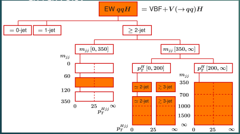


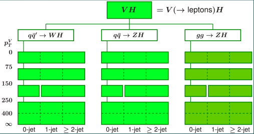


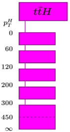
Simplified Template Cross Section (STXS)

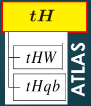
- Many target bins: 43 total bins (44 for ATLAS with tHW, tHqb)
- Some STXS signal regions are inaccessible (e.g. low yield) or too similar from some other bins.
  - These bins are left unmeasured or merged with adjacent or similar bins.
  - Merging schemes are uniquely constructed per analysis.











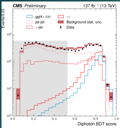
10 bins (4 rest bins)	15 bins	5 bins (+1 tH bin)

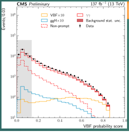
H→γγ Signal/Bkg BDTs

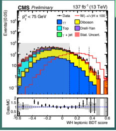
DOUBLE NEW!

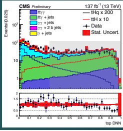
- Both collaborations train BDTs in STXS events classes.
- Further division into categories based on the score (see dashed lines below).

CMS

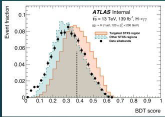


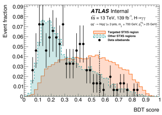


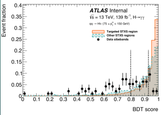


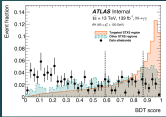


ATLAS









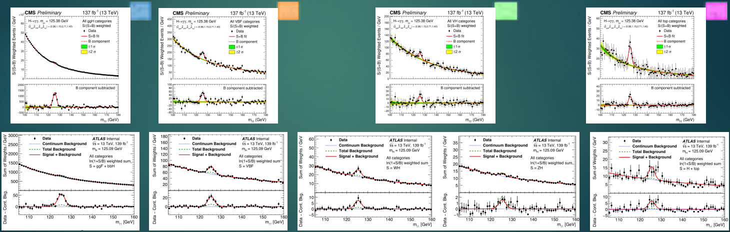
H→γγ Mass Distributions

DOUBLE NEW!

- For all categories the invariant mass distributions are then fit to extract signal and background estimates simultaneously.
- Below are the fit results with fitted signal modifiers for each production mode (~~ATLAS VH→WH+ZH~~)
- All channels in both experiments have visible excess above fitted background.

CMS

ATLAS



H→γγ Overall Results

DOUBLE NEW!

- Assuming SM coupling and excluding theory uncertainties both experiments achieve about 8% uncertainty on the signal strength of H→γγ production.

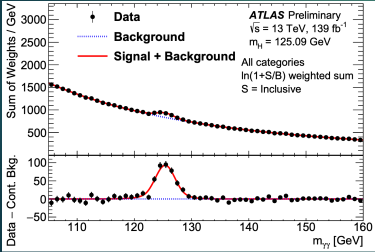
ATLAS

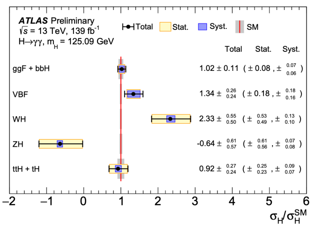
$$(\sigma \times B_{\gamma\gamma})_{\rm obs} = 127 \pm 10\,{\rm fb} = 127 \pm 7\,({\rm stat.}) \pm 7\,({\rm syst.})\,{\rm fb}$$

$$(\sigma \times B_{\gamma\gamma})_{\rm exp} = 116 \pm 5\,{\rm fb}$$

CMS

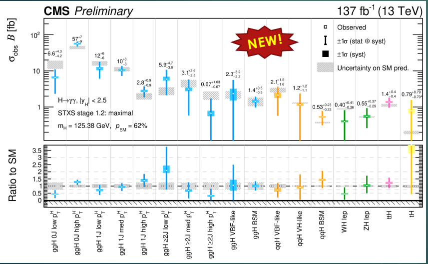
$$\mu = 1.03^{+0.11}_{-0.09} = 1.03^{+0.07}_{-0.05}\,({\rm theo})^{+0.04}_{-0.03}\,({\rm syst})^{+0.07}_{-0.06}\,({\rm stat})$$

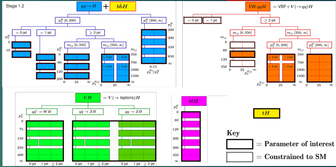




CMS H→γγ STXS Results

- Of the 43 target bins, 17 bins are measured.
  - STXS bins are merged until their expected uncertainty is less than 150% of the SM prediction.
  - Good agreement with the SM.

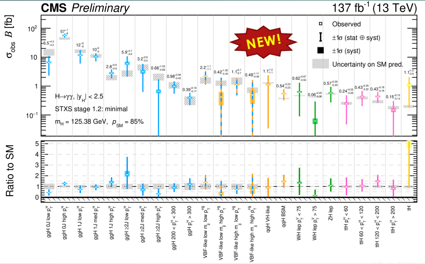


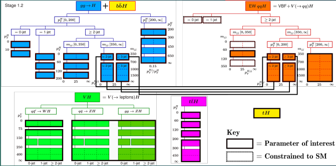


- ggH
  - Merge all 2 jet bins with mjj>350 GeV
  - Merge all bins with pT (H) > 200 GeV
- VBF
  - Reduced to three bins in total
- Only 1 bin per process for WH, ZH, ttH, and tH
- "Rest bins" of VBF fixed to SM
- Minimal splitting scheme shown in backup

CMS H→γγ STXS Results

- Of the 43 target bins, 24 bins are measured.
  - Selected by ensuring correlations among parameters is less than 0.75.
  - Good agreement with the SM.





- VBF and ggH main di-jet topology bins are measured together.
- More merging the VlepH sector
- WH pT (V) split at75 GeV
- "Rest bins" of VBF fixed to SM
- Maximal splitting scheme already shown

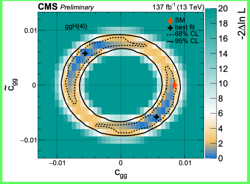
H→ZZ→4l Anomalous Couplings, CMS

NEW!

- New results from CMS take advantage of:
  - Full Higgs decay information in ZZ4l (angular distributions)
  - Full Run 2 dataset
- Results interpreted as both
  - Anomalous amplitude couplings
  - **Effective Field Theory**
- **Two dimension projection of EFT fit of coupling involving Z**

$\delta c_z, c_{zz}, c_{z\Box}$, and $\tilde{c}_{zz}$

  - **Largest difference in** δc_z
  - **Compatible with SM**

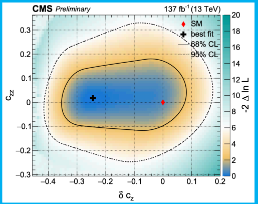


$$c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^a_{\mu\nu} \qquad \tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}$$

- **Anomalous couplings to gluons**
  - **Compatible with SM**

$$c_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}Z_{\mu\nu} \qquad \tilde{c}_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu}$$

$$(1+\delta c_z)\frac{(g^2+g'^2)v^2}{4}Z_\mu Z_\mu \qquad c_{z\Box}g^2 Z_\mu\partial_\nu Z_{\mu\nu}$$

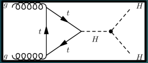


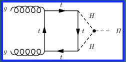
ICHEP talk by S. Kyriacou

HIG-19-009

Self-coupling with HH+H (best κ_λ)

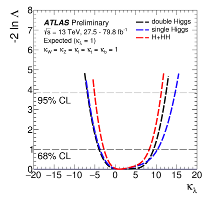
- The future of the LHC Higgs program is probing the Higgs potential.
  - That future is now!
- Right now we constrain $\kappa_\lambda = \lambda/\lambda_{SM}$ with:
  - **Double Higgs searches**
  - **Single Higgs searches**

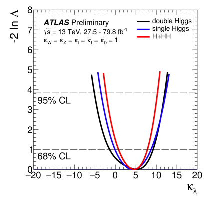




Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (excluding $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau^+\tau^-$	36.1
VH, $H \to b\bar{b}$	79.8
$t\bar{t}H$, $H \to b\bar{b}$	36.1
$t\bar{t}H$, $H \to$ multilepton	36.1
$HH \to b\bar{b}b\bar{b}$	27.5
$HH \to b\bar{b}\tau^+\tau^-$	36.1
$HH \to b\bar{b}\gamma\gamma$	36.1

Model	$\kappa_{\lambda}{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% CL]	
κ_λ-only	$4.6^{+3.2}_{-3.8}$	$[-2.3, 10.3]$	obs.
	$1.0^{+7.3}_{-3.8}$	$[-5.1, 11.2]$	exp.
Generic	$5.5^{+3.5}_{-5.2}$	$[-3.7, 11.5]$	obs.
	$1.0^{+7.6}_{-4.5}$	$[-6.2, 11.6]$	exp.





ICHEP talk by M. Swiatlowski   ATLAS-CONF-2019-049

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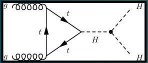
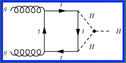
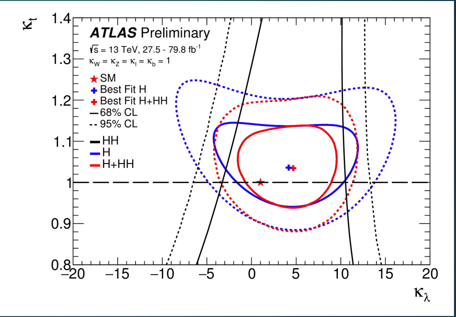
- Right now we constrain $\kappa_\lambda=\lambda/\lambda_{SM}$ with:
  - **Double Higgs searches**
  - **Single Higgs searches**





Model	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% CL]	
κ_λ-only	$4.6^{+3.2}_{-3.8}$	$[-2.3, 10.3]$	obs.
	$1.0^{+7.3}_{-3.8}$	$[-5.1, 11.2]$	exp.
Generic	$5.5^{+3.5}_{-5.2}$	$[-3.7, 11.5]$	obs.
	$1.0^{+7.6}_{-4.5}$	$[-6.2, 11.6]$	exp.



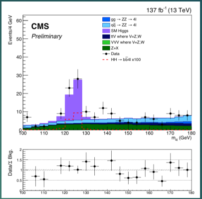
ICHEP talk by M. Swiatlowski ATLAS-CONF-2019-049

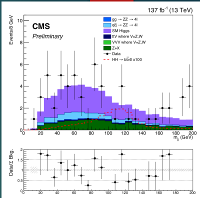
HH→bbZZ→bb4l, CMS

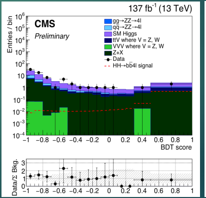
- Based strongly on CMS H→ZZ→4l analysis
- Add two jets compatible with b-jets
- Cut tightly on m4l mass

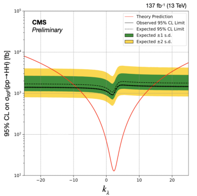
- HH→bbZZ→bb4l in CMS
  - Observed at 95% CL: $-9 < k_\lambda < 14$
  - Expected at 95% CL: $-10.5 < k_\lambda < 15.5$

First results in any non-resonant HH search in this channel at LHC!





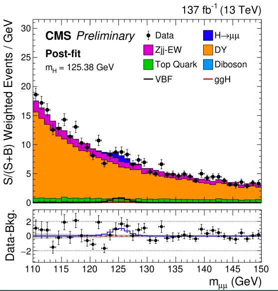


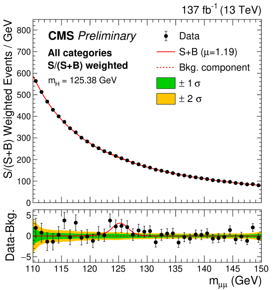


H→μμ, CMS

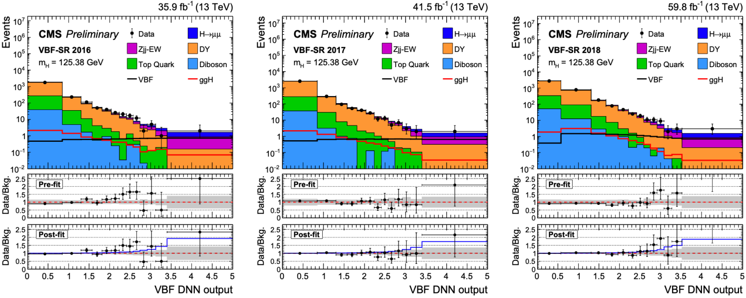
- VBF
  - Samples for Zjj-EW
    - MadGraph+Herwig simulation (nominal)
    - Madgraph+Pythia with dipole recoil ON as alternative/syst
  - In data-driven method statistical uncertainty is 60%

Uncertainty source	Δμ	
Total uncertainty	+0.44	−0.42
Statistical uncertainty	+0.41	−0.39
Total systematic uncertainty	+0.17	−0.16
Size of simulated samples	+0.07	−0.06
Total experimental uncertainty	+0.12	−0.10
Total theoretical uncertainty	+0.10	−0.11

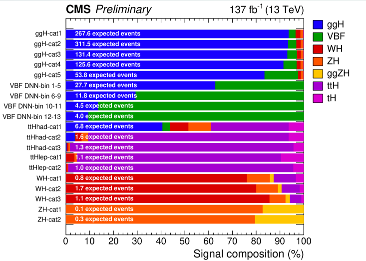


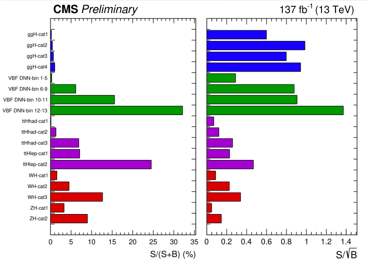


H→μμ, CMS, VBF SRs per Year

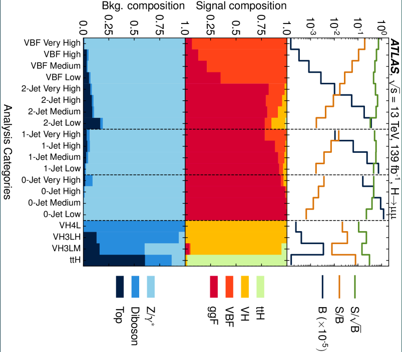


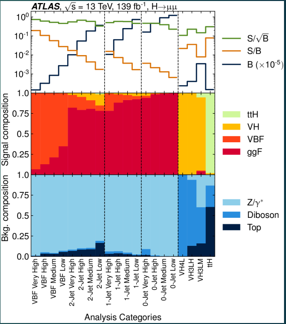
H→μμ, CMS Categories





H→μμ, ATLAS Categories





H→ττ - CP Violation Search (CMS)

NEW!

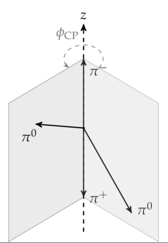
- The hypothetically allowed Yukawa couplings are:

$$\mathcal{L}_Y = -\frac{m_\tau}{v}\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau$$

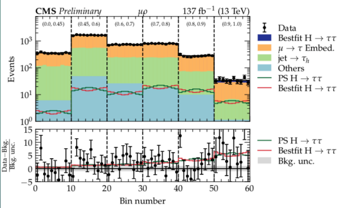
- Where the first term is CP-even (SM) and the second is CP-odd.
- The aim of this type of search is to measure the ratio of the coupling strengths where:
  - 0˚ is CP-even
  - 90˚ is CP-odd

$$\tan\phi_{\tau\tau} = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

- Only $\tau_h\tau_h$ and $\mu\,\tau_h$ channels are considered.
- The system is boosted to the zero momentum frame (ZMF) of the charged decay products.
- The angle, Φ_{CP}, is measured as shown. This angle is sensitive to $\Phi_{\tau\tau}$.



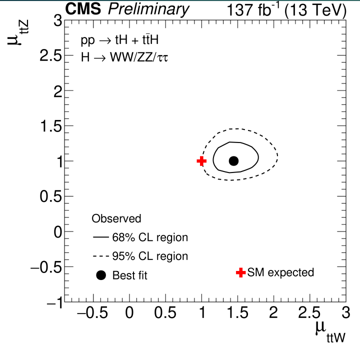
DNN for signal isolation; Φ_{CP}, shape is in each bin

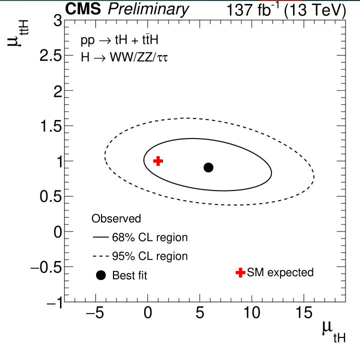


ttH Multilepton Systematics, Fit Results

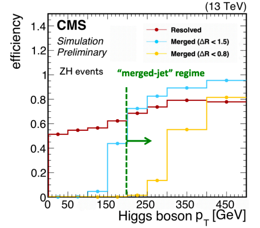
Source	$\Delta\mu_{ttH}/\mu_{ttH}$ [%]	$\Delta\mu_{tH}/\mu_{tH}$ [%]	$\Delta\mu_{ttW}/\mu_{ttW}$ [%]	$\Delta\mu_{ttZ}/\mu_{ttZ}$ [%]
Trigger efficiency	2.3	8.1	1.2	1.9
e, μreconstruction and identification efficiency	2.9	7.1	1.7	3.2
τ_h identification efficiency	4.6	9.1	1.7	1.3
b tagging efficiency and mistag rate	3.6	13.6	1.3	2.9
Misidentified leptons and flips	6.0	36.8	2.6	1.4
Jet energy scale and resolution	3.4	8.3	1.1	1.2
MC and sideband statistical uncertainty	7.1	27.2	2.4	2.3
Theory-related sources	4.6	18.2	2.0	4.2
Normalization of MC-estimation processes	13.3	12.3	13.9	11.3
Luminosity	2.2	4.6	1.8	3.1
Statistical uncertainty	20.9	48.0	5.9	5.8

ttH Multilepton Systematics, Fit Results





VH(H→cc) General Analysis Strategy



Channel	Resolved-jet	Merged-jet
$Z(\nu\nu)H(cc)$: 0L	$p_T(Z) > 170$ GeV	$p_T(V) > 200$ GeV
$W(\ell\nu)H(cc)$: 1L	$p_T(W) > 100$ GeV	
$Z(\ell\ell)H(cc)$: 2L	$p_T(Z) > 50$ GeV	

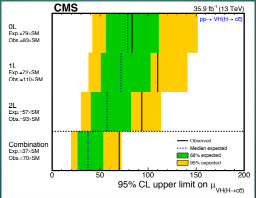
- **Resolved-jet topology**
  - Higgs decay products resolved in two AK4 (R=0.4) jets (di-jet)
  - Probe larger fraction of the available signal cross-section (95% of events have $p_T(V)<200$ GeV)
  - DeepCSV tagger (CvsL, CvsB)
- **Merged-jet topology**
  - A single AK15 (R=1.5) jet to reconstruct the H→cc decay
  - Allows to better exploit the correlations between the two charms
  - DeepAK15 tagger

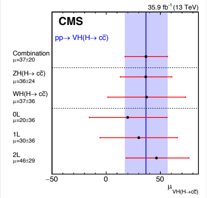
Final results: combination of the two topologies to maximize the sensitivity

VH(H→cc) Combination

- Combination:
  - Resolved-jet: $p_T(V)$ < 300 GeV
  - Merged-jet: $p_T(V)$ > 300 GeV
  - Systematics: correlated, but: c/cc-tagging efficiency & PDF, μR, μF for V+jets
- Validation with VZ(Z→cc)
  - $\mu_{VZ(Z\to cc)} = 0.55^{+0.86}_{-0.84}$
  - 0.7σ obs. (1.3σ exp.)

95% C.L. Exclusion Limits						
	Resolved-jet	Boosted-jet	Combination			
	$p_T(V)$<300 GeV	$p_T(V)$>300 GeV	0L	1L	2L	**All. Ch.**
Exp.	45^{+18}_{-13}	73^{+34}_{-22}	79^{+32}_{-22}	72^{+31}_{-21}	57^{+25}_{-17}	$\mathbf{37^{+16\,(+35)}_{-11\,(-17)}}$
Obs.	86	75	83	**110**	93	**70**





Two Higgs doublet models

125 GeV Higgs boson is (so far) consistent with SM predictions

However an extended Higgs sector is strongly motivated
(Hierarchy problem, baryon asymmetry, dark matter/energy...)

Many BSM theories require 2 Higgs doublets ϕ_1 and ϕ_2 (2HDMs)

2 important free parameters : α **and** $\tan\beta$
(mixing angle of h and H, and ratio of the VEVs of ϕ_1 and ϕ_2)

EFT Higgs Basis Definitions

- From yellow report 4

$$
\begin{aligned}
\mathcal{L}_{\text{hvv}} \;=\; & \frac{h}{v}\Bigg[(1+\delta c_w)\,\frac{g^2 v^2}{2} W_\mu^+ W_\mu^- + (1+\delta c_z)\,\frac{(g^2+g'^2)v^2}{4} Z_\mu Z_\mu \\
& + c_{ww}\frac{g^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww}\frac{g^2}{2} W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- + c_{w\Box} g^2 \left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) \\
& + c_{gg}\frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2} Z_{\mu\nu} A_{\mu\nu} + c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu} Z_{\mu\nu} \\
& + c_{z\Box} g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A_{\mu\nu} \\
& + \tilde{c}_{gg}\frac{g_s^2}{4} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2} Z_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu} \tilde{Z}_{\mu\nu}\Bigg]
\end{aligned}
$$