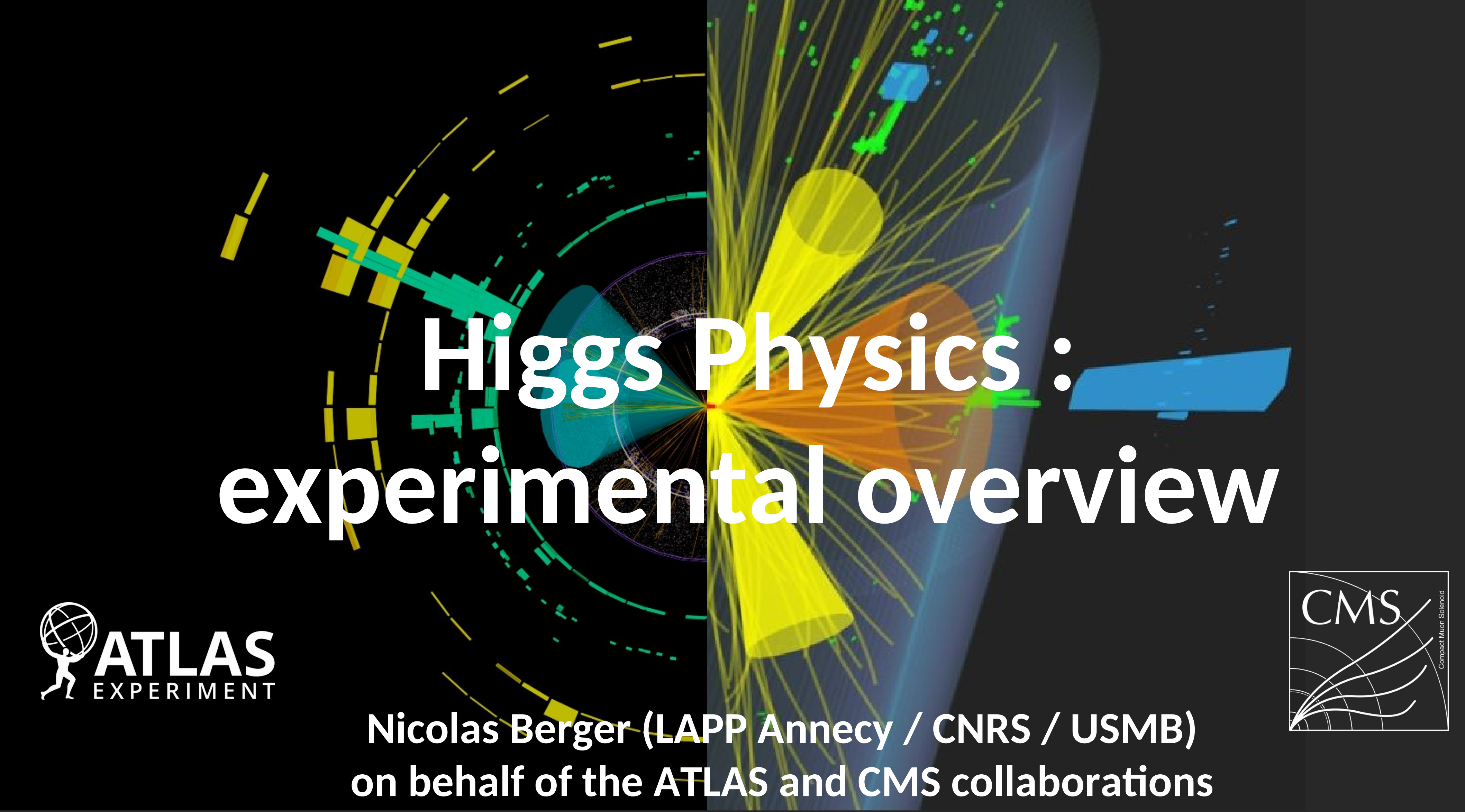
Higgs Physics : experimental overview



Nicolas Berger (LAPP Annecy / CNRS / USMB)
on behalf of the ATLAS and CMS collaborations

ATLAS EXPERIMENT

CMS Compact Muon Solenoid

Peter Higgs (1929 - 2024)

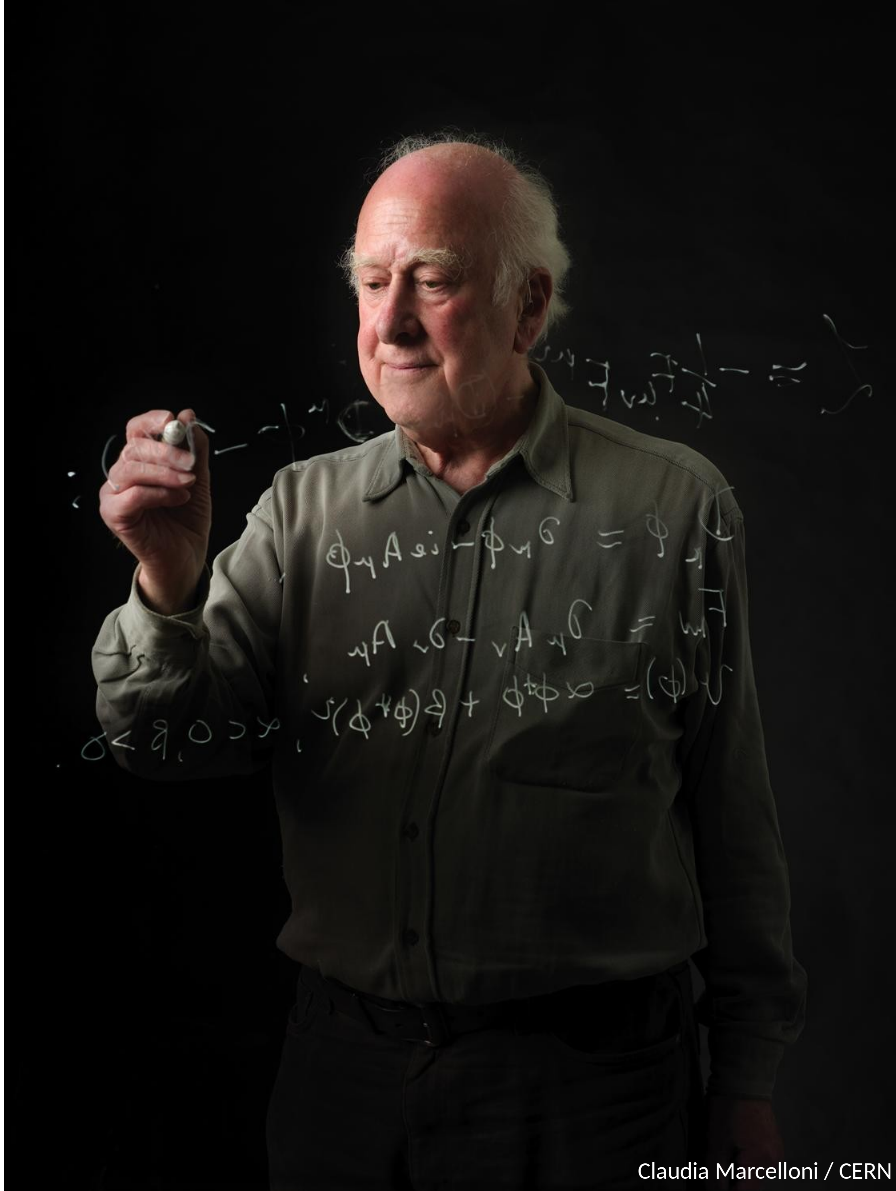
VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

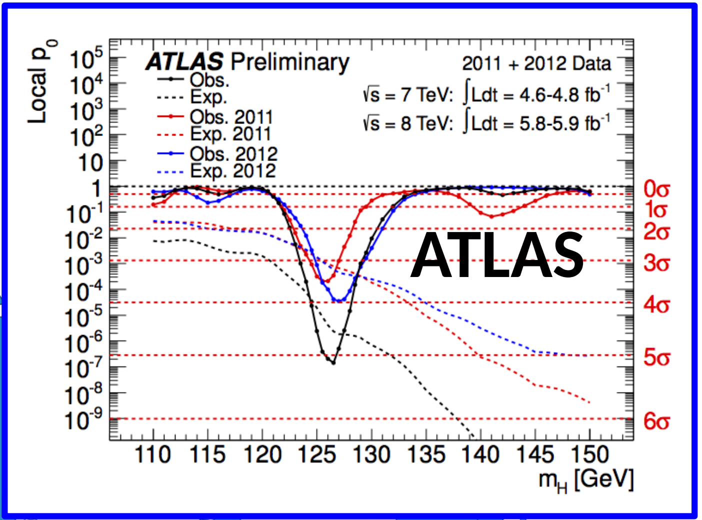
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

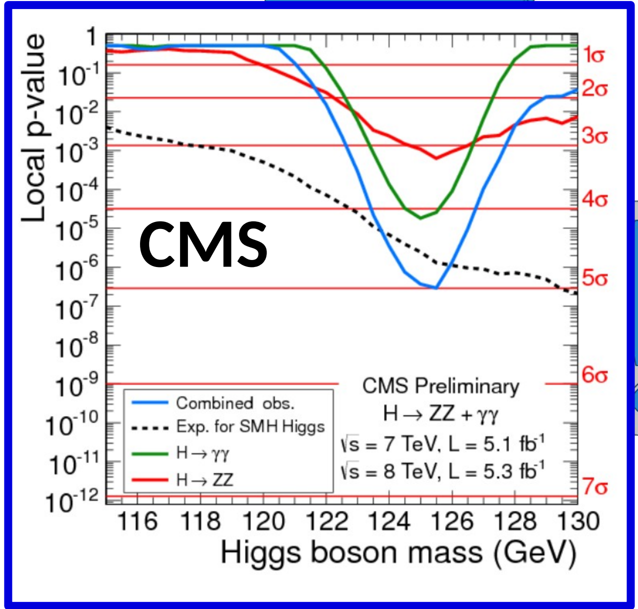

Maximilien Brice / CERN


Denis Balibouse/AFP


Claudia Marcelloni / CERN

Twelve years since the discovery





CERN

Melbourne

ICHEP 2012

Higgs boson with $m_H \sim 125$ GeV announced by ATLAS and CMS on July 4, 2012, during ICHEP 2012

Article

A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

https://doi.org/10.1038/s41586-022-04893-w
The ATLAS Collaboration*✉
Received: 21 March 2022

Article

A portrait of the Higgs boson by the CMS experiment ten years after the discovery

https://doi.org/10.1038/s41586-022-04892-x
The CMS Collaboration*✉
Received: 21 March 2022

Current state-of-the-art

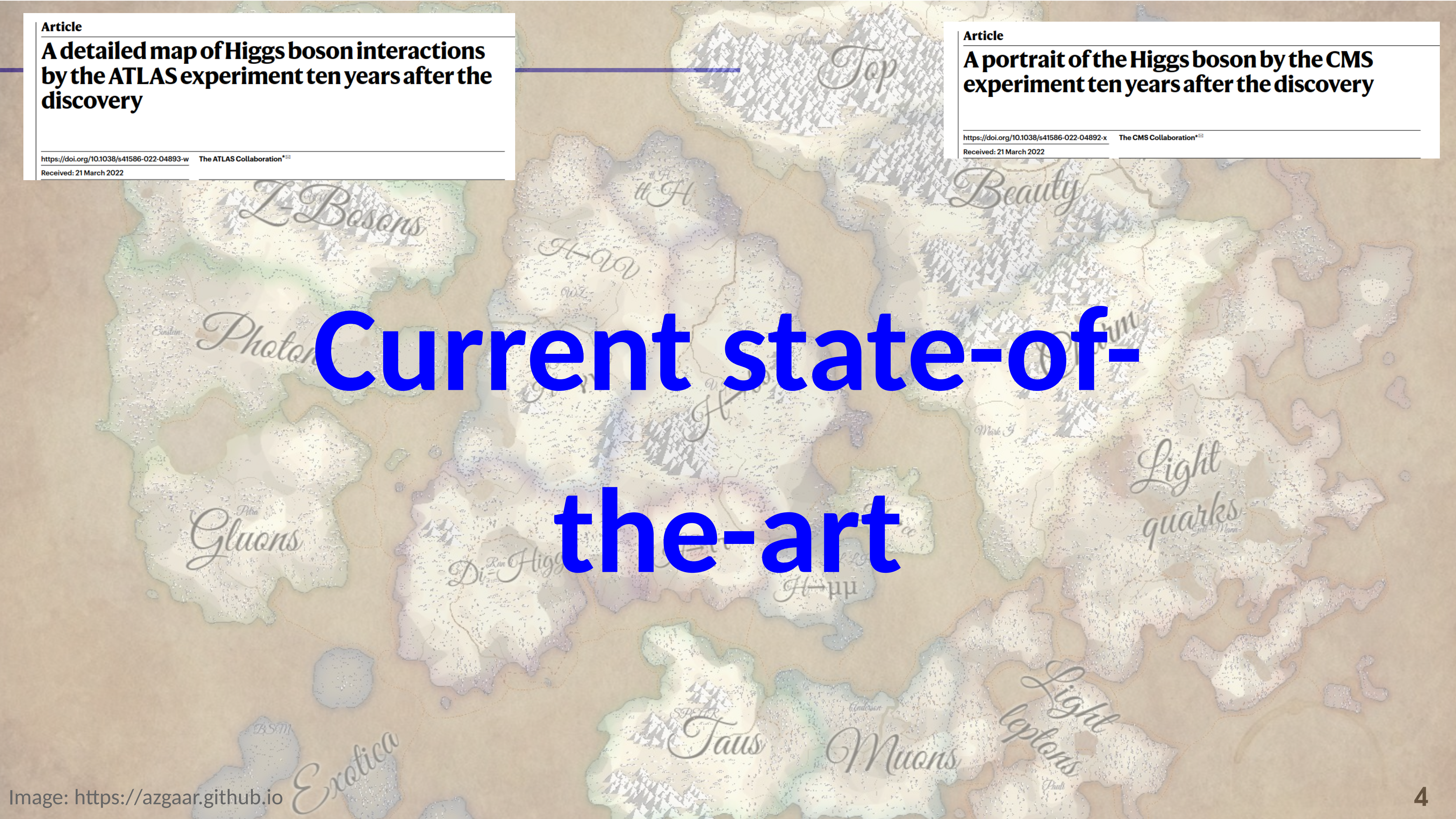
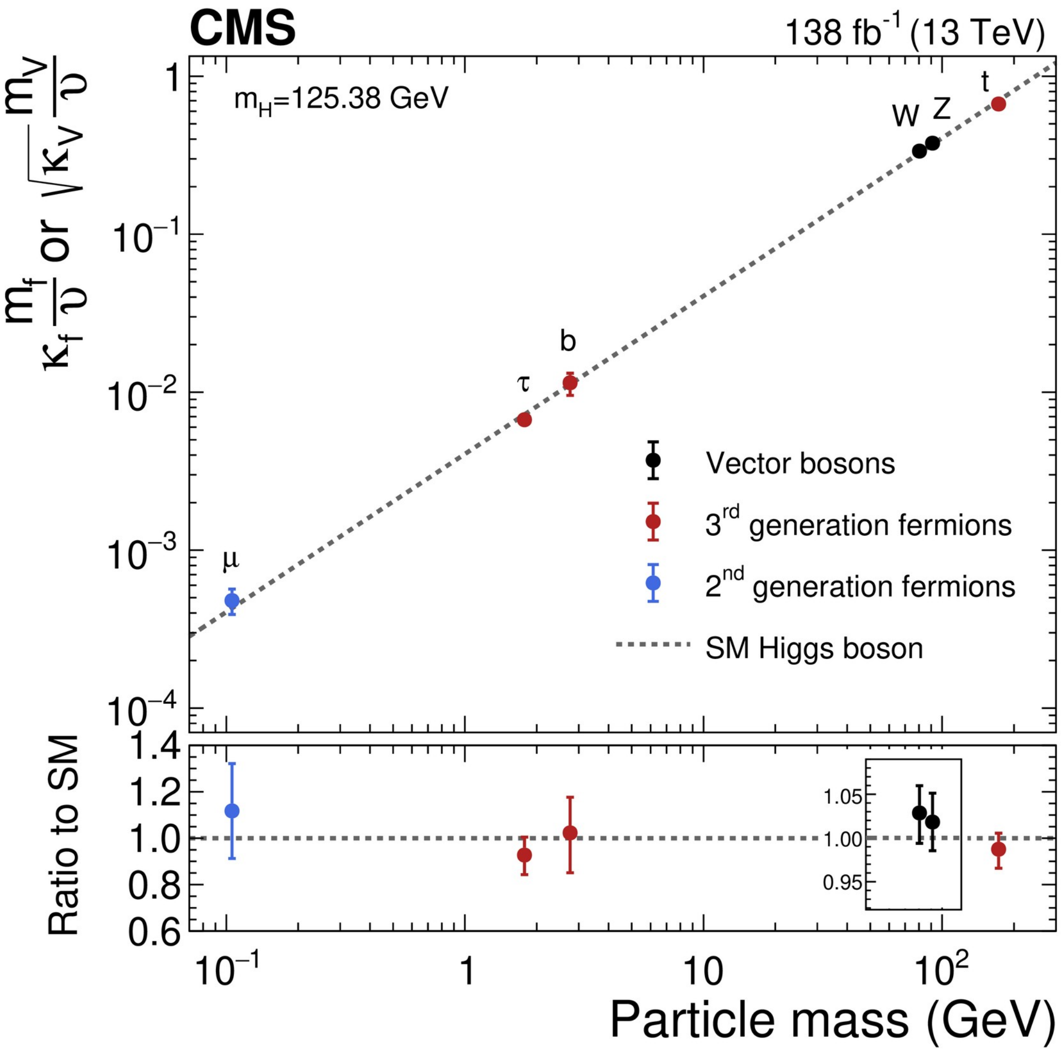
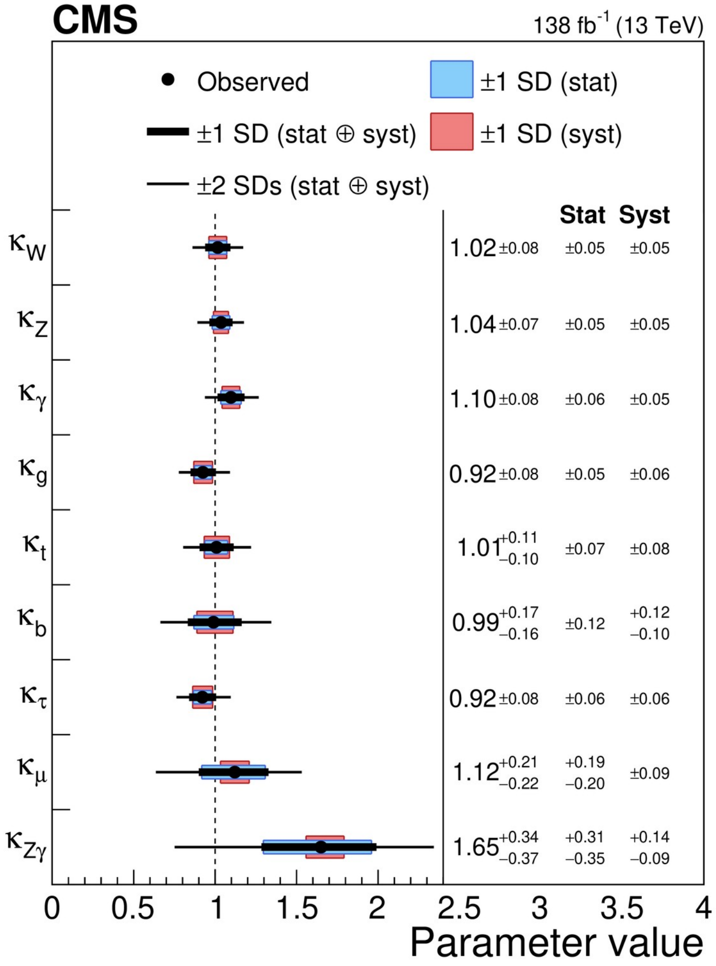


Image: https://azgaar.github.io

Current state-of-the-art: Higgs boson couplings

Nature 607 (2022) 60
Nature 607 (2022) 52



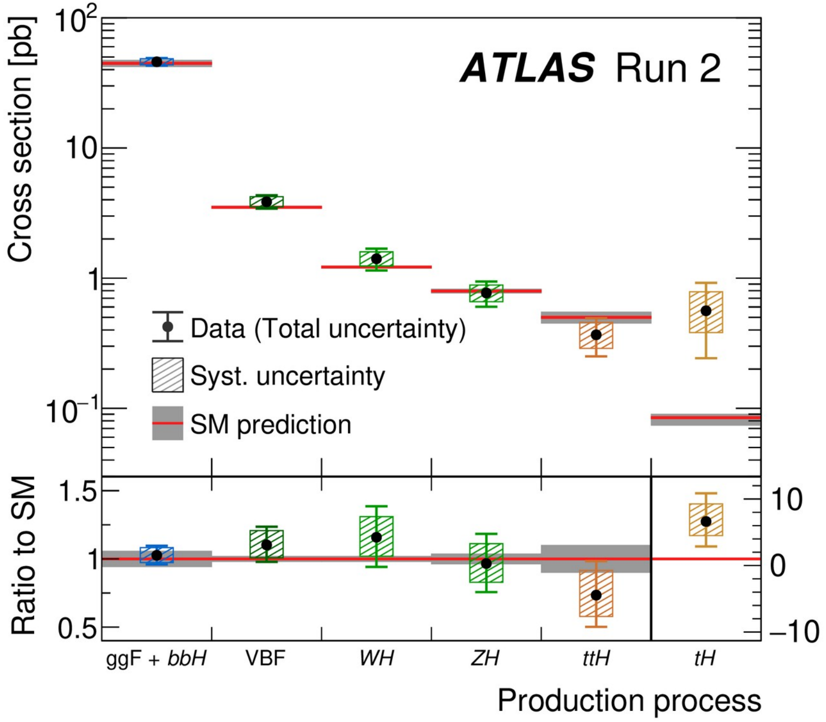


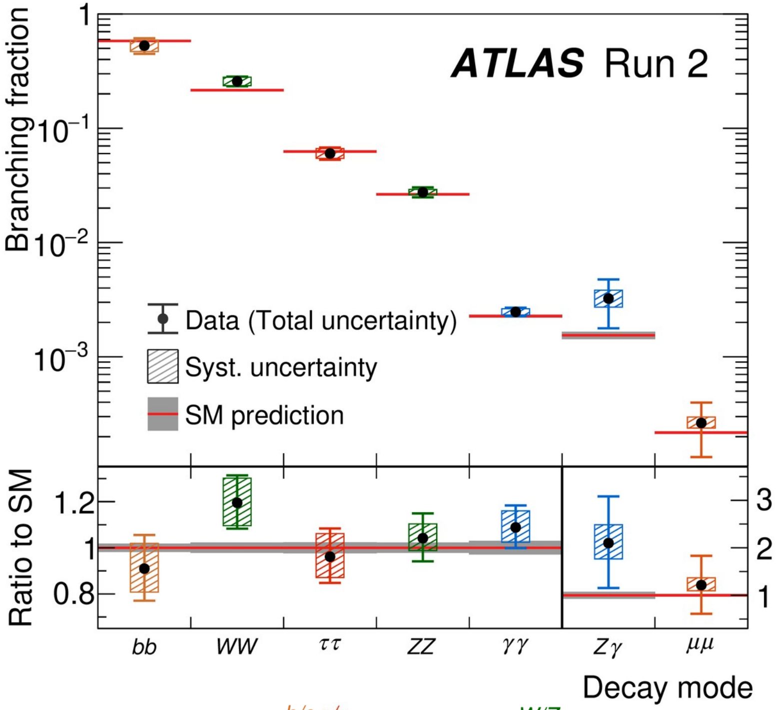
$$\kappa = \frac{g}{g_{SM}}$$

~7-8%
~10%
~15%
~ 8%
~20%
~35%

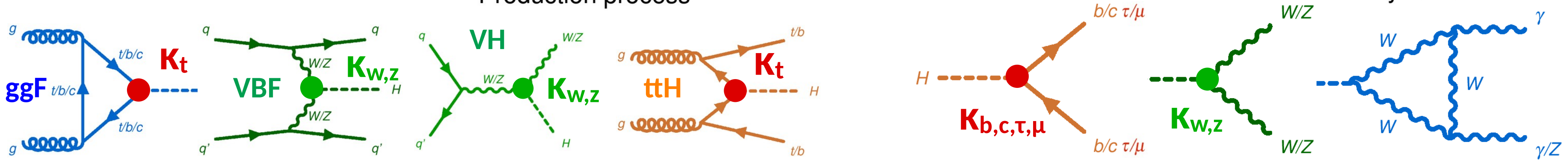
Current state-of-the-art: Production and Decay

Nature 607 (2022) 52
Nature 607 (2022) 60





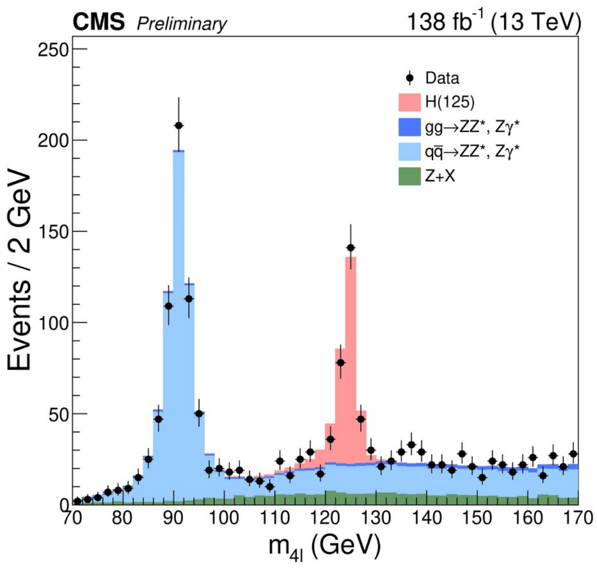
See talks by Xiao Yang and Jan Lukas Späh for more



Main production and decay processes observed, measured with <10% – 20% precision

Current state-of-the-art: Mass

CMS: using **H→ZZ*→4l** : **CMS-PAS-HIG-21-019**



$$\mathbf{m_H = 125.08 \pm 0.10\ (stat) \pm 0.05\ (syst)\ GeV}$$

Most precise single measurement (< 1 ‰)

ATLAS: combining H→4l + H→γγ : **Phys. Lett. B 843 (2023) 137880**, **Phys. Lett. B 847 (2023) 138315**

See taks by Camila Pazos, Léo Boudet, Badder Marzocchi and Federica Primavera for details

$$\mathbf{m_H = 125.11 \pm 0.11\ GeV\ (syst:\ 0.09\ GeV)}$$

Most precise measurement to date

JINST 19 (2024) P02009

H→γγ mass resolution systematics reduced by a factor 4 !

Open questions remain … which the Higgs boson can help address

Higgs boson couplings to t, b, c μ, τ W, Z

Higgs boson self-coupling

CP violation in Higgs boson processes

Higgs boson decays, total width

What is the origin of quark and lepton masses ?

- *Fermion flavor violating Higgs boson decays ?*
- ***Are there modified Higgs couplings to other particles ?***

Why is the EW interaction much stronger than gravity ?

- **Are there anomalies in HVV interactions ?**
- New particles at the TeV scale
- Is the Higgs boson elementary ?

Why is there more matter than antimatter ?

- **Higgs boson self-coupling ⇒ strong first-order EWPT ?**
- Are there multiple Higgs sectors?
- **Are there CP-violating Higgs boson decays**

What is dark matter?

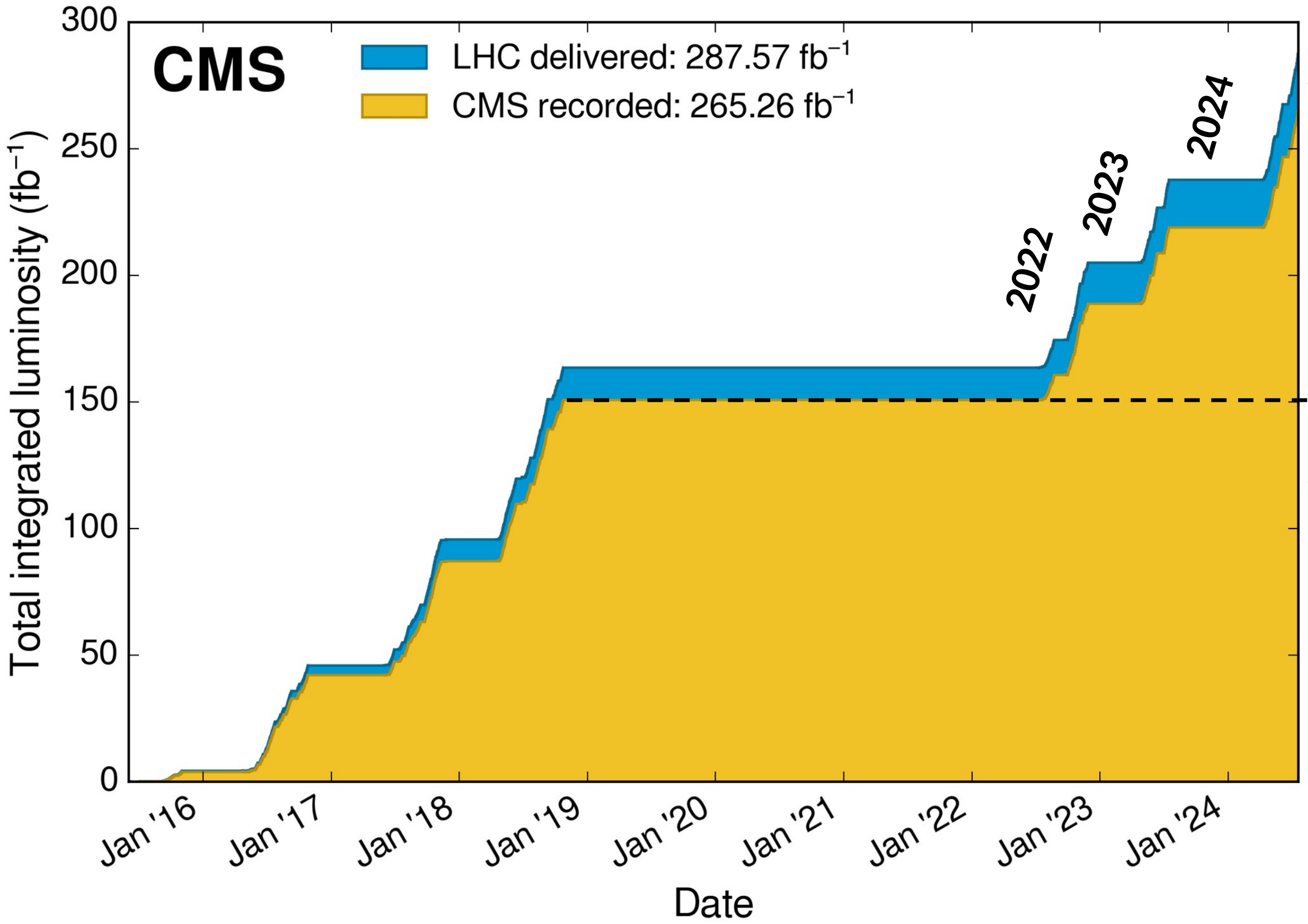
- Can the Higgs boson provide a portal to dark matter ?
- **New decay modes of the Higgs boson ?**
- **Higgs lifetime consistent with the SM ?**

Complementary with direct searches presented in Livia Soffi's talk

Adapted from G. Salam et al, Nature volume 607, pages 41–47 (2022)

LHC Datasets

Excellent accelerator performance over many years!



Run 3 dataset (13.6 TeV)

Being collected now

~60 fb^{-1} good for physics in 2022-2023, expect **300 fb^{-1}** at the end of 2025

Run 2 dataset (13 TeV)

Per experiment:

~140 fb^{-1} good for physics

~ 7M Higgs bosons produced

~ 5000 reconstructed $H \rightarrow \gamma\gamma$

Overview

Focus on new results released for ICHEP

New

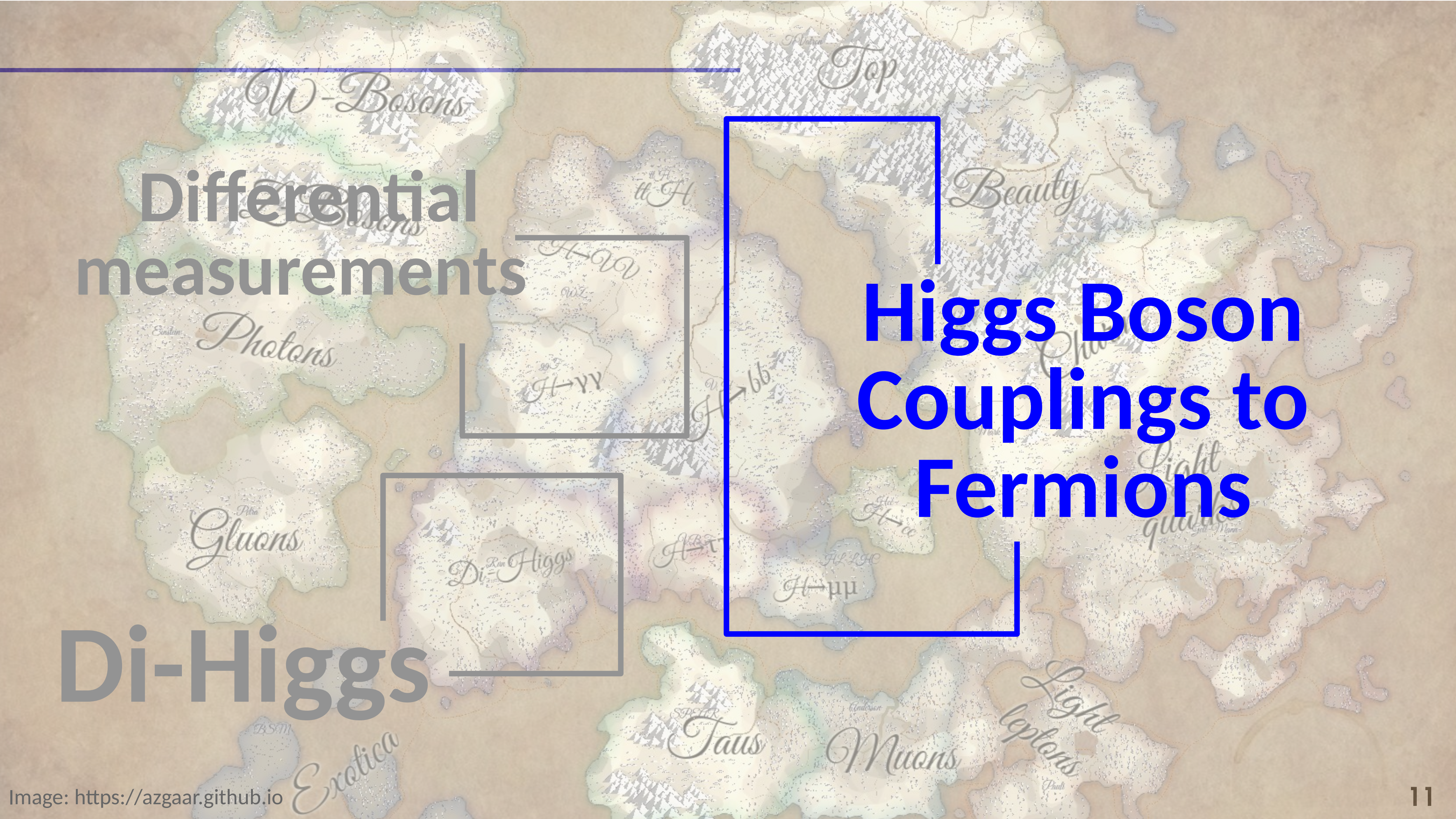
Latest Run 2 results

- Higgs boson couplings to fermions
- Higgs pair production

Precise SM measurements

Search for BSM at high energies

Fresh-off-the-press results using Run 3 data



Differential measurements

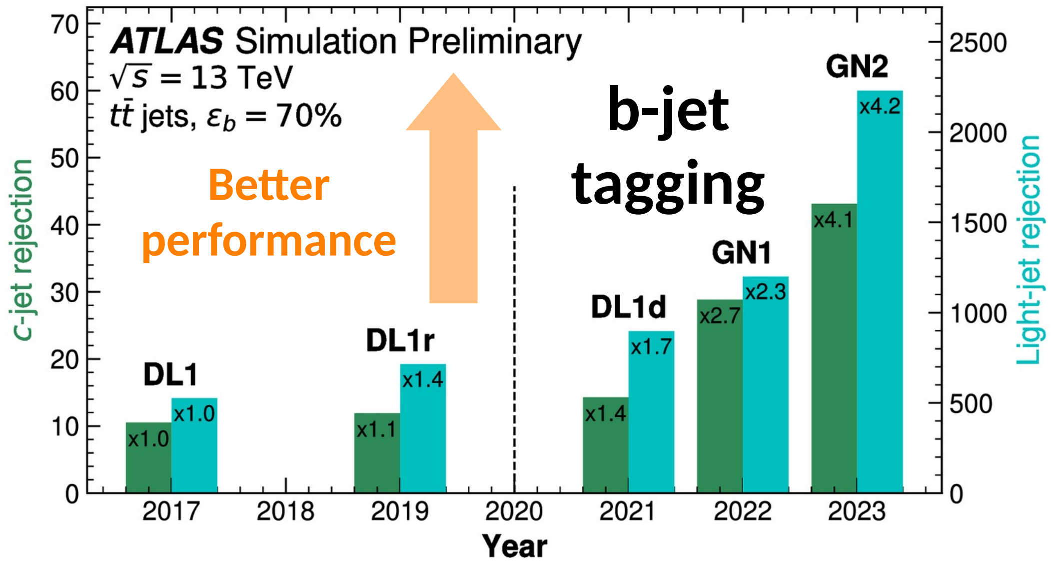
Higgs Boson Couplings to Fermions

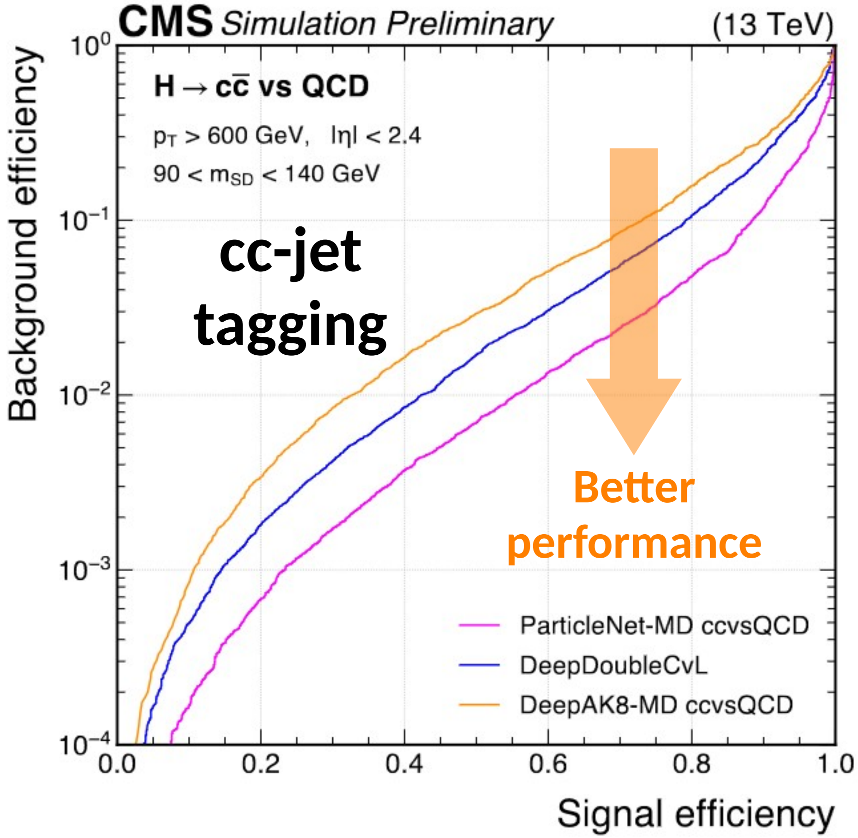
Di-Higgs

Image: https://azgaar.github.io

Aside: Improvements in flavor tagging

ATLAS: Eur. Phys. J. C 83 (2023) 681, FTAG-2023-01

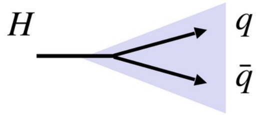




CMS: CERN-CMS-BTV-22-001-PAS

Rapid progress in techniques: **BDTs** → **feed-forward DNNs** → **Graph NNs, transformer networks**…

- Single b-jet and c-jet tagging
- Merged H→bb|cc|ττ tagging



More details in Maxence Draguet's talk

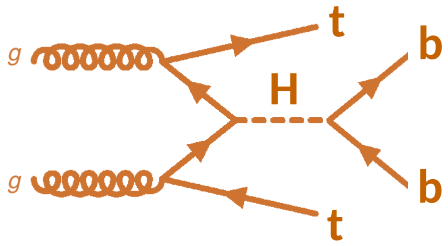
Large gains in past years, still improving quickly! → Major driver of sensitivity increases

ATLAS Final Run 2 ttH→bb measurement

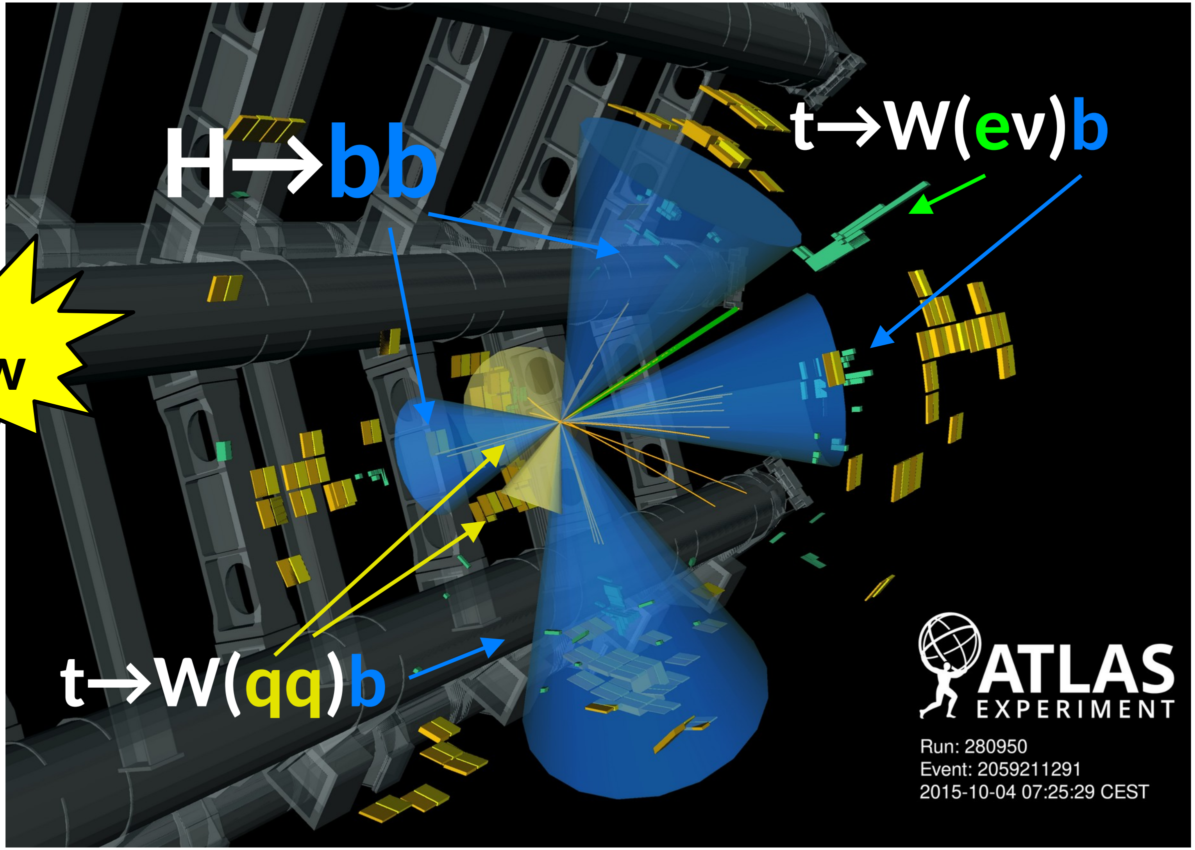
More details in Filip Nechansky's talk and Yusong Tian's and Zef Rozario's posters

ttH ⇒ **tree-level Higgs-top coupling**

H→bb ⇒ largest Higgs BR (58%)



New



Complex signature: 4b + 2 W

1 or 2 leptons (e|μ)

Reanalysis of JHEP 06 (2022) 97 with

- Improved b-tagging (DL1r)
- **Improved modeling of backgrounds (tt+b(b)…), looser selection for better control.**
- Use of transformer networks to separate signal and background, reconstruct p_T^H

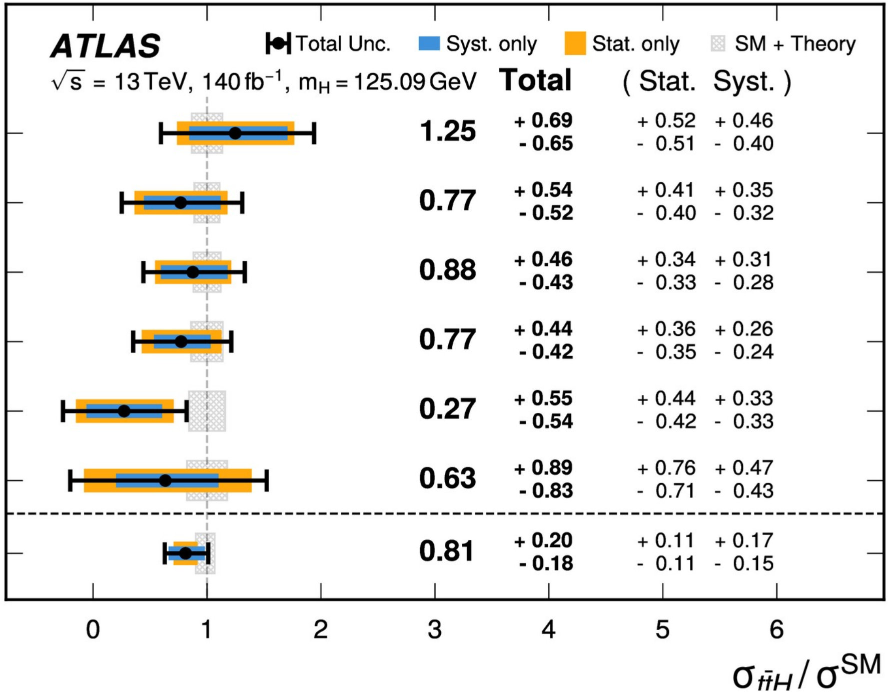
ATLAS Final Run 2 ttH→bb measurement

More details in Filip Nechansky's talk

New

$$\mu_{ttH} = 0.81\,^{+0.22}_{-0.19}\left(\,^{+0.20}_{-0.16}\ \text{syst.}\right)$$ relative to SM expectation

Overall uncertainty improved by factor 1.8, 4.6σ observed



Measure σ_{ttH} in p_T^H bins

up to 450 GeV

Best single measurement to date.

⇒ Test SM in extreme phase-space

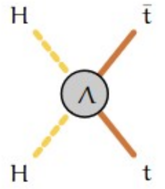


Image credits: R. Balasubramanian

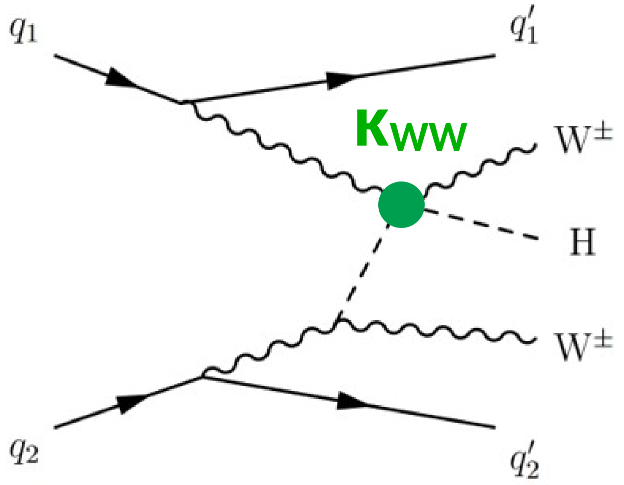
CMS Results with similar sensitivity: HIG-19-011

CMS Search for WW H→bb Vector-boson Scattering

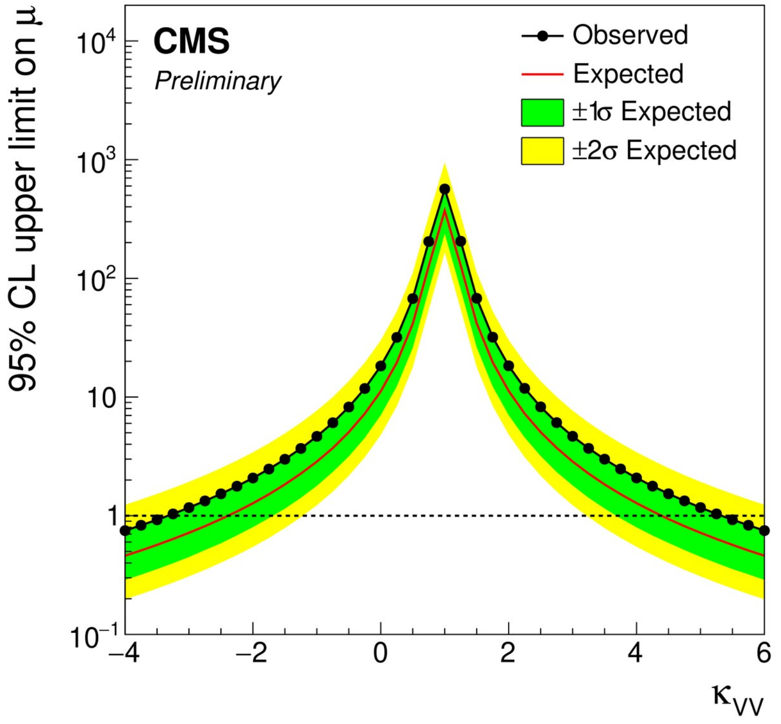
CMS-PAS-HIG-24-001

Analysis of **H→bb** + **W±W±→lvlv** in VBS production

Sensitive to WWHH coupling → **κ_{WW}**.

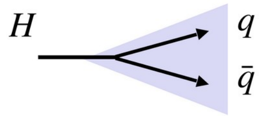


New



-3.33 < κ_{WW} < 5.33 @ 95% CL

Reconstruct H→bb as a single bb-tagged jet

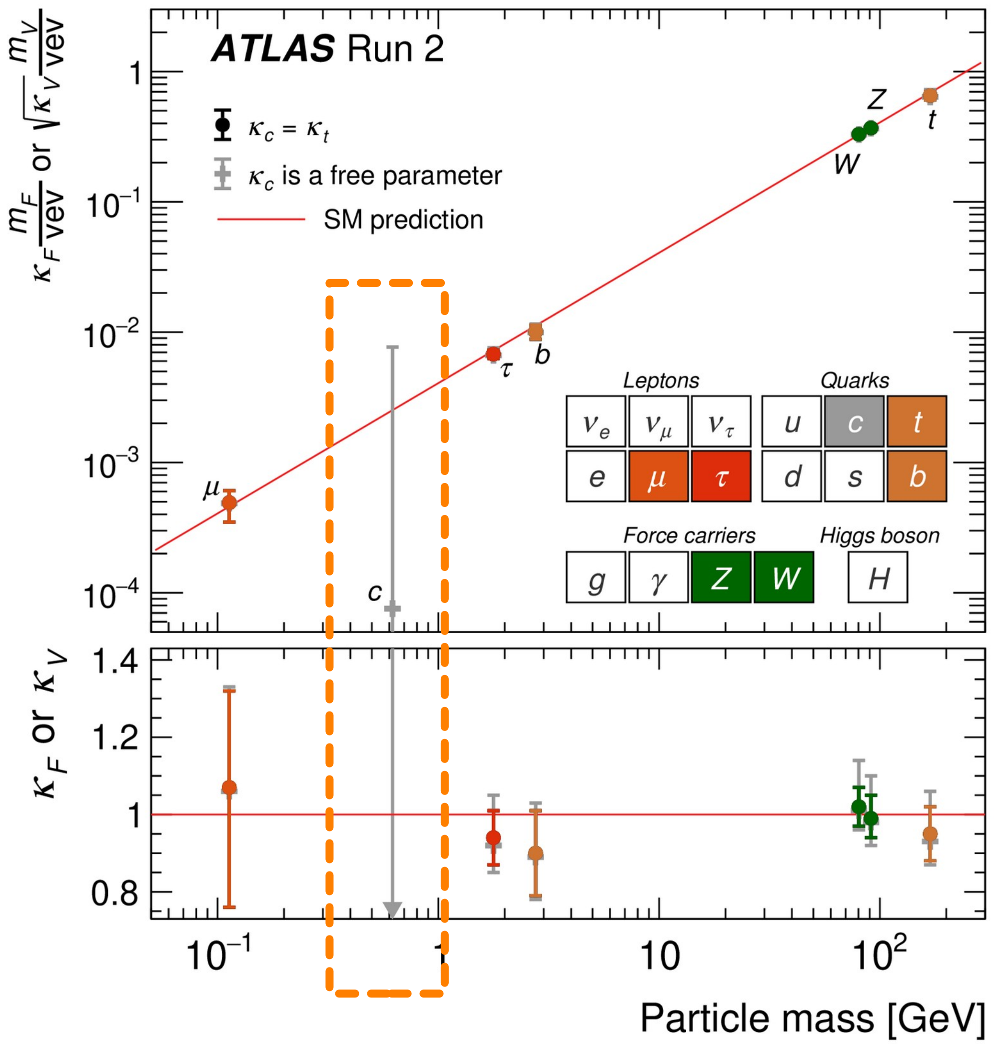


First analysis targeting κ_{VV} using single-H VBS production, can be extended to other modes

Aside: Higgs-charm coupling

Only accessible second-generation quark Yukawa coupling

⇒ Important check of the Higgs mechanism, but currently very large uncertainties

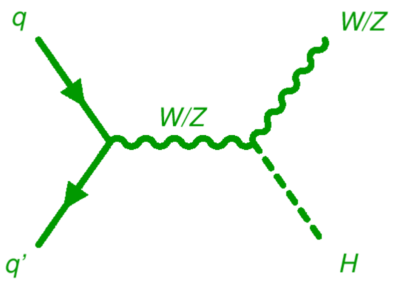


ATLAS Final Run 2 VH→bb|cc

H→bb ⇒ largest Higgs BR (58%)

H→cc ⇒ largest BR to 2nd gen. fermions (2.9%)

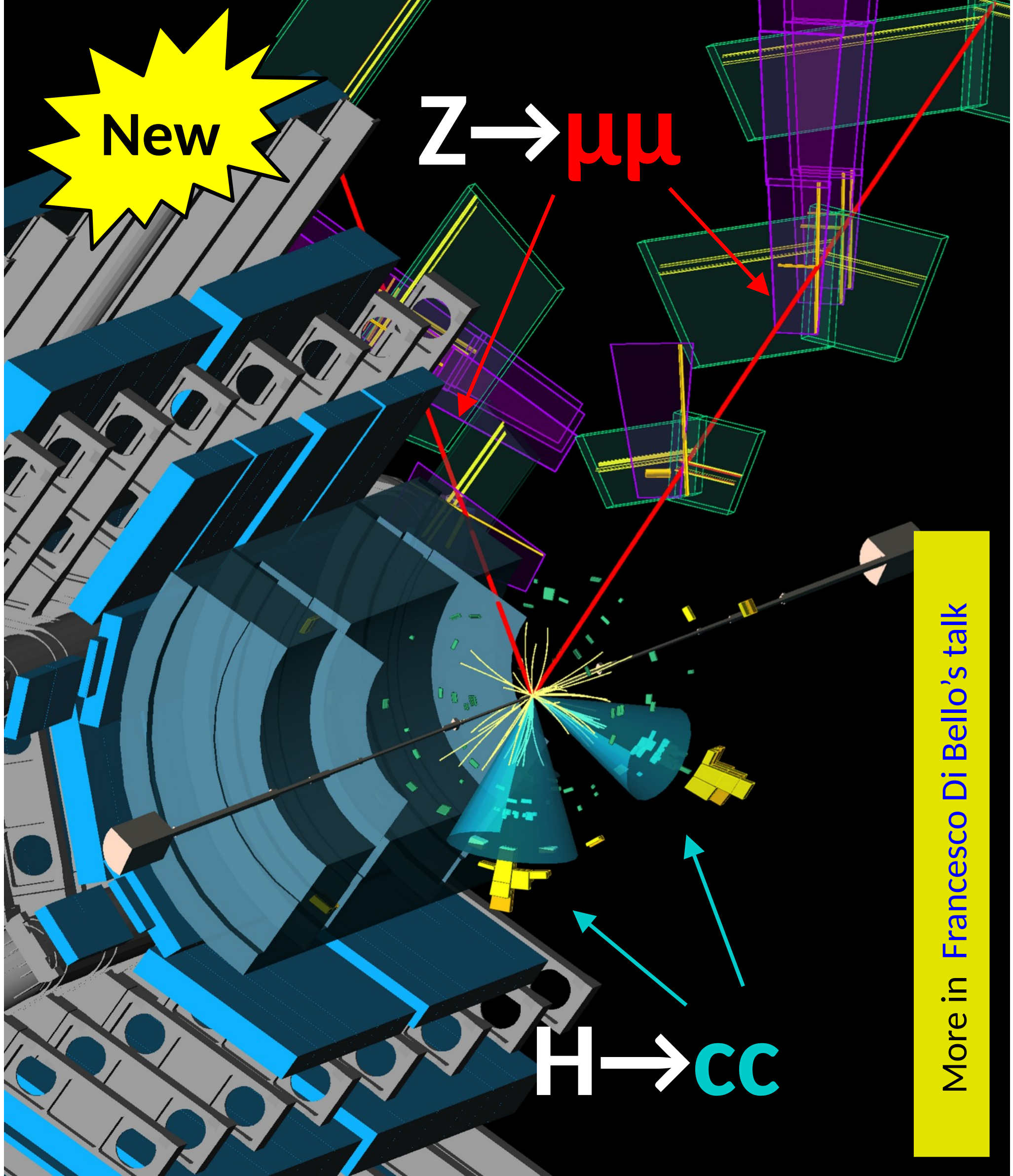
(V→lep)H most sensitive mode to access both.



Require b-jets or c-jets, split signal in

$N_{leptons}$ = 0 (Z→νν), 1 (W→lν) or 2 (Z→ll)

Reanalysis of previous VH→bb and cc results.



ATLAS Final Run 2 VH→bb measurement

More in Francesco Di Bello's talk

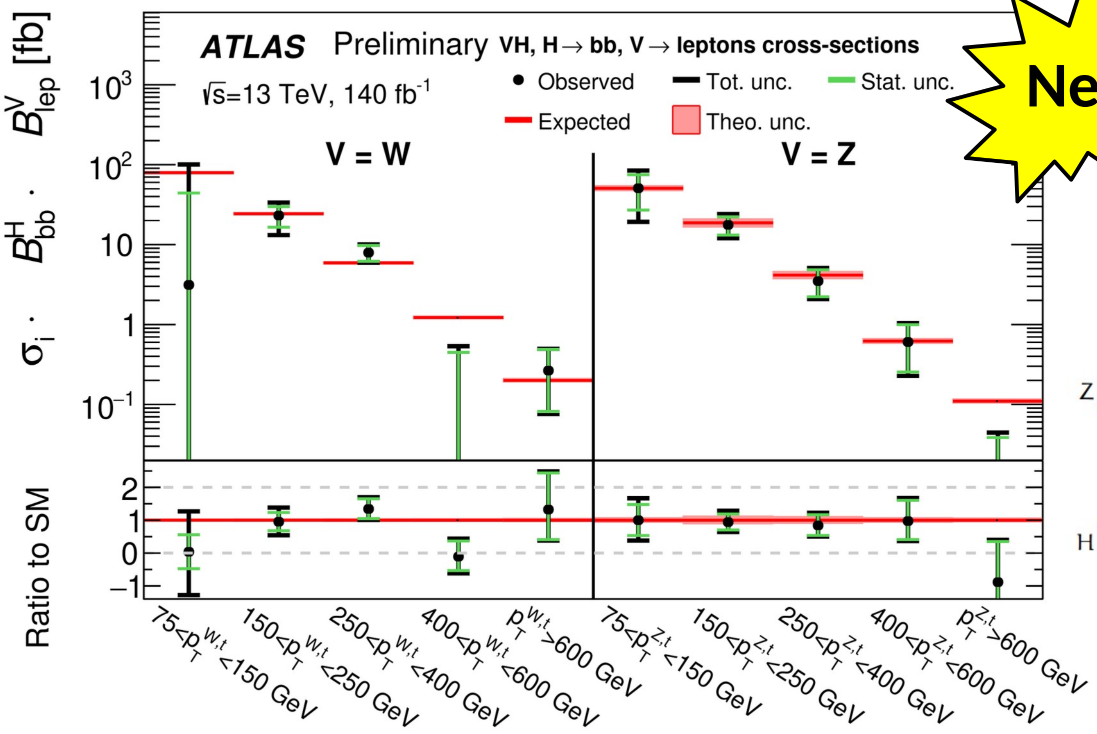
New

$$\mu_{WH} = 0.95\,^{+0.21}_{-0.19}\left(\,^{+0.15}_{-0.13}\ \text{syst.}\right)$$
$$\mu_{ZH} = 0.87\,^{+0.23}_{-0.20}\left(\,^{+0.18}_{-0.14}\ \text{syst.}\right)$$

Results compatible with SM

Uncertainties reduced by ~20%, most precise to date

First observation of WH→bb (5.3σ)



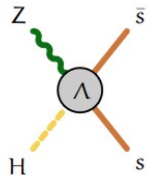


Image credits: R. Balasubramanian

Probe p_T^V spectrum up to 600 GeV for both WH and ZH

CMS Results with similar sensitivity PRD 109 (2024) 092011

ATLAS and CMS VH→cc

More in Andrea Cardini's talk and Maarten de Coen's poster

ATLAS VH→cc

New

Simultaneous fit with VH→bb

$\mu_{VH\to cc}$ **< 11.3 @ 95% CL** (10.4 exp.)

Best limit to date

Factor 2.5 improvement over previous limit !

More in Francesco Di Bello's talk

⇒ **$|\kappa_c|$ < 4.2** @ 95% CL

Factor 2 improvement over previous

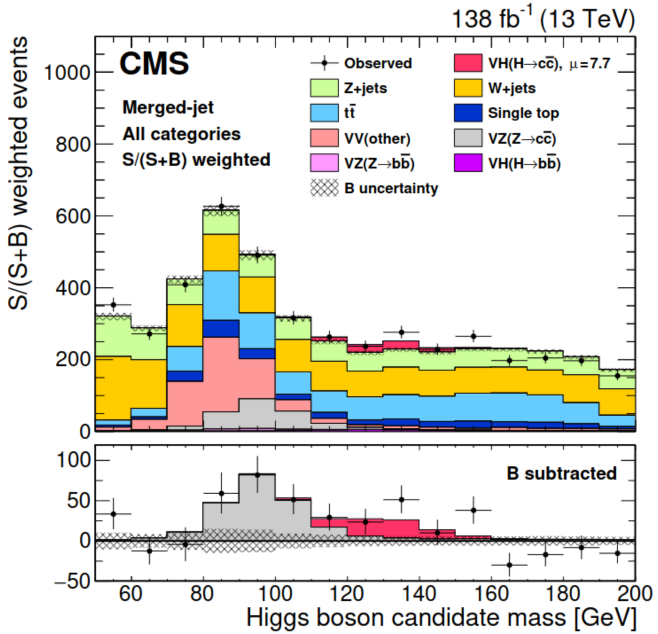
CMS VH→cc :

Includes boosted H→cc (p_T^H > 300 GeV)

$\mu_{VH\to cc}$ **< 14 (7.6)** @ 95% CL **best sensitivity**

⇒ **1.1 < $|\kappa_c|$ < 5.5**

First observation of Z→cc in hadronic collisions.



PRL 131 (2023) 041801,
PRL 131 (2023) 061801

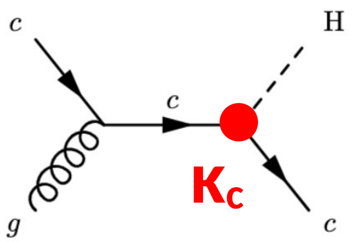
ATLAS & CMS H→γγ + c

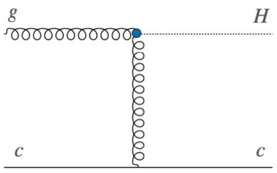
More in Andrea Cardini's talk

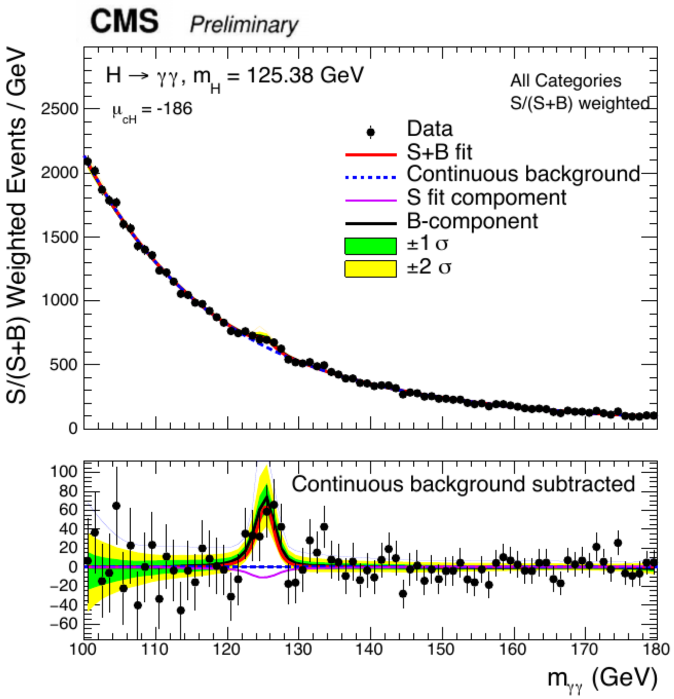
Background modeling using Gaussian process regression

Target pp→H+c production

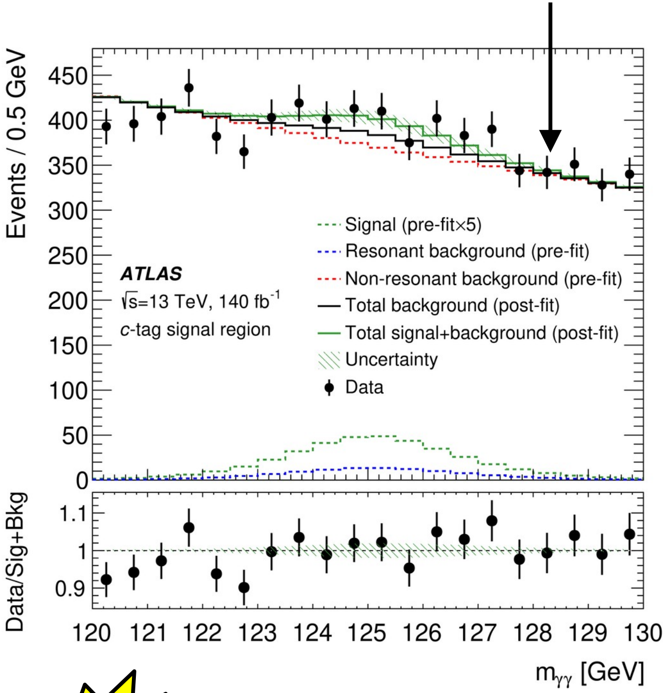
Potential to constrain κ_c, also large contributions from non-κ_c-dependent processes.







CMS-PAS-HIG-23-010



New

CERN-EP-2024-175

Large backgrounds ⇒ use clean **H→γγ** decay

ATLAS: target inclusive H+c → **σ(H+c) = 5.2 ± 3.0 pb** (SM: 2.9 pb), **< 10.4 pb** @ 95% CL

CMS: target κ_c-dependent part : μ_{cH} **< 243** (355) ⇒ **|κ_c| < 38.1 (72.5)** @ 95% CL

Differential measurements

Di-Higgs

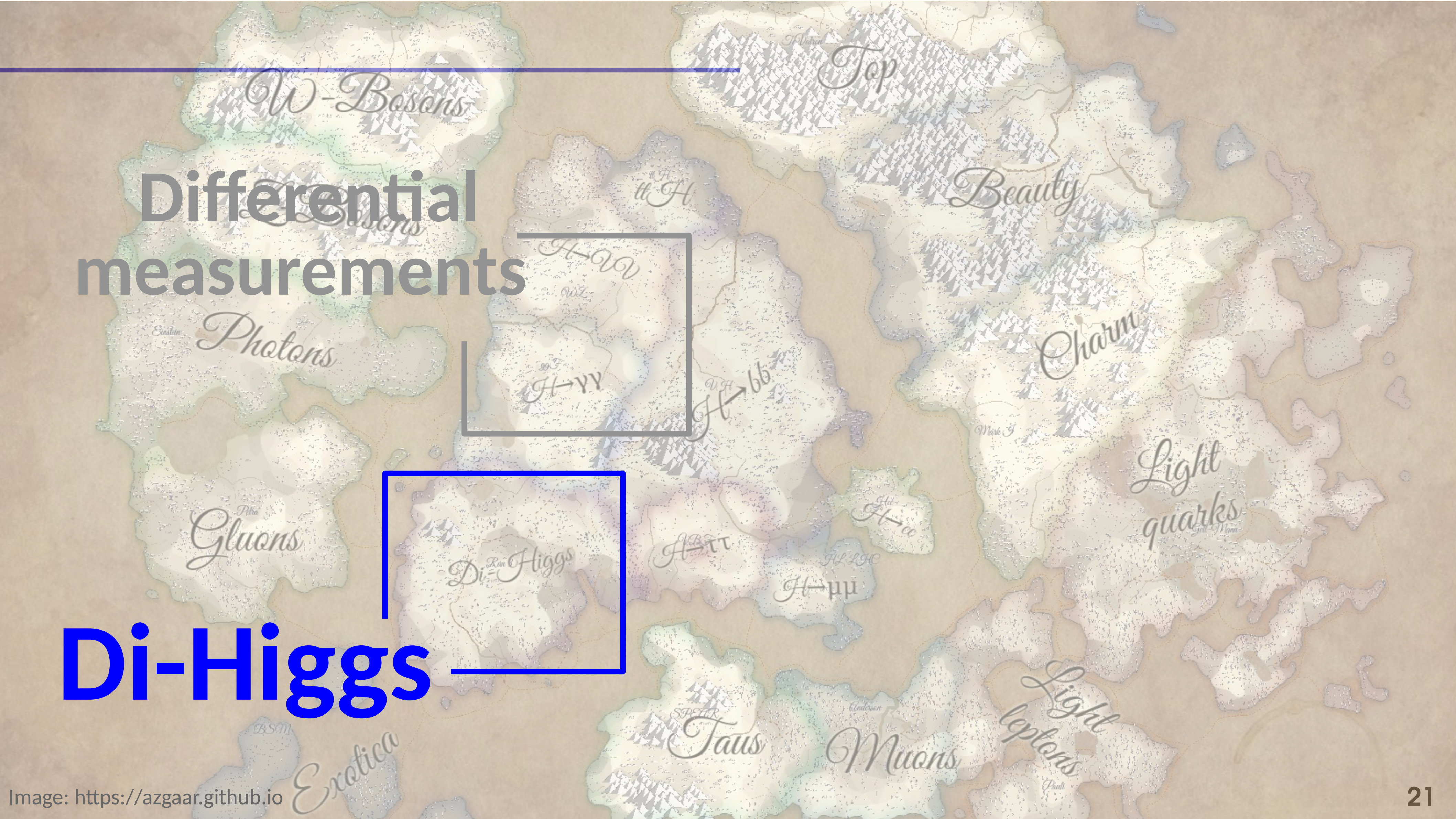
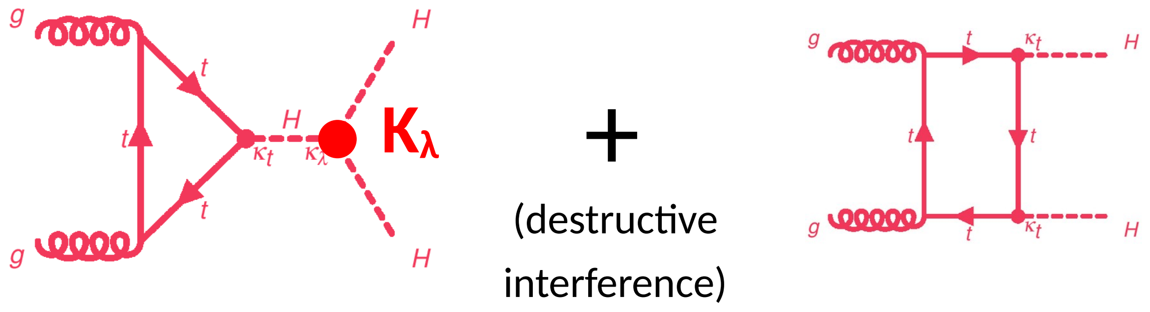


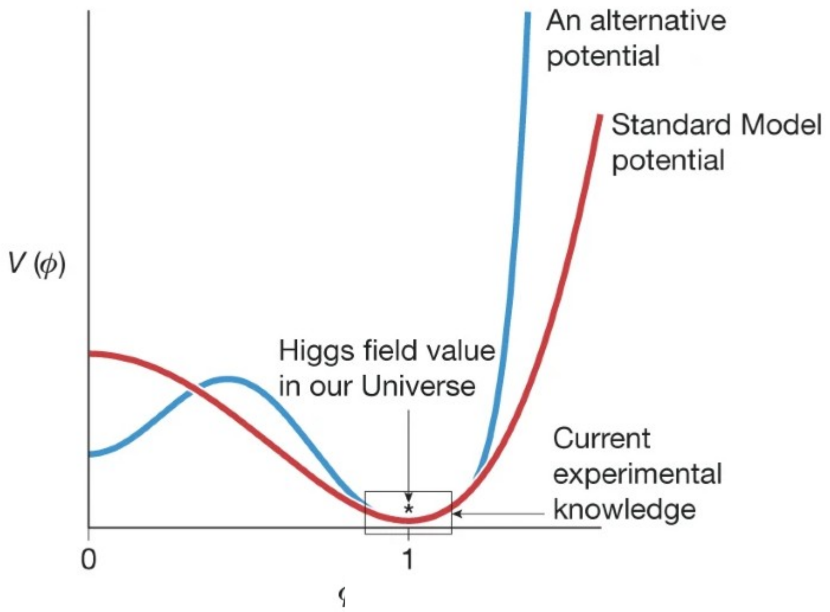
Image: https://azgaar.github.io

Higgs pair production at LHC

From G. Salam et al, Nature volume 607, pages 41–47 (2022)

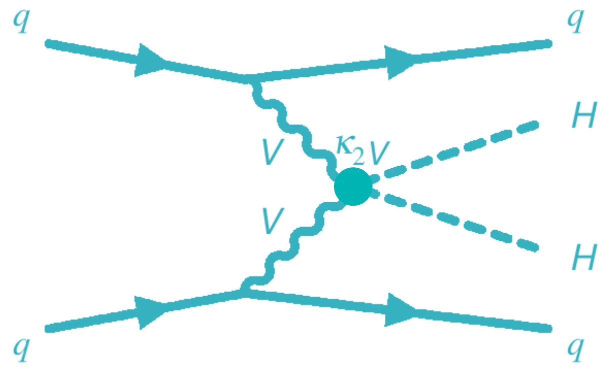
pp→HH : 1000× smaller than pp→H





Access the triple Higgs boson coupling (→ κ_λ)

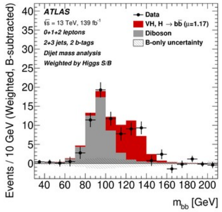
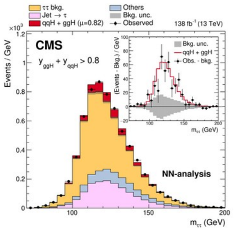
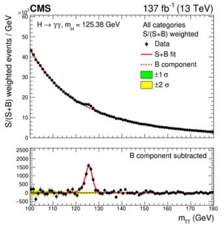
⇒ Probe the shape of the Higgs potential



Also accesses other interactions, e.g. VVHH (→ κ_{2V}).

HH decays

More on HH in talks by Dilia Maria Portillo Quintero and Cristina Ana Mantilla Suarez

Others		H→bb	H→ττ	H→γγ	H→WW|ZZ
H→bb (58%)		**HH→bbbb (34%)** μ < 3.9 (CMS)			
H→ττ (6.3%)		**HH→bbττ (7.3%)** μ < 3.3 (CMS)	**HH→ττττ**	HH→WWγγ	HH→ττWW
H→γγ (0.23%)		**HH→bbγγ (0.26%)** μ < 4.0 (ATLAS)	**HH→ττγγ**	**HH→γγγγ**	
H→WW|ZZ (24%)		**HH→bbVV** (25%) μ < 14 (CMS)	**HH→ττVV**	**HH→γγVV**	**HH→VVVV**

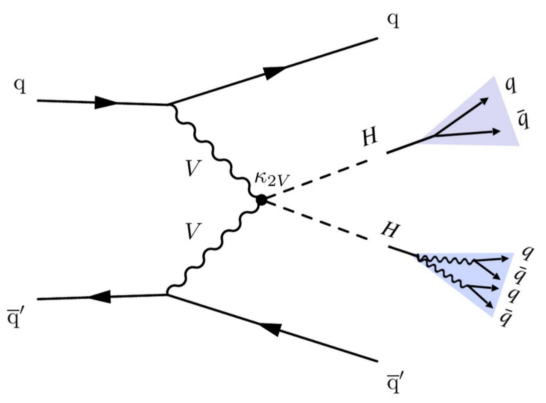
HH→multileptons
μ < 17 (ATLAS)

Best current 95% CL observed upper limits on μ are shown

CMS VBF HH→bbVV

Search for VBF HH→bbVV production

Consider collimated hadronic decays: use H→bb tagging + new **H→VV→qqqq tagging**

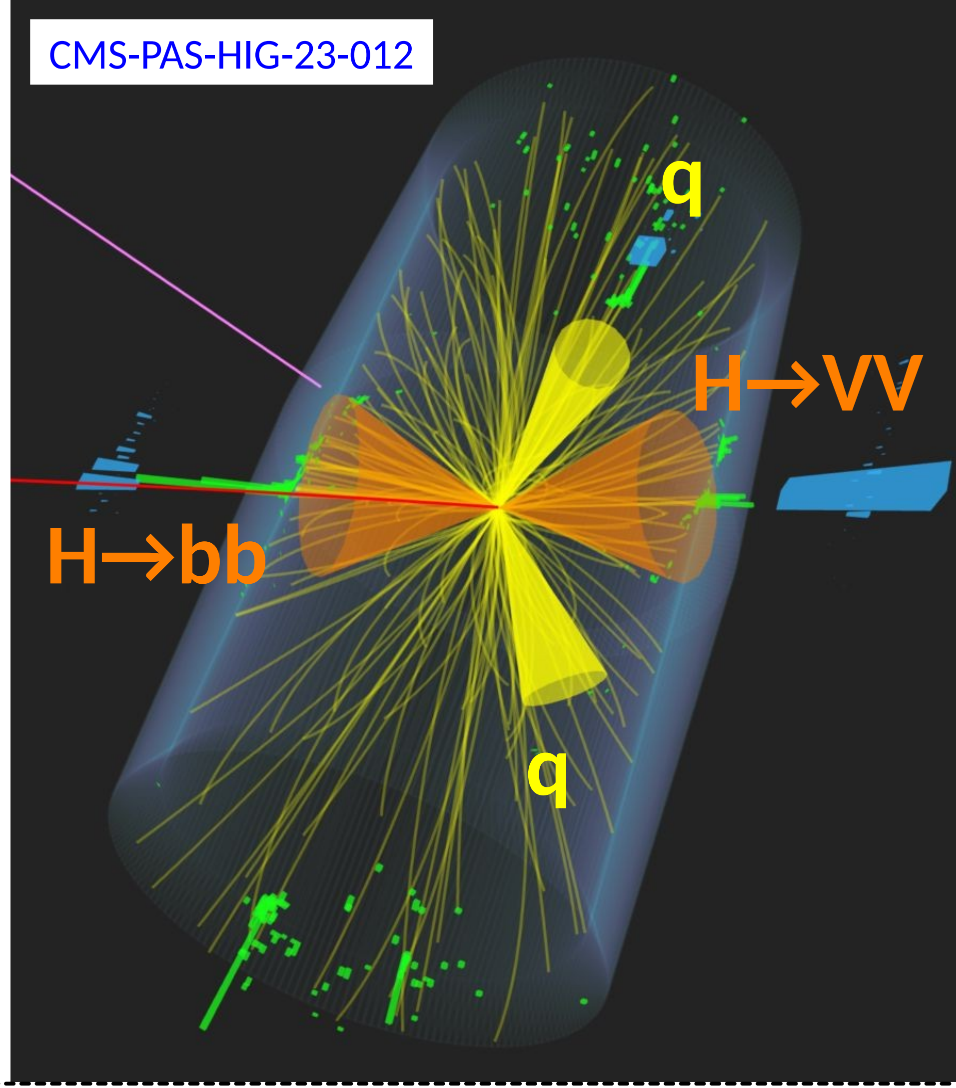


New

More in Cristina Ana Mantilla Suarez's talk

Observe **μ_{HH} < 142** (69 exp.)

and **-0.04 < κ_{2V} < 2.05** @ 95% CL



ATLAS: search in VBF HH→bbbb channel, **0.55 < κ_{2V} < 1.49** @ 95% CL CERN-EP-2024-092

ATLAS Run 2 Di-Higgs Combination

CERN-EP-2024-160

More in Dilia Portillo's talk and Song-Ming Wang's talk on HL-LHC prospects

Combine HH→bbττ + bbγγ + bbbb + multileptons + bbll+MET:

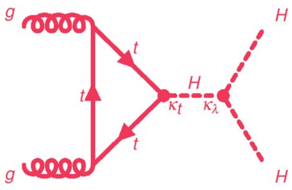
$$\mu_{HH} = 0.5 \,^{+1.2}_{-1.0} \left(\,^{+0.7}_{-0.6} \text{ syst.} \right)$$

Uncertainty comparable to SM signal!

-1.2 < κ$_\lambda$ < 7.2 @ 95% CL

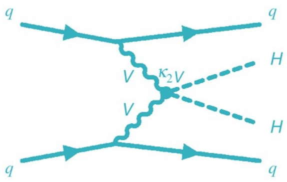
dominated by γγbb + ττbb

Best constraint to date on λ$_3$ coupling!

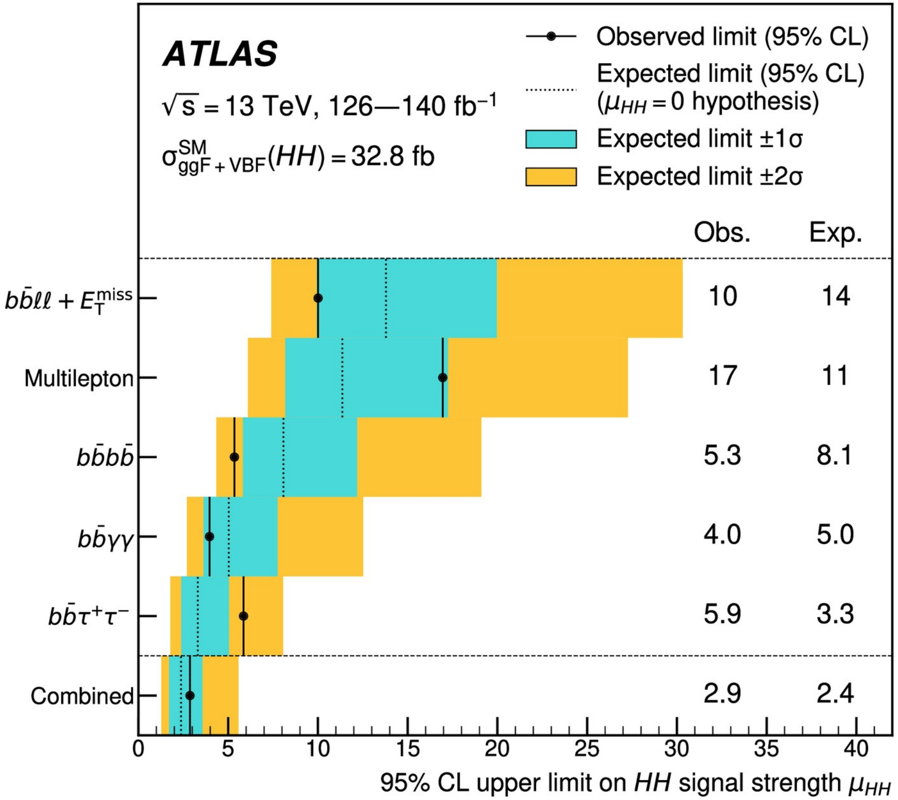


0.6 < κ$_{2V}$ < 1.5 @ 95% CL

dominated by VBF HH→bbbb



Best constraint from CMS: **0.67 < κ$_{2V}$ < 1.38** @ 95% CL



CMS HH Combination results: Nature 607 (2022) 60

Differential measurements

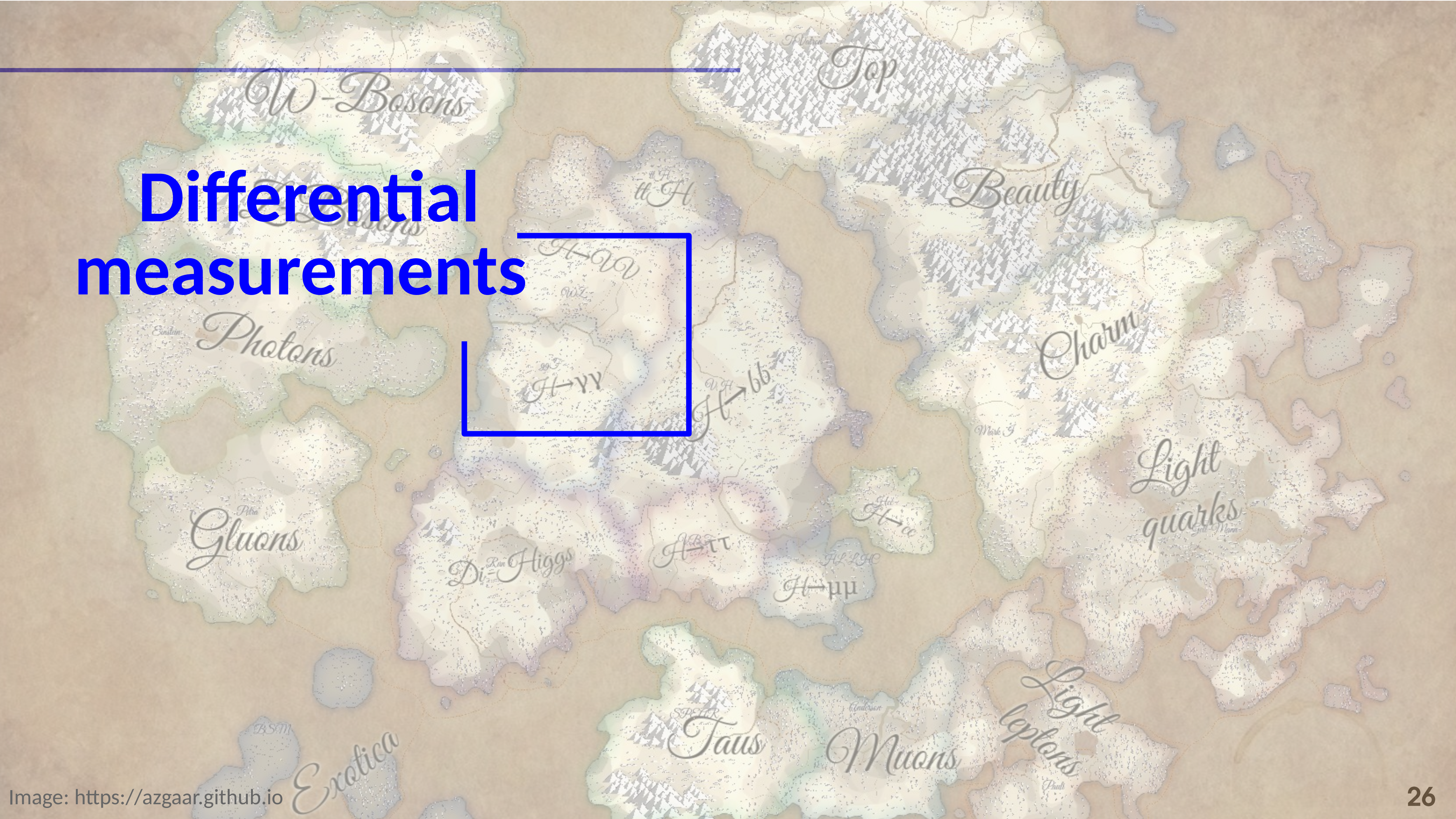


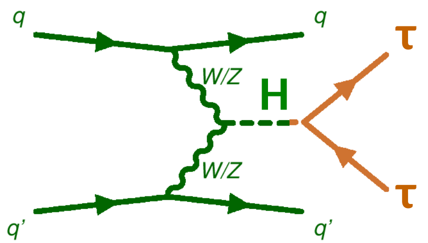
Image: https://azgaar.github.io

ATLAS Higgs CP in H→ττ

See Chris Young's talk for more info

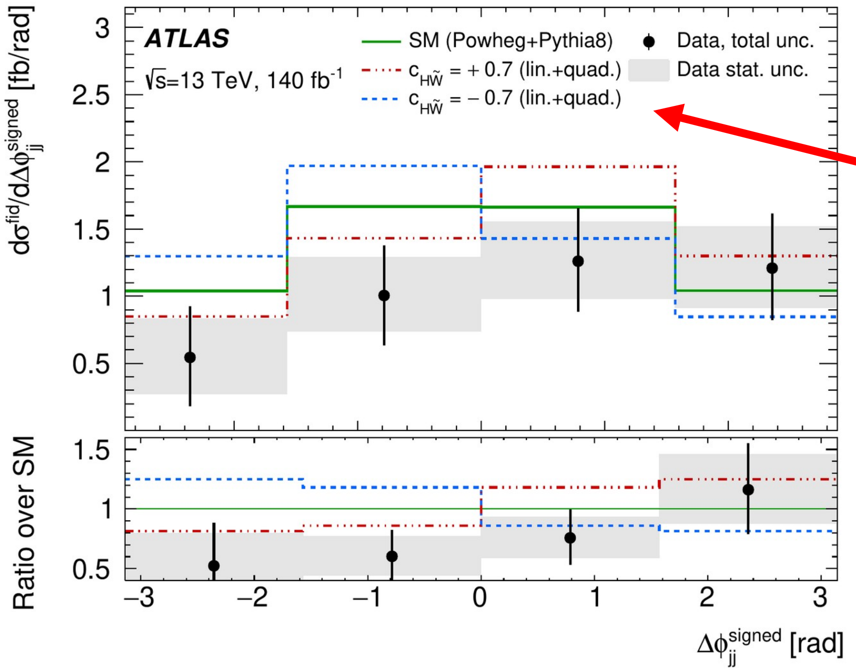
CERN-EP-2024-198

Reanalyis of JHEP 08 (2022) 175, improving VBF and ttH



$$\mu_{\mathrm{VBF}} = 0.93\,^{+0.17}_{-0.15}$$ Most precise single measurement of VBF.

Fiducial differential cross-sections, e.g. $\Delta\varphi_{jj}$, sensitive to Higgs CP.

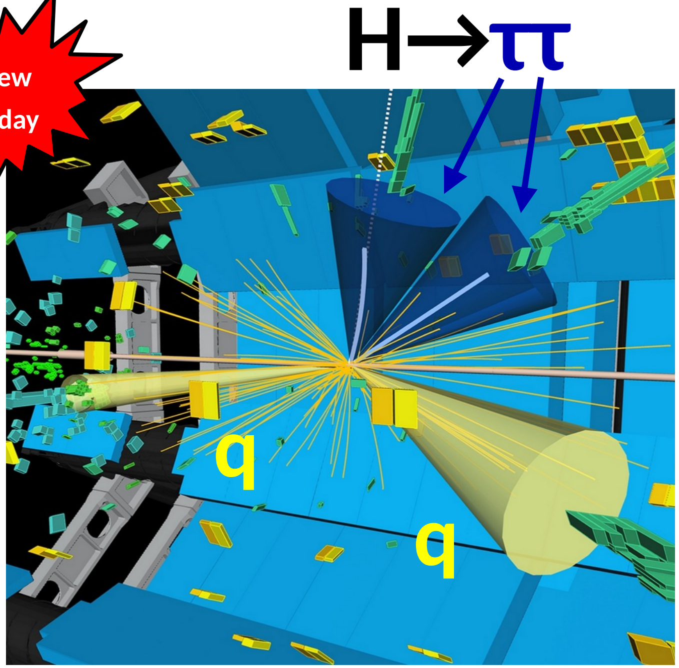


New Today

CP-odd effective coupling

$$\frac{c_{H\widetilde{W}}}{\Lambda^2}|\phi|^2 W^a_{\mu\nu}\widetilde{W}^{\mu\nu}_a$$

More on CP topics in talks by Matthew Basso and Dermot Anthony Moran



$\Rightarrow\ -0.31 < c_{H\widetilde{W}} < 0.88$ @ 95% CL (Λ = 1 TeV) Best constraint to date

CMS Run 2 differential combination

Combined measurements using:

- **H→γγ**
- **H→ZZ*→4l**
- **H→WW***
- **H→ττ**
- **H→ττ boosted**

High-precision channels (H→γγ, H→ZZ*→4l)

Sensitive to high-p_T^H region (H→ττ, H→ττ boosted)

New

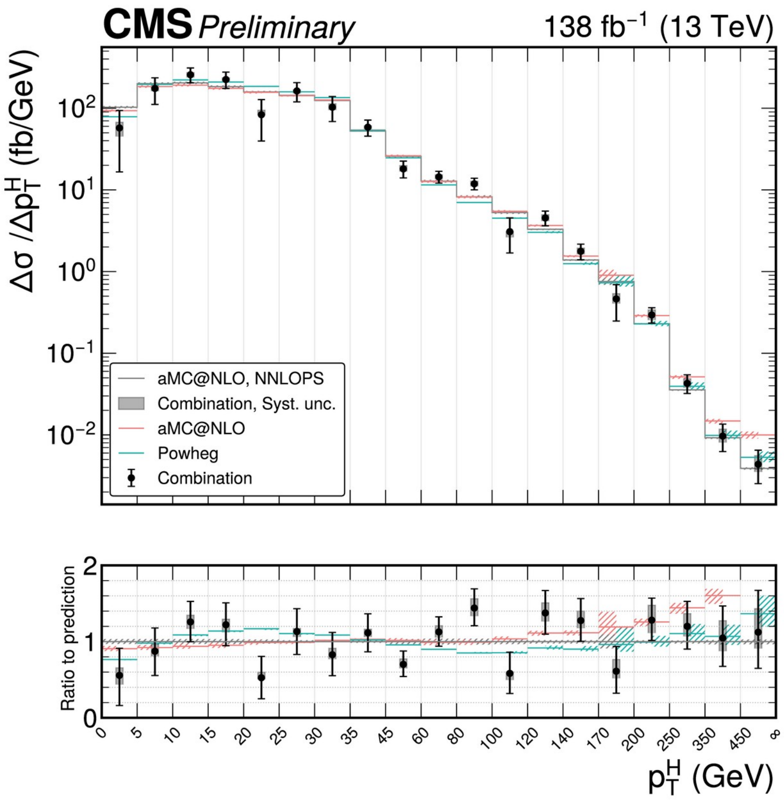
Test of the SM over a wide p_T^H range

Also N_{jets}, p_T^{j1}, $\Delta\varphi_{jj}$, …

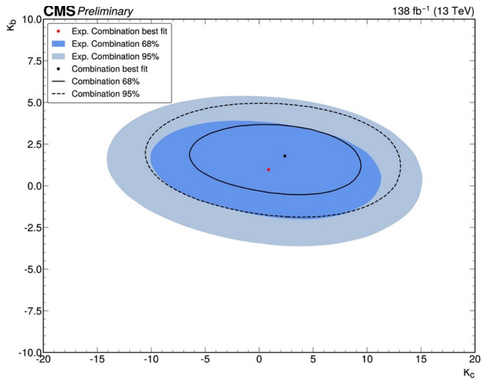
Interpretations in terms of κ_c, EFT parameters

⇒ Good agreement with SM predictions in all distributions

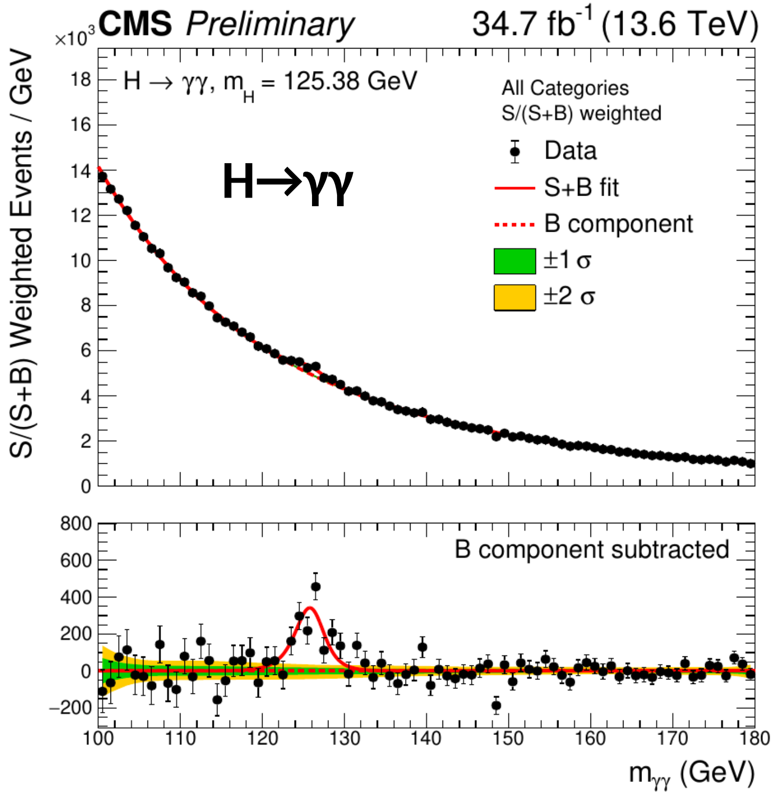
See Irene Dutta's talk for more on EFT



CMS-PAS-HIG-23-013



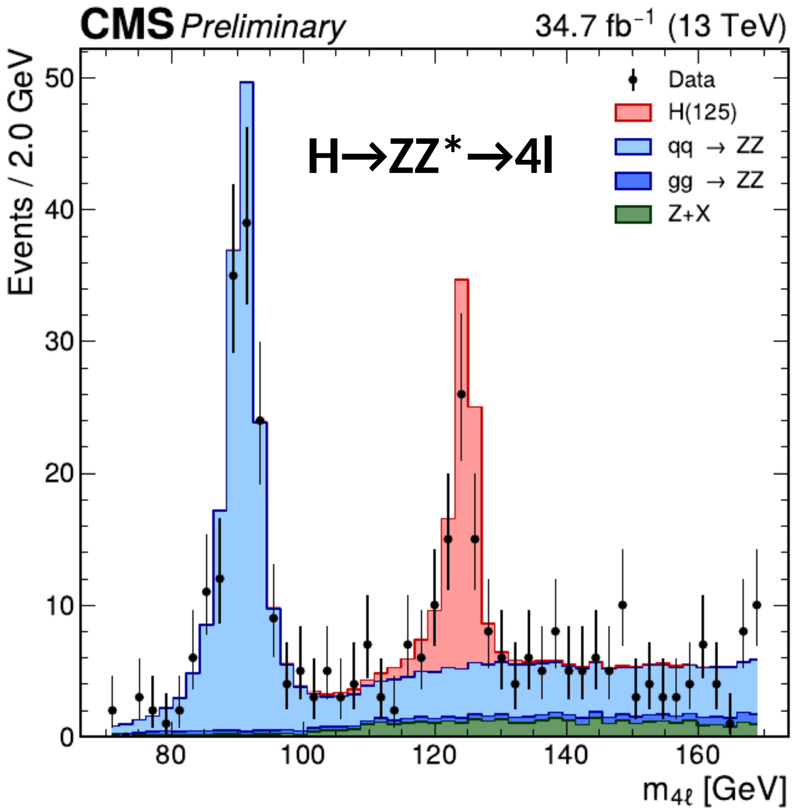
CMS Run 3 H→γγ and H→4l at 13.6 TeV



New

CMS-PAS-HIG-23-014

CMS-PAS-HIG-24-013



More in Jan Lukas Späh's talk

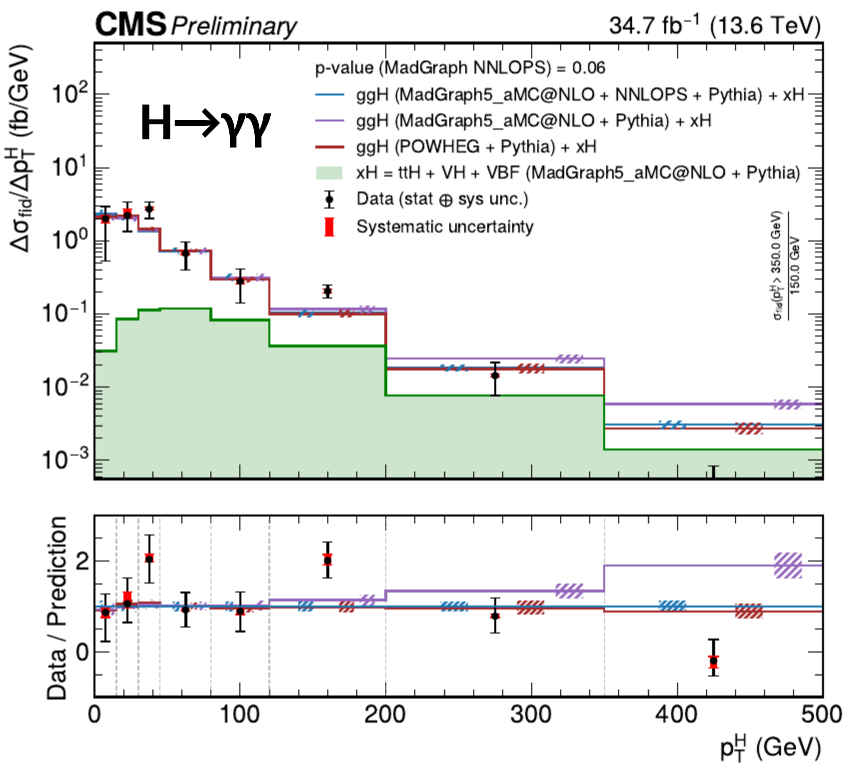
Measure H→γγ and H→ZZ*→4l in Run 3 data (34.7 fb^{-1} collected in 2022)

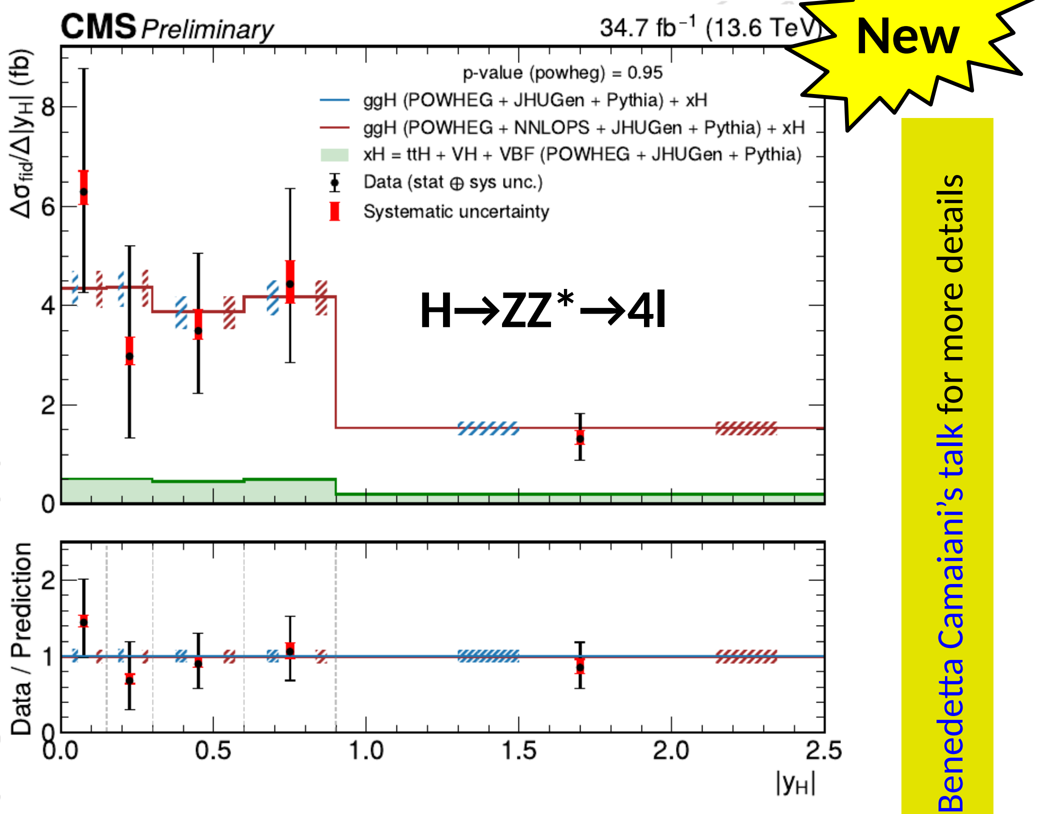
Fiducial XS: $\sigma_{fid,\gamma\gamma} = 78 \pm 11 \text{ (stat.)} ^{+6}_{-5} \text{ (syst.) fb}$ (SM: 67.8 ± 3.4 fb)

$\sigma_{fid,4l} = 2.94^{+0.53}_{-0.49} \text{ (stat.)} ^{+0.29}_{-0.22} \text{ (syst.) fb}$ (SM: $3.09^{+0.39}_{-0.31}$ fb)

Comparable ATLAS results in EPJC 84 (2024) 78

CMS Run 3 H→γγ and H→4l at 13.6 TeV





See Benedetta Camaiani's talk for more details

Measure H→γγ and H→ZZ*→4l in Run 3 data (34.7 fb^{-1} collected in 2022)

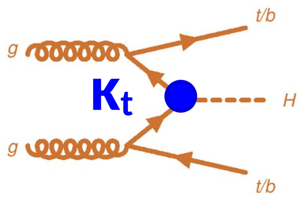
Differential distributions in p_T^H, N_{jets}, … **All in good agreement with SM expectations.**

ATLAS Higgs width from 4-top production

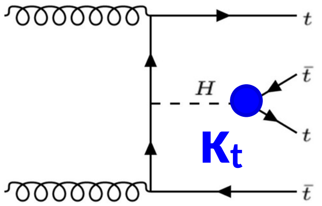
New

CERN-EP-2024-190

Top processes with on-shell and off-shell Higgs:



$$\sigma(pp \to ttH) \sim \frac{\kappa_t^2 \kappa_f^2}{\Gamma_H}$$

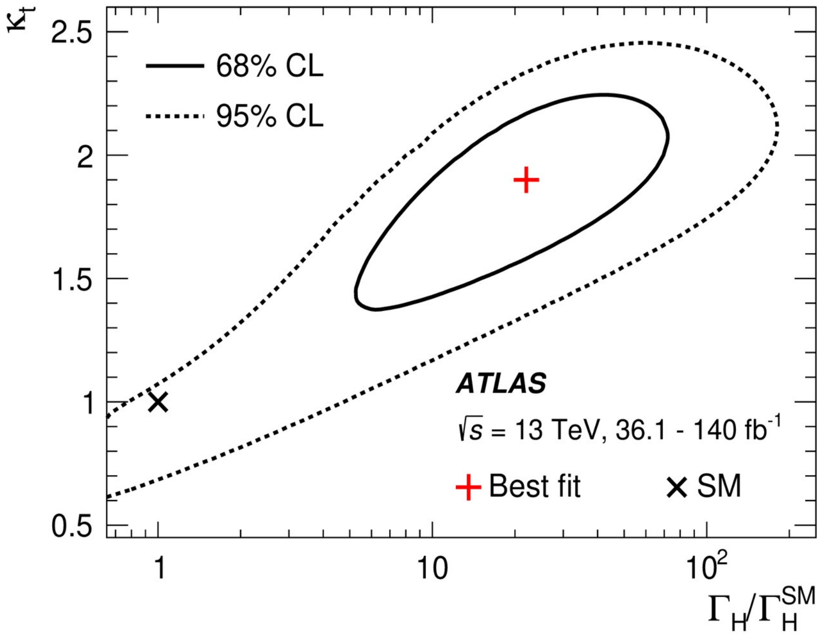


$$\sigma(pp \to tttt) \sim f(\kappa_t^2)$$

Eur. Phys. J. C 83 (2023) 496:

$\mu(pp \to tttt) = 1.9^{+0.8}_{-0.5}$

Combination constrains Γ_H



See Rafael Coelho Lopes De Sa's talk for details

Similar technique as used in H→ZZ (Γ_H < 7.9 × SM, with coupling assumptions, CMS-PAS-HIG-21-019)

Use full Higgs combination to constrain other couplings

Γ_H < 110 × SM (expected 18 × SM) Larger observed due to observed excess in pp→ tttt

ttH → tree-level processes, no BSM in loops ⇒ complementary to HVV

Conclusions

Very broad ongoing Higgs boson physics program at CMS and ATLAS

- Precision measurements: few-% level on some couplings, 0.1% on m_H.
- Significant reduction in uncertainties on charm coupling
- Di-Higgs is already reaching SM sensitivity with Run 2 data only!

Improvements driven by better analysis techniques and performance.

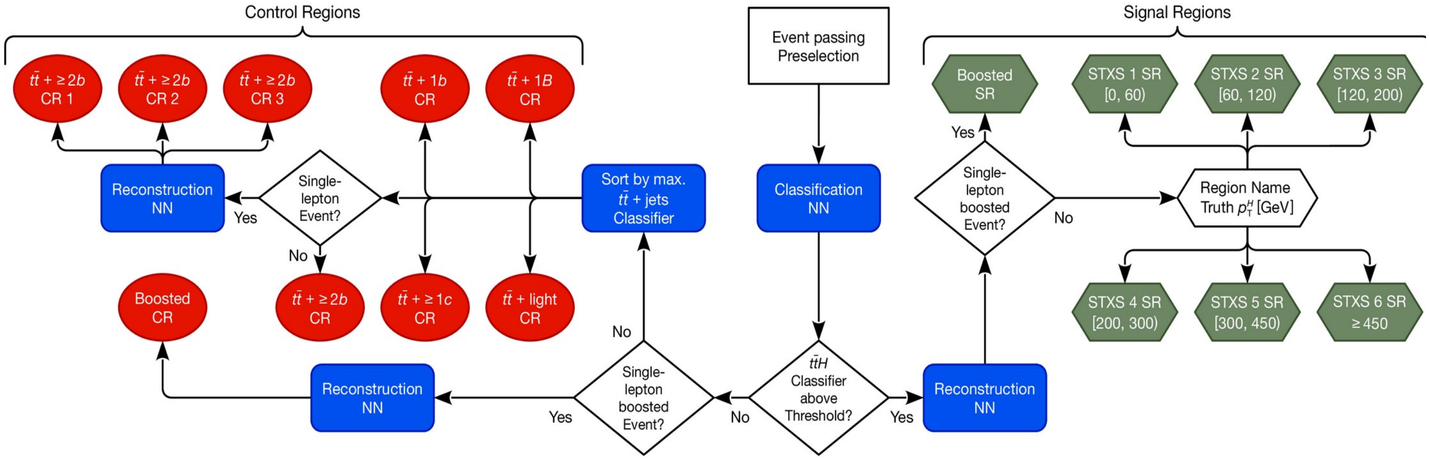
Run 2 physics harvest is ending, but interesting results coming
→ In particular final Run 2 ATLAS+CMS combinations

Focus now on Run 3 : higher collision energy and aiming for 2 × larger dataset – There is much more to come!

Additional Material

ttH→bb

ATLAS Final Run 2 ttH→bb measurement



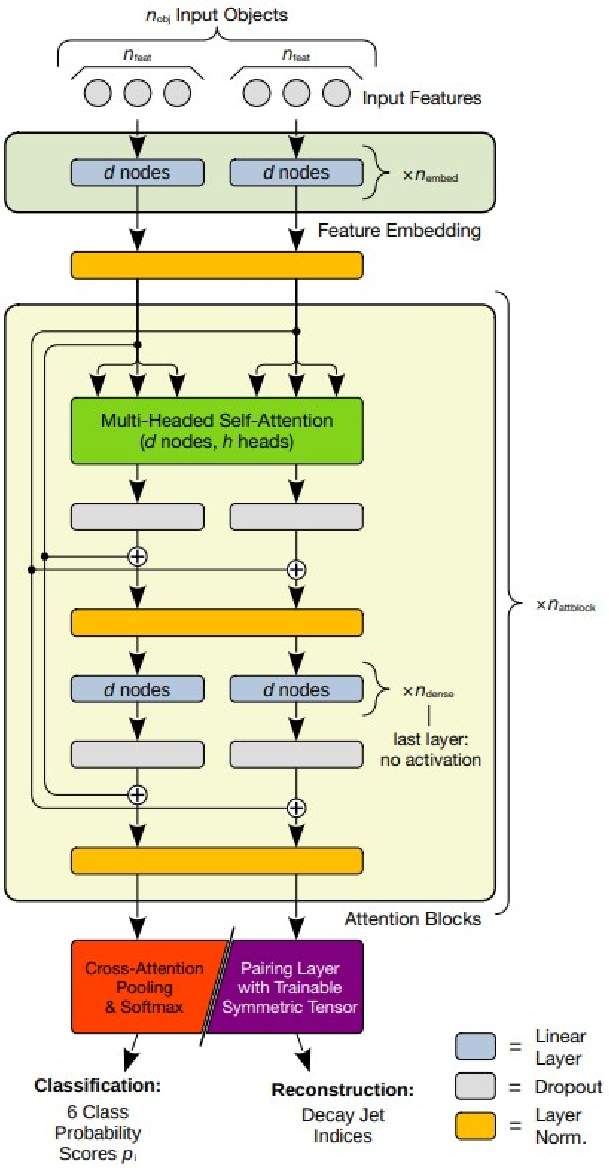
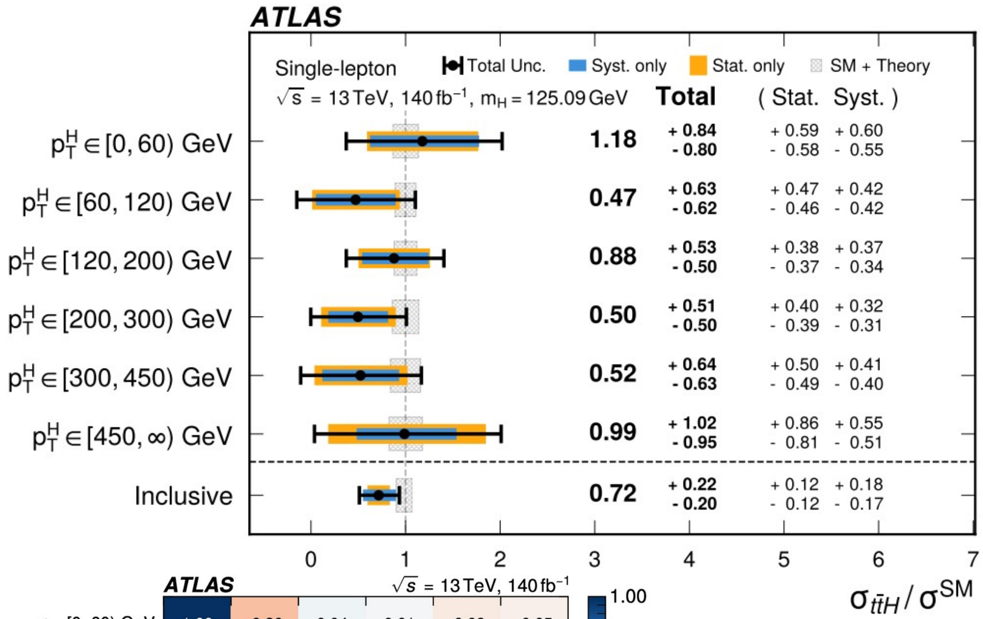
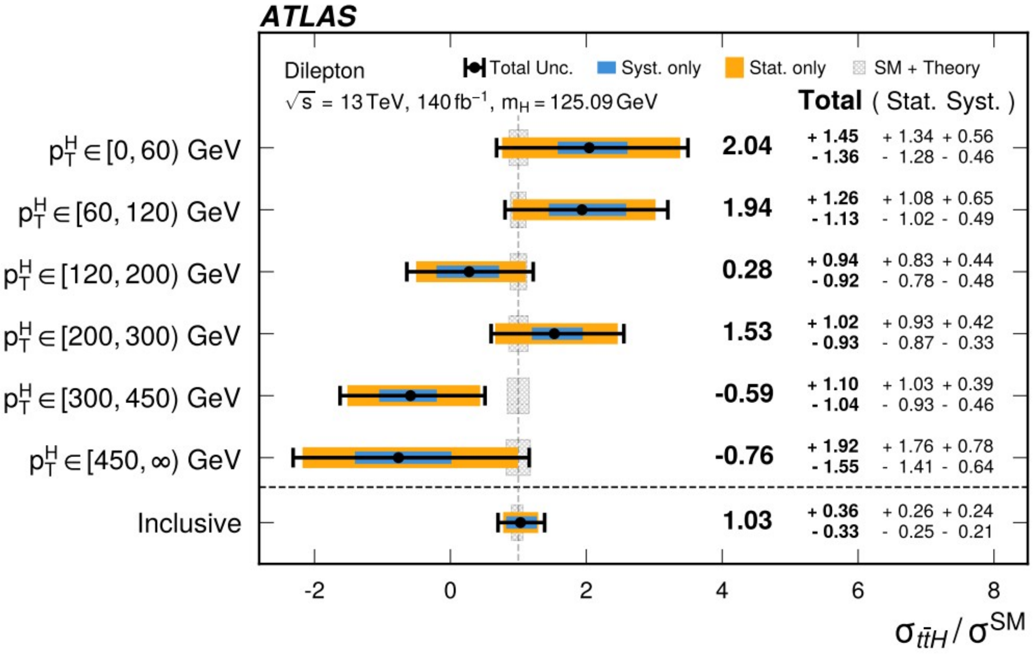
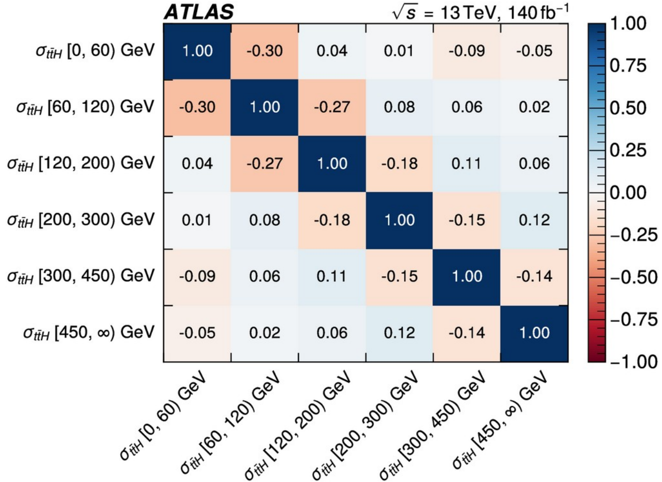


Figure 18: Schematic of the classification and reconstruction neural networks using a permutation-invariant transformer architecture. Feature embedding is performed using two fully connected feed-forward layers ($n_{\text{embed}} = 2$) that transform the object-wise input features into $d = 256$ (128) latent features for the classification (reconstruction) task. The latent feature representation is then passed through multi-headed attention blocks, each composed of a self-attention layer with $h = 4$ (8) attention heads for the classification (reconstruction) task. The attention layers are followed by object-wise feed-forward blocks. Depending on the top decay channel and the task, 8 to 11 attention blocks (n_{attblock}) and 3 to 5 dense layers (n_{dense}) are used. For the event classification task, the latent features are transformed into a single output node per class, using a cross-attention layer followed by a single fully connected feed-forward layer. For the p_T^H reconstruction, a pairing layer with a similar structure to SPANet's *tensor attention* [Phys. Rev. D **105** (2022) 112008] is used to identify the two jets originating from the Higgs boson decay.

ATLAS Final Run 2 ttH→bb measurement

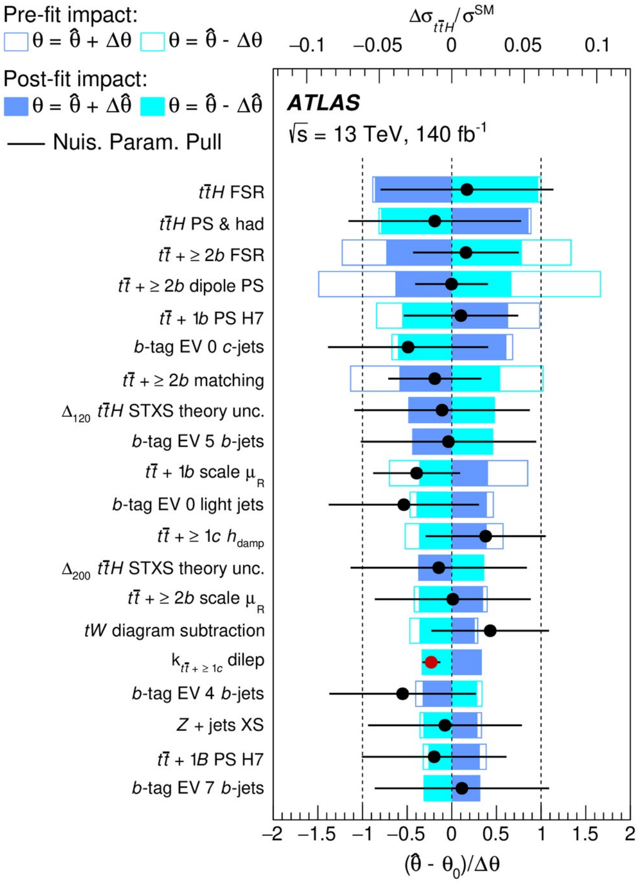




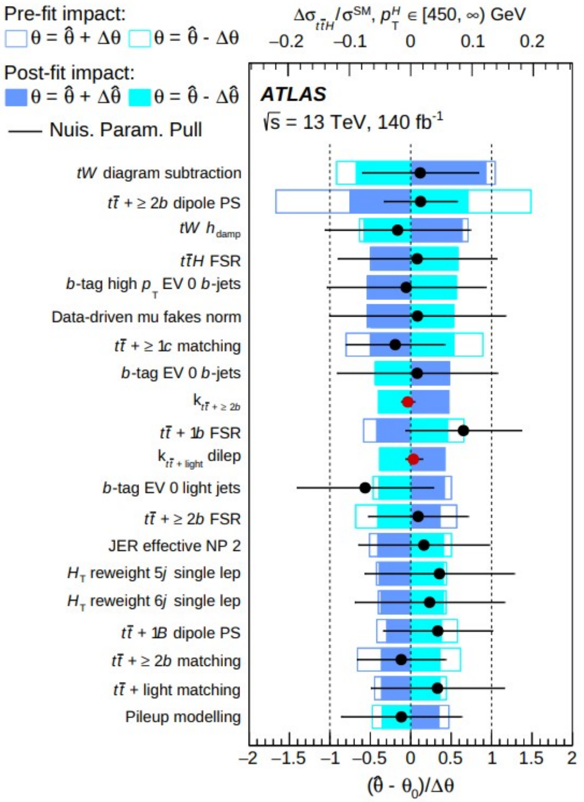


Normalisation factor	$t\bar{t}+$ light	$t\bar{t}+\geq 1c$	$t\bar{t}+1b$	$t\bar{t}+1B$	$t\bar{t}+\geq 2b$
Single-lepton	$0.78^{+0.08}_{-0.08}$	$1.51^{+0.19}_{-0.18}$	$1.06^{+0.10}_{-0.10}$	$1.15^{+0.15}_{-0.14}$	$0.94^{+0.08}_{-0.08}$
Dilepton	$0.88^{+0.11}_{-0.10}$	$1.36^{+0.10}_{-0.10}$	$1.24^{+0.09}_{-0.09}$		

ATLAS Final Run 2 ttH→bb measurement



Uncertainty source	$\Delta\sigma_{t\bar{t}H}$ (fb)		$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ (%)	
Process modelling				
$t\bar{t}H$ modelling				
$t\bar{t}H$ radiation	+35	−21	+9	−5
$t\bar{t}H$ parton shower	+32	−19	+8	−5
$t\bar{t}H$ matching	<0.1	−0.3	<0.1	−0.1
$t\bar{t}H$ theory	+25	−17	+6	−4
$t\bar{t}+\geq 1b$ modelling				
$t\bar{t}+\geq 1b$ radiation	±31		±8	
$t\bar{t}+\geq 1b$ parton shower	±29		±7	
$t\bar{t}+\geq 1b$ matching	±19		±5	
$t\bar{t}+\geq 1c$ modelling	±18		±4	
$t\bar{t}$ + light modelling	±5		±1	
tW modelling	±16		±4	
Minor background modelling	±19		±5	
Flavour tagging	±36		±9	
Jet modelling	±22		±5	
Monte-Carlo statistics	±17		±4	
Other instrumental	±10		±2	
Total systematic uncertainty	+85	−75	+21	−18
Normalisation factors	±21		±5	
Total statistical uncertainty	±54		±13	
Total uncertainty	+101	−92	+25	−22



ATLAS Final Run 2 ttH→bb measurement

Combined $\mu_{t\bar{t}H} = 0.81^{+0.22}_{-0.19} = 0.81 \pm 0.11(\text{stat.})\,^{+0.20}_{-0.16}(\text{syst.}).$ 4.6σ (5.4σ)

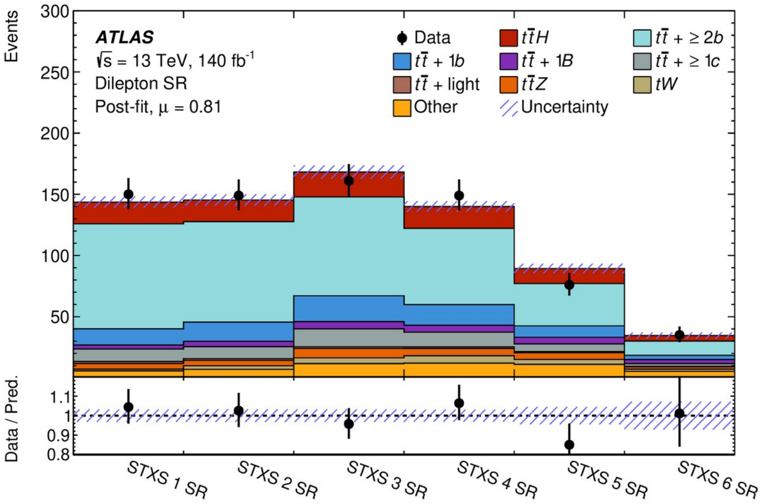
1l $\mu_{t\bar{t}H} = 0.72 \pm 0.12(\text{stat.})\,^{+0.21}_{-0.17}(\text{syst.})$

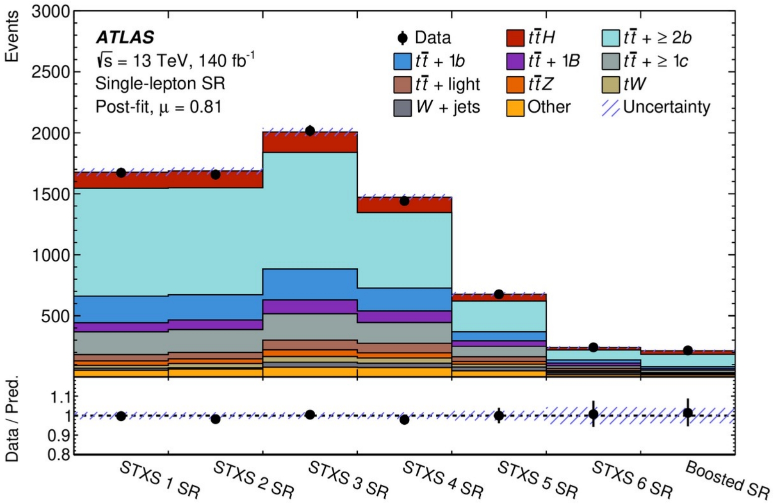
2l $\mu_{t\bar{t}H} = 1.03 \pm 0.26(\text{stat.})\,^{+0.28}_{-0.22}(\text{syst.}).$

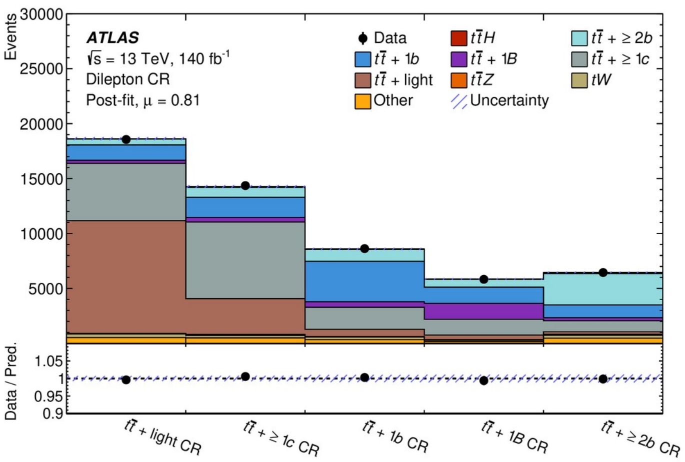
$$\sigma_{t\bar{t}H} = 411\,^{+101}_{-92}\text{ fb} = 411 \pm 54(\text{stat.})\,^{+85}_{-75}(\text{syst.})\text{ fb},$$ (SM: 507^{+35}_{-50} fb)

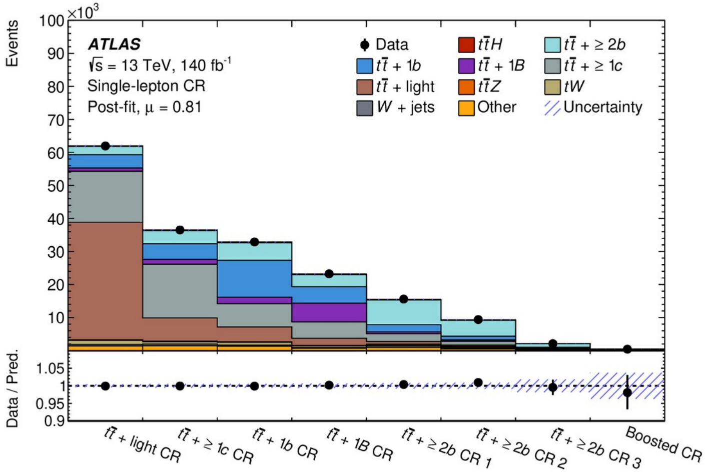
Compared with the previous analysis using the same dataset, the current analysis selects 64% (29%) new events in the single-lepton (dilepton) SR that didn't enter the selection of the previous analysis. This is consistent with the increase of the overall acceptance by a factor of three. The statistical correlation between the two analyses is estimated using a booststrap method to be 19%, assuming that the systematic uncertainties are independent. This assumption is justified by the fact that the systematic model of the most important $t\bar{t} + \geq 1b$ background is different between the two analyses and the experimental uncertainties are updated. Based on this, the probability that the current result is compatible with the result of Ref. [20] is estimated as 21%.

ATLAS Final Run 2 ttH→bb measurement

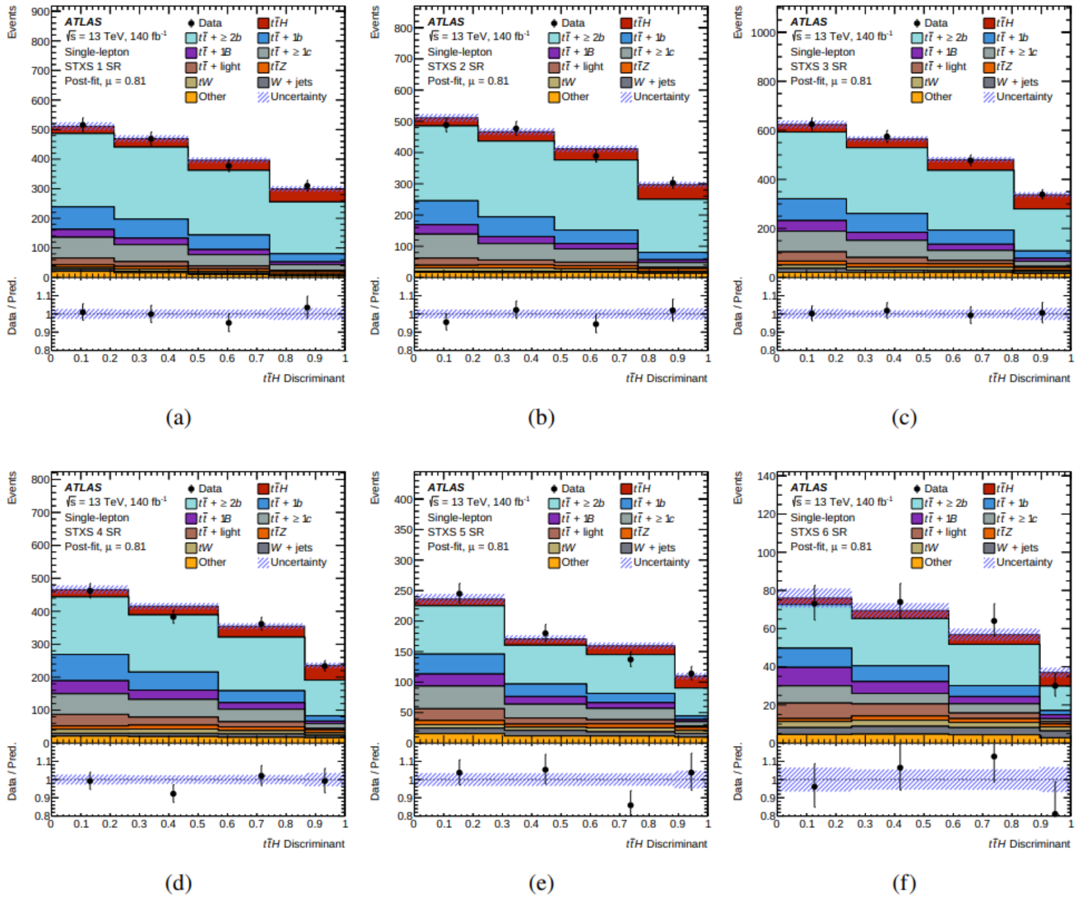


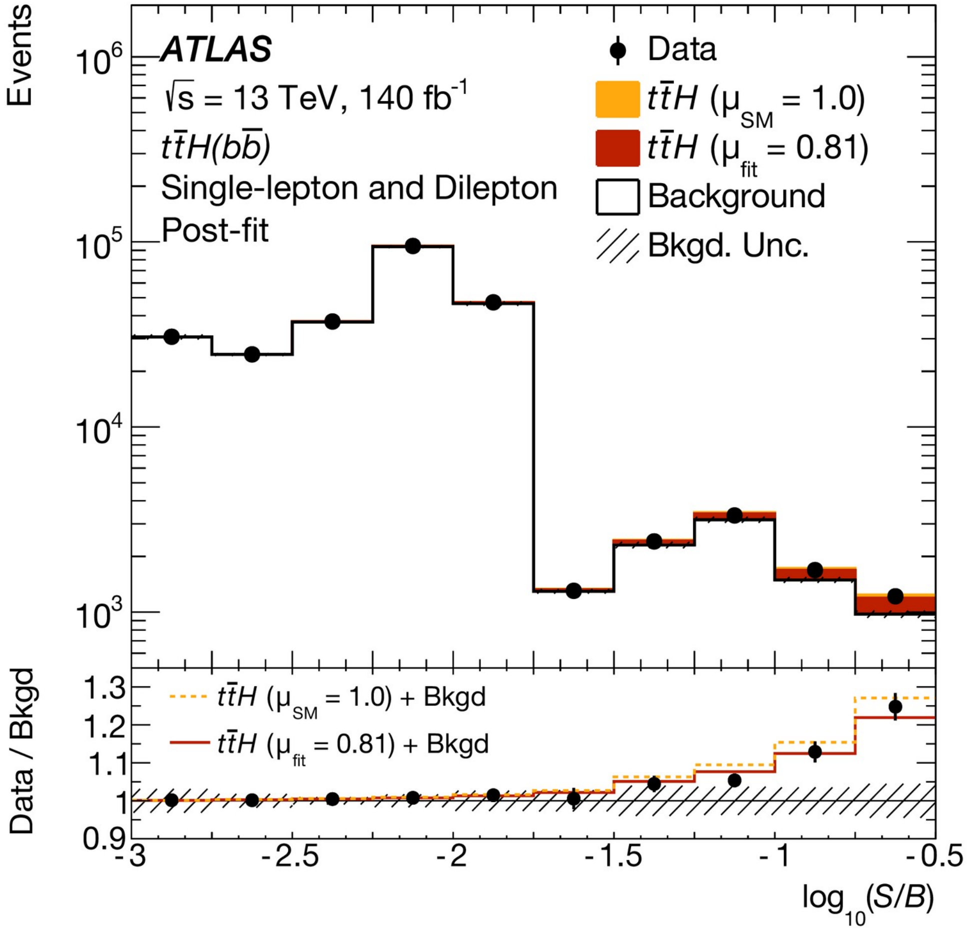






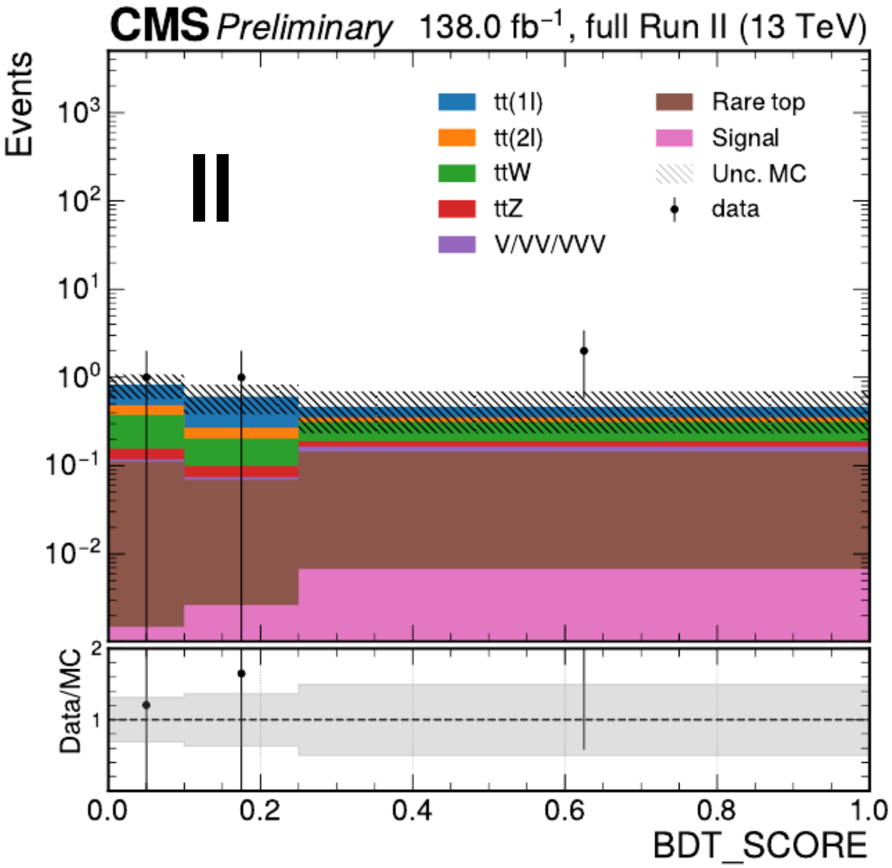
ATLAS Final Run 2 ttH→bb measurement

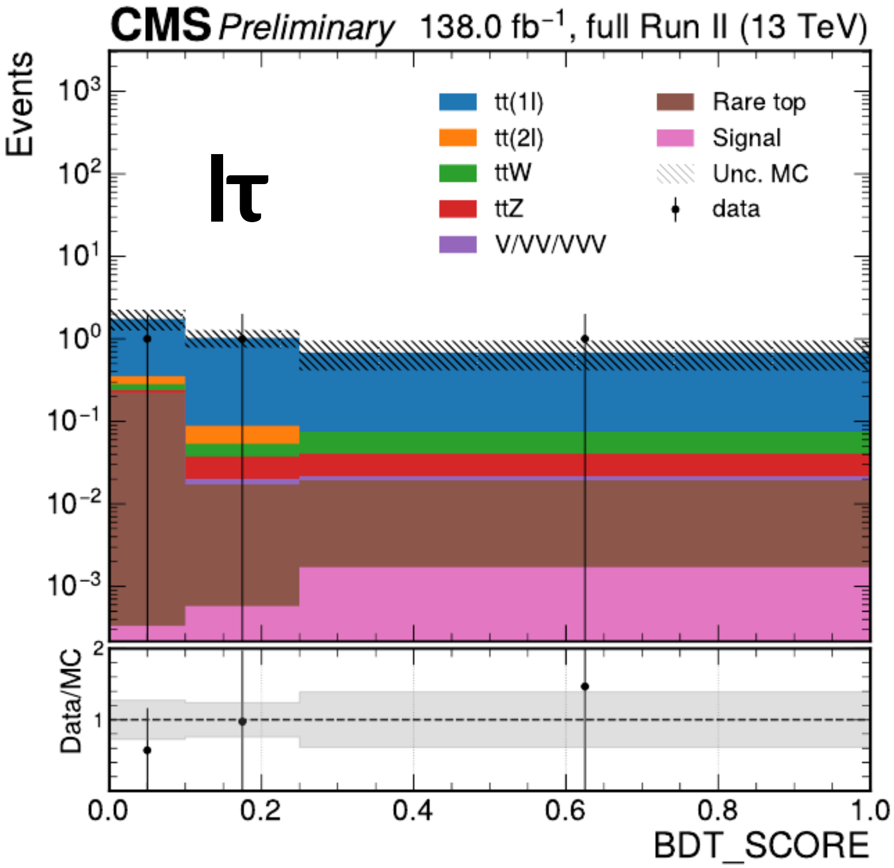




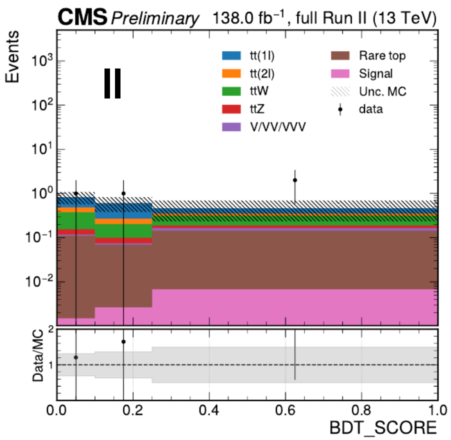
CMS WW $H \rightarrow bb$

CMS Search for WW H→bb in Vector-boson Scattering

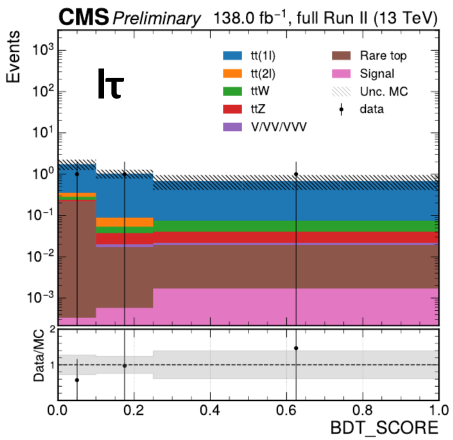




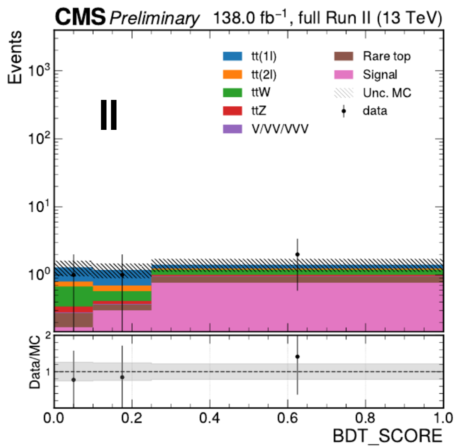
CMS Search for WW H→bb in Vector-boson Scattering



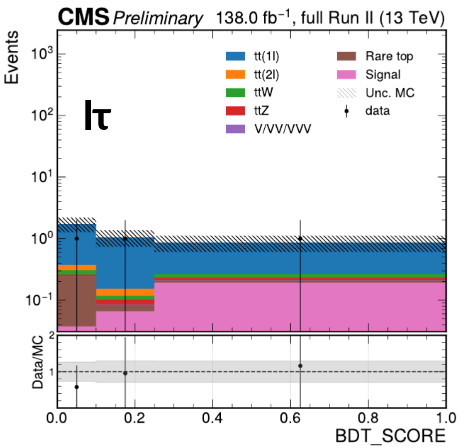
(a)



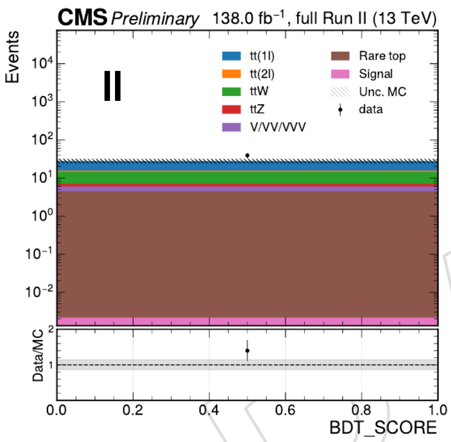
(b)

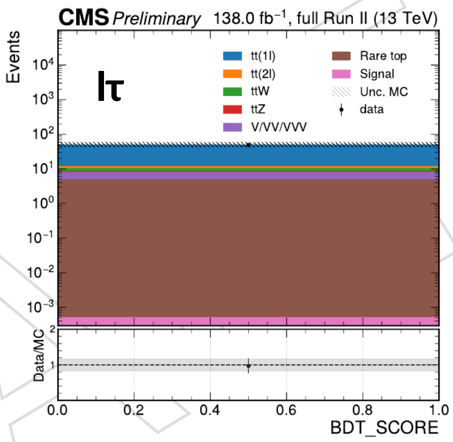


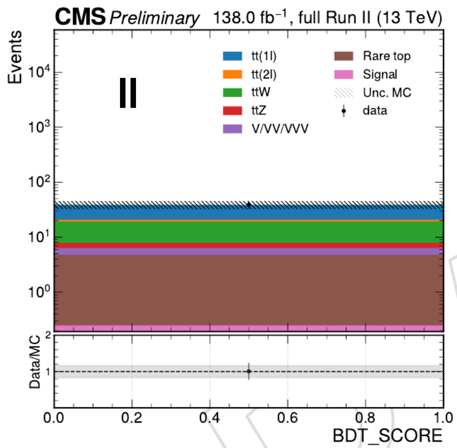
(a)

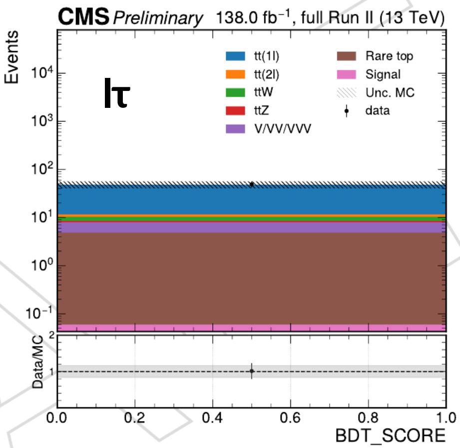


(b)



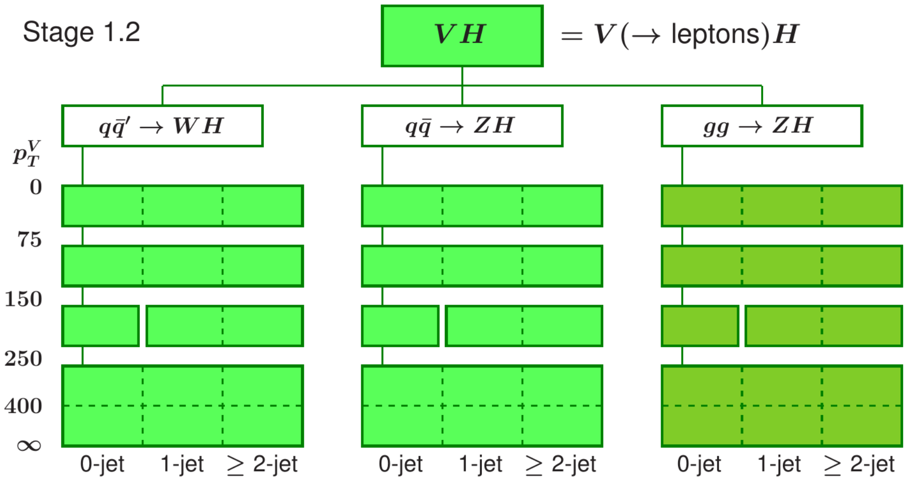


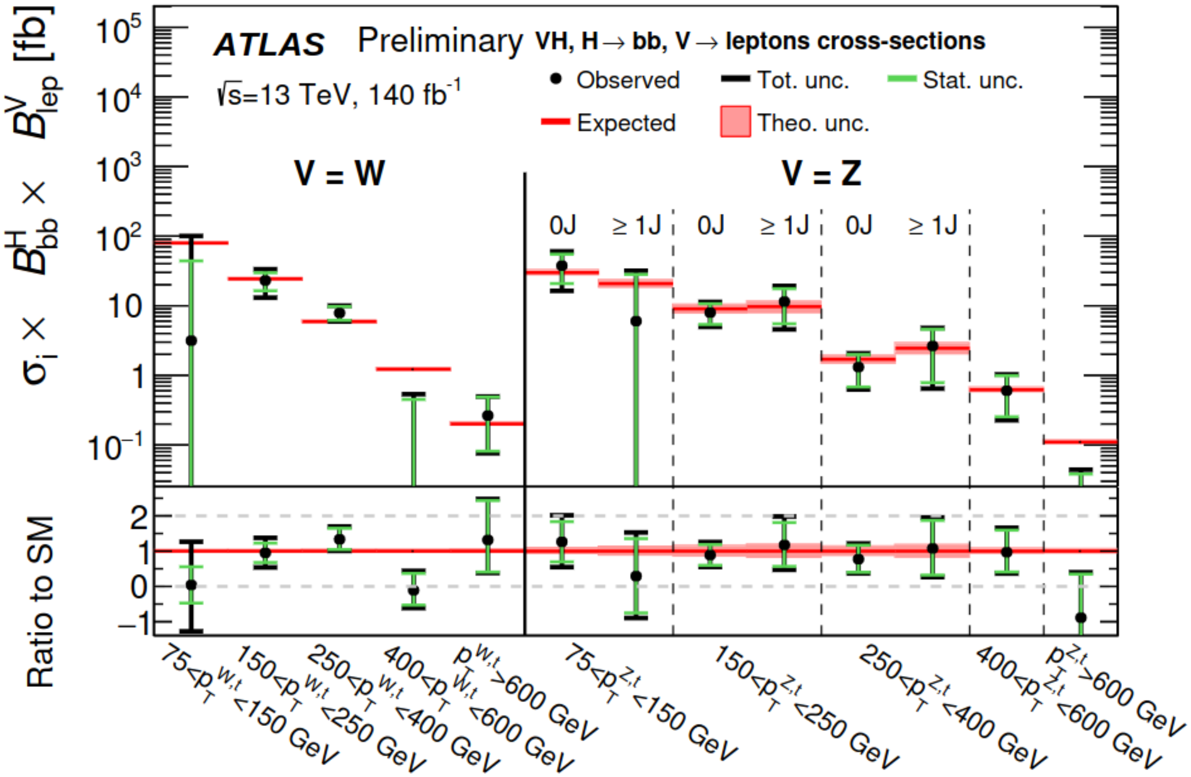




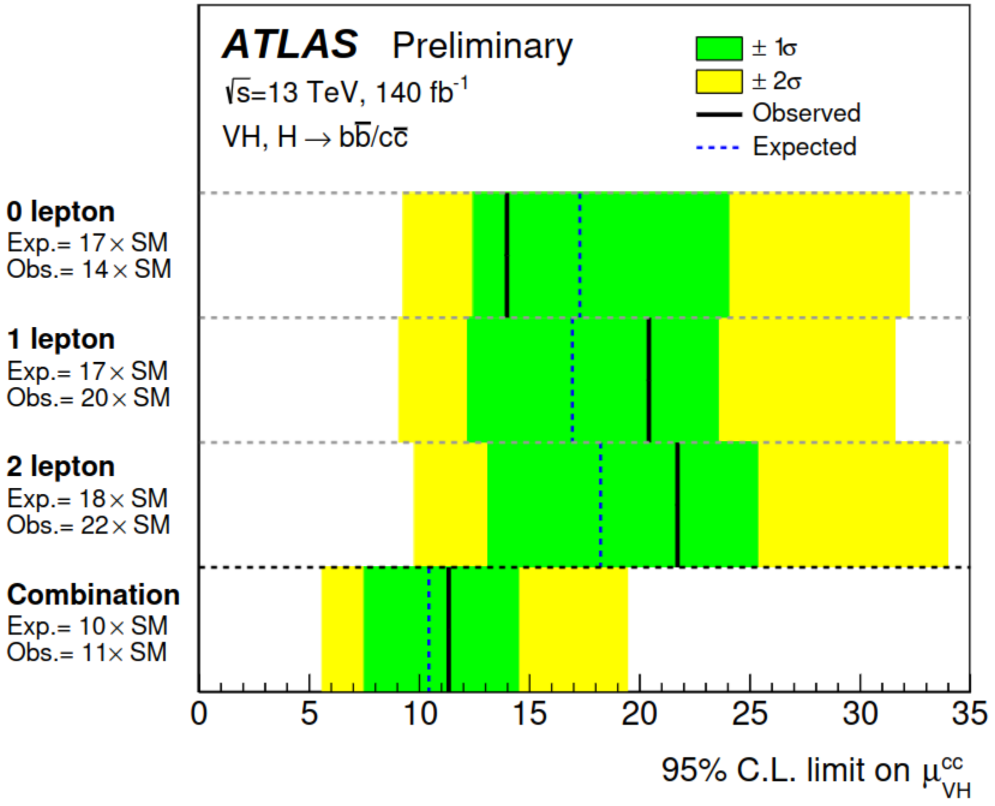
ATLAS VH→bb|cc

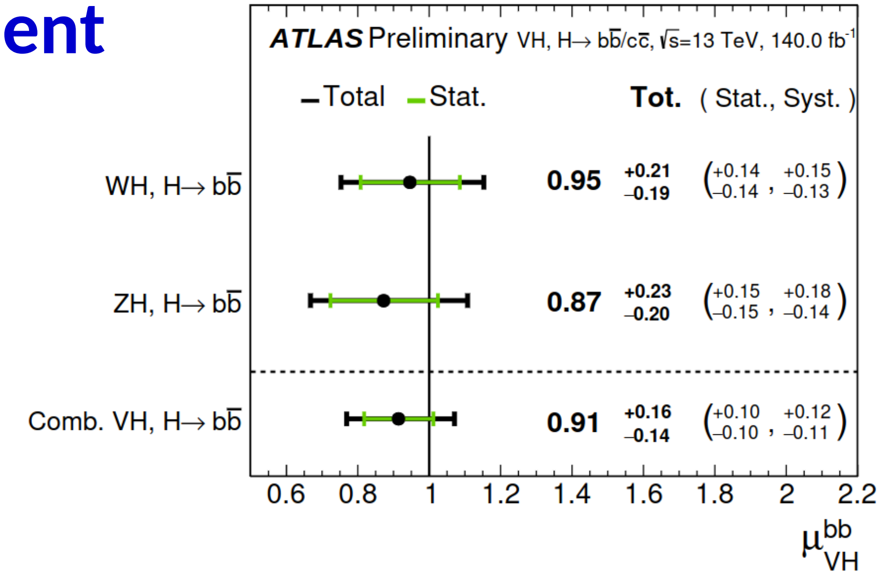
ATLAS Final Run 2 VH→bb|cc measurement

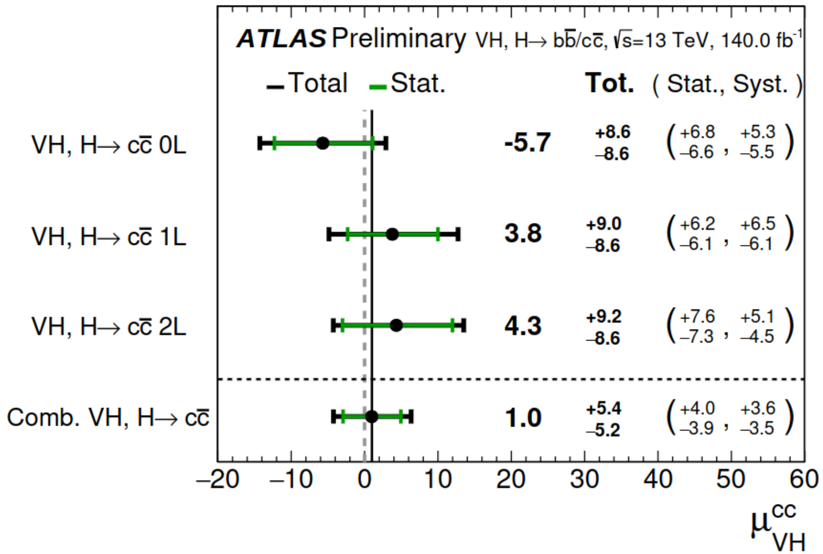




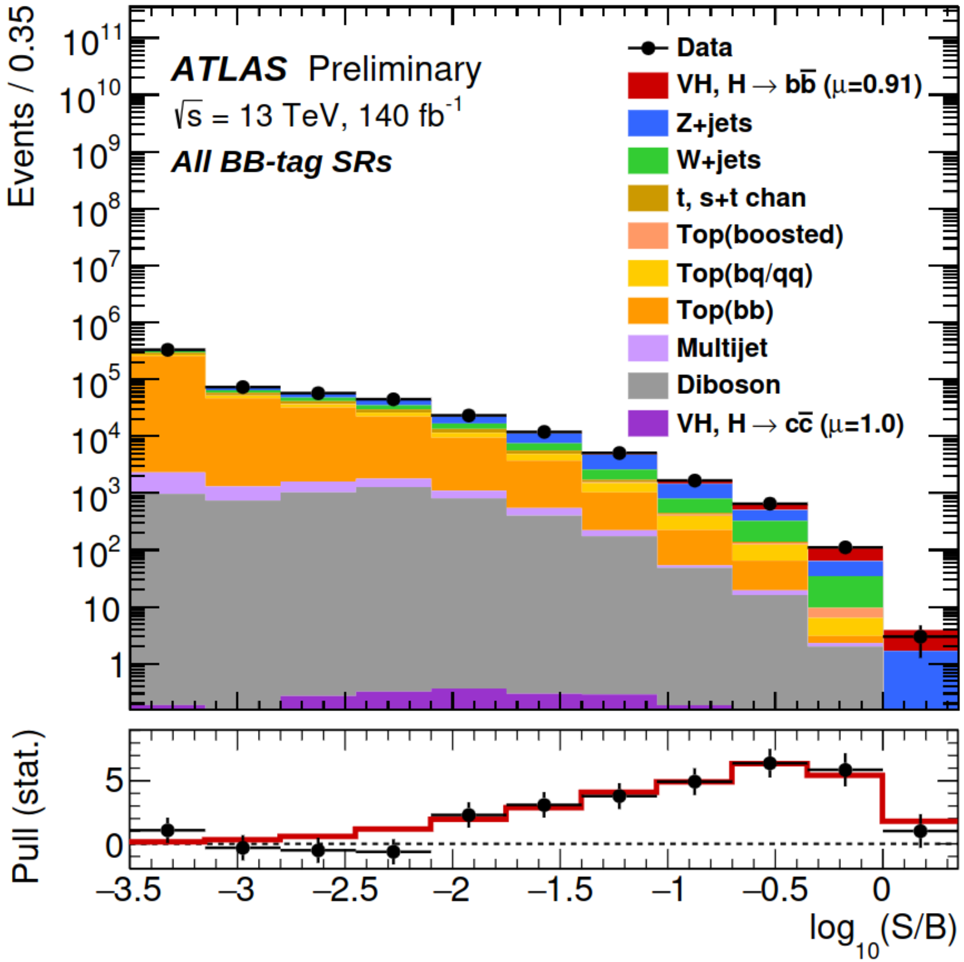
ATLAS Final Run 2 VH→bb measurement

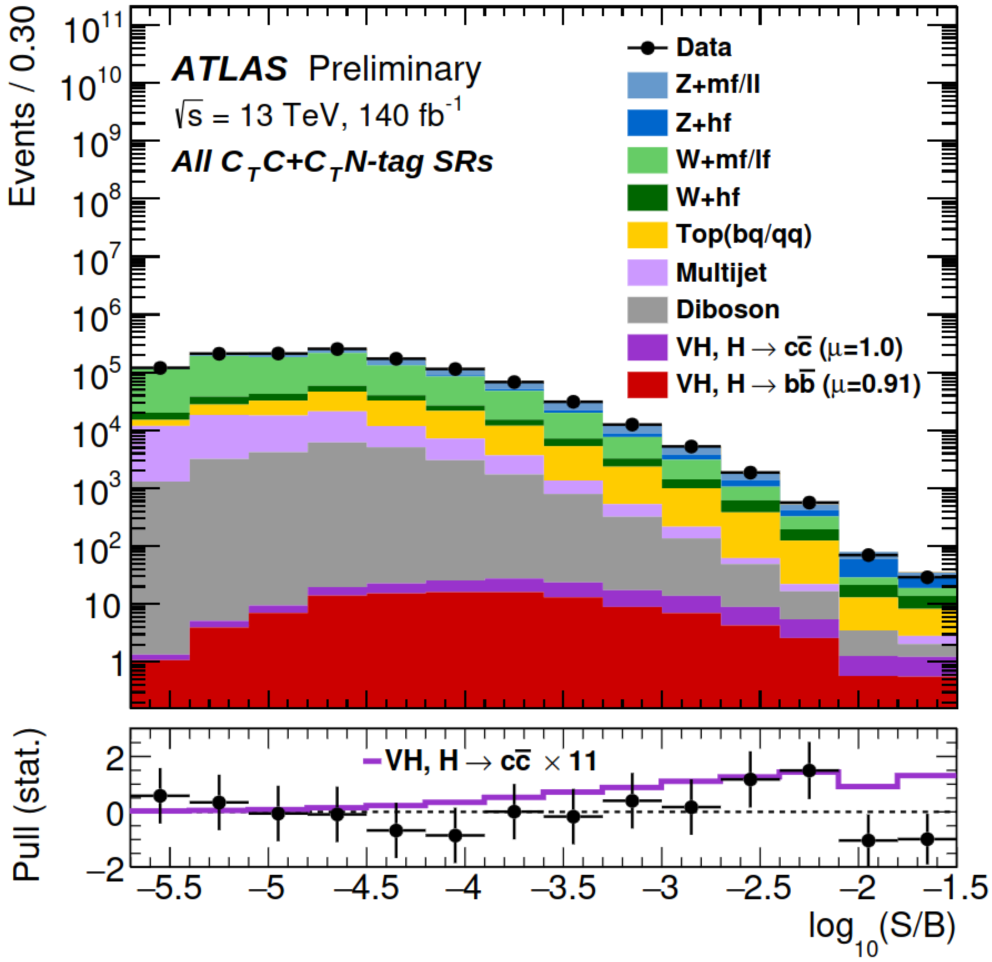




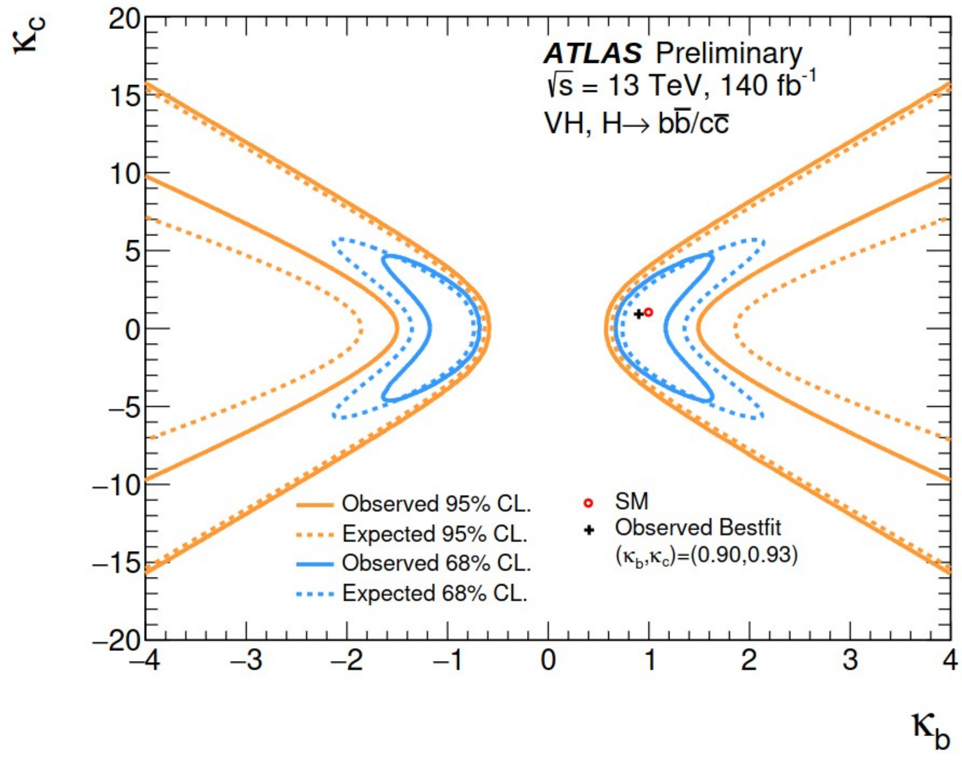


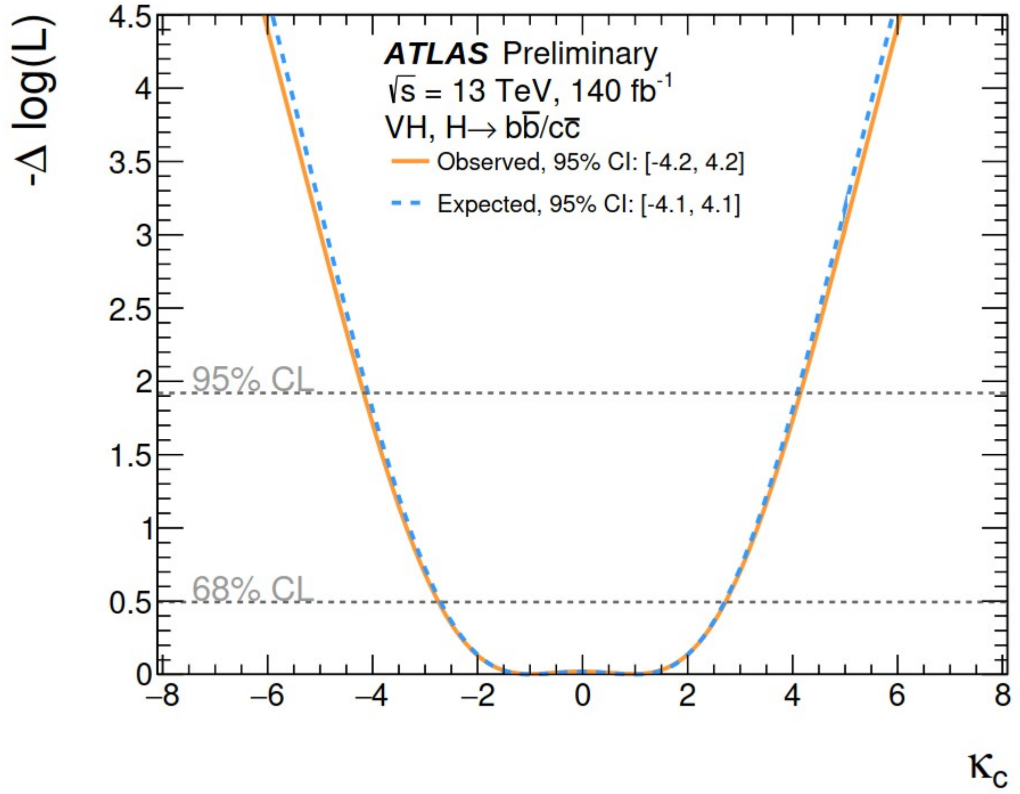
ATLAS Final Run 2 VH→bb measurement





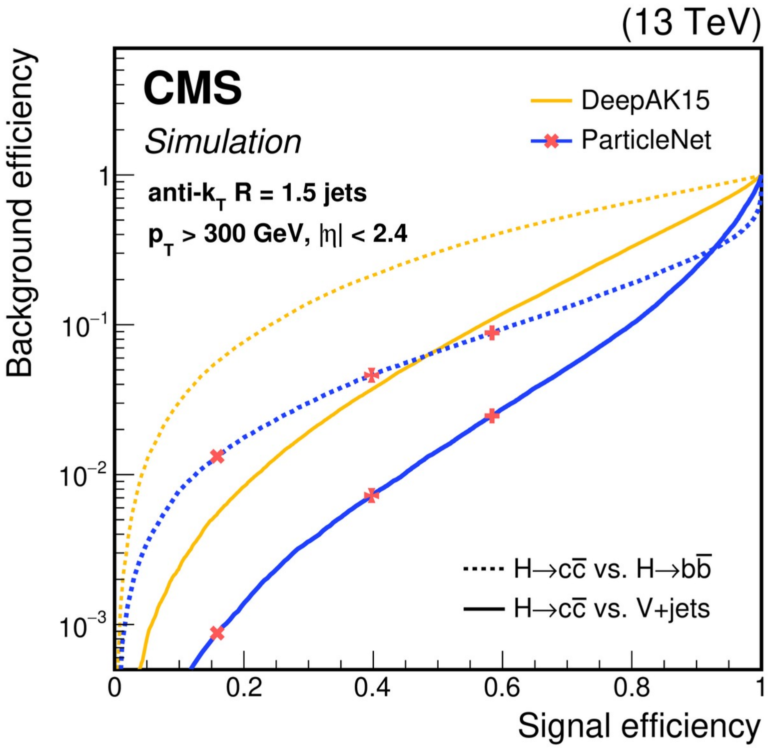
ATLAS Final Run 2 VH→bb measurement





CMS VH→cc

CMS H→cc



Uncertainty source	$\Delta\mu / (\Delta\mu)_{tot}$
Statistical	85%
Background normalizations	37%
Experimental	48%
Sizes of the simulated samples	37%
c jet identification efficiencies	23%
Jet energy scale and resolution	15%
Simulation modeling	11%
Integrated luminosity	6%
Lepton identification efficiencies	4%
Theory	22%
Backgrounds	17%
Signal	15%

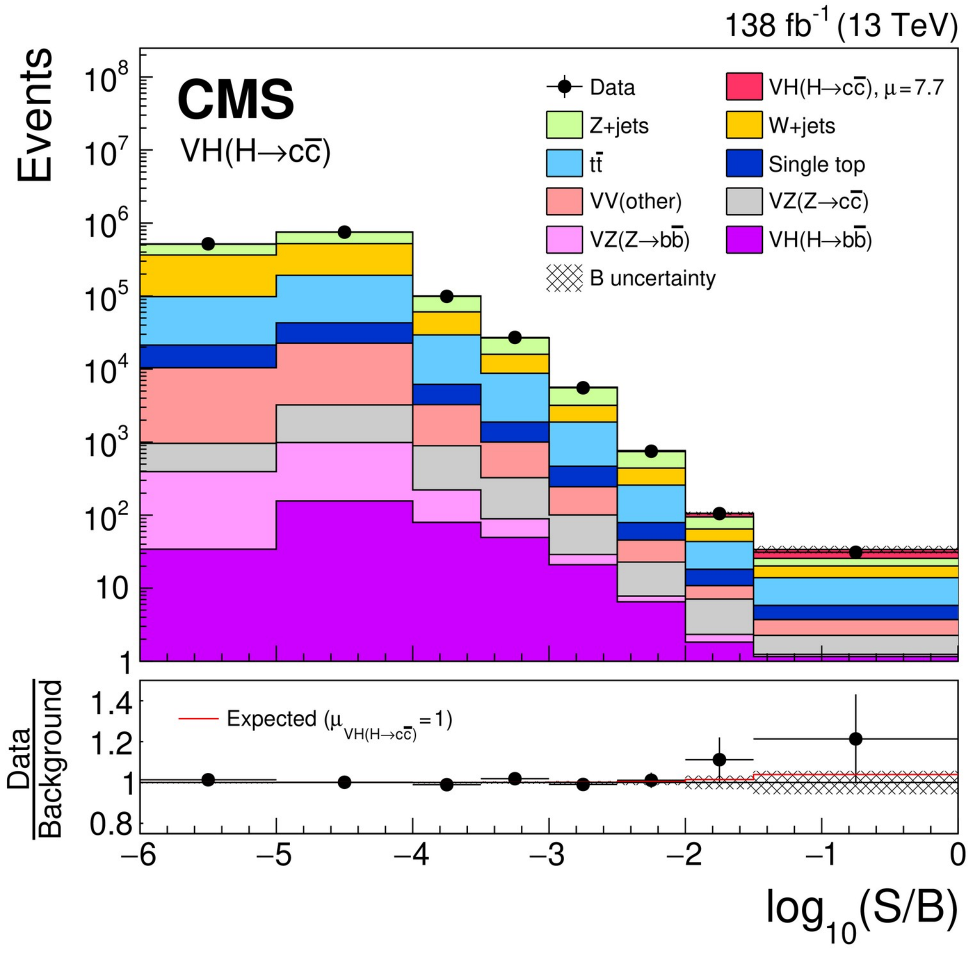
μ(VH→cc) = $7.7^{+3.8}_{-3.5}$

Expected $|\kappa_c| < 3.4$, observed $1.1 < |\kappa_c| < 5.5$

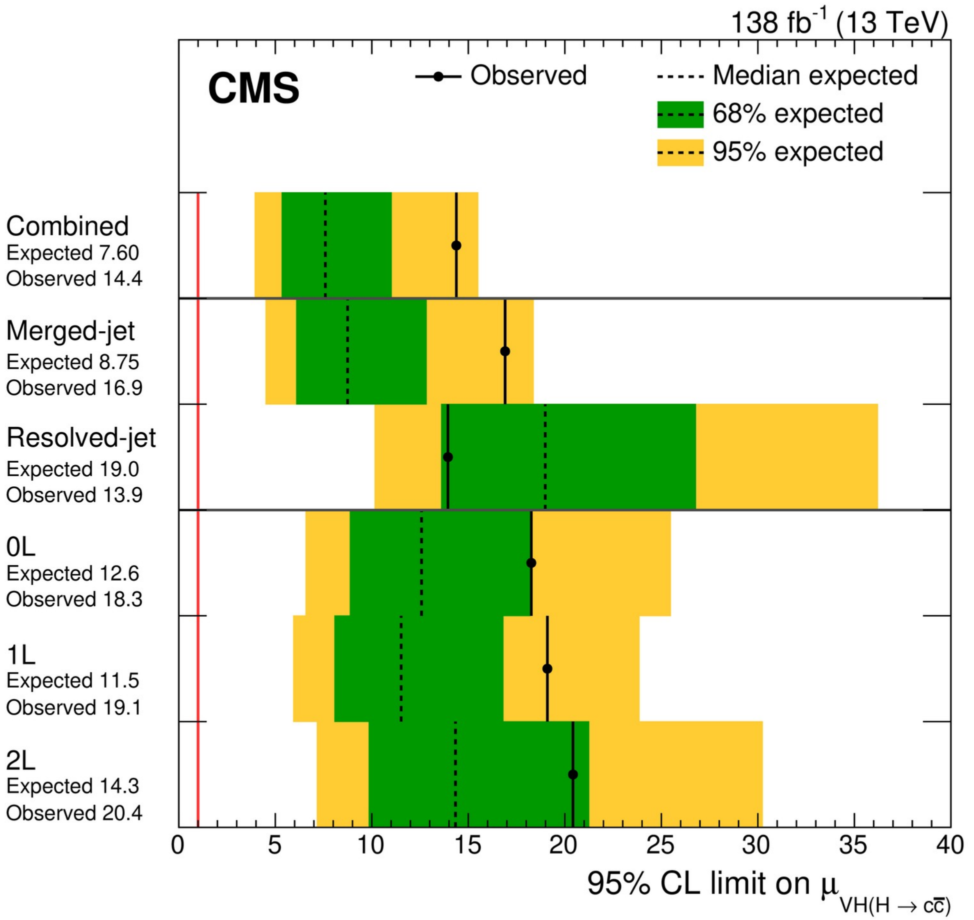
μ(VZ→cc) = $1.01^{+0.23}_{-0.21}$ ⇒ 5.7σ (5.9σ)

$$\mu_{VH(H\to c\bar{c})} = \frac{\kappa_c^2}{1 + \mathcal{B}_{SM}(H \to c\bar{c})\,(\kappa_c^2 - 1)}$$

CMS H→cc

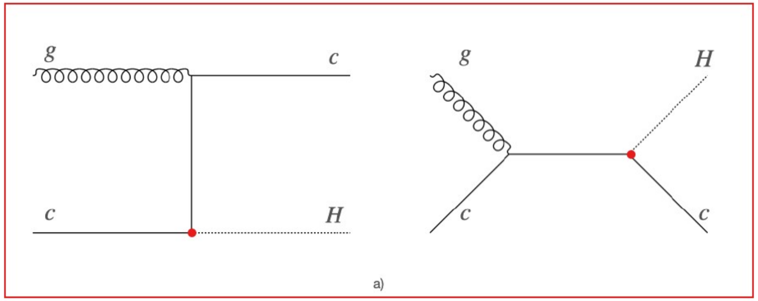


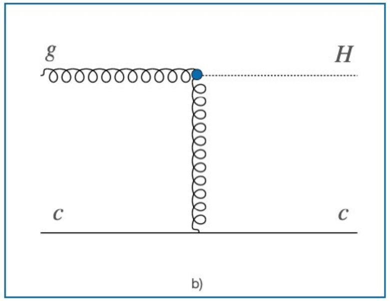
138 fb-1 (13 TeV)
CMS
VH(H→cc̄)
Data
VH(H→cc̄), μ = 7.7
Z+jets
W+jets
tt̄
Single top
VV(other)
VZ(Z→cc̄)
VZ(Z→bb̄)
VH(H→bb̄)
B uncertainty
Events
Data/Background
Expected (μVH(H→cc̄) = 1)
log10(S/B)



138 fb-1 (13 TeV)
CMS
Observed
Median expected
68% expected
95% expected
Combined
Expected 7.60
Observed 14.4
Merged-jet
Expected 8.75
Observed 16.9
Resolved-jet
Expected 19.0
Observed 13.9
0L
Expected 12.6
Observed 18.3
1L
Expected 11.5
Observed 19.1
2L
Expected 14.3
Observed 20.4
95% CL limit on μVH(H → cc̄)

CMS H→γγ + c

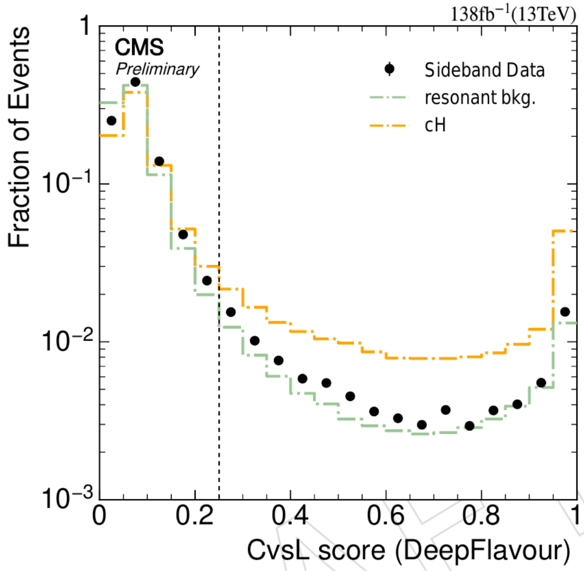




$$\sigma_{cH} = 90\,\text{fb and } \sigma_{bH} = 660\,\text{fb.}$$

	cH	ggH	ttH	VBF	VH	bH	Resonant bkg.	Continuous bkg. ($\times 10^3$)	S/B
Category 0	0.0128	2.03 (84%)	0.00059 (0.0245%)	0.128 (5.3%)	0.083 (3.4%)	0.181 (7.5%)	2.42	0.50	2.55×10^{-5}
Category 1	0.0158	2.61 (80%)	0.0108 (0.33%)	0.192 (5.9%)	0.210 (6.4%)	0.242 (7.4%)	3.26	1.53	1.03×10^{-5}
Category 2	0.0072	1.27 (72%)	0.071 (4.0%)	0.146 (8.3%)	0.161 (9.2%)	0.113 (6.4%)	1.76	7.4	9.7×10^{-7}
Category 3	0.0034	0.94 (73%)	0.00087 (0.067%)	0.208 (16.1%)	0.076 (5.8%)	0.072 (5.6%)	1.29	0.166	2.03×10^{-5}
Category 4	0.0087	2.39 (68%)	0.044 (1.24%)	0.56 (16.0%)	0.35 (9.9%)	0.173 (4.9%)	3.5	0.96	9.0×10^{-6}
Category 5	0.0094	2.74 (54%)	0.75 (14.6%)	0.69 (14.7%)	0.69 (13.5%)	0.182 (3.6%)	5.1	9.9	9.5×10^{-7}
Category 6	0.000289	0.22 (42%)	0.0099 (1.90%)	0.222 (42%)	0.063 (12.1%)	0.0077 (1.5%)	0.52	0.0192	1.47×10^{-5}
Category 7	0.00095	0.79 (43%)	0.253 (13.8%)	0.46 (25.1%)	0.31 (16.7%)	0.0232 (1.26%)	1.83	0.159	5.9×10^{-6}
Category 8	0.00165	1.19 (36%)	1.04 (31%)	0.50 (15.0%)	0.56 (16.7%)	0.036 (1.08%)	3.3	1.89	8.7×10^{-7}
All categories	0.060	14.2 (61%)	2.19 (9.5%)	3.22 (13.9%)	2.49 (10.8%)	1.03 (4.4%)	23.1	22.5	2.66×10^{-6}

Table 1: Number of expected events of cH, ggH, ttH, VBF, bH, resonant background and continuous background, as well as signal-over-background ratio (S/B), in the mass window [122.88, 127.88] GeV for all categories. For ggH, ttH, VBF, and bH, their fractions in resonant background are also given.

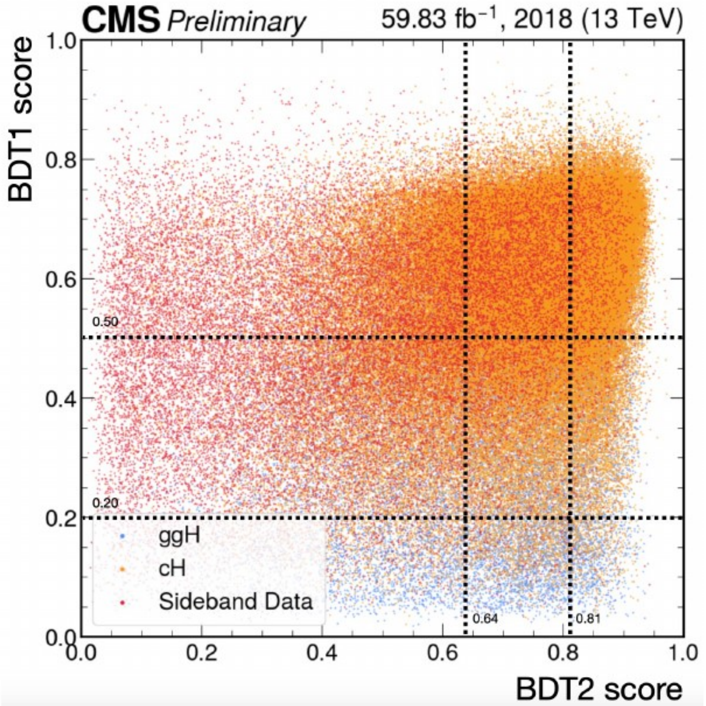


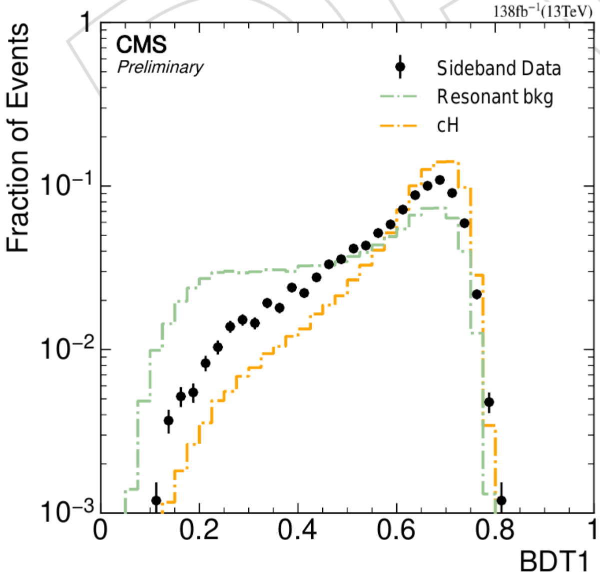
CMS H→γγ + c

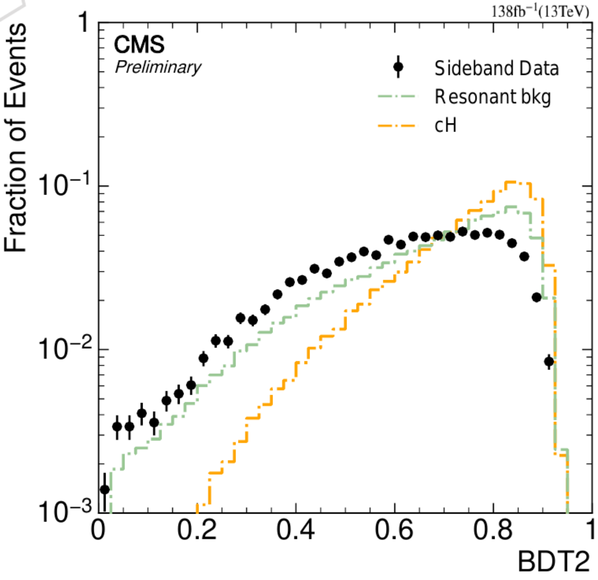
Theoretical uncertainties on cH signal	37%
Theoretical uncertainties on resonant background	41%
Experimental uncertainties on yields	37%
Experimental uncertainties on mass shapes	negligible
Luminosity uncertainties	negligible

~30% uncertainty on cH and bH FS

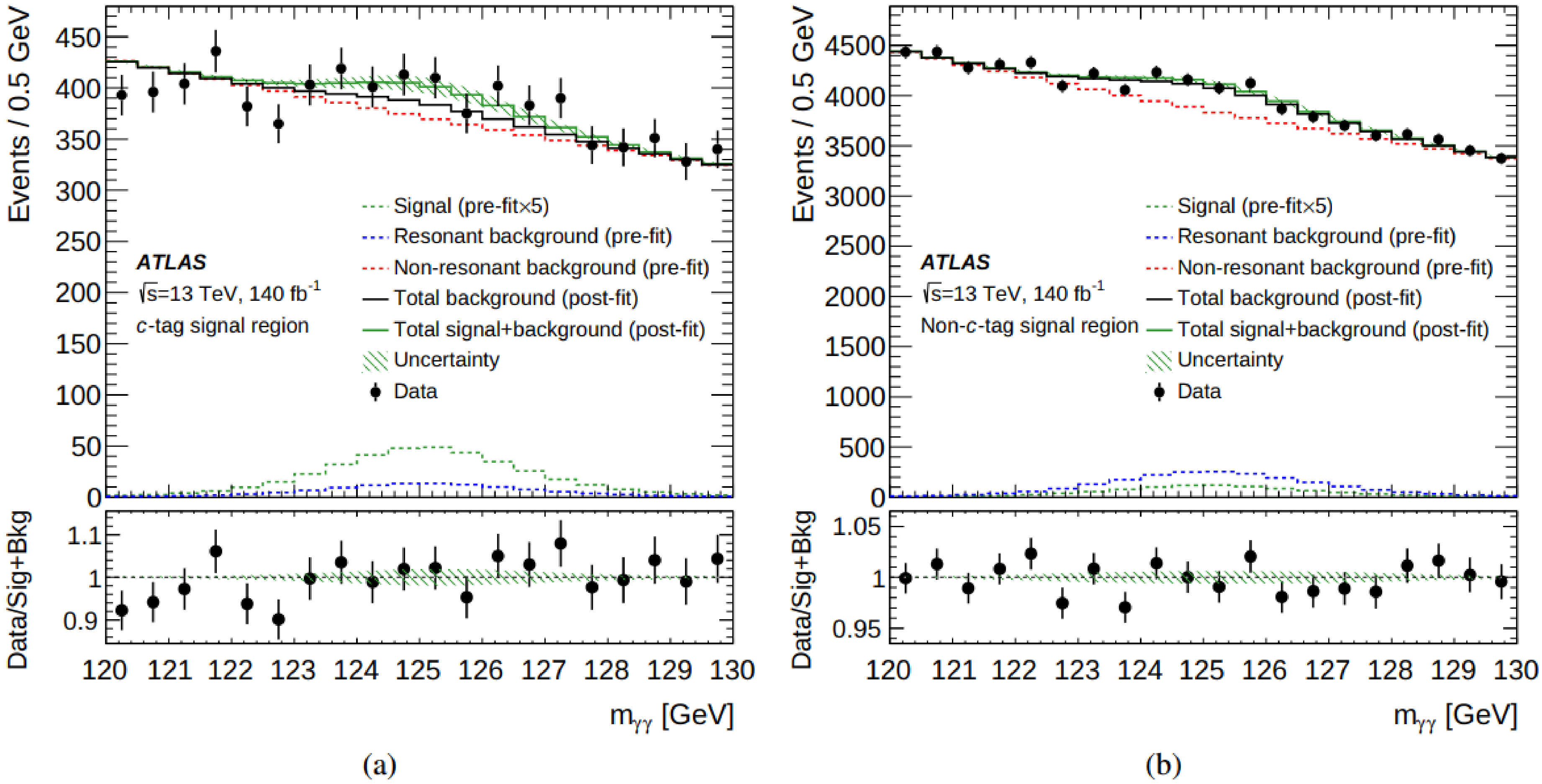
~50% uncertainty on ggF+HF







ATLAS H+c



Events / 0.5 GeV
Signal (pre-fit×5)
Resonant background (pre-fit)
Non-resonant background (pre-fit)
Total background (post-fit)
Total signal+background (post-fit)
Uncertainty
Data
ATLAS
√s=13 TeV, 140 fb^{-1}
c-tag signal region
Data/Sig+Bkg
$m_{\gamma\gamma}$ [GeV]
(a)
Events / 0.5 GeV
Signal (pre-fit×5)
Resonant background (pre-fit)
Non-resonant background (pre-fit)
Total background (post-fit)
Total signal+background (post-fit)
Uncertainty
Data
ATLAS
√s=13 TeV, 140 fb^{-1}
Non-c-tag signal region
Data/Sig+Bkg
$m_{\gamma\gamma}$ [GeV]
(b)

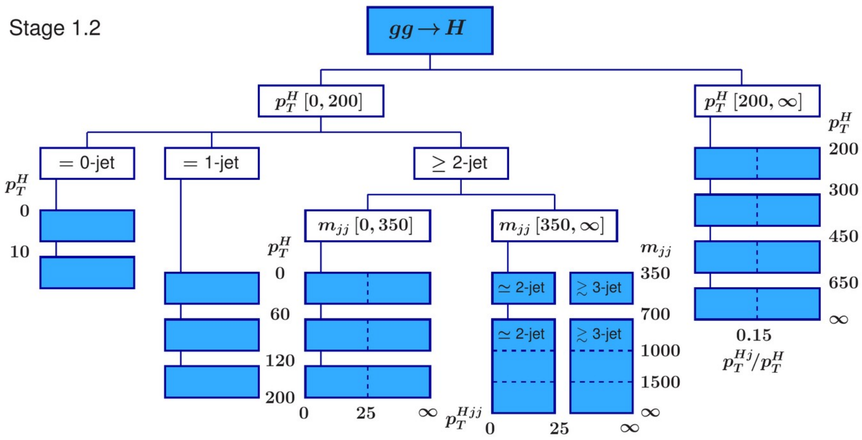
ATLAS H+c

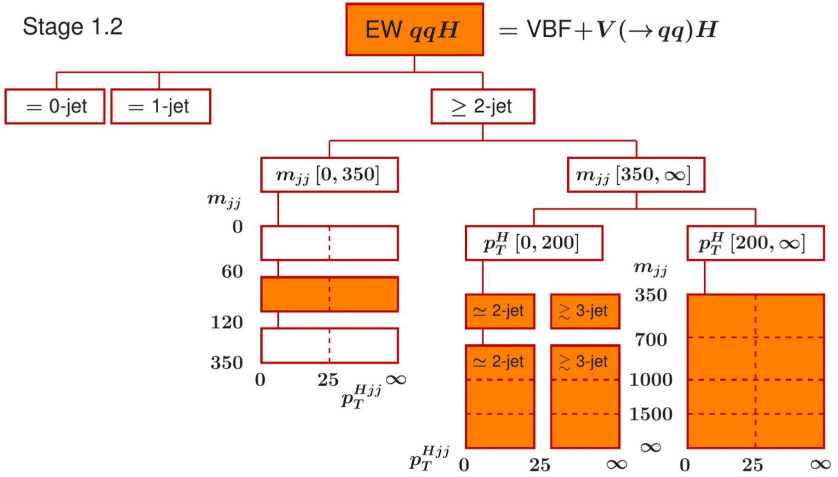
Uncertainty	$H + c$ uncertainty impact
Statistical (incl. GPR)	79%
GPR posterior	47%
Systematic (excl. GPR)	61%
Theory	40%
Photons	29%
c-tagging	29%
Jets	22%
Spurious signal	12%
Pile-up	5%

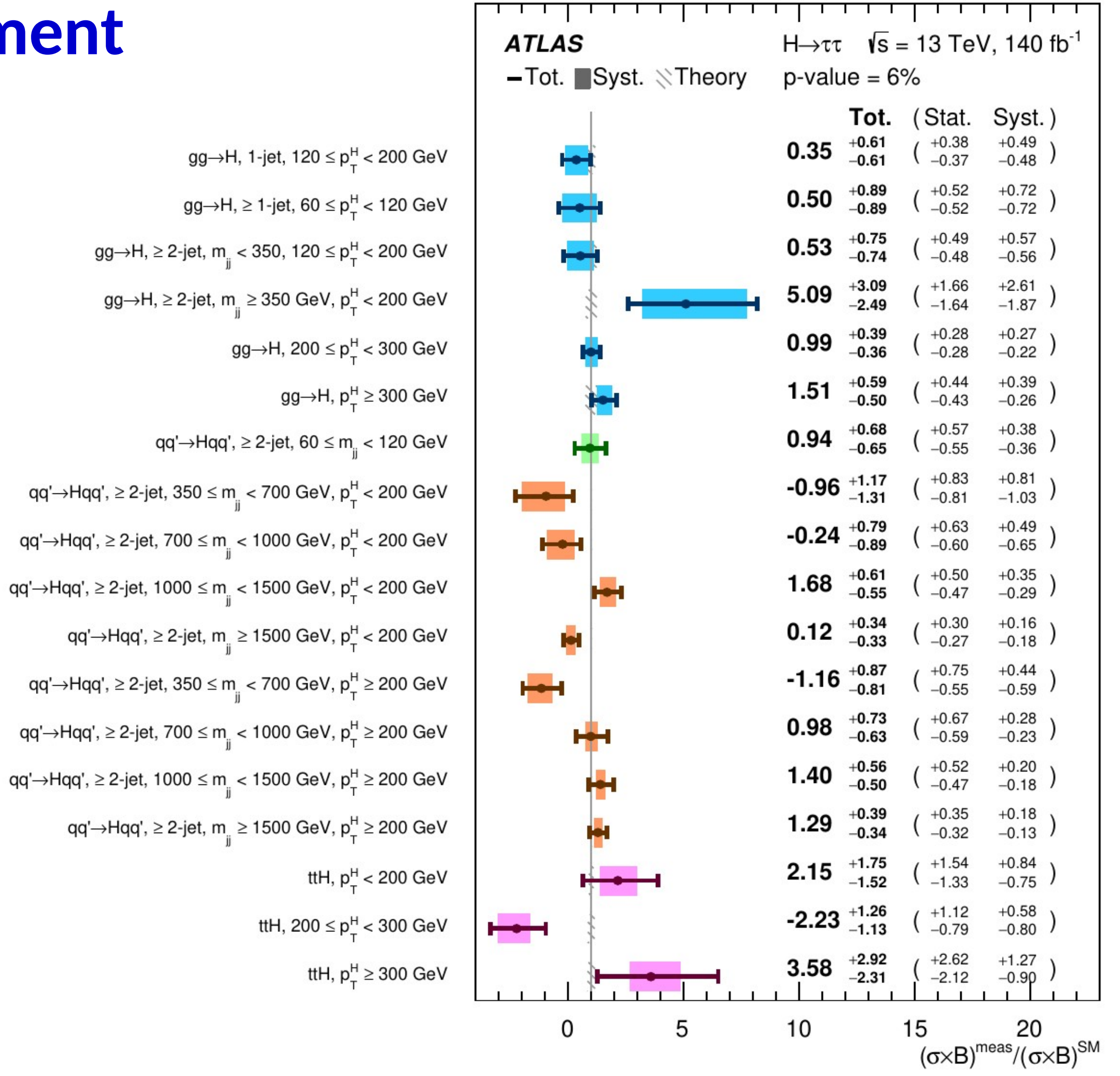
Process	c-tag signal region		Non-c-tag signal region	
	Signal	Resonant background	Signal	Resonant background
ggF H	39	82	110	1800
VBF H	17	13	34	220
WH	9.5	4.7	23	59
ZH	4.5	5.1	7.8	50
$t\bar{t}H$	7.0	4.6	20	24
$b\bar{b}H$	0.11	1.9	0.35	16
y_c-sensitive $H + c$	0.37	0.046	0.78	0.48

ATLAS H→ττ

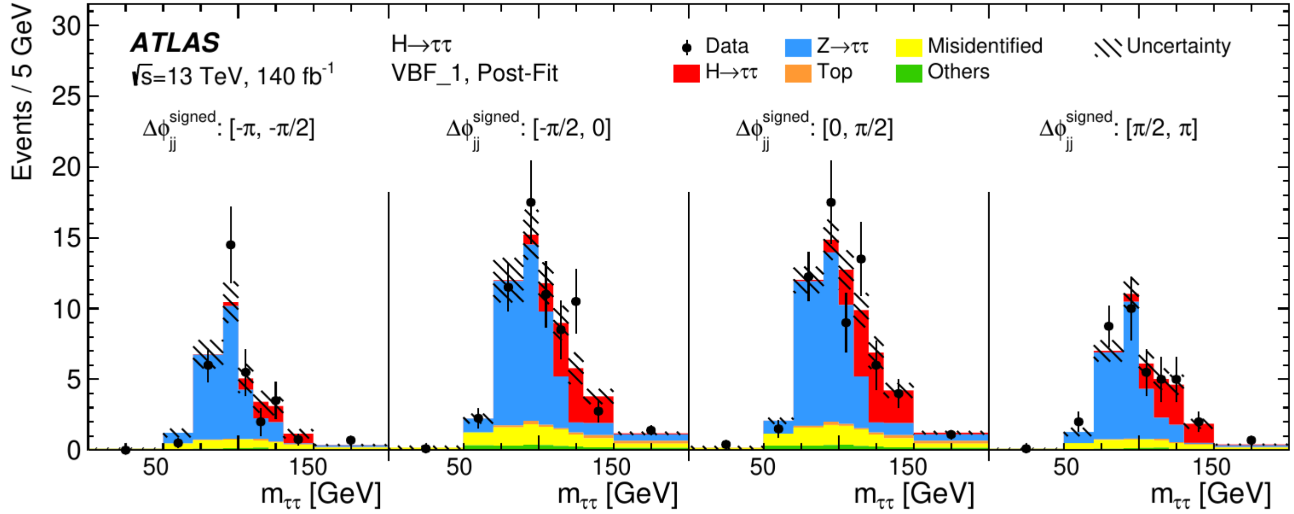
ATLAS H→ττ STXS Measurement

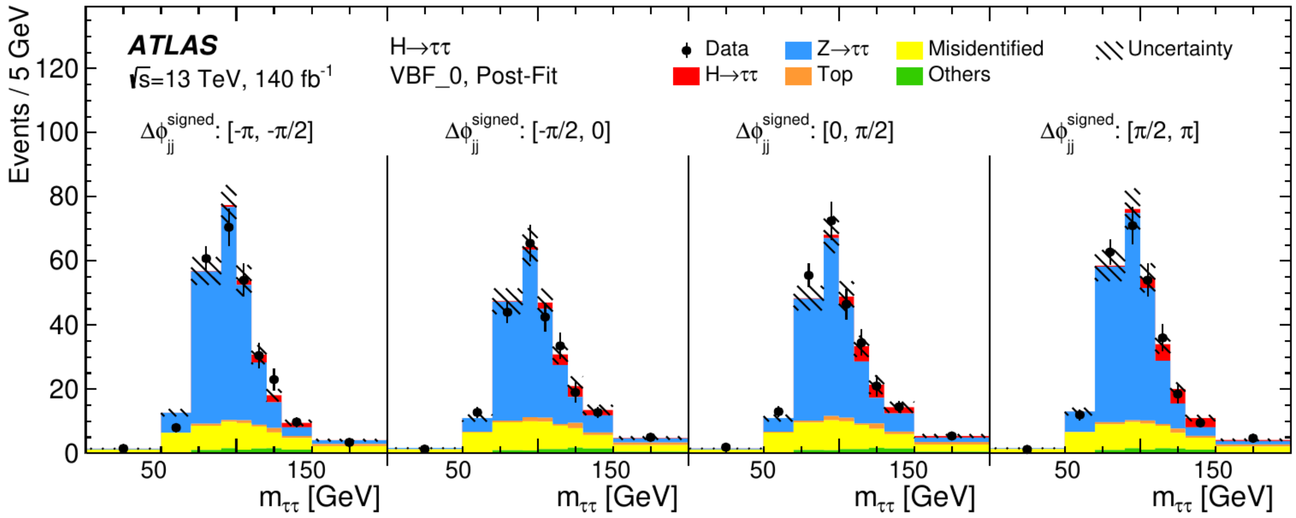


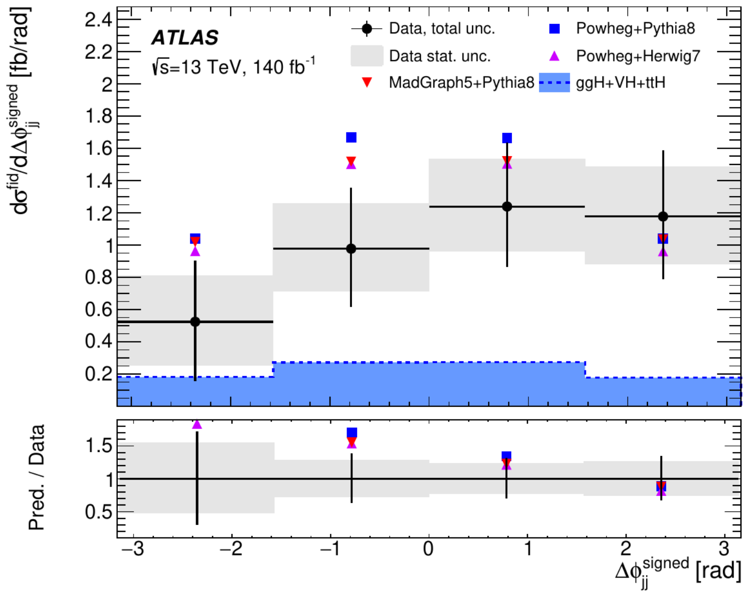




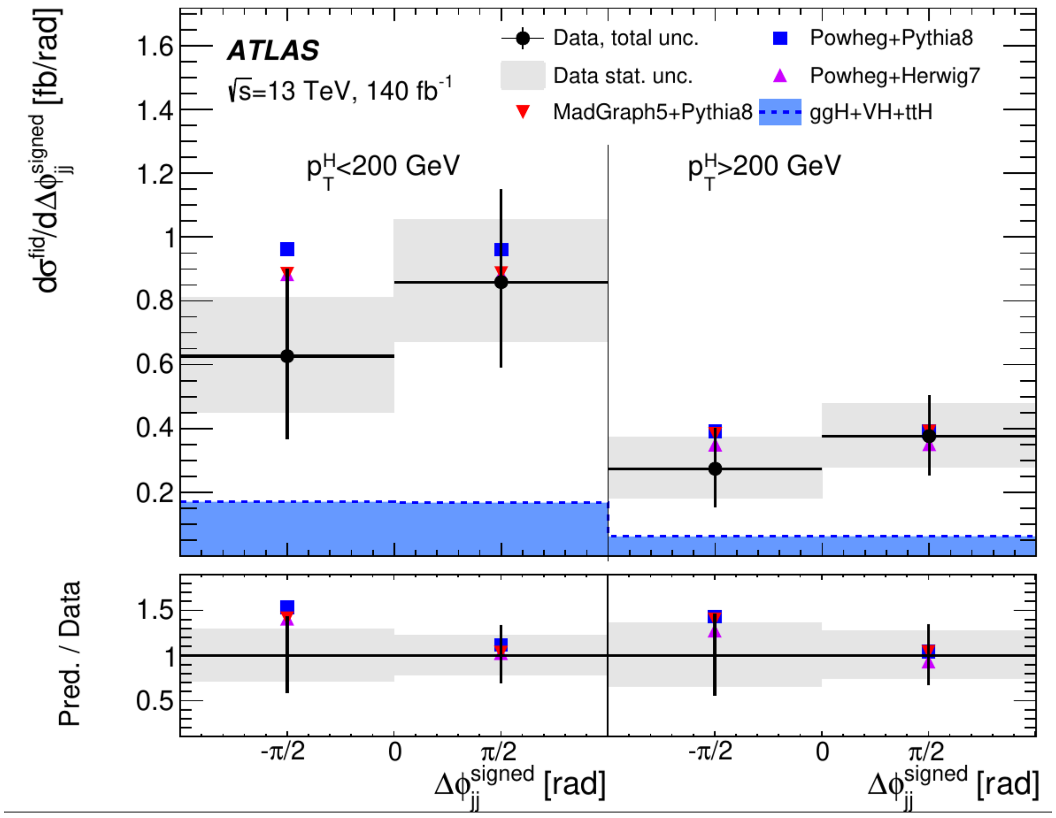
H→ττ Fiducial Cross-section Measurement

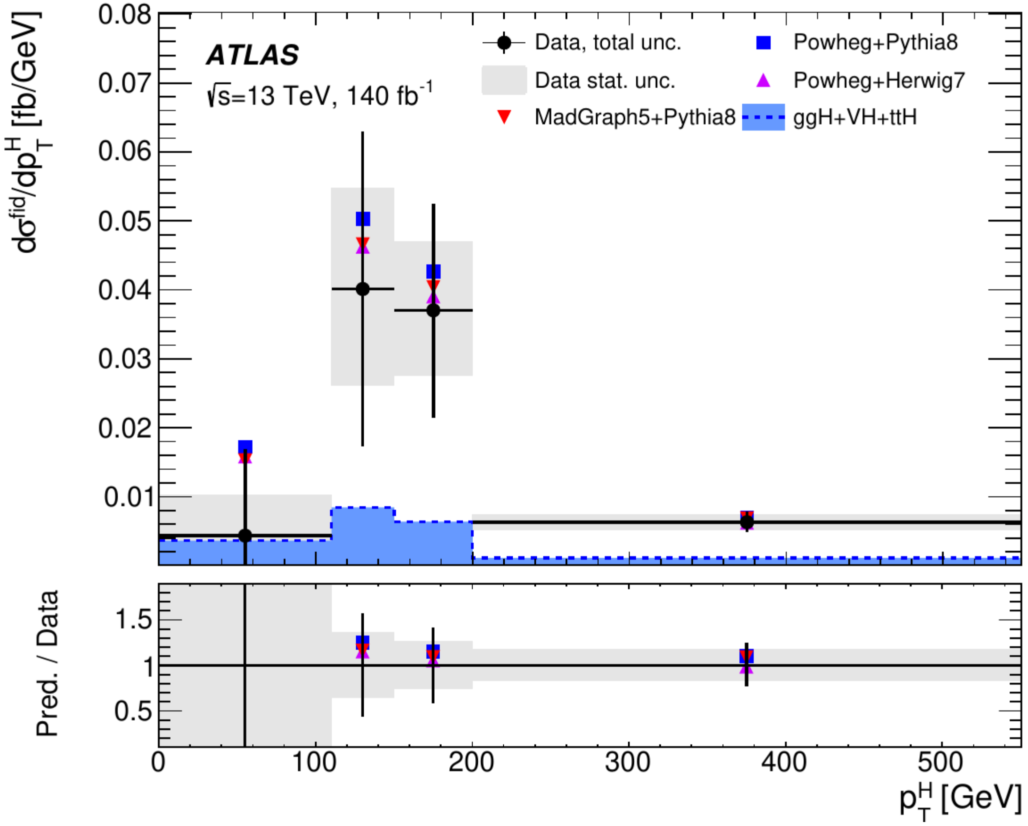




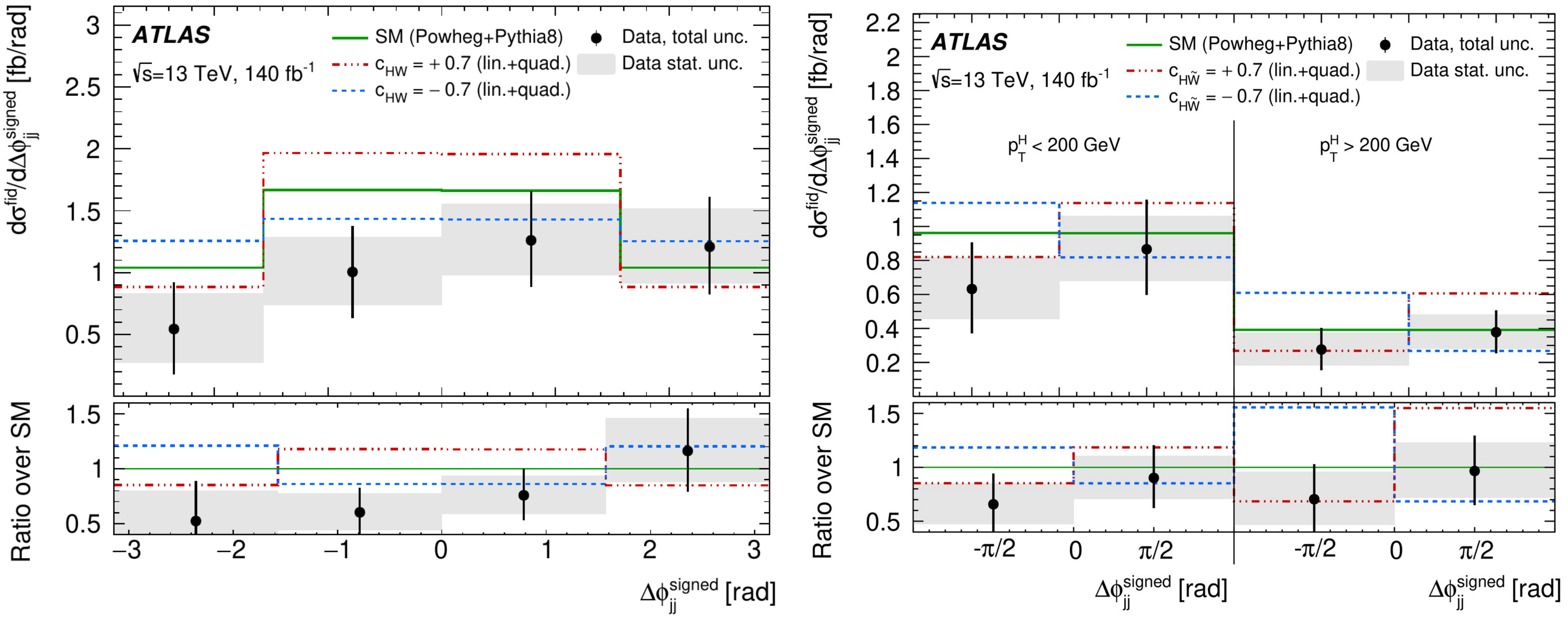


H→ττ Fiducial Cross-section Measurement

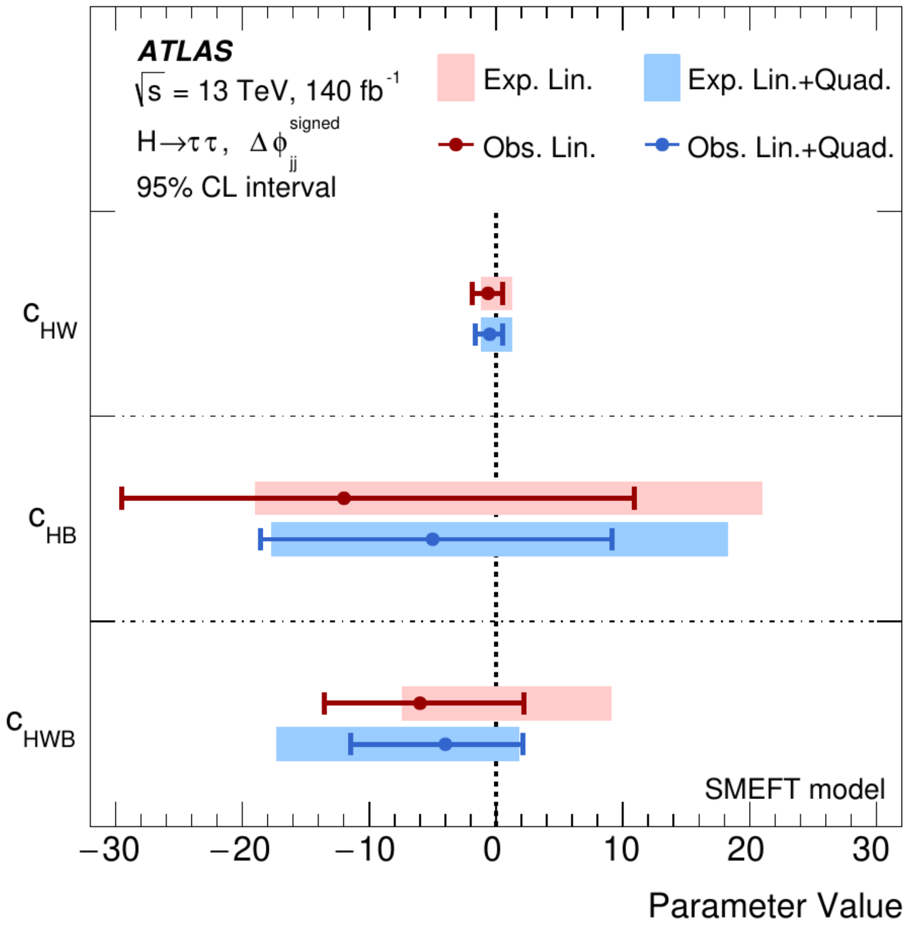


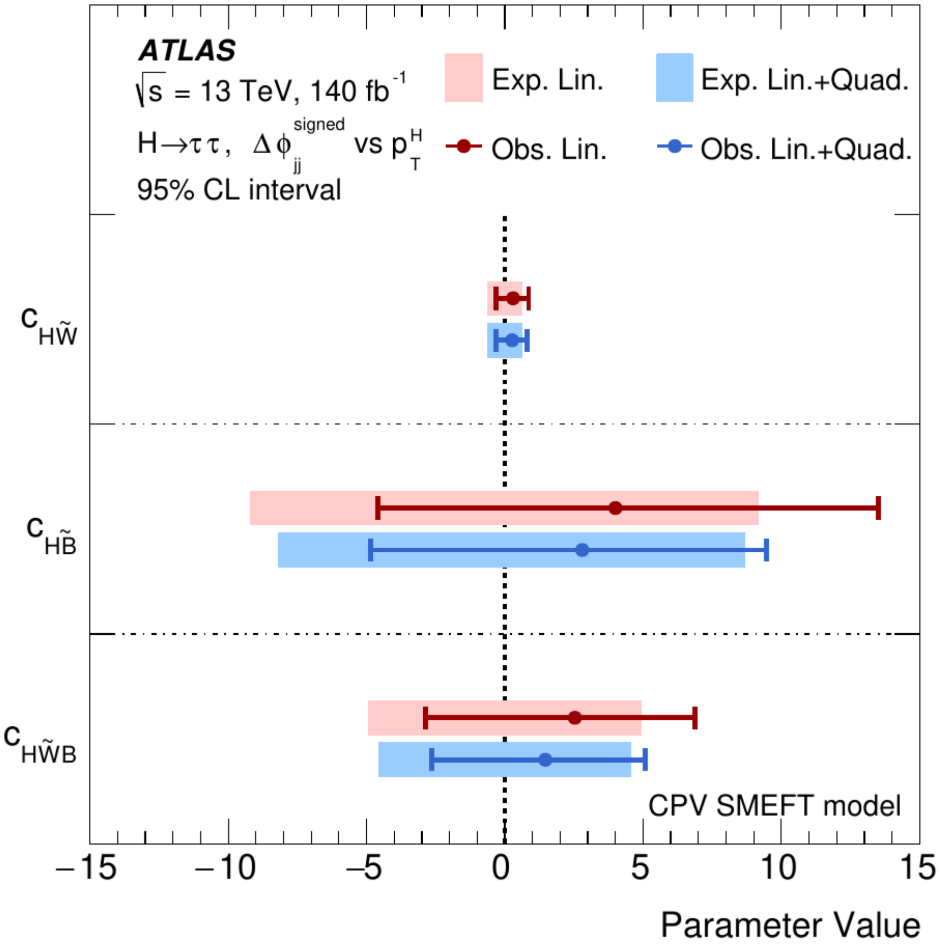


H→ττ Fiducial Cross-section Measurement

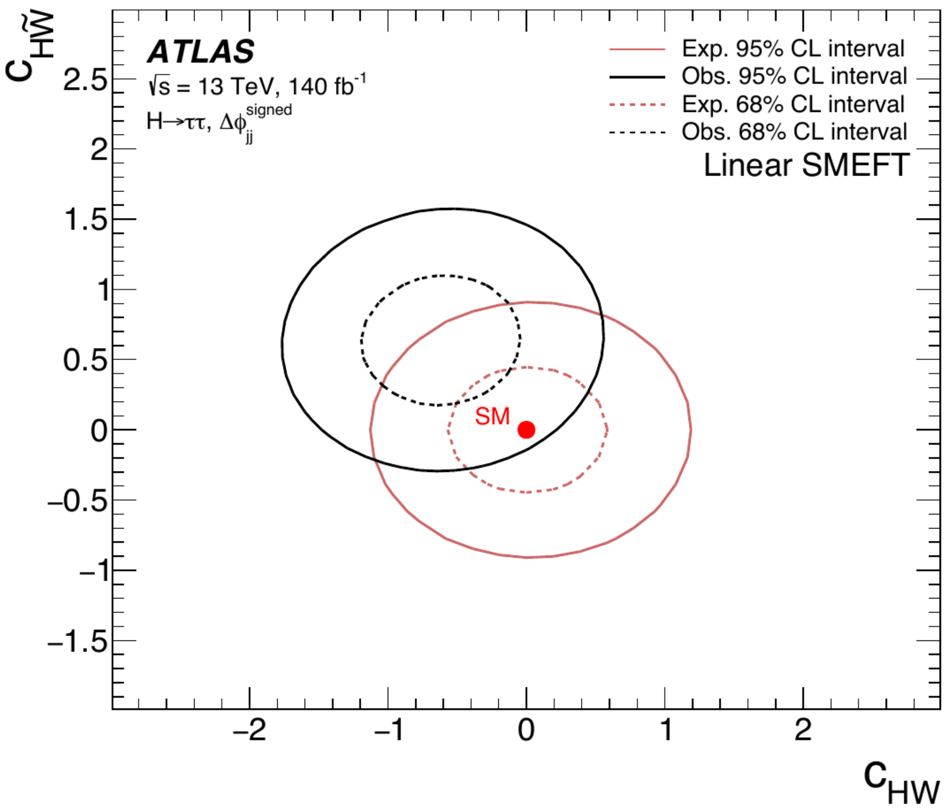


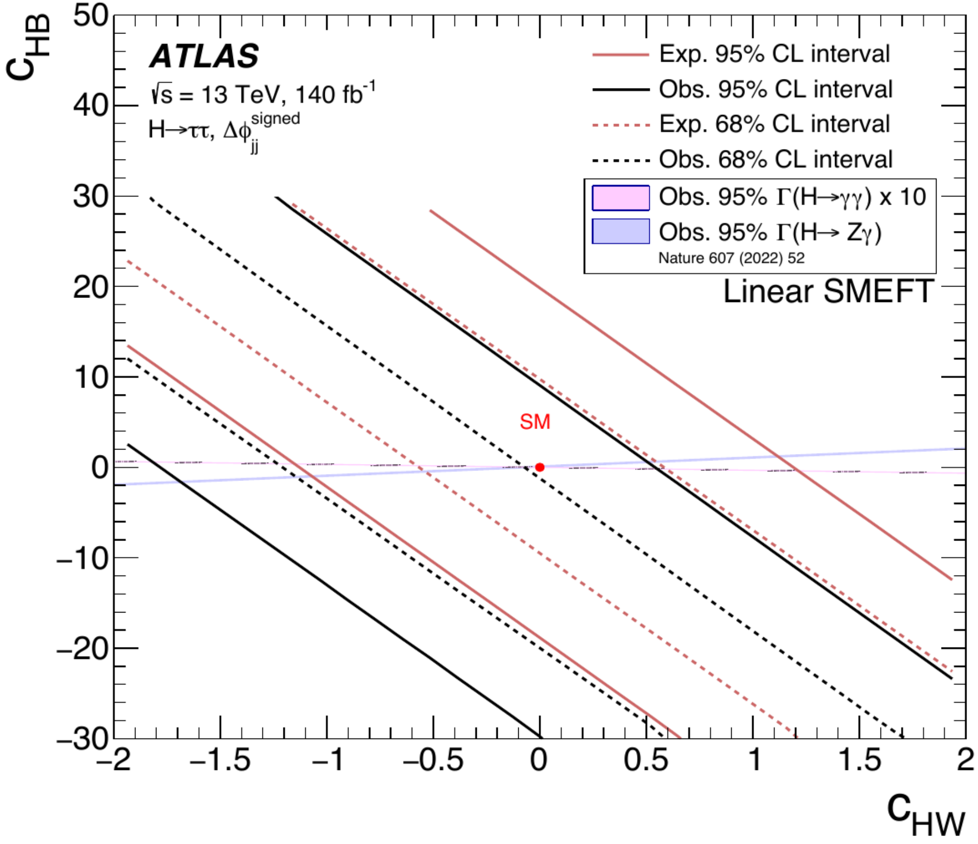
H→ττ Fiducial Cross-section Measurement



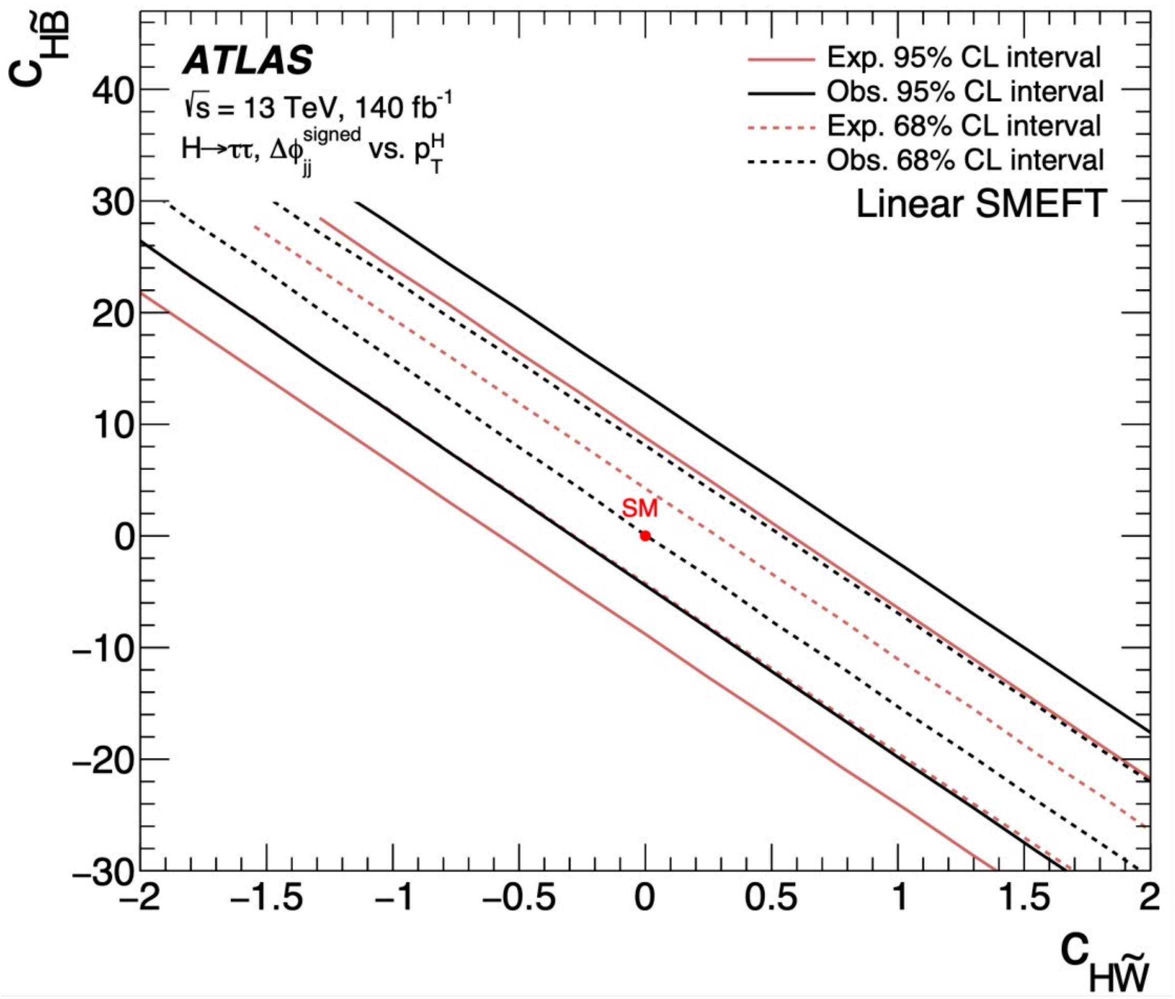


H→ττ Fiducial Cross-section Measurement





H→ττ Fiducial Cross-section Measurement



Higgs Pair Production

Di-Higgs production and λ_3

From G. Salam et al, Nature volume 607, pages 41–47 (2022)

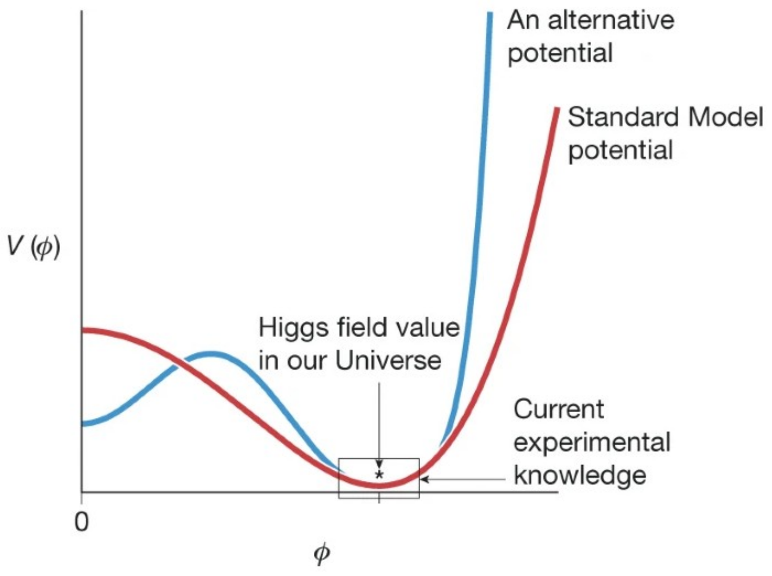
$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4$$

In the SM, specified by

v ~ 246 GeV (from G_F)

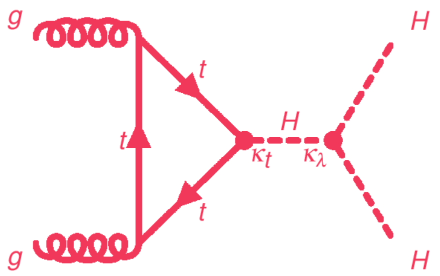
and **m_H ~ 125 GeV**

$$\lambda_3 = \lambda_4 = \frac{m_H^2}{2v^2}$$

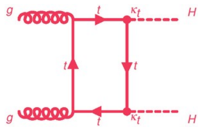


General case: only local information near the minimum

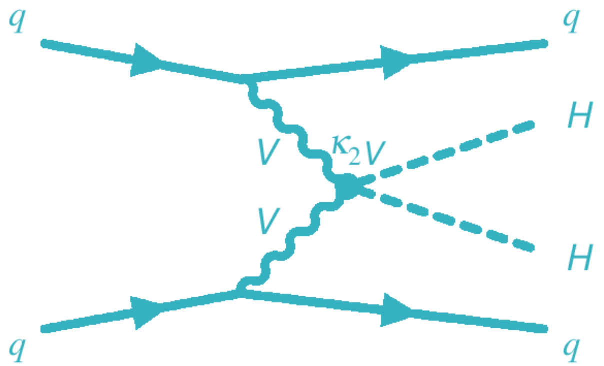
⇒ Probe V(H) by measuring λ_3 in pp→HH



1000x smaller than pp→H !

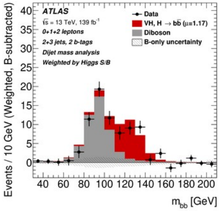
\+  (destructive interference)

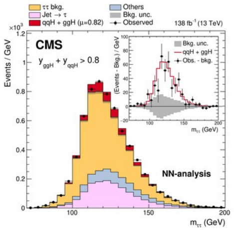
Also probes other interactions, e.g. VVHH (→ κ_{2V}).

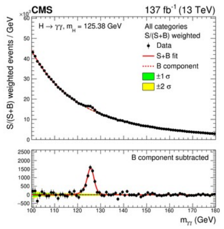


HH decays

Others







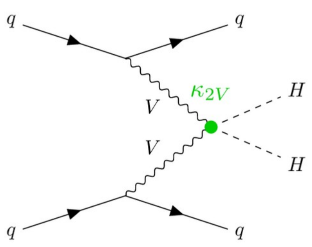
	H→bb	ττ	γγ	Others
H→bb (58%)	**HH→bbbb (34%)** μ < 3.9 (7.8) [C,R] μ < 9.9(5.1) [C,B] μ < 5.3 (8.1) [A]			
H→ττ (6.3%)	**HH→bbττ (7.3%)** μ < 3.3 (5.2) [C] μ < 5.9 (3.3) [A]	**HH→ττττ**		**HH→multileptons** μ < 21 (19) [C] μ < 17 (11) [A]
H→γγ (0.23%)	**HH→bbγγ (0.26%)** μ < 7.7 (5.2) [C] μ < 4.0 (5.0) [A]	**HH→γγττ**	**HH→γγγγ**	
Others	**HH→bbWW** (25%) μ < 14 (18) [C] μ < 10 (14) [A,bbll]	**HH→VVττ**	**HH→VVγγ**	**HH→VVVV**

VBF HH→bbbb and κ_{2V}

CERN-EP-2024-092

Require 2 double-b-tagged large-R jets + VBF jets

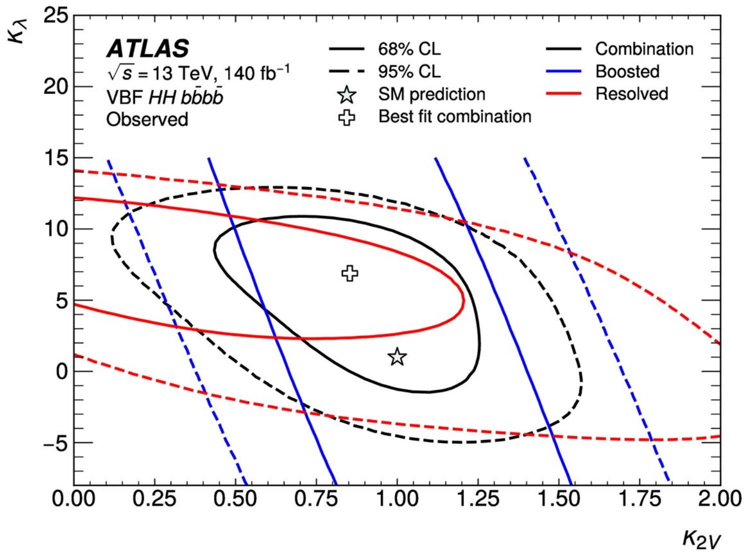
BSM κ_{2V} ⇒ Enhancement at high p_T^H.

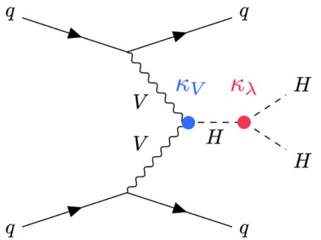


Combined with resolved HH→bbbb,

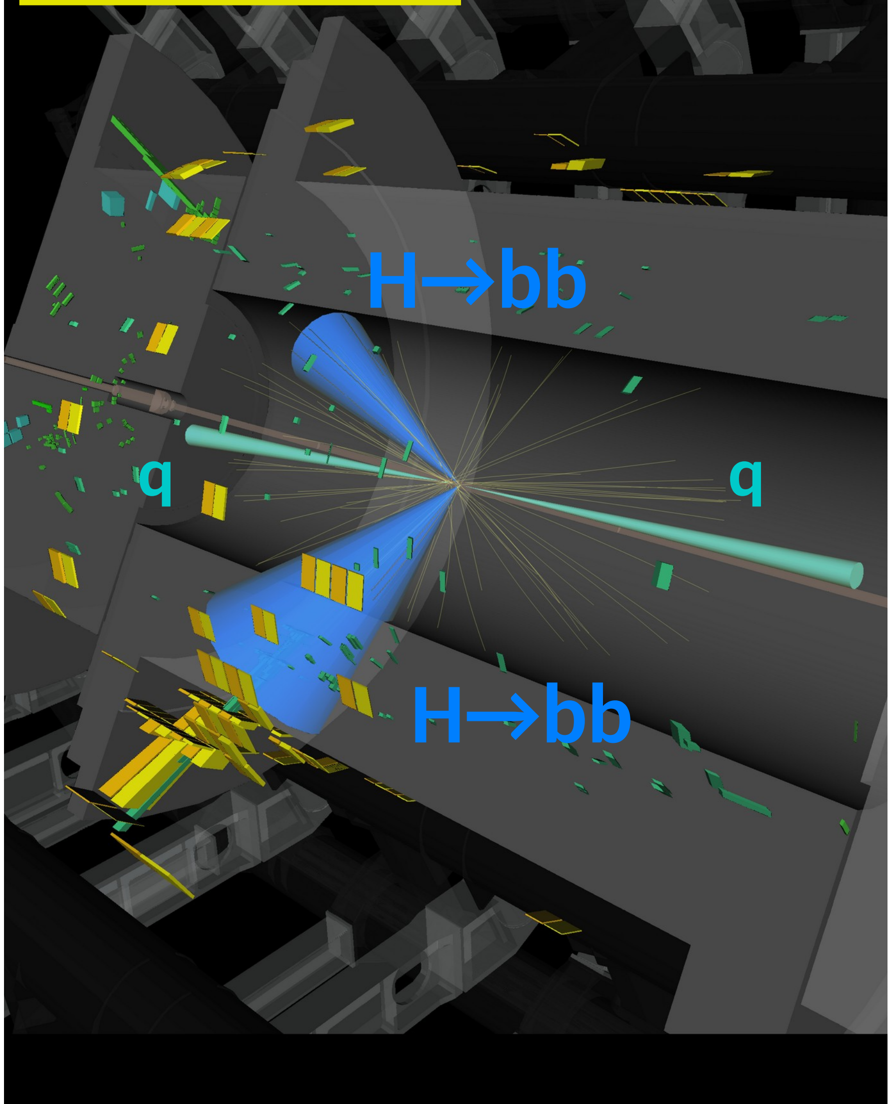
0.55 < κ_{2V} < 1.49 @ 95% CL

Compatible with SM (κ_{2V}=1), 3.8σ from κ_{2V} = 0

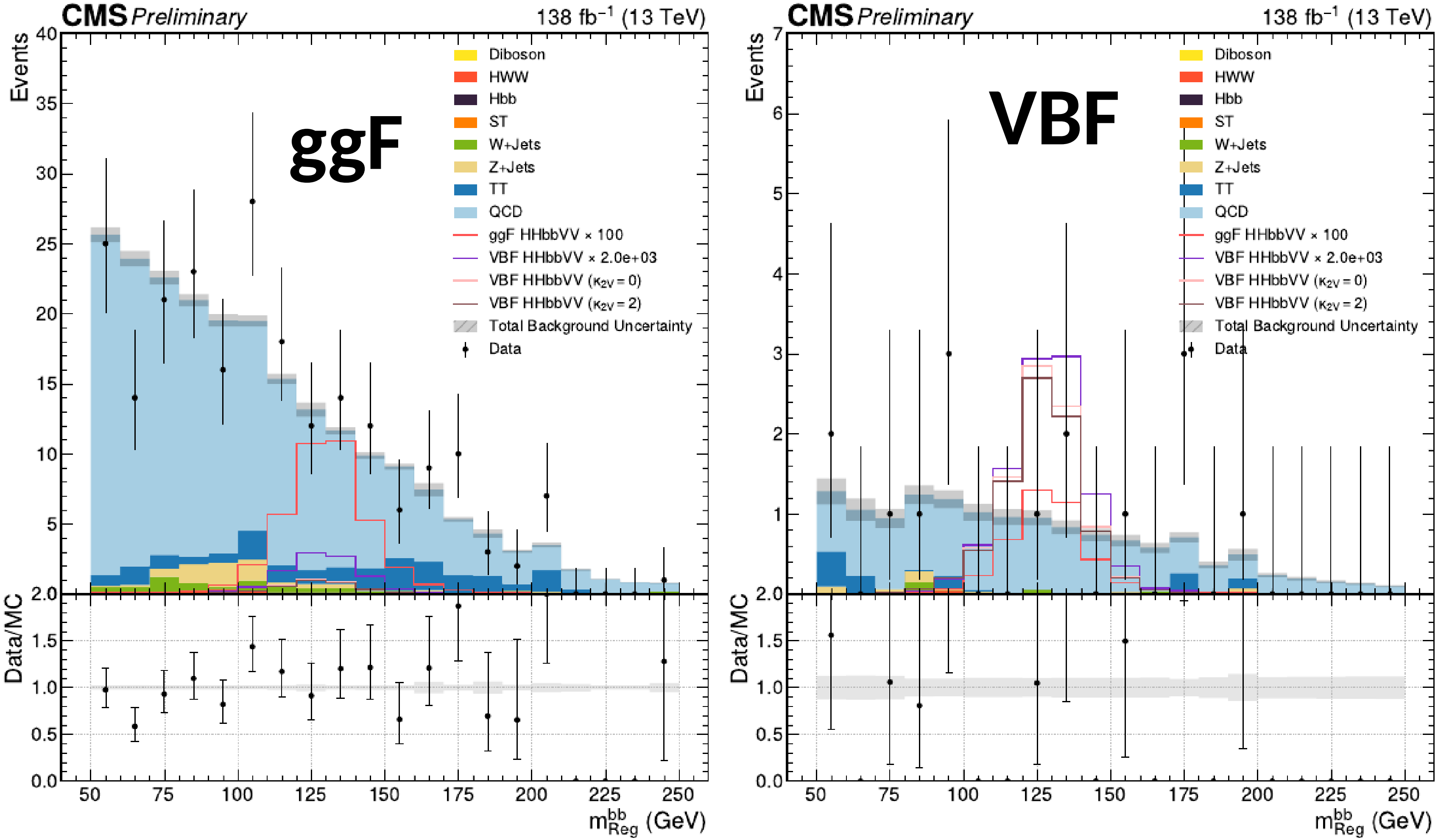




More in Dilia Portillo's talk



CMS VBF HH→bbVV



ATLAS HH combination

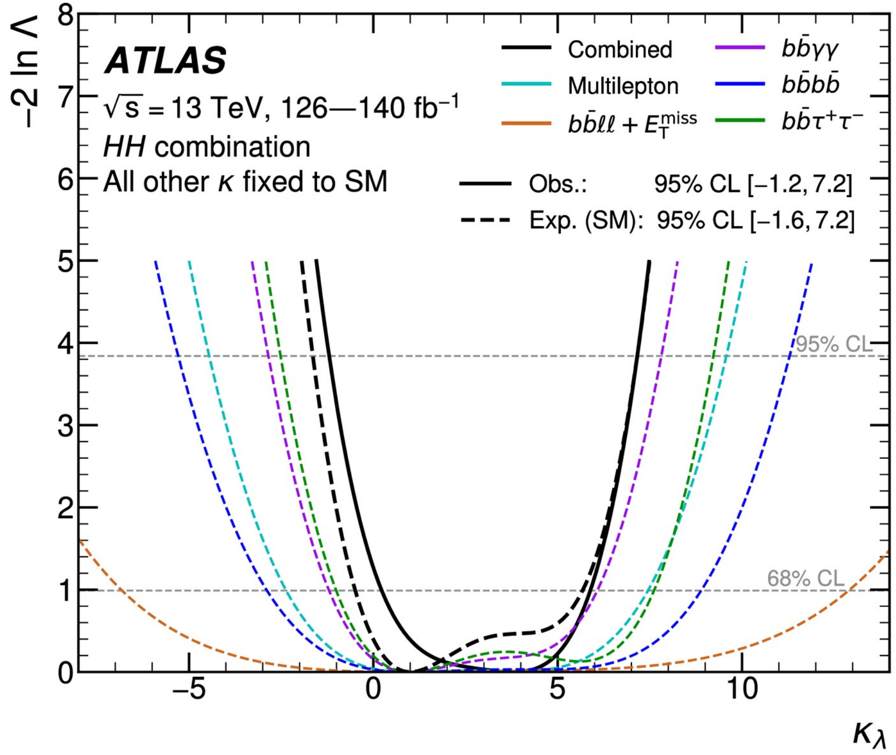
CERN-EP-2024-160,
Nature 607 (2022) 60

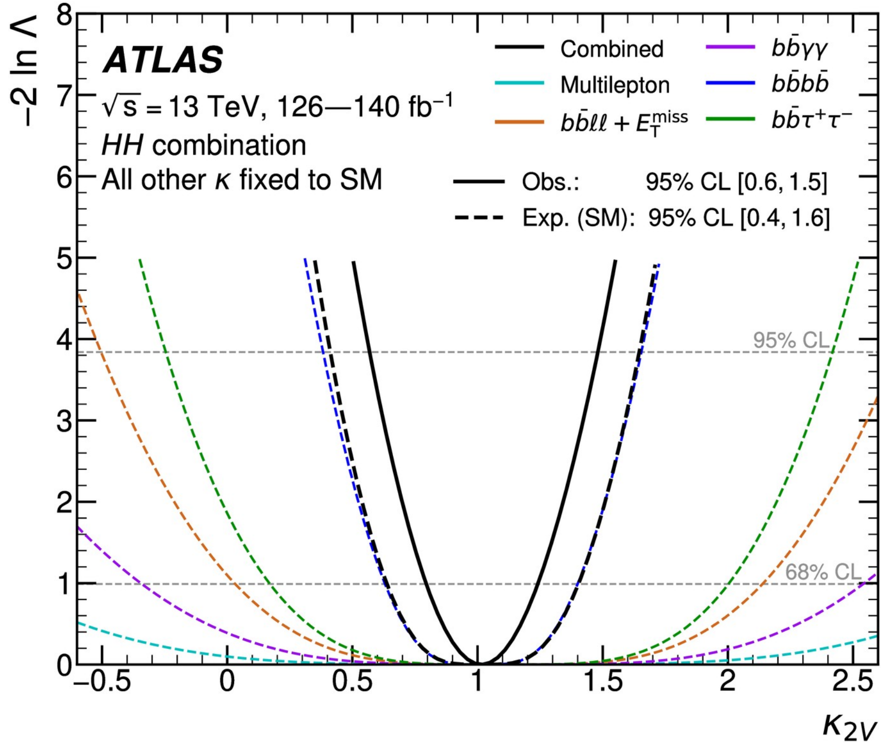
More in Dilia Portillo's talk and Song-Ming Wang's talk on HL-LHC prospects

Combine HH→ττbb + γγbb + bbbb + multileptons + bbll+MET

-1.6 < κ_λ < 7.2 @ 95% CL (dominated by γγbb + ττbb) ⇒ Best constraint on κ_λ to date

0.6 < κ_{2V} < 1.5 @95% CL (dominated by VBF HH→bbbb) ⇒ Best constraint on κ_{2V} to date

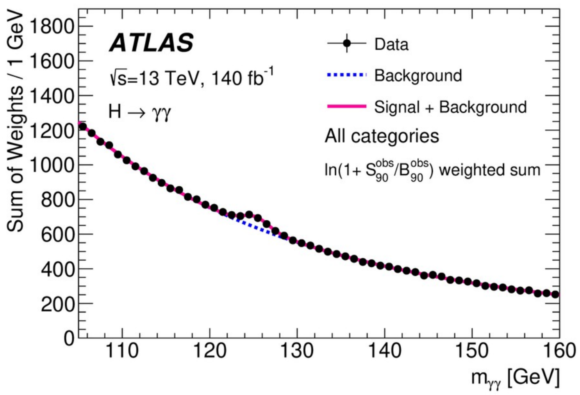




Higgs Boson Mass and Width

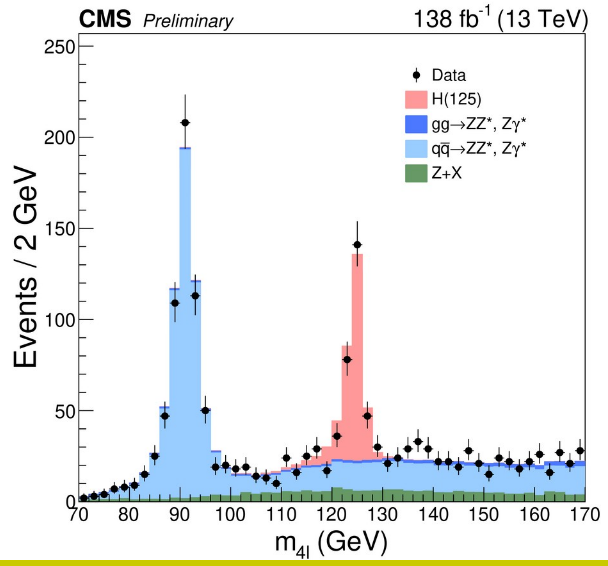
Higgs mass measurements

ATLAS : JINST 19 (2024) P02009, Phys. Lett. B 843 (2023) 137880, Phys. Lett. B 847 (2023) 138315
CMS: CMS-PAS-HIG-21-019 , Phys. Lett. B 805 (2020) 135425



H→γγ: small BR (~0.2%), clean signature, relies on E_γ calibration
⇒ ATLAS: factor 4 reduction in systematics for final Run 2 value.

See Leo Boudet's talk for details



H→4l : tiny BR (~0.01%) but excellent S/B driven by p(μ) calibration
→ CMS: 50 MeV systematic uncertainty (<0.05%),

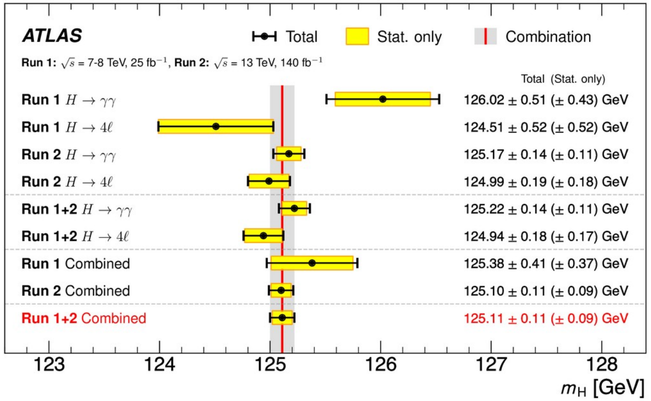
See taks by Camila Pazos, Badder Marzocchi and Federica Primavera for details

m_H = 125.08 ± 0.10 (stat) ± 0.05 (syst) GeV,
Best single-channel measurement

ATLAS H→4l + H→γγ (Run 1 + Run 2):

m_H = 125.11 ± 0.11 GeV

Most precise measurement to date



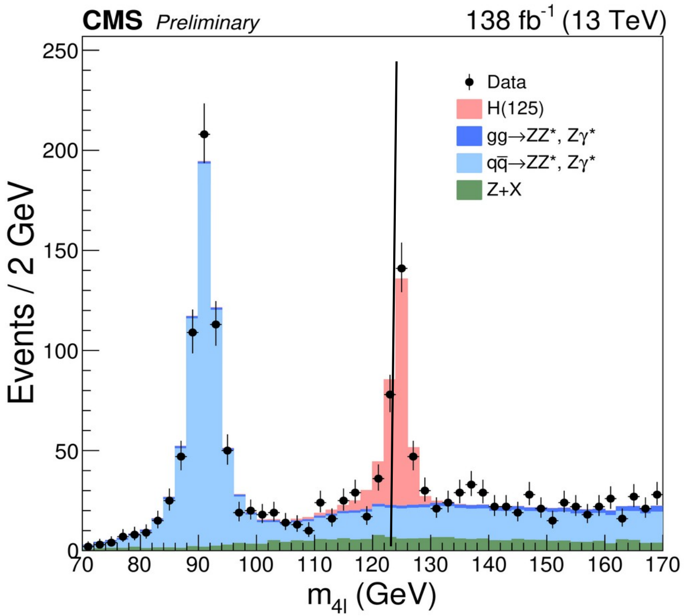
Higgs Width Measurements

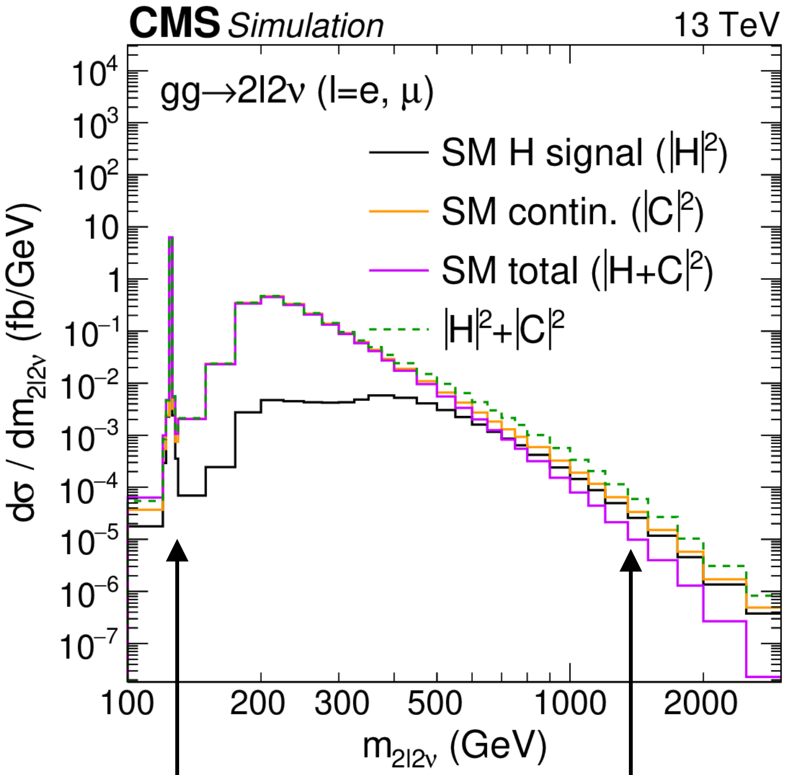
More details in talks by Rafael Coelho Lopes De Sa and Badder Marzocchi

Direct measurement not sensitive to SM:

Mass resolution ~ 1 GeV ↔ Γ_H ~ 4 MeV in SM

⇒ Indirect measurement using off-shell : SM-level sensitivity, with assumptions on off-shell couplings.





on-shell ~ $\frac{\sigma_{pp\to H}\Gamma_{4l}}{\Gamma_H}$

off-shell ~ $\frac{\sigma_{pp\to H}\Gamma_{4l}}{(m_{4l}^2 - m_H^2)^2}$

Higgs Width

More details in talks by
Rafael Coelho Lopes De Sa
and Badder Marzocchi

Direct measurement not sensitive to SM:

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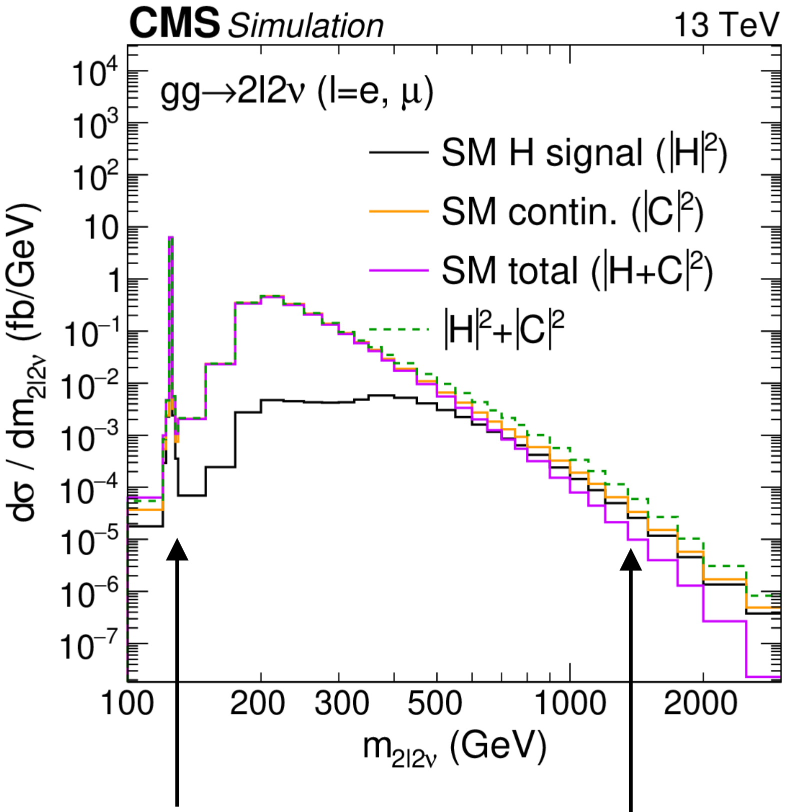


on-shell ~ $\dfrac{\sigma_{pp\to H}\,\Gamma_{4l}}{\Gamma_H}$

off-shell ~ $\dfrac{\sigma_{pp\to H}\,\Gamma_{4l}}{(m_{4l}^2 - m_H^2)^2}$

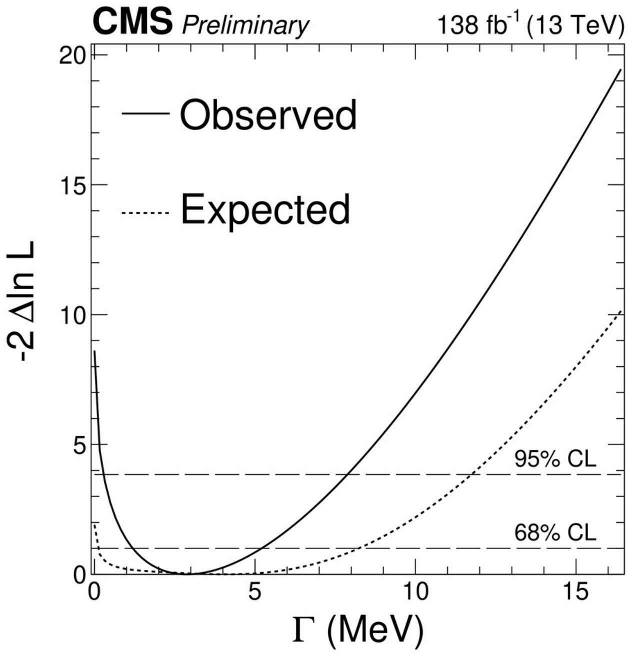
CMS: CMS-PAS-HIG-21-019

$$\Gamma_H = 2.9^{+2.3}_{-1.7}\ \text{MeV}$$

(expected $4.1^{+4.1}_{-4.0}$ MeV)

ATLAS: PLB 846 (2023) 138223

$$\Gamma_H = 4.5^{+3.3}_{-2.5}\ \text{MeV}$$

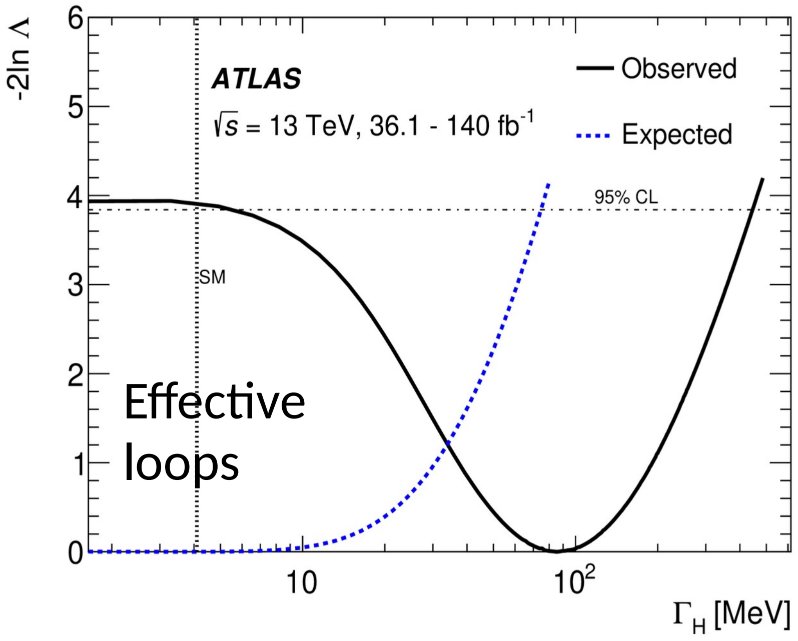


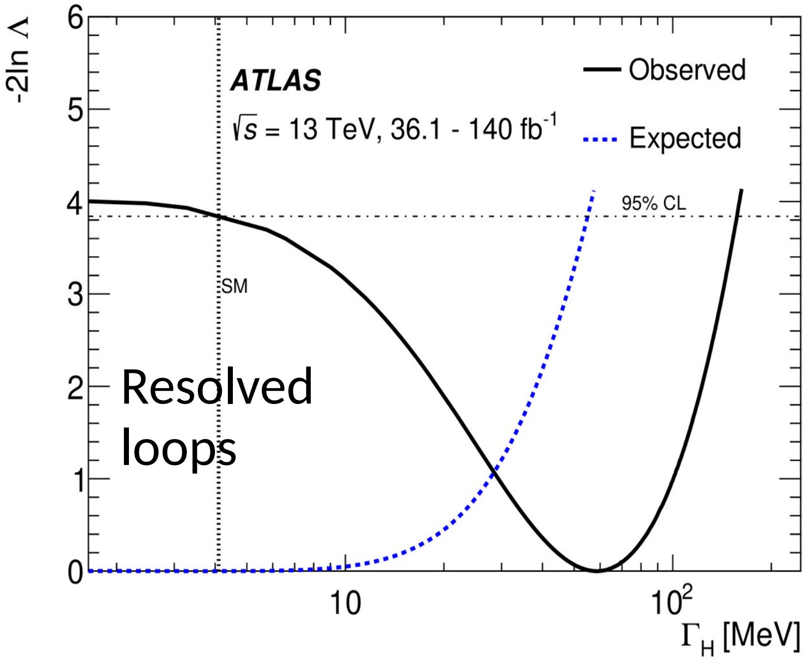
Higgs width measurement from 4-tops

$\Gamma_H < 450$ (75) MeV $\Rightarrow \Gamma_H < 110 \times$ SM ($18 \times$ SM)
$\Gamma_H < 44$ MeV expected for no systematics)
2σ tension with SM (1.8σ tension in pp→tttt)

$$\Gamma_H = 86^{+110}_{-49}\ \text{MeV}$$

$\Gamma_H < 160$ MeV (55 MeV) for resolved loops



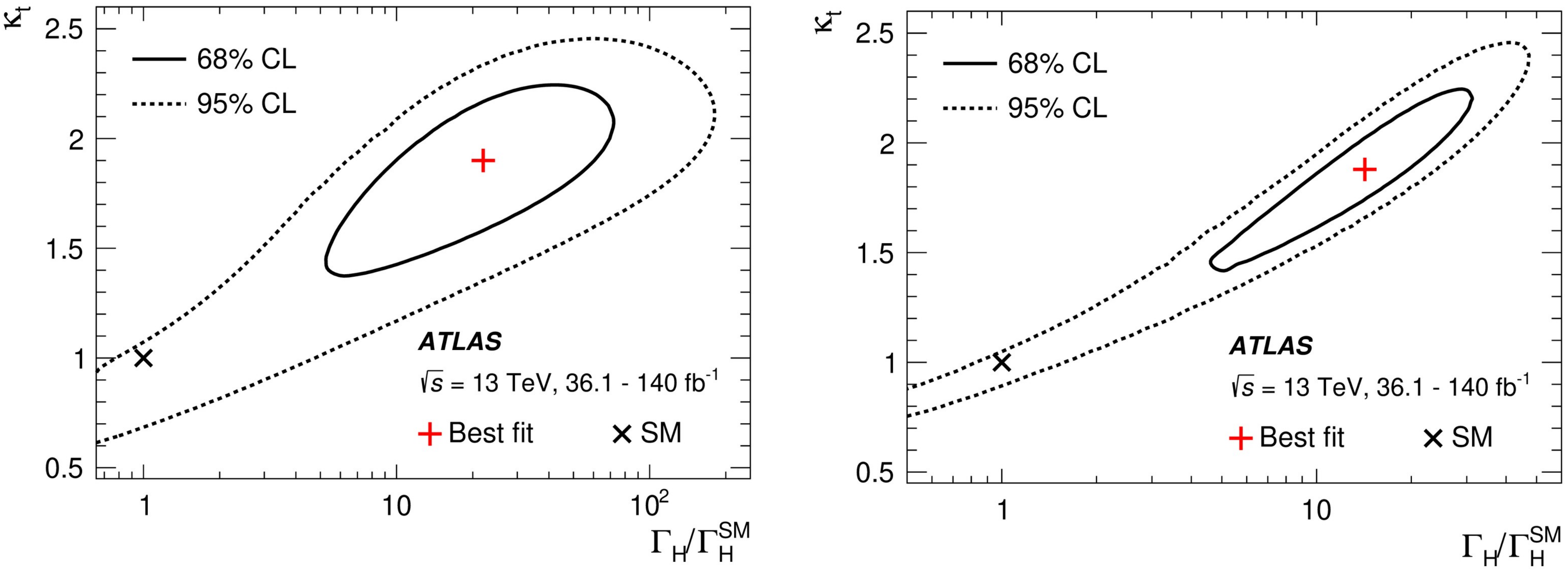


Higgs width measurement from 4-tops

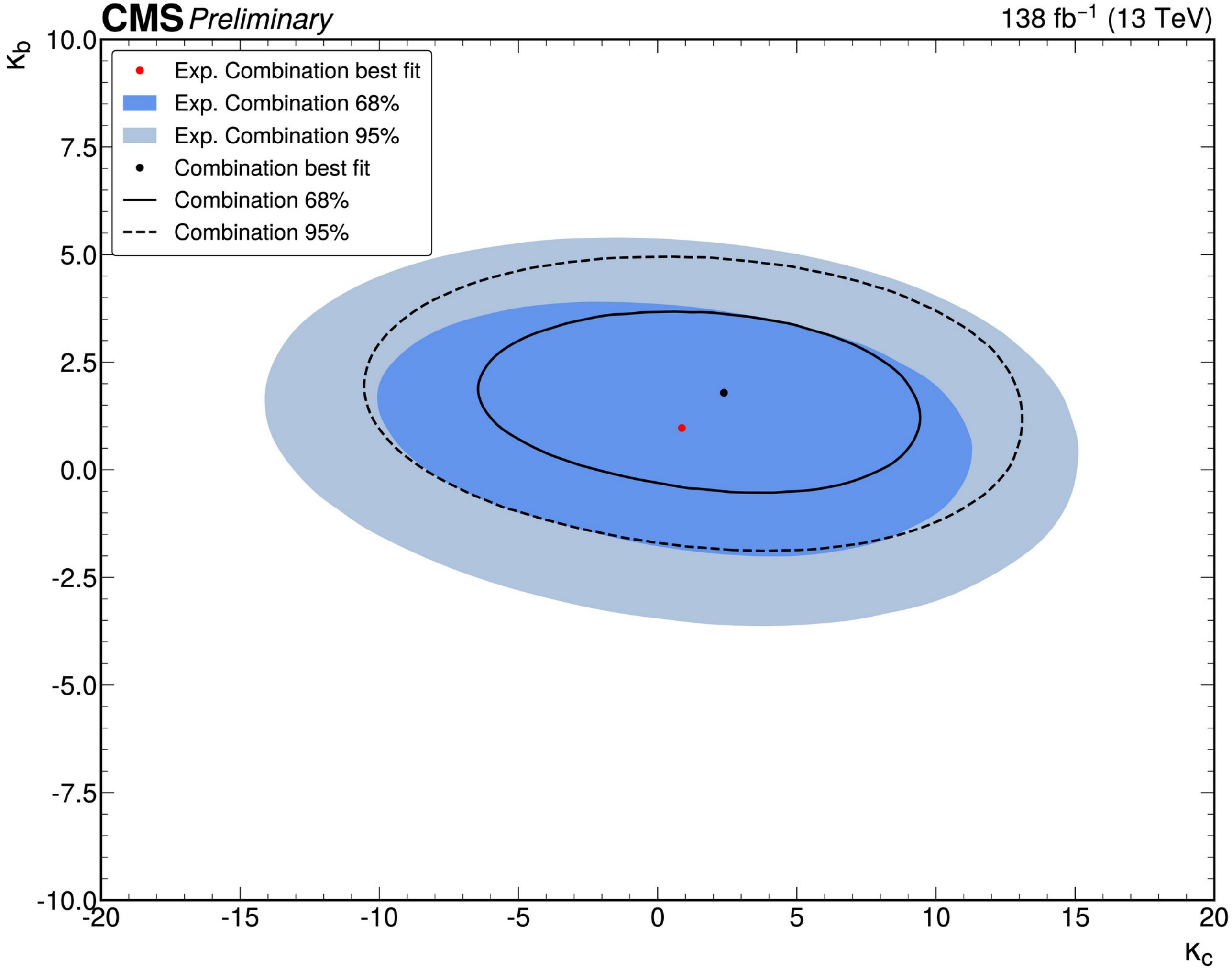
Systematic uncertainty	Impact on 95% CL upper limit on Γ_H Expected [%]	Observed [%]
Theory	37	33
$t\bar{t}t\bar{t}$ production	25	13
Higgs boson production/decay	5	6
Other processes	10	16
Experimental	2	2
Jet flavour tagging	2	1
Jet and missing transverse energy	< 1	< 1
Leptons and photons	< 1	< 1
All other systematic uncertainties	< 1	< 1

Target processes	
Off-shell measurement	
$pp \to t\bar{t}t\bar{t}$	
On-shell measurement	
Production	Decay
ggF, VBF, WH, ZH, $t\bar{t}H$, tH	$H \to \gamma\gamma$
$t\bar{t}H + tH$	$H \to b\bar{b}$
WH, ZH	$H \to b\bar{b}$
VBF	$H \to b\bar{b}$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to ZZ$
ggF, VBF	$H \to WW$
WH, ZH	$H \to WW$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to \tau\tau$
ggF+ $t\bar{t}H + tH$, VBF+ $WH + ZH$	$H \to \mu\mu$
Inclusive	$H \to Z\gamma$

Higgs width measurement from 4-tops



CMS Run 2 Cross-sections



Run 3 Results

Run 3: Higgs production at 13.6 TeV

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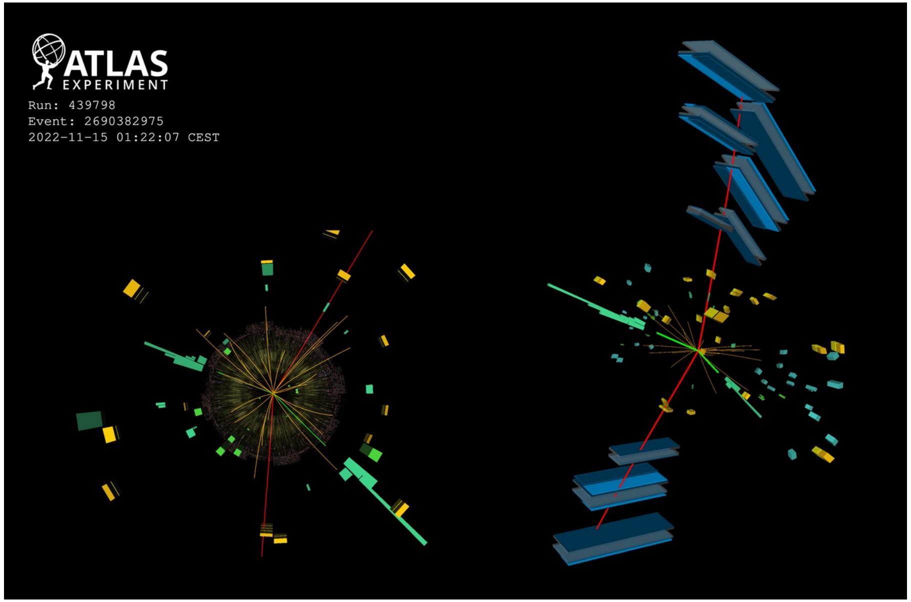
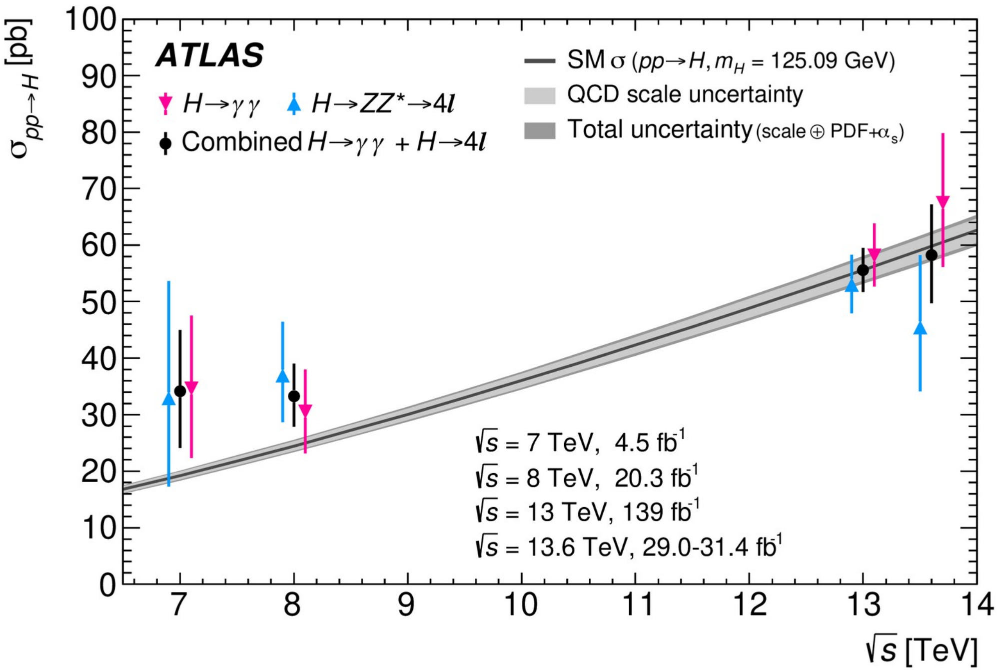
Higgs production at 13.6 TeV measured in H→γγ and H→4l using 2022 data





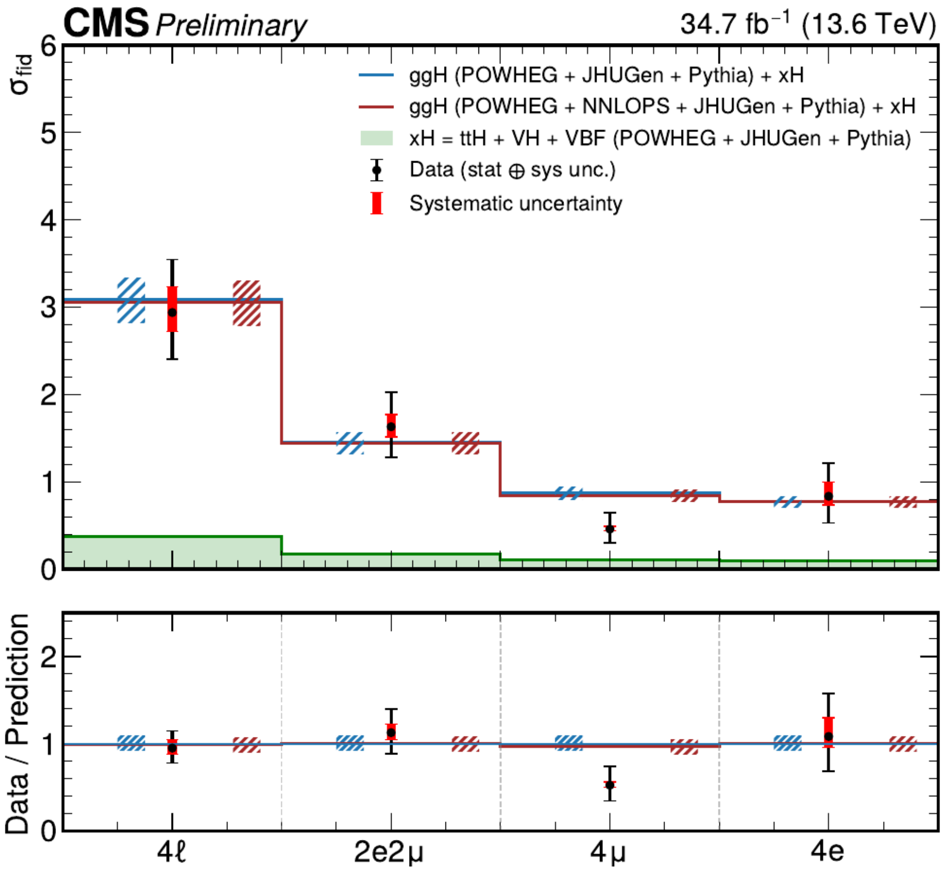
Combined H→γγ + H→4l total XS

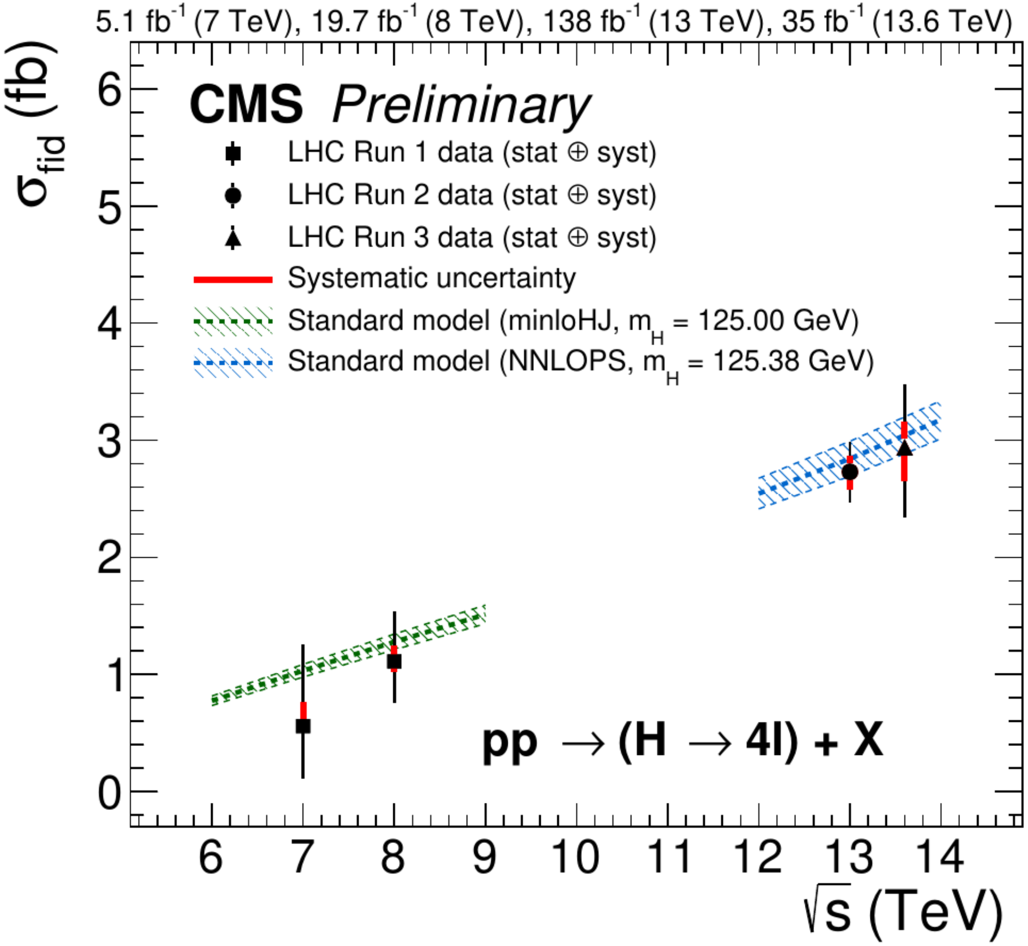
σ(pp→H) = 58.2 ± 8.7 pb (SM: 59.9 ± 2.6 pb)

$$\sigma_{\mathrm{fid},\gamma\gamma} = \mathbf{76 \pm 11\ (stat.)\ ^{+9}_{-7}\ (syst.)\ fb}\ (\mathrm{SM:}\ 67.6 \pm 3.7\ \mathrm{fb})$$

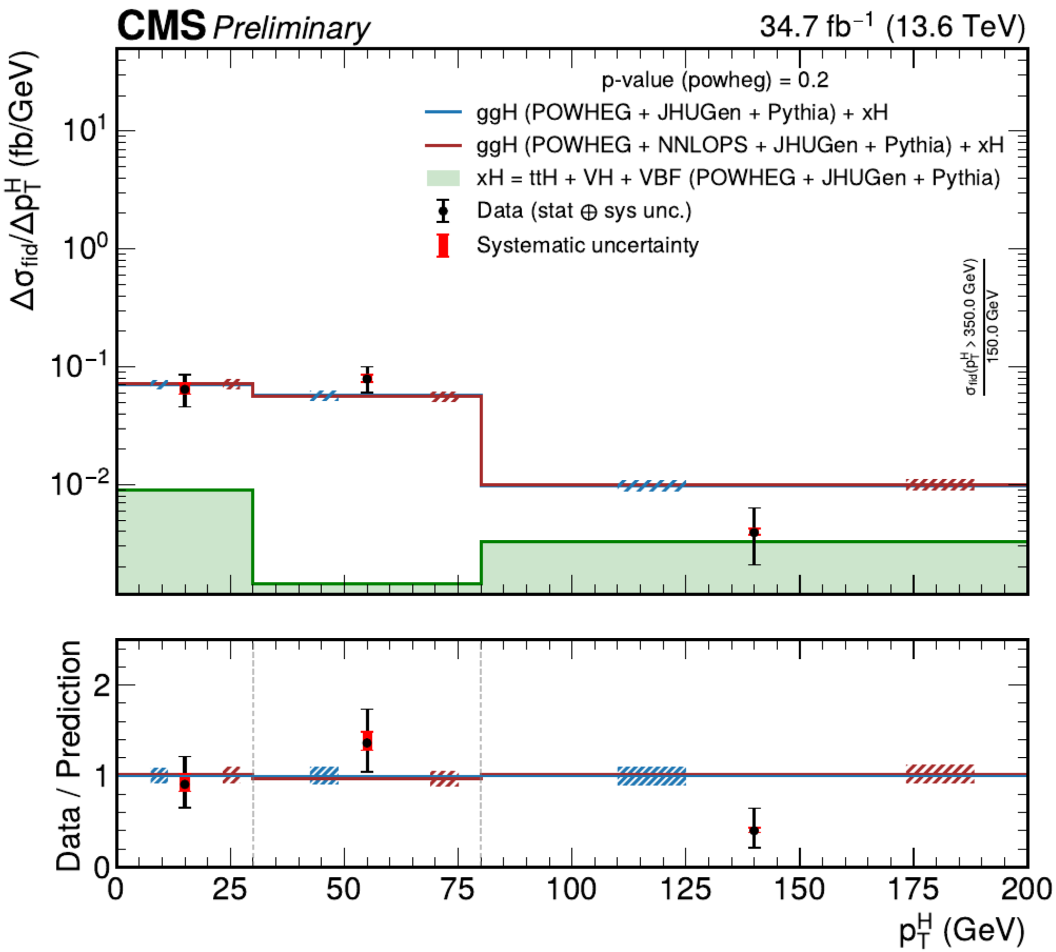
$$\sigma_{\mathrm{fid},4l} = \mathbf{2.80 \pm 0.70\ (stat.) \pm 0.21\ (syst.)\ fb}\ (\mathrm{SM:}\ 3.67 \pm 0.19\ \mathrm{fb})$$

CMS Run 3 H→4l Cross-sections





CMS Run 3 H→4l Cross-sections



Requirements for the H → 4ℓ fiducial phase space	
Lepton kinematics and isolation	
leading lepton p_T	$p_T > 20$ GeV
next-to-leading lepton p_T	$p_T > 10$ GeV
additional electrons (muons) p_T	$p_T > 7(5)$ GeV
pseudorapidity of electrons (muons)	$\|\eta\| < 2.5(2.4)$
p_T sum of all stable particles within $\Delta R < 0.3$ from lepton	less than $0.35 \cdot p_T$
Event topology	
existence of at least two SFOS lepton pairs, where leptons satisfy criteria above	
inv. mass of the Z_1 candidate	40 GeV $< m(Z_1) <$ 120 GeV
inv. mass of the Z_2 candidate	12 GeV $< m(Z_2) <$ 120 GeV
distance between selected four leptons	$\Delta R(\ell_i \ell_j) > 0.02$ for any $i \neq j$
inv. mass of any opposite sign lepton pair	$m(\ell^+ \ell'^-) > 4$ GeV
inv. mass of the selected four leptons	105 GeV $< m_{4\ell} <$ 140 GeV
the selected four leptons must originate from the H → 4ℓ decay	