The Higgs boson: from cornerstone of the SM to a tool to search for BSM

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Introduction

Higgs boson discovery in 2012: more than just one more particle

A **whole new sector** of the SM Lagrangian to study !

- Study of EW symmetry breaking mechanism
  - Gauge couplings
  - More Higgs bosons ?
  - Composite Higgs ?
- Is the Higgs we found the SM one ?
  - Couplings, properties
- It couples to mass... so does it couple to BSM particles ?
  - Portal to Dark Matter
  - Non-SM decays
  - Higgs in decay of new particles

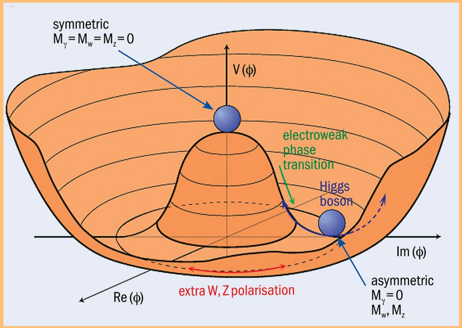
Outline

1. Higgs boson phenomenology at the LHC
2. Higgs production and decay measurements
3. Properties
4. Couplings
5. Constraints on new physics

Higgs phenomenology at the LHC

The Higgs mechanism

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



Spontaneous Electroweak Symmetry Breaking

- Initial (high T state) symmetric
- "Mexican hat" potential for the Higgs field

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

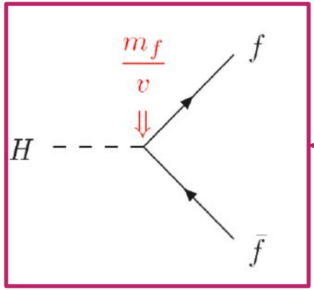
- EW phase transition:
  - Higgs potential takes a ≠ 0 vev:

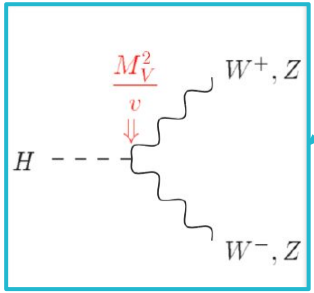
$$v = \frac{|\mu|}{\sqrt{\lambda}} = \frac{2M_W}{g} = 246\text{GeV}$$

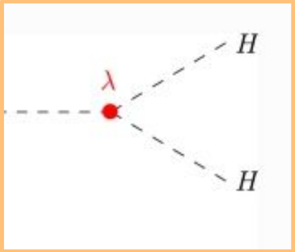
  - Interaction with EW gauge bosons:
    - Masses of W, Z
    - No massless Goldstone particle
  - Fermions acquire their mass incidentally

Higgs boson couplings

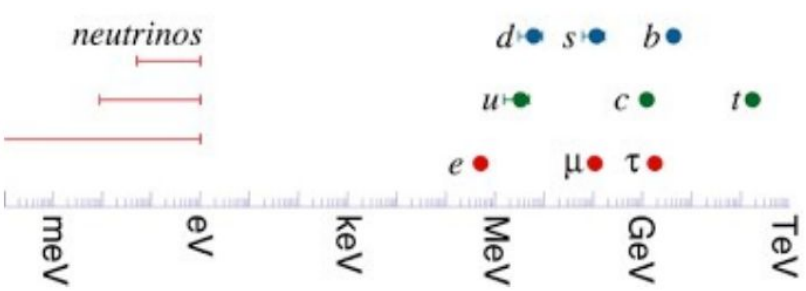
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi + h.c. + \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$







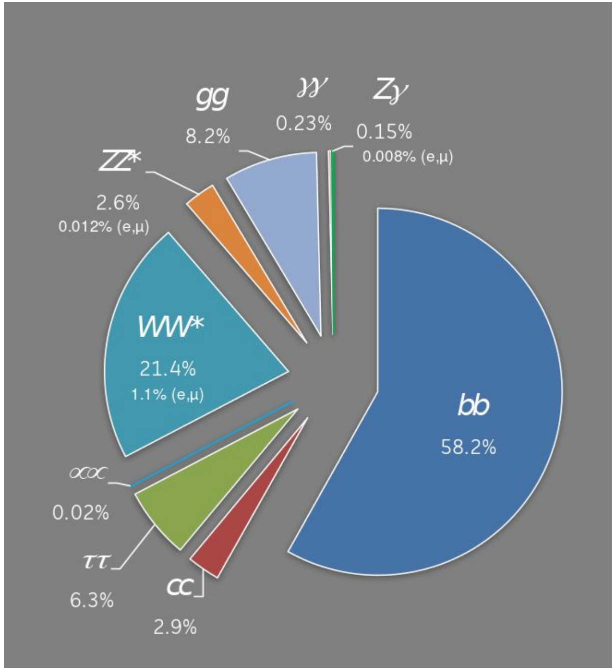
Hierarchy of fermion masses ⇔ Hierarchy of couplings to Higgs

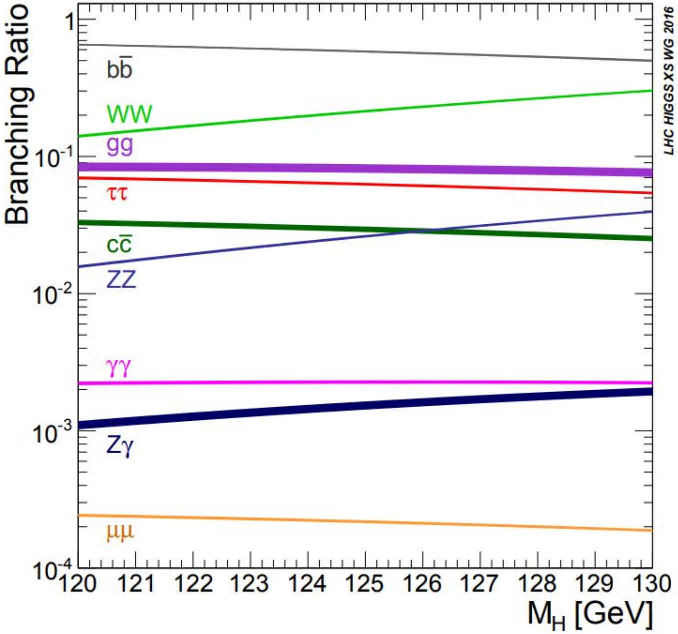


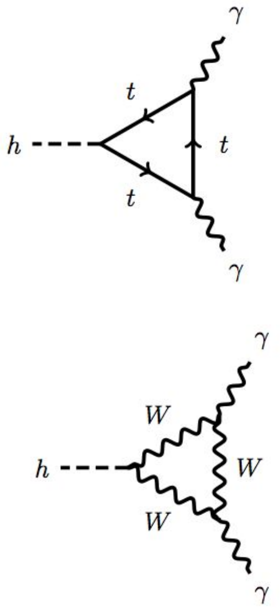
Higgs boson decays

Significant hierarchy in Higgs boson BRs

NB: Decays to massless particles (gluons, photons) through loops

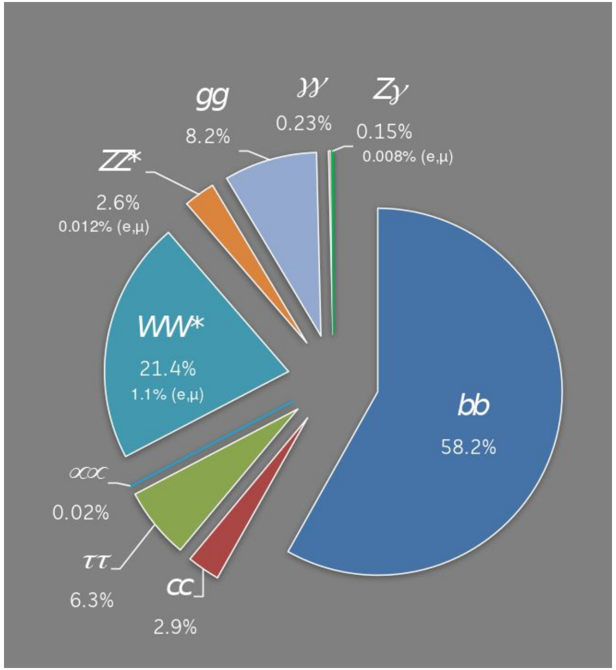




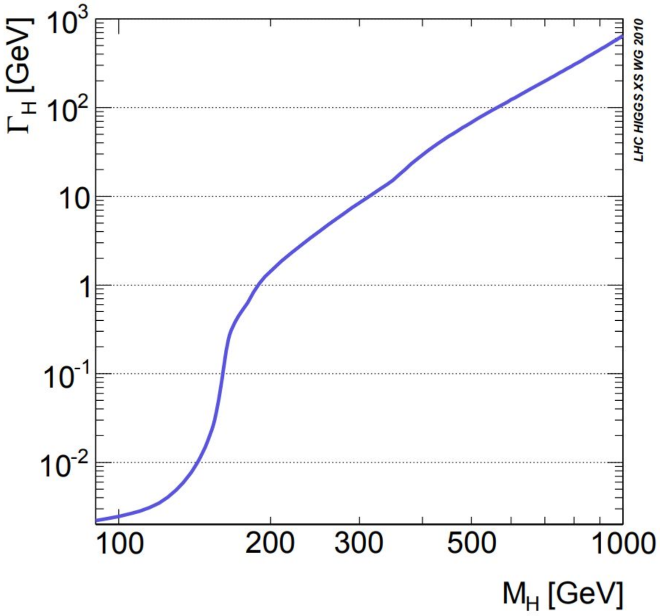


Higgs boson decays

Significant hierarchy in Higgs boson BRs

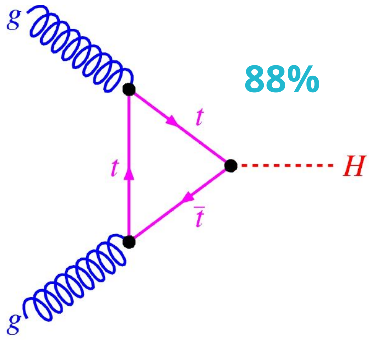


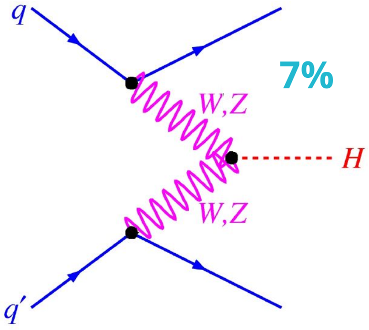
Narrow resonance at 125 GeV:
width ~ 4 MeV

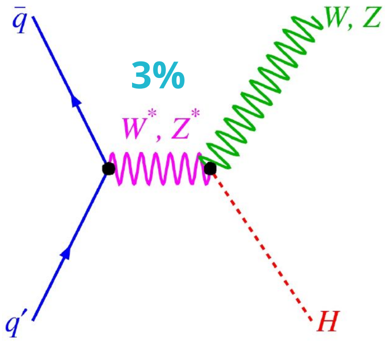


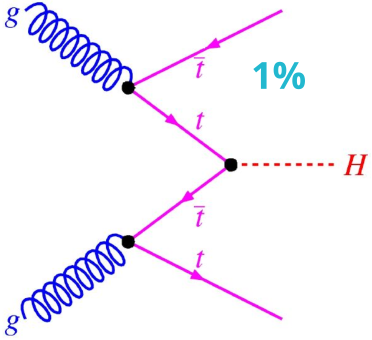
Higgs boson production mechanisms

4 main production modes at the LHC. Total cross-section ~ 56 pb at 13 TeV









Gluon fusion

- No particular signature

Vector boson fusion

- Two high-pT jets, large invariant mass and pseudorapidity separation

Higgsstrahlung

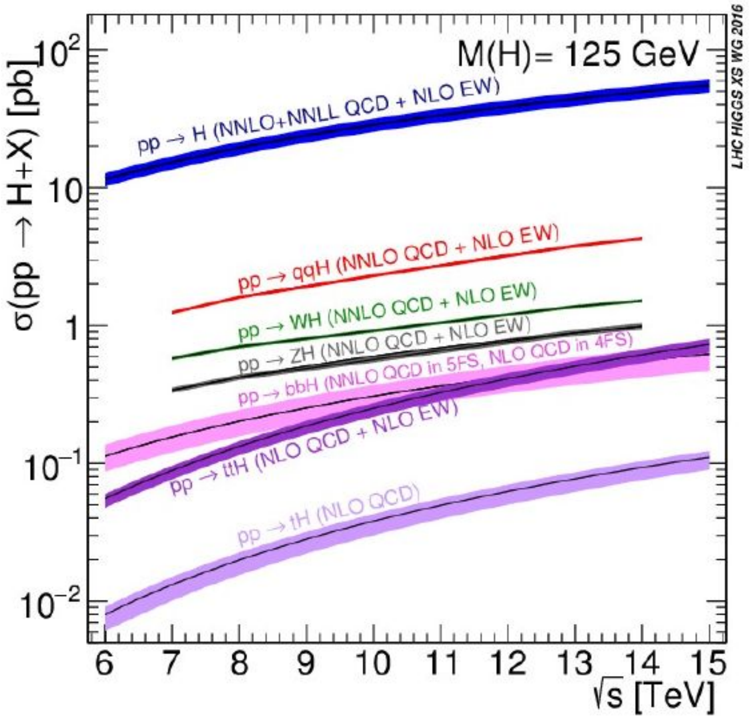
- Tagged by W/Z decays (mostly leptonic decays)

ttH

- Tagged by ttbar decay signatures

Higgs production cross-sections

Hierarchy mostly unchanged, except for ttH x-section (phase space)

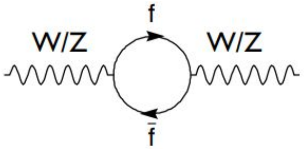


The Higgs boson in the global electroweak fit

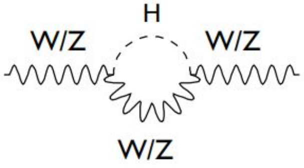
The SM is overconstrained from many EW precision measurements: powerful self-consistency check

- At tree-level, EW gauge sector described by G_F, α and M_Z
- At higher-order important corrections from other parameters, esp. m_t and M_H

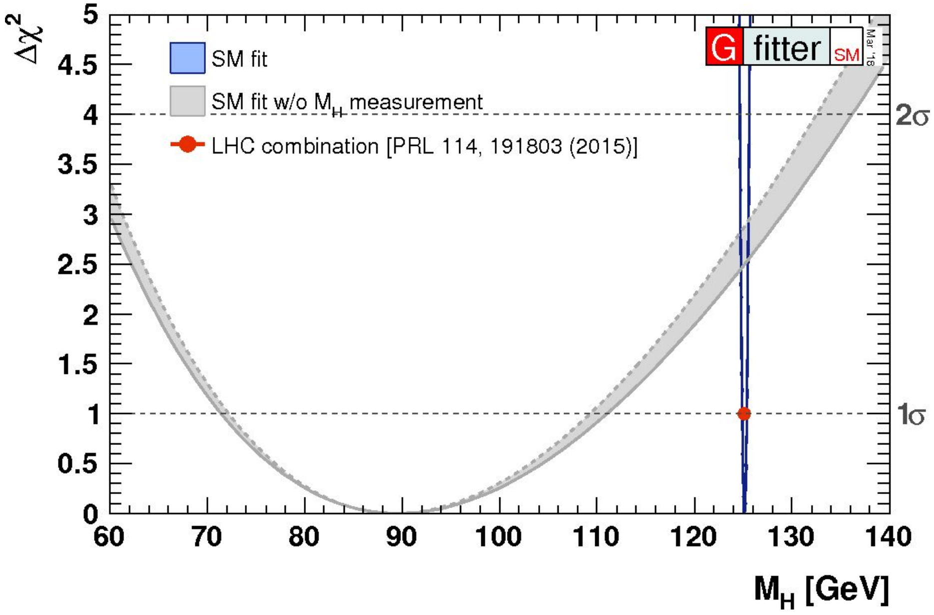
$$M_W^2 = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1-\Delta r)}{G_f M_Z^2}}\right)$$



$\propto N_C m_f^2$



$\propto \ln \frac{M_H^2}{M_W^2}$



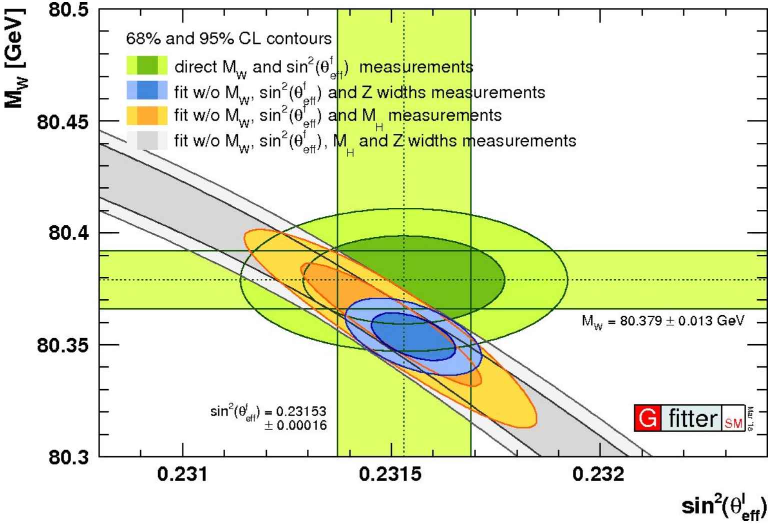
Global fit without M_H:
MH estimation through its NLO effects on other variables (MW)
$M_H = 90^{+21}_{-18}$ GeV

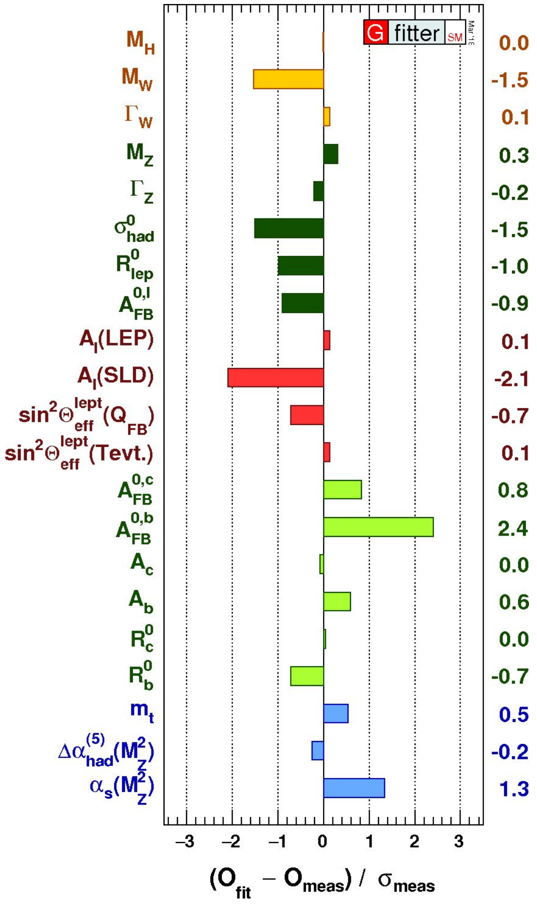
Global electroweak fit

Excellent consistency check of the SM

χ^2 = 18.6 for 15 degrees of freedom

p-value: 0.23





Measuring the Higgs at the LHC

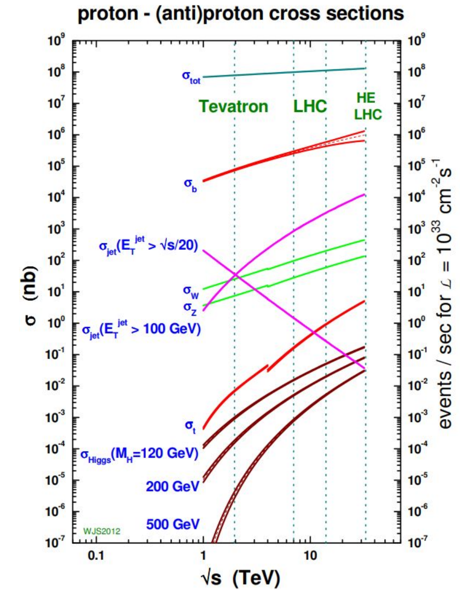
Not all channels are born equal

Sensitivity of a measurement depends on several factors

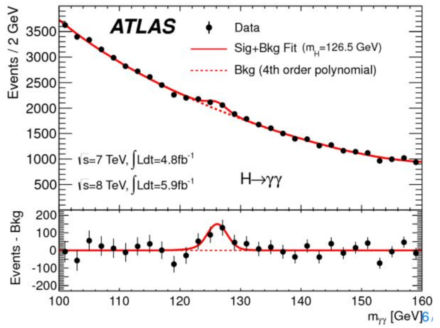
- Number of events produced
  - Production x-section, BR
- Acceptance / selection efficiency
- S/B
  - Amount of background
  - Discrimination power (e.g narrow peak)

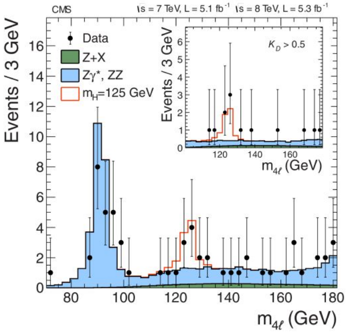
Higgs bosons per fb^{-1} (13 TeV)

	produced	selected
$H \to \gamma\gamma$	130	46
$H \to ZZ^*$	1400	1.5
$H \to WW^*$	12000	42
$H \to \tau\tau$	3500	17
$H \to b\bar{b}$	32000	66



Discovery channels: relatively low stats, but high S/B





No stone left unturned

Higgs studies have come a long way since 2012: full matrix prod ⨯ decay covered

	ggH	qqH	VH	ttH/tH
H→γγ	ATLAS, CMS	ATLAS, CMS	ATLAS, CMS	ATLAS, CMS
H→ZZ	ATLAS, CMS	ATLAS, CMS	ATLAS, CMS	ATLAS, CMS
H→WW	ATLAS, CMS	ATLAS, CMS	ATLAS, CMS	ATLAS, CMS
H→ττ	ATLAS, CMS	ATLAS, CMS	ATLAS, CMS	ATLAS, CMS
H→bb	ATLAS, CMS	ATLAS, CMS	ATLAS, CMS	ATLAS, CMS
H→μμ	ATLAS, CMS	ATLAS, CMS	ATLAS, CMS	ATLAS, CMS
H→cc	CMS		ATLAS, CMS	
H→Zγ	ATLAS, CMS	ATLAS, CMS	ATLAS, CMS	ATLAS, CMS
H→inv	CMS	ATLAS, CMS	ATLAS, CMS	

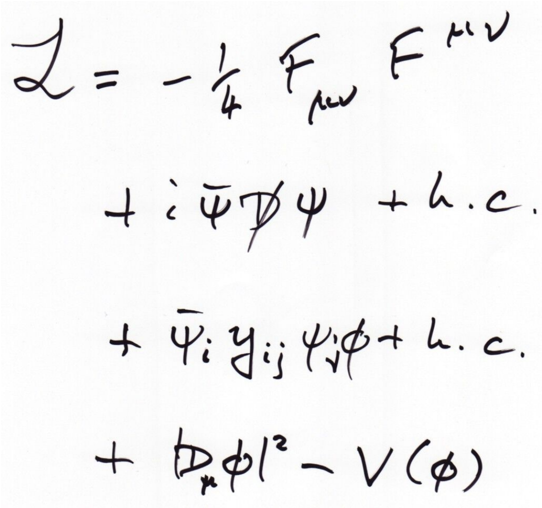
Precision measurements everywhere

Two main questions to answer

- Are the couplings as predicted by the SM ?
  - Improve analysis precision
  - Analyse more and more data

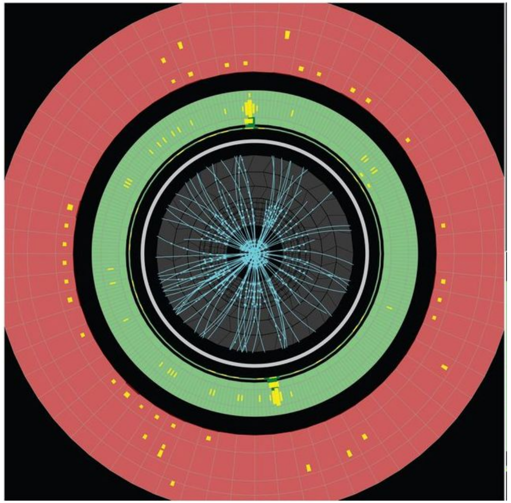
- Is the structure of the Lagrangian the SM one ?
  - Probe differential distributions to look for shape deviations
  - CP-sensitive variables

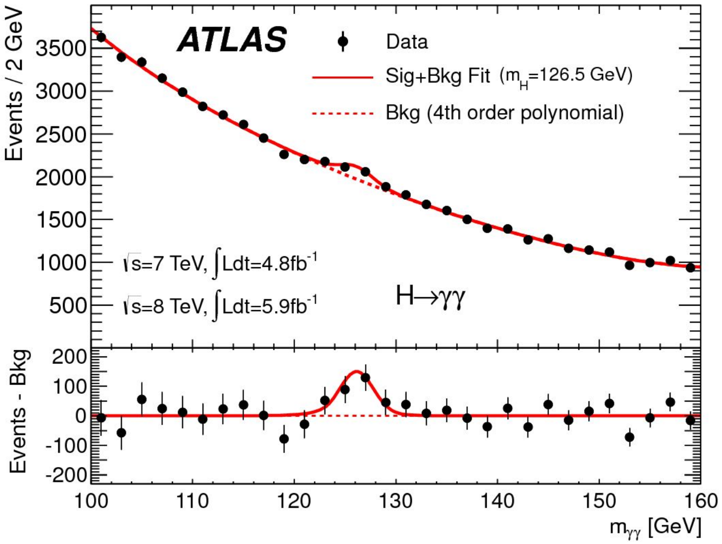
- Price to pay: analysis complexity
  - Many categories
  - Machine learning everywhere



$H \rightarrow \gamma\gamma$

- Key features
  - Clean signature: 2 isolated photons
  - Fairly high signal yield
  - S/B fairly good
  - Excellent diphoton mass resolution
  - Precise background estimation under signal peak from sidebands



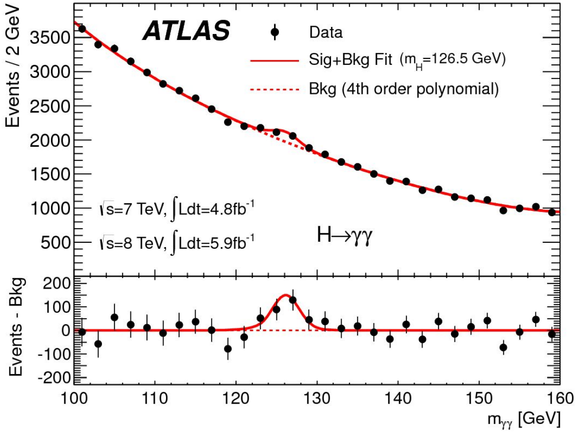


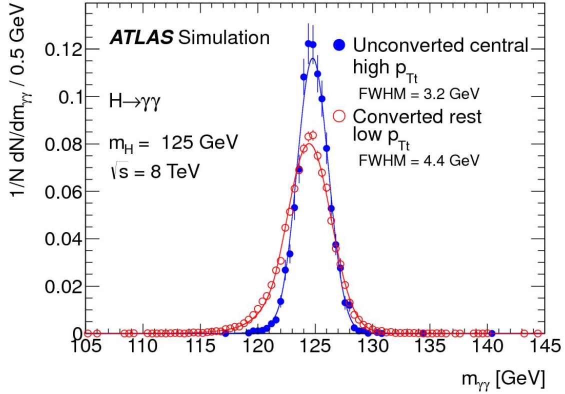
H → γγ back in 2012

hep-ex:1207.7214

Optimise for discovery with few years of data-taking

- Simple cut-based photon ID algorithm
  - 74% real γγ events
- 10 analysis categories
  - 1 optimised for VBF
  - 9 to classify events based on the expected purity of real γγ events and of the expected S/B
    - Central unconverted photons being the best
- Polynomial fit to the data
  - With large systematic uncertainties
- Result
  - ATLAS: $\mu = 1.8 \pm 0.5$



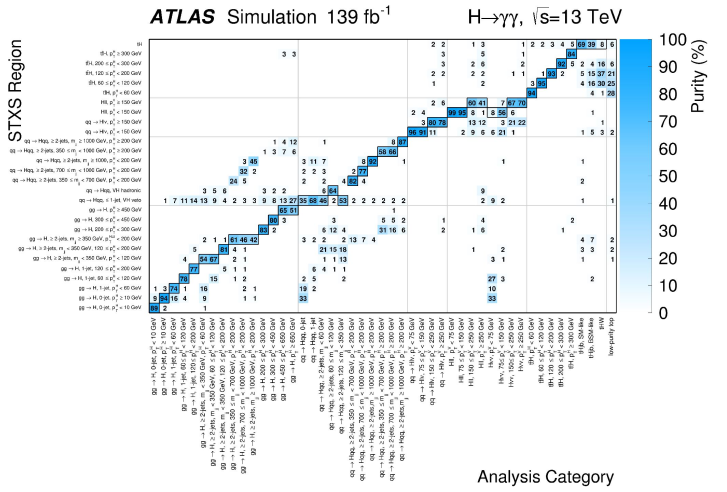


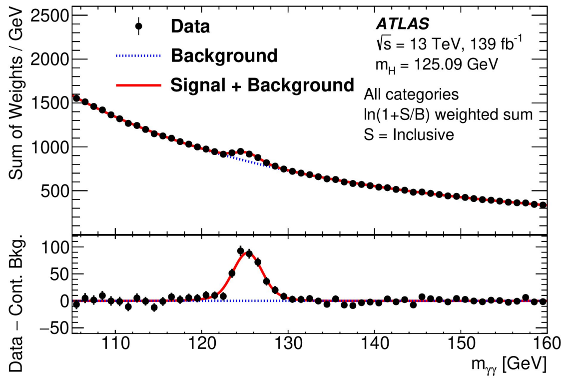
$H \to \gamma\gamma$ in 2022

hep-ex:2207.00348

With ×30 more Higgs bosons, goals are shifting

- 101 analysis categories
  - Using machine learning multiclassifiers
  - Classify by S/B and probe specific fiducial regions at the same time
- More elaborate analysis
  - Photon ID from ML, better vertex reco
  - More inclusive analysis, but using more fine-grained categories
  - Better calibrations
- Results
  - ATLAS: $\mu = 1.04 \pm 0.10$
  - Production modes cross-sections
  - Differential distributions
  - Constraints on new physics scenarios





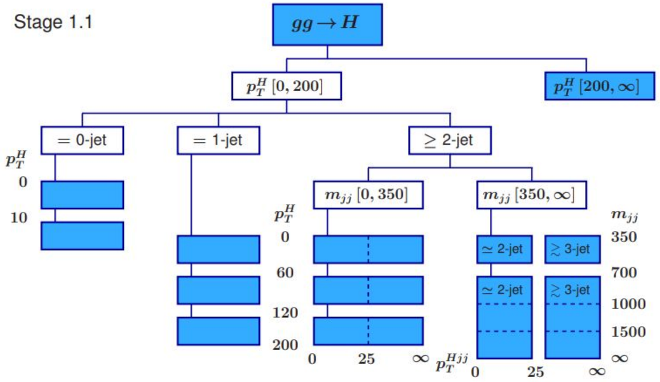
STXS: Simplified Template Cross-Sections

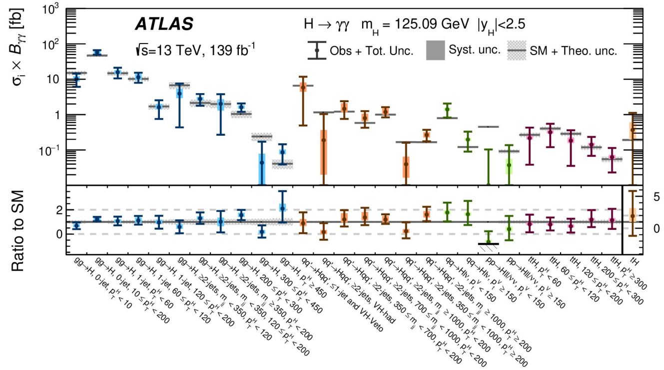
Theory-experiment agreement for fiducial definitions of production modes

- Target all production modes
  - Regardless of decay
  - Evolutive definitions: “Stages” (1.2)
  - Probes relevant kinematic variables
    - Relevant for theory uncertainties
    - Esp. regarding new physics searches, i.e high-Q^2 regions

- Main benefits
  - Combinations of channels
  - Future ATLAS+CMS combination
  - Central calculation of theory uncertainties
  - Regions can be merged when necessary

- $H \to \gamma\gamma$: 28 STXS regions measured

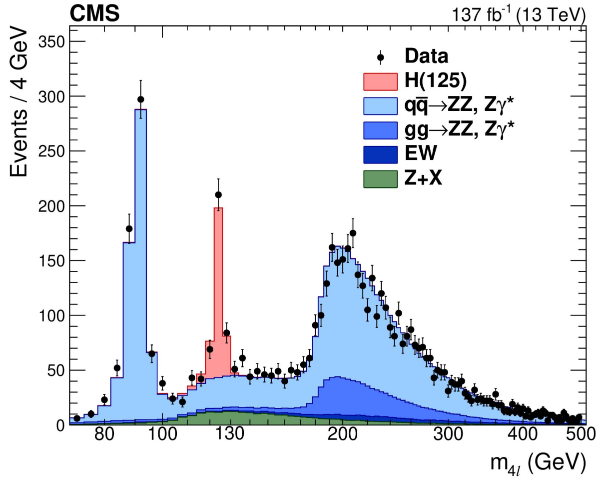


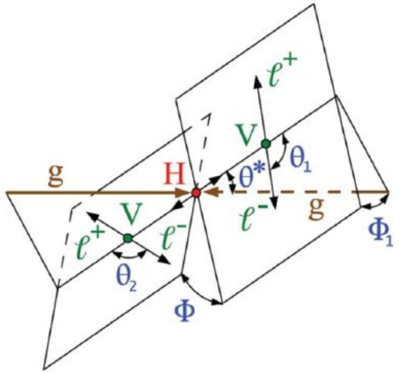


$H \to ZZ^* \to 4l$

The "golden channel"

- Key features
  - Very high S/B
  - Low event counts
  - Excellent mass resolution (1-2%)
  - Backgrounds easy to deal with
- Analysis strategy
  - 2 pairs of isolated electron/muon
  - One pair at m_Z
  - Invariant mass as key distribution
  - Fully reconstructed kinematics allows for efficient bkg reduction
- Results
  - Similar set of results as $H \to \gamma\gamma$
  - Kinematics allow to probe spin/CP

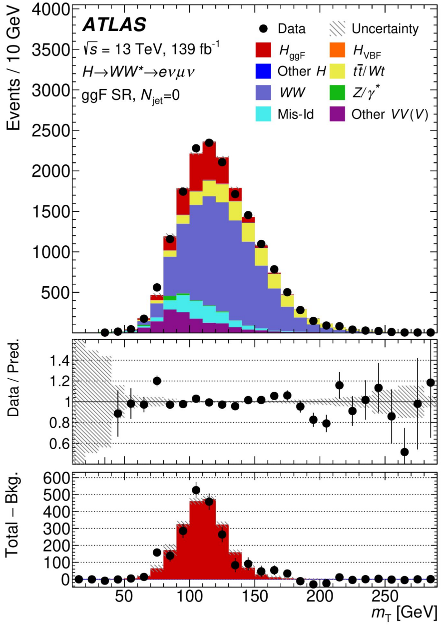


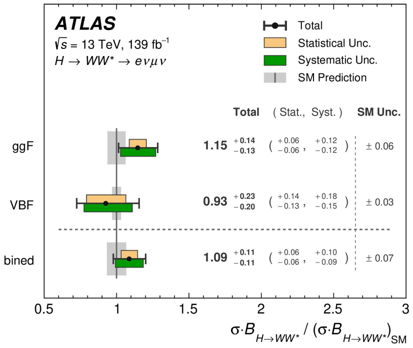


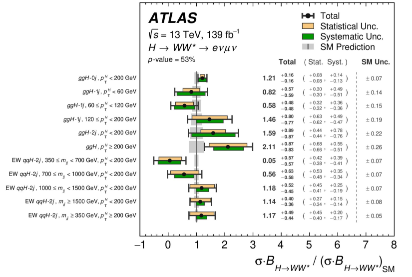
$H \rightarrow WW^* \rightarrow l\nu l\nu$

A different trade-off

- Key features
  - Good S/B
  - High event yields
  - Poor mass resolution (20%): neutrinos !
  - Some difficult backgrounds
- Analysis strategy
  - 2 isolated electron/muon
  - Mostly opposite-flavour
  - Transverse mass as key distribution
  - But DNN with full kinematic information provides large improvement
- Results
  - Good channel for ggF and VBF productions
  - Significant impact of syst. uncertainties





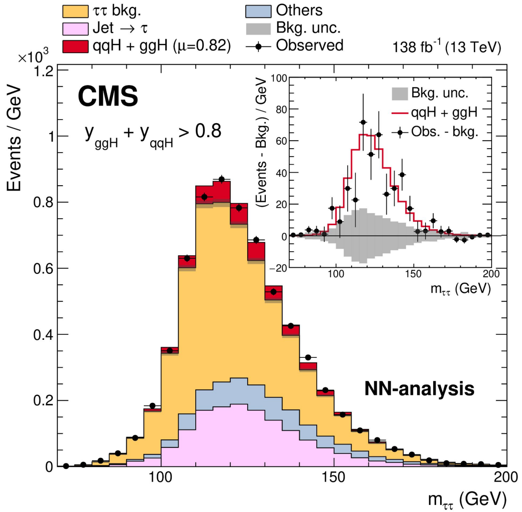


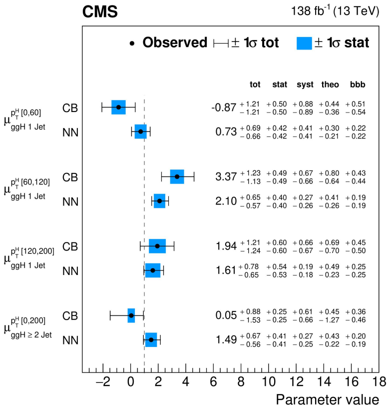
Channel for the discovery of Yukawa couplings

- Key features
  - Medium S/B
  - Medium event yields
  - Poor mass resolution
  - Difficult background modelling

- Analysis strategy
  - 2 taus (hadronic/leptonic)
  - Invariant mass as key distribution
  - But NN with full kinematic information provides large improvement
  - Embedding techniques to deal with Z background

- Results
  - Observation of Yukawa coupling in Run1 ATLAS+CMS combination
  - Then in Run 2 separately





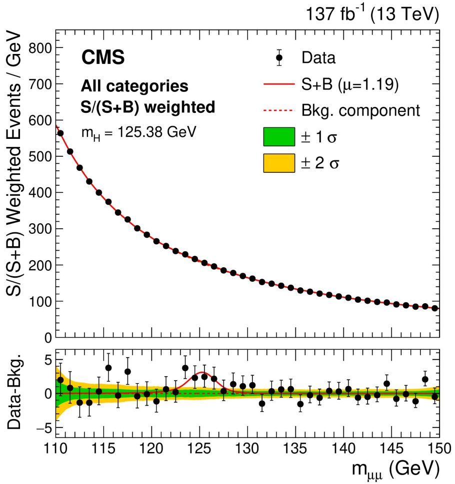
H → μμ

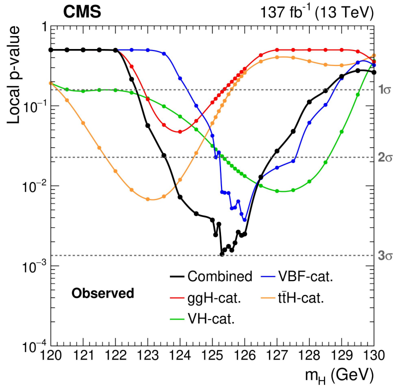
A bit like H → γγ, but harder

- Key features
  - Tiny S/B
  - Small event yields
  - Excellent mass resolution
  - Simple background modelling

- Analysis strategy
  - 2 muons
  - Invariant mass as key distribution
  - Classification by production mode + use of DNN for improved sensitivity

- Results
  - Evidence for H → μμ by CMS in Run 2 !
  - $\mu = 1.2 \pm 0.4$, $Z = 3.0\ \sigma$

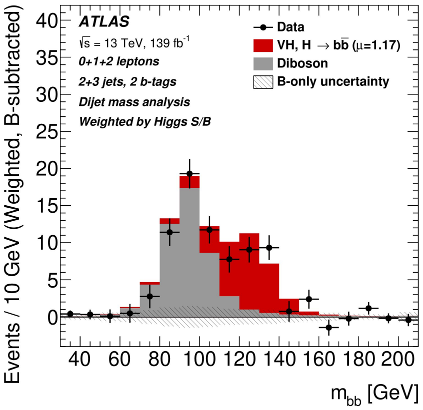


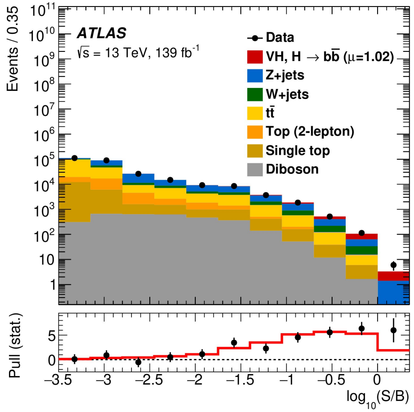


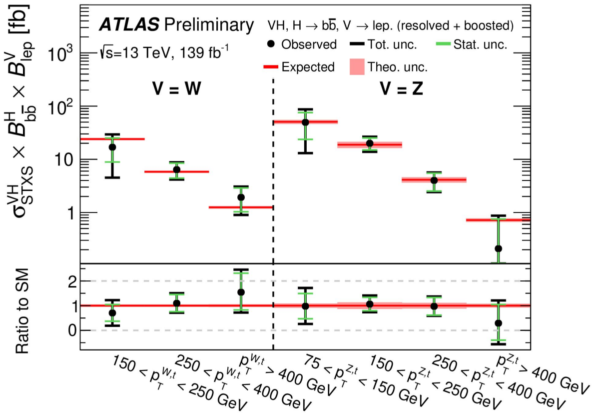
VH, H → bb

Main channel for H → bb observation

- Key features
  - Small S/B ~ 0.05
  - Medium event yields (VH production)
  - Medium mass resolution (10%)
  - Many difficult backgrounds
- Analysis strategy
  - 0/1/2 leptons, 2 b-jets
  - Invariant mass as key distribution
  - Use of NN for improved sensitivity
  - Boosted large-R jet categories to access very high p_T regime
  - Validation with VZ, Z → bb
- Results
  - Observation by ATLAS and CMS in 2018
  - $\mu = 1.02 \pm 0.18$
  - 5σ for ZH, 4σ for WH



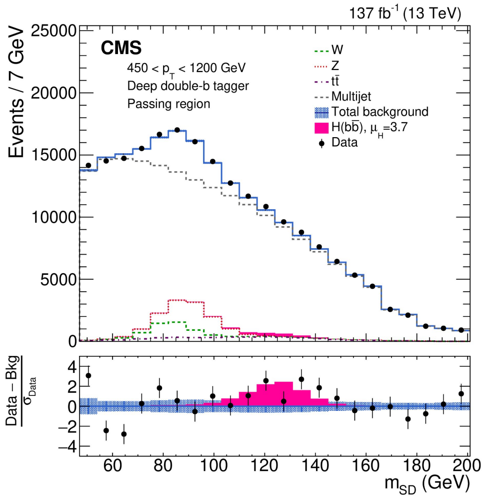


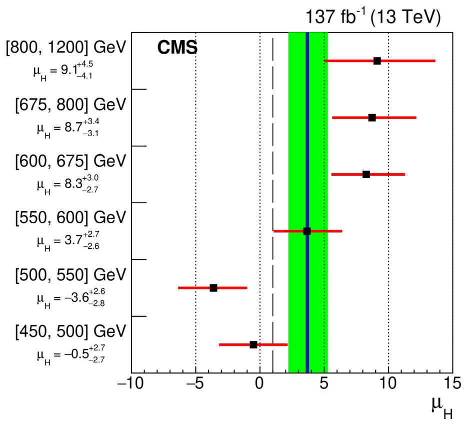


H → bb in boosted regime

Inclusive H → bb long thought impossible at the LHC

- “True” inclusive H → bb really impossible
  - S/B way too low wrt QCD bb production
  - Cannot even trigger on the events
- High-pT regime accessible through specific reconstruction techniques
  - Large-R jet
  - 2-prong, with 2 b-tags
  - Dedicated background estimation techniques
  - Validation with Z → bb process
- Results
  - Small excess wrt SM at high-p_T: 2.5σ observed for 0.7σ expected

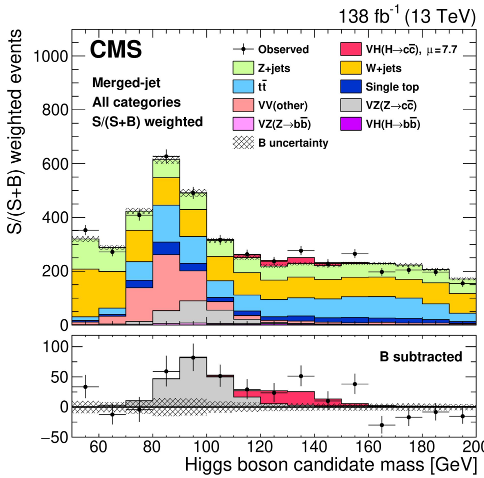


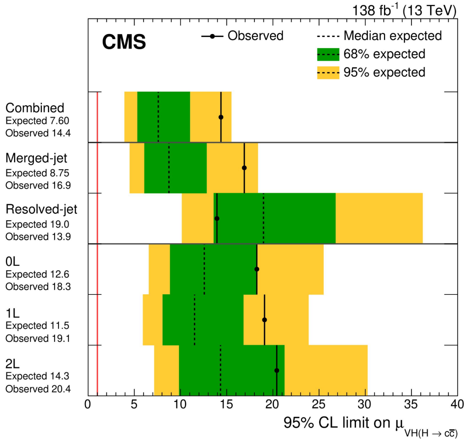


VH, H → cc

Another surprise from Run 2 data

- Like VH, H → bb, but harder
  - Lower BR (2.9% vs 58%)
  - c-tagging less performant than b-tagging
    - Higher backgrounds
  - Overall very low S/B
- Analysis strategy
  - Same as VH, H → bb
  - Make use of “resolved” and “merged” topologies
  - Powerful H → cc DNN tagger (CMS)
  - Validation with VZ, Z → cc (μ = 1.01)
- Results
  - Observation of Z → cc at 5.7σ
  - Limit on VHcc at 14 SM (7.8 expected)
  - Constraints on Higgs-charm coupling





Higgs combinations

Combining measurements allows to lift degeneracies and measure with fewer assumptions

- Combined likelihood: multiplication of likelihoods for each input analysis
  - Constraint terms included only once

$$L(\boldsymbol{\alpha}, \boldsymbol{\theta}, \text{data}) = \prod_{k \in \text{cat}} \prod_{b \in \text{bins}} P(n_{k,b} | n_{k,b}^{\text{signal}}(\boldsymbol{\alpha}, \boldsymbol{\theta}) + n_{k,b}^{\text{bkg}}(\boldsymbol{\theta})) \prod_{\theta \in \boldsymbol{\theta}} G(\theta)$$

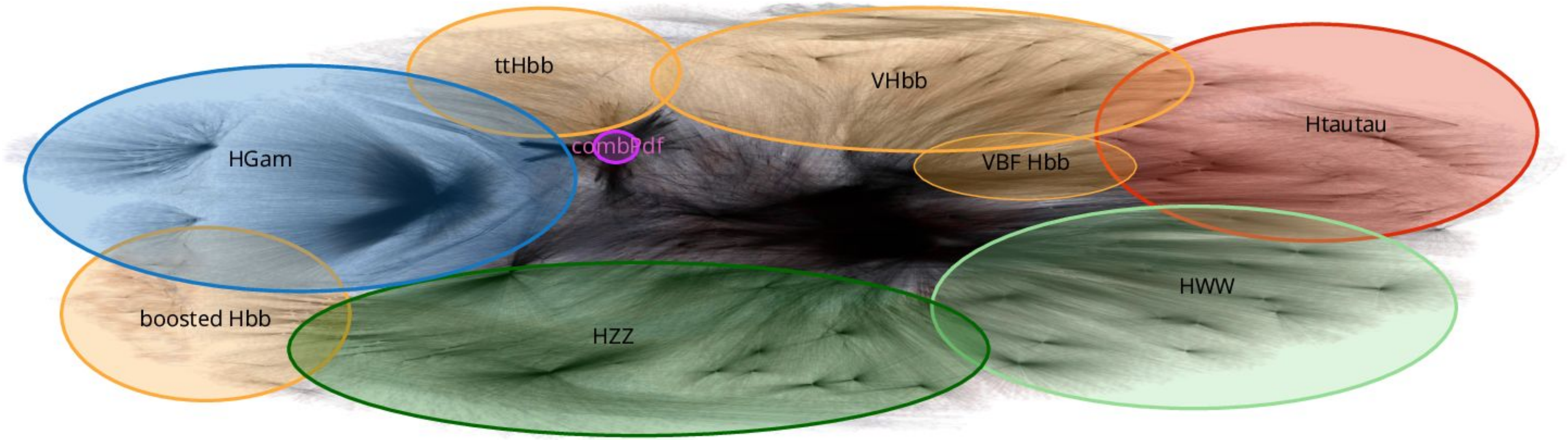
  - The parameters of interest can be reparameterized in many ways depending on the measurement
    - Production cross-section (decays then fixed to SM)
    - Decays BR (productions then fixed to SM)
    - etc…

$$n_k^{\text{signal}} = \mathcal{L}_k \sum_i \sum_f (\sigma_i B_f)(A\epsilon)_{if}^k$$

- Points of attention
  - Compatible set of systematic uncertainties between analyses
  - No (or at least negligible) statistical overlap between the analyses included

Combined Higgs likelihood

Over 2600 systematic uncertainties included

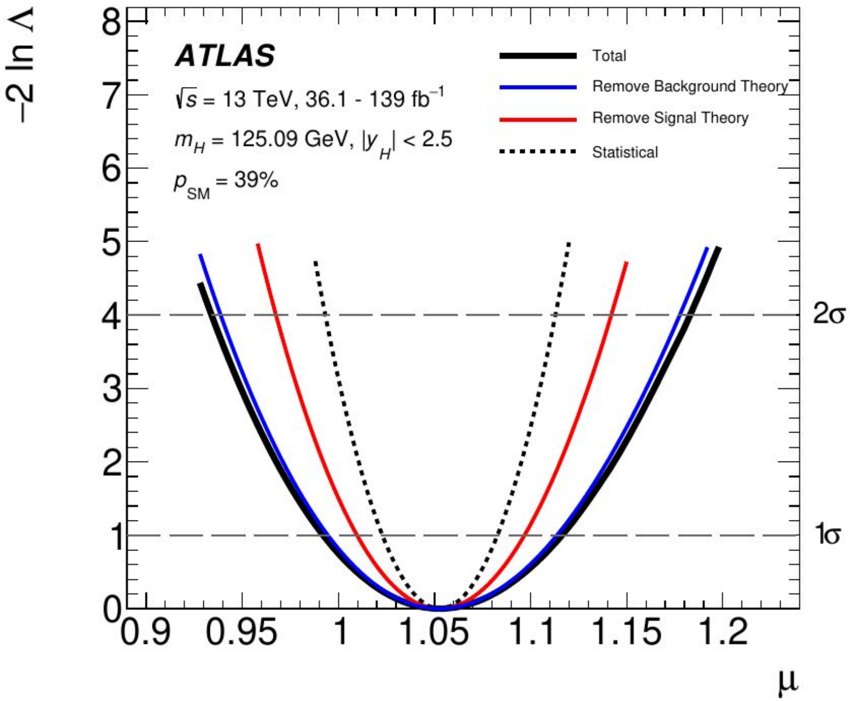


Representation of the likelihood of the ATLAS combination.
Each terminal node is one term in the likelihood

Combined signal strength

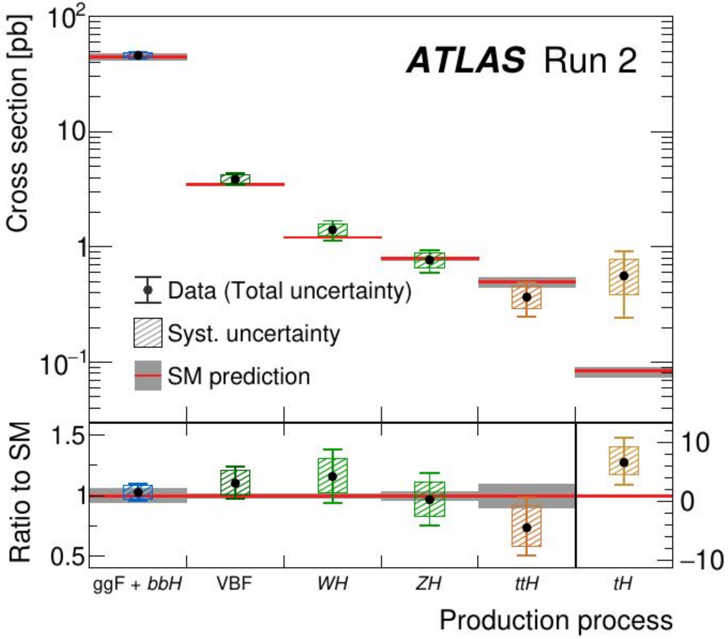
Systematic uncertainties (esp. theoretical ones) dominate

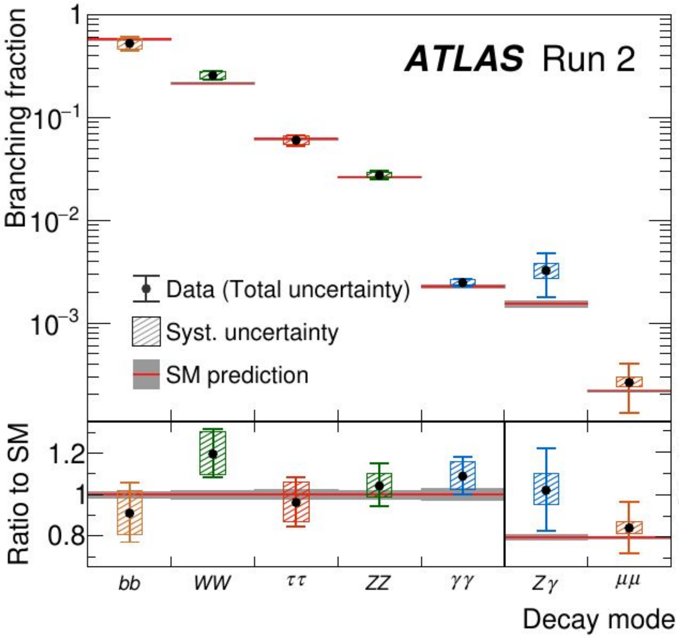
$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.})$$



Higgs production and decay

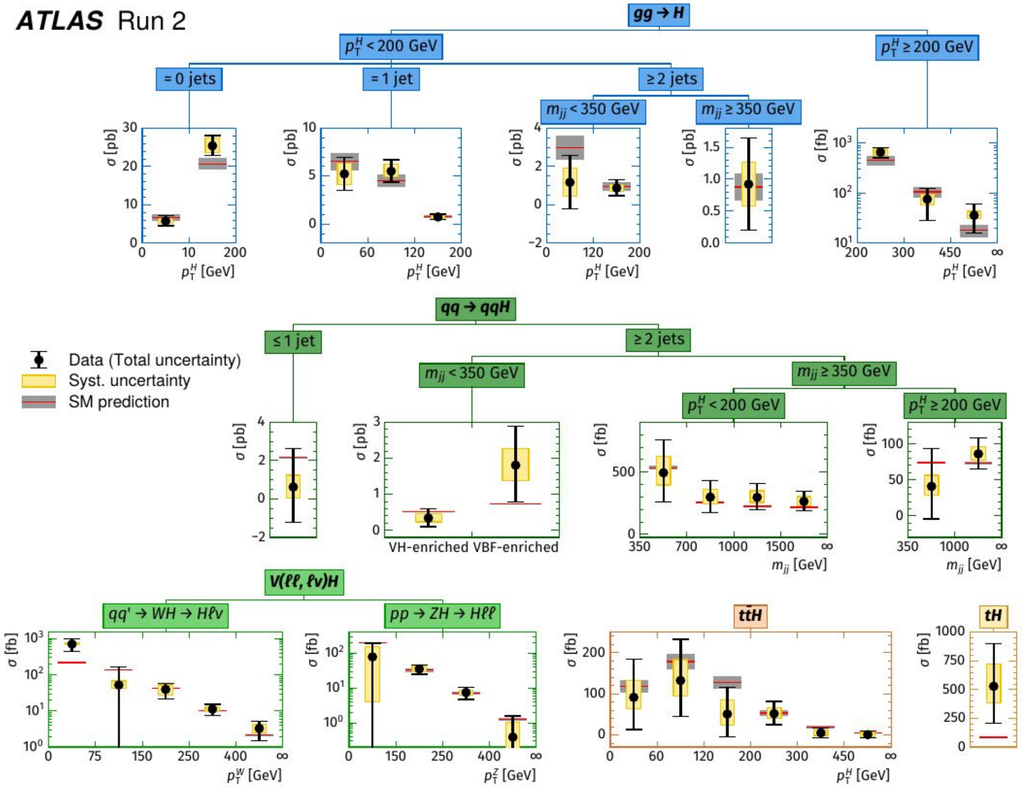
- All main production and decay modes at the LHC now observed
- Evidence for H → μμ, interesting limits on H → cc
- Interesting limits on tH production





Combined STXS measurements

Probing 36 kinematic regions simultaneously



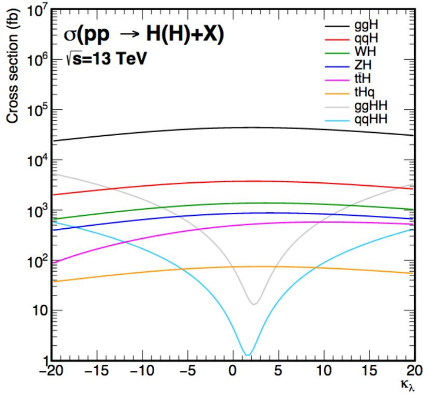
- Very different sensitivities depending on the kinematic regions
- At high pT, larger error bar still provides better constraints on new physics scenarios

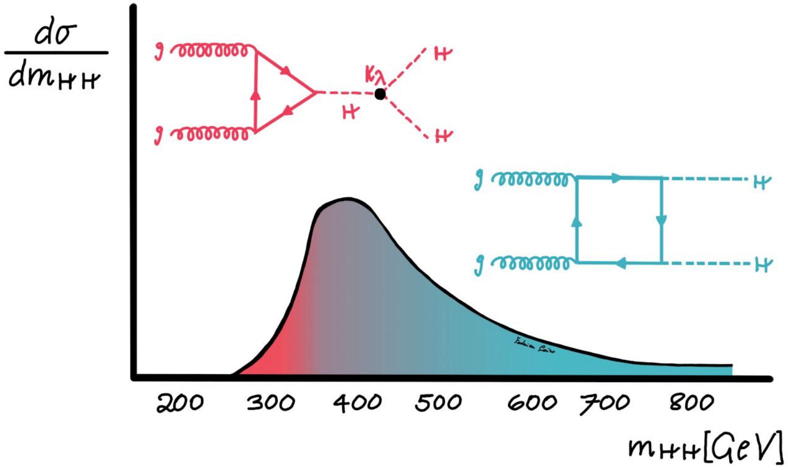
Di-Higgs searches

Run 2: progress much greater than anticipated

- Ultimate goal: measure Higgs self-coupling
  - How: observe HH production
  - But: negative interference between self-coupling and other diagrams
- Small cross-sections
  - At least one $H \to bb$
  - Main channels: bbbb, bbττ, bbγγ

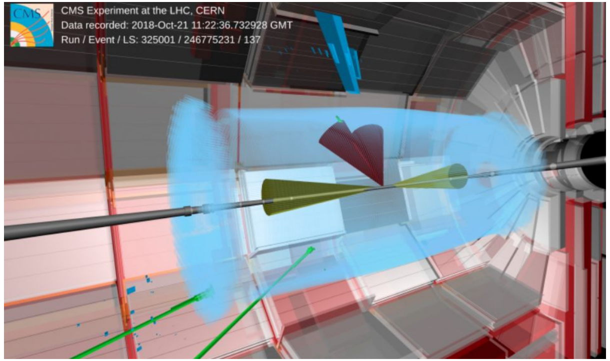
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

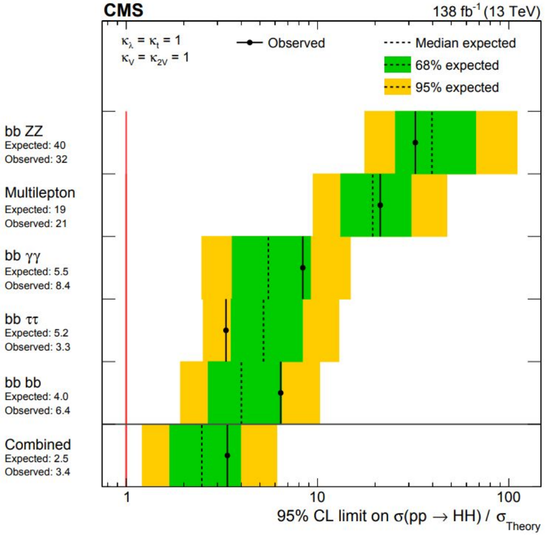


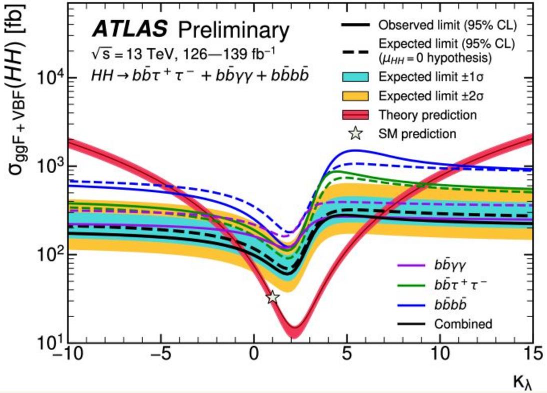


Di-Higgs searches with Run 2

- Significant improvements in analysis techniques
  - In all channels
  - ML, use of boosted regime, …
- Limits on σ(HH):
  - 2.4 SM for ATLAS
  - 3.4 SM for CMS
- Constraints on κ_λ
  - $-0.4 < \kappa_\lambda < 6.3$
- Quite promising for Run 3 and Run 4





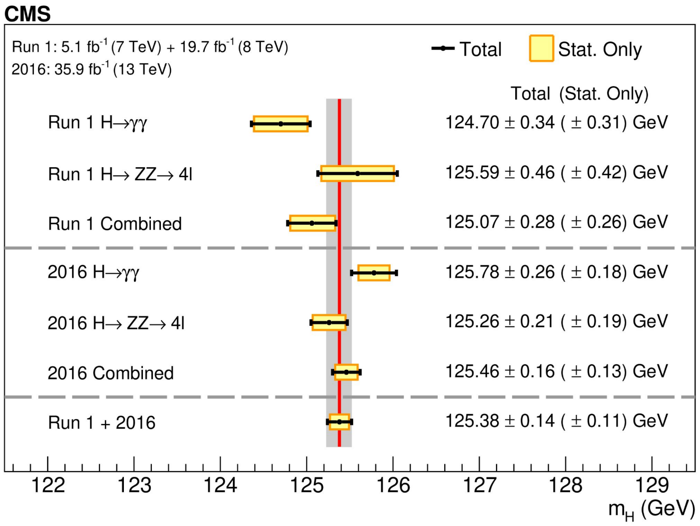


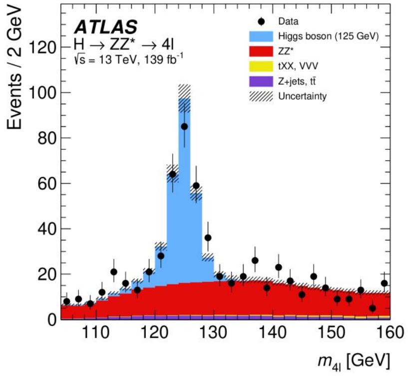
Higgs properties

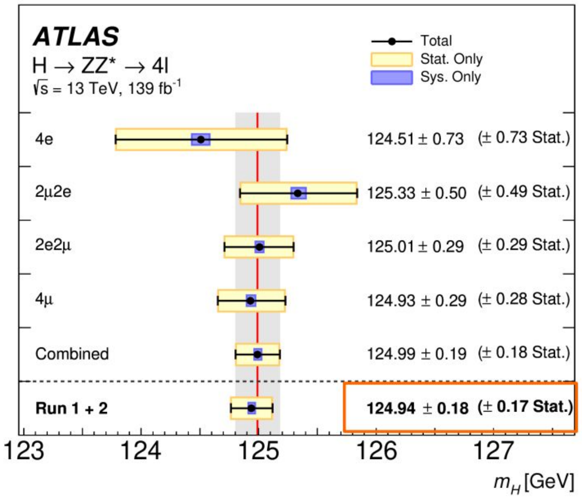
Higgs mass

High-resolution H → 4l and H → γγ channels

- Requires ultimate precision for lepton and photon energy calibration
- H → γγ: higher stat, but larger systematics
- H → 4l, esp. H → 4μ: low stat, but ultimate precision in the long term
- Combined precision ~ 0.1%



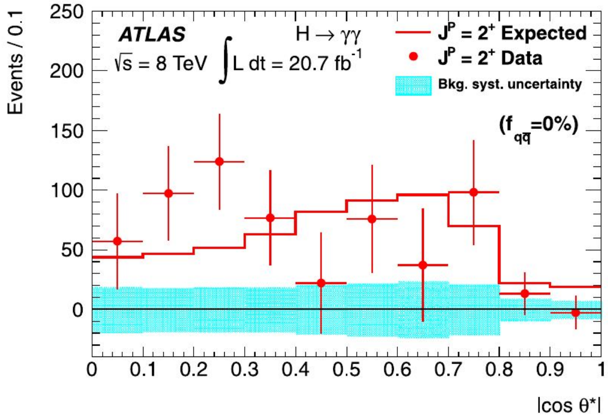


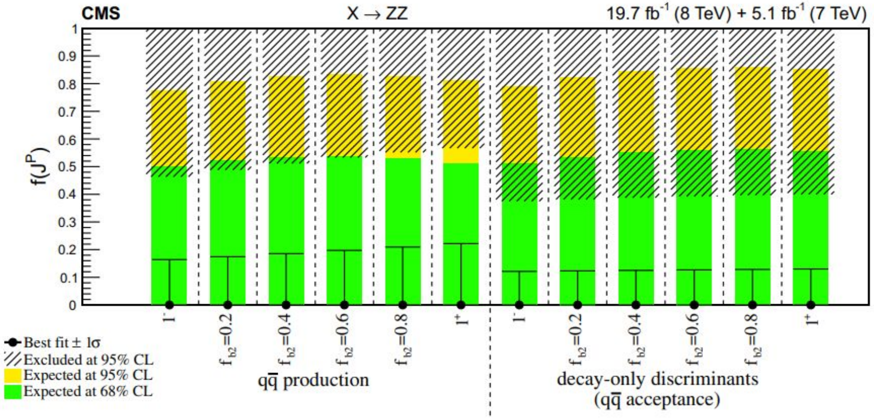


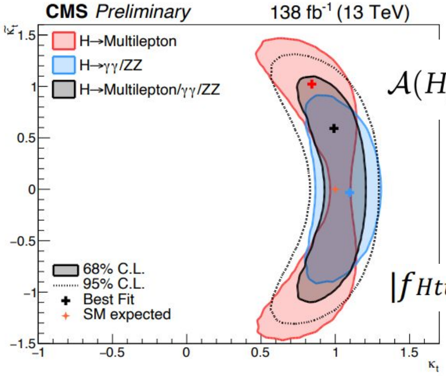
Spin and parity

- Question settled with Run 1 data
  - Observation of $H \to \gamma\gamma$ forbids spin 1
  - All other hypotheses than 0^+ disproved using angular distributions in γγ, WW and ZZ channels

- Some level of CP violation still allowed in Higgs production and decay vertices
  - Probed using VBF production, ttH production, $H \to ZZ$ and $H \to \tau\tau$ decays
  - Everything compatible with SM so far





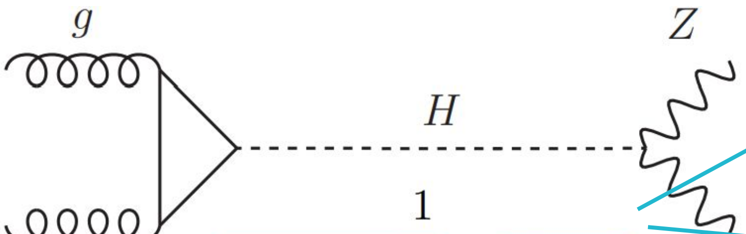


$$\mathcal{A}(Hff) = \frac{m_f}{v}\bar{\psi}_f(\kappa_t + i\tilde{\kappa}_t\gamma_5)\psi_f$$

$|f_{Htt}| = 0.28$ (< 0.55 at 1σ)

Higgs Width

- Direct measurement of Higgs width (4 MeV) impossible at the LHC
- Powerful indirect constraint in the H → ZZ* channel
  - Comparison of on-shell and off-shell signal strengths
  - Hidden assumption: no Q^2 dependence of the Higgs couplings, as in the SM



$$\frac{1}{(m^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}$$

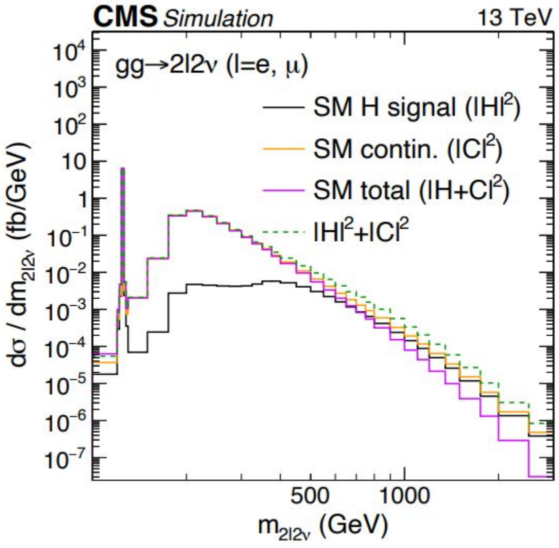
$$\sigma^{\text{on-shell}}_{vv\to H\to 4\ell} \propto \frac{g^2_{\text{gluon}} g^2_V}{\Gamma_H}$$

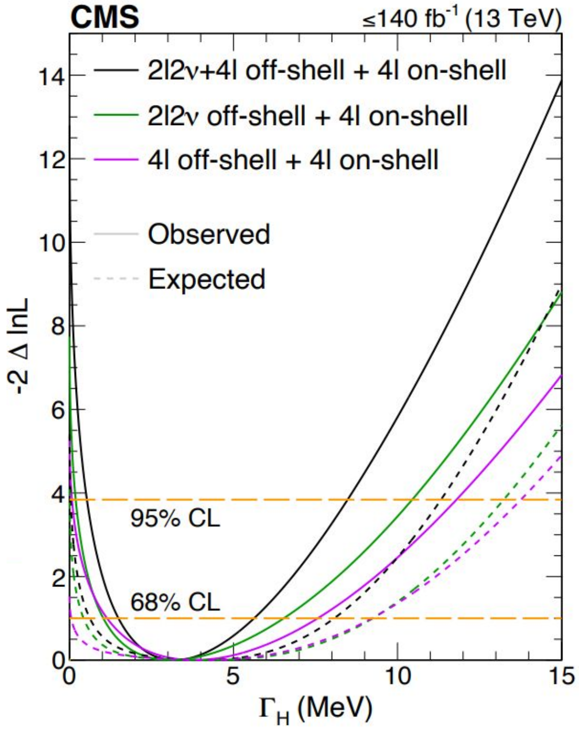
$$\sigma^{\text{off-shell}}_{vv\to H\to 4\ell} \propto g^2_{\text{gluon}} g^2_V$$

$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma}{\Gamma_{\text{SM}}}$$

Higgs width II

- Off-shell cross-section not so small when $Q^2 > 2m_Z$
- Interference with ZZ continuum
- > 3σ evidence for Higgs width by ATLAS and CMS
  - CMS: $\Gamma_H = 3.2^{+2.5}_{-1.7}$ MeV





Higgs couplings

The kappa framework

Higgs production and decay mechanisms can be reinterpreted in terms of couplings

- Parameterization can be obtained at different orders for loop processes
- Assumes that only couplings strengths can change, not the kinematics

$$\sigma(i \to H \to f) = \sigma_i B_f = \frac{\sigma_i(\boldsymbol{\kappa})\Gamma_f(\boldsymbol{\kappa})}{\Gamma_H(\boldsymbol{\kappa}, B_{\text{inv.}}, B_{\text{u.}})}$$

Production cross section	Effective coupling	Parametrization in terms of coupling strength modifiers
$\sigma(\text{ggF})$	κ_g^2	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(\text{VBF})$	-	$0.733\,\kappa_W^2 + 0.267\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	κ_Z^2
$\sigma(gg \to ZH)$	-	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t - 0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(WH)$	-	κ_W^2
$\sigma(t\bar{t}H)$	-	κ_t^2
$\sigma(tHW)$	-	$2.909\,\kappa_t^2 + 2.310\,\kappa_W^2 - 4.220\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	$2.633\,\kappa_t^2 + 3.578\,\kappa_W^2 - 5.211\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	-	κ_b^2

Partial decay width		
Γ^{bb}	-	κ_b^2
Γ^{WW}	-	κ_W^2
Γ^{gg}	κ_g^2	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	κ_τ^2
Γ^{ZZ}	-	κ_Z^2
Γ^{cc}	-	$\kappa_c^2\ (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t$ $+0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b - 0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	$\kappa_{Z\gamma}^2$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$
Γ^{ss}	-	$\kappa_s^2\ (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	-	κ_μ^2

The kappa framework

Higgs production and decay mechanisms can be reinterpreted in terms of couplings

- Parameterization can be obtained at different orders for loop processes
- Assumes that only couplings strengths can change, not the kinematics

$$\sigma(i \to H \to f) = \sigma_i B_f = \frac{\sigma_i(\boldsymbol{\kappa})\Gamma_f(\boldsymbol{\kappa})}{\Gamma_H(\boldsymbol{\kappa}, B_{\text{inv.}}, B_{\text{u.}})}$$

$$\kappa_H^2(\boldsymbol{\kappa}, B_{\text{inv.}}, B_{\text{u.}}) = \frac{\sum_p B_p^{\text{SM}} \kappa_p^2}{(1 - B_{\text{inv.}} - B_{\text{u.}})}$$

Total width ($B_{\text{inv.}} = B_{\text{u.}} = 0$)		
Γ_H	κ_H^2	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2 + 0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{Z\gamma}^2 + 0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

- Different choices possible for parameterization of Higgs width
  - Varies with SM couplings
  - Can leave room for invisible and undetected decays
  - In all cases, an **assumption** has to be made

What to look for

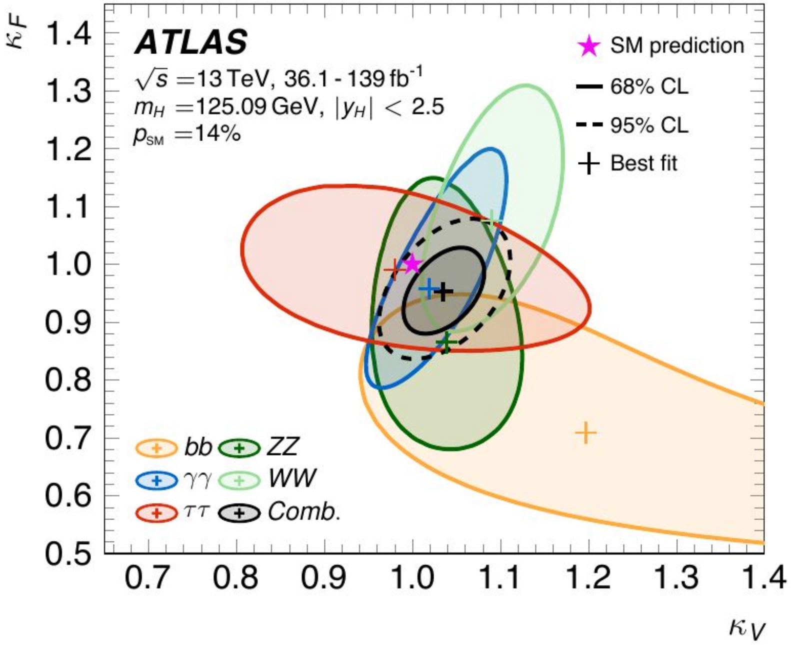
Typical models predict from <1% to 10% deviations

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

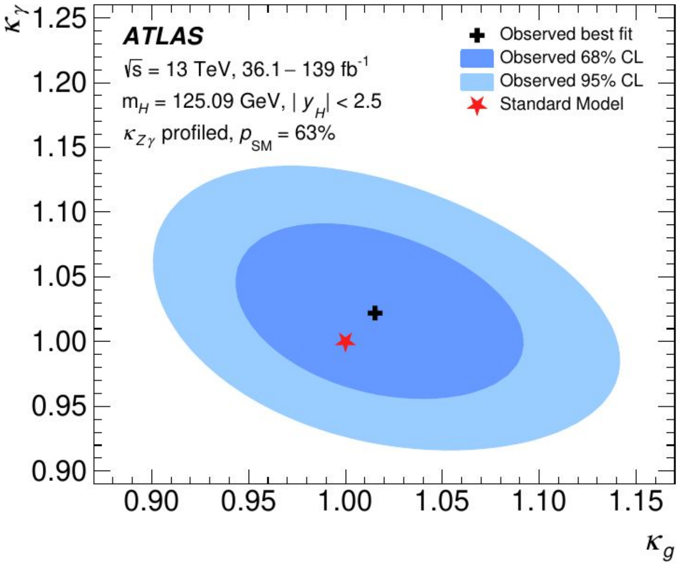
Simple models

Different kappa parameterizations to probe various possible SM deviations

Couplings to fermions and bosons (assumes no new BSM couplings)



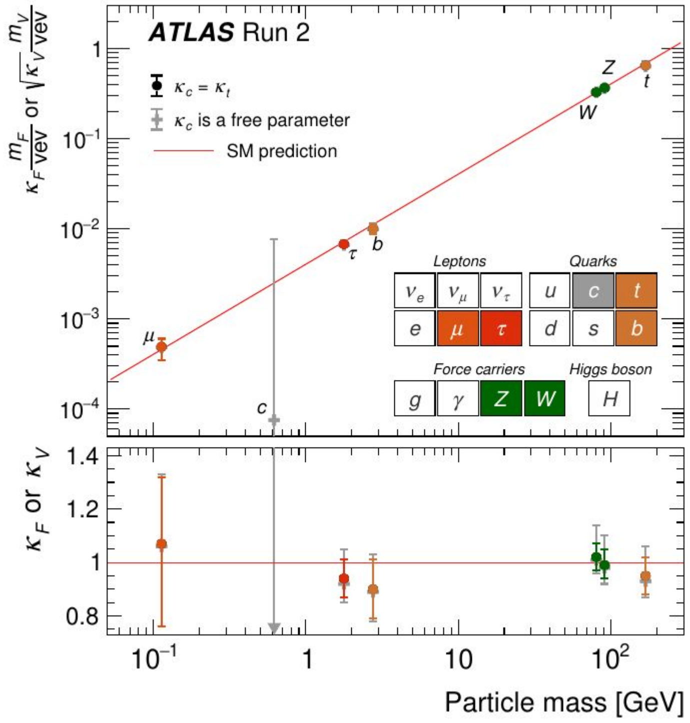
Effective couplings to photons and gluons



Useful in case BSM manifests itself in loops

Particle couplings

Probes the scaling between couplings and masses



Very SM-like Higgs so far !

- 5% precision on boson couplings
- 10–20% precision on fermion couplings

Constraining BSM through Higgs

2HDM models

Quite generic extension of the SM: 2 Higgs doublets instead of 1

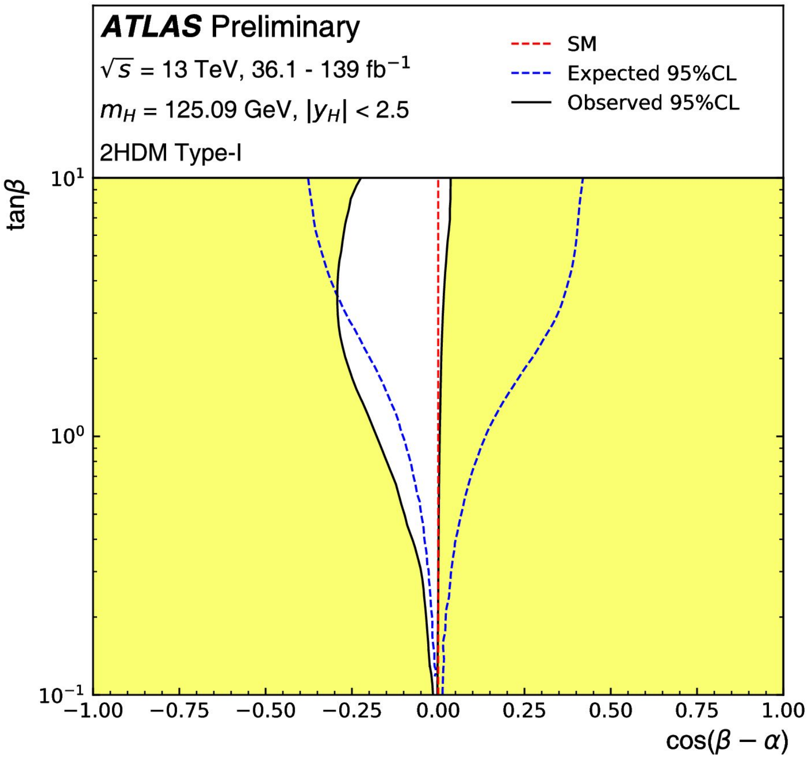
- Very rich phenomenology
  - 5 Higgs bosons: light h, heavy H, charged $H^{\pm}$, pseudoscalar A
  - Classification in 4 types
    - Type I: one doublet couples to fermions, the other to bosons
    - Type II: one doublet couples to up-type quarks, the other to down-type quarks and charged leptons
    - Type II is the Higgs sector of the MSSM
    - Type III and IV: more exotic variations
  - 2 parameters: $\tan\beta = v_2 / v_1$, α mixing angle between h and H

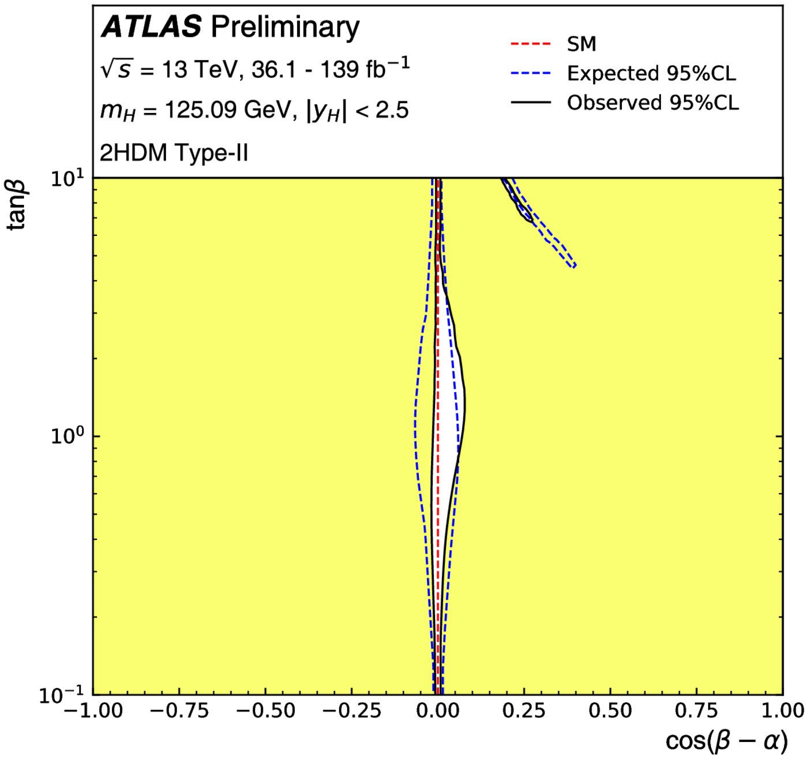
- Numerous possible constraints
  - Direct searches for additional Higgs bosons in many channels
    - $A \to \tau\tau$, $A \to Zh$ ($h \to bb$), …
  - Couplings deviations in "SM" Higgs (h)

Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V		$s_{\beta-\alpha}$		
κ_u	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$
κ_d	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} - \tan\beta\, c_{\beta-\alpha}$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} - \tan\beta\, c_{\beta-\alpha}$
κ_l	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} - \tan\beta\, c_{\beta-\alpha}$	$s_{\beta-\alpha} - \tan\beta\, c_{\beta-\alpha}$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$

2HDM constraints

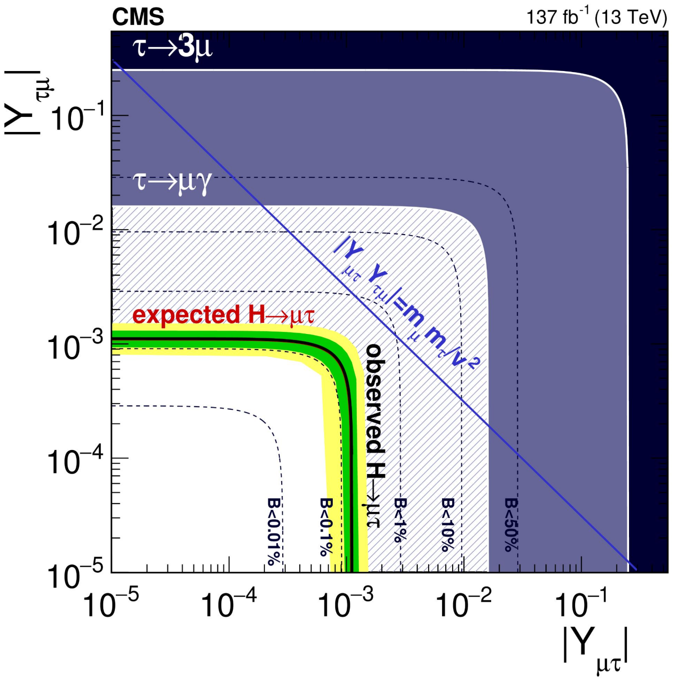
Phase space very well constrained from existing measurements





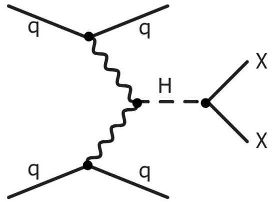
Searches for BSM Higgs decays: LFV

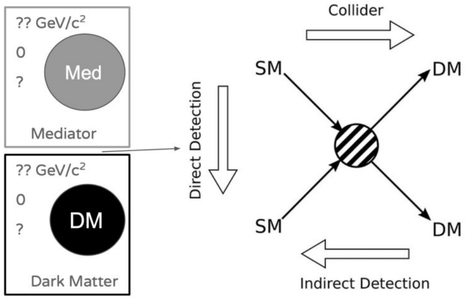
- Lepton flavour violation would be a striking signature of new physics
  - Interest also spurred by B anomalies
- Searches in the Higgs decays
  - Typically $H \to \tau\mu$ or $H \to \tau e$
  - Competitive limits wrt other LFV channels
  - Limits:
    - $BR(H \to \tau\mu) < 0.15\%$
    - $BR(H \to \tau e) < 0.22\%$

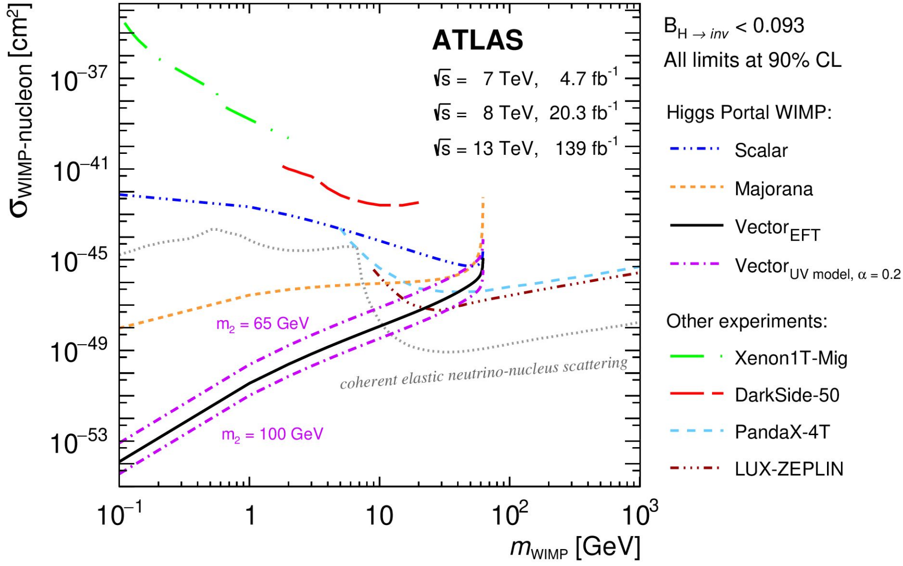


Search for BSM Higgs decays: invisible decays

- BR(H → inv) is tiny in SM (H→ZZ→4ν)
- Larger contribution can come from BSM decays
  - Can be candidate for dark matter
- Searches in all production modes
  - Main sensitivity from VBF production
  - Two forward jets, large missing transverse energy
- Results:
  - BR(H → inv) < 0.11 at 95% CL
  - Interpretation in "Higgs portal" models
    - Competitive limits with direct DM experiments under these assumptions







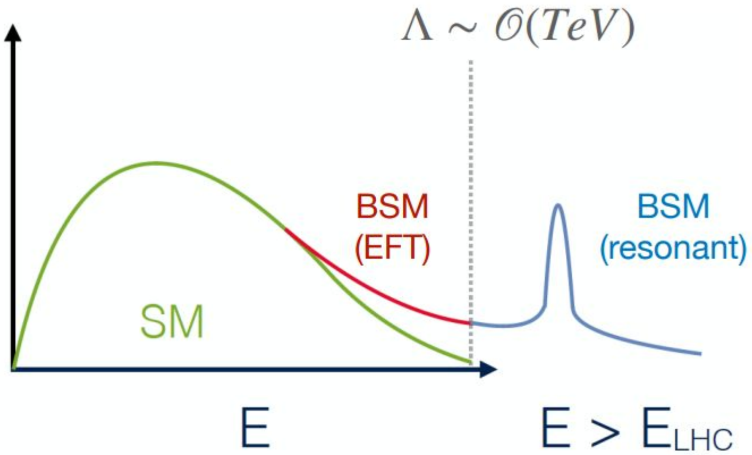
Effective field theories

No direct evidence for new physics at the LHC so far

- View SM as **low-energy approximation** of a more fundamental theory
- Search for BSM by looking for deviations in precision SM measurements

- Effective Field Theory Lagrangian
  - Systematic parameterization of deviations from SM
  - Add all higher-order operators allowed by symmetries, suppressed by powers of **cut-off scale Λ**
  - Constraints on associated Wilson coefficients

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$



EFT parameterizations

A huge task !

- dim 5 and 7 operators induce large baryon and lepton flavour violation
  - Usually not considered

- Typical effect on cross-sections (BR and acceptance effects have to be included as well):

$$\sigma = \sigma_{\mathrm{SM}} + \sigma_{\mathrm{int}} + \sigma_{\mathrm{BSM}} = \sigma_{\mathrm{SM}} \left(1 + \sum_i a_i^{(6)} \frac{c_i^{(6)}}{\Lambda^2} + \sum_{ij} b_{ij}^{(6)} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} + \ldots\right)$$

Linear terms **Quadratic terms**

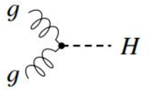
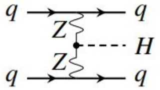
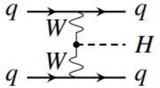
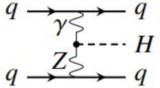
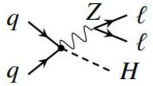
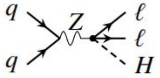
- Dim 6: 2499 operators with baryon number conservation
  - Additional symmetries can simplify the problem
  - O(30) operators in flavour-universal scenarios
  - aka “SMEFT”

- Dim 8: 36971 operators
  - Studied only in very specific cases

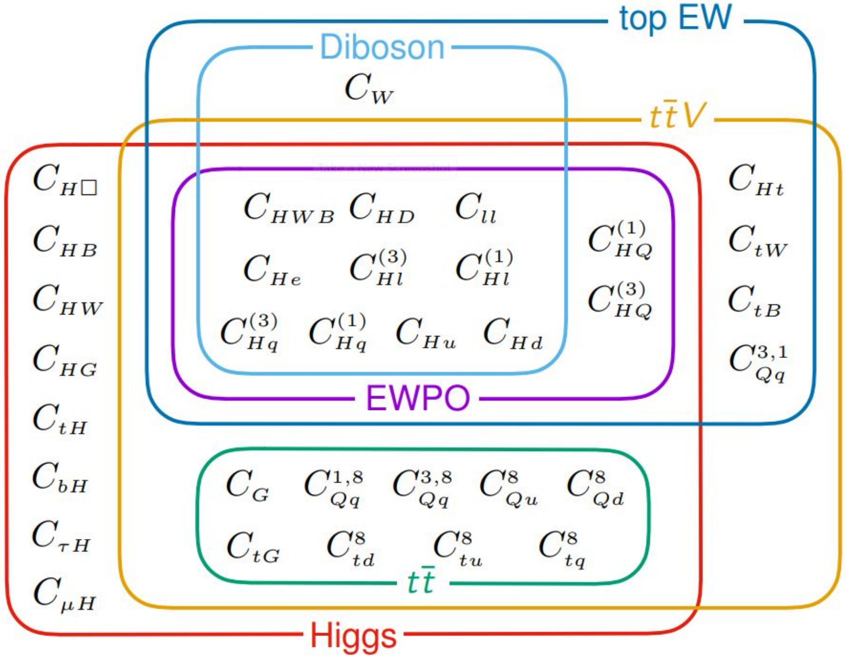
Non unique choice of operators ⇒ different choices of bases possible

EFT in the Higgs sector

- Choice of basis: "Warsaw"
- A given operator has effects on many processes (not only Higgs)

Wilson coefficient	Operator definition	Example diagram
c_{HG}	$\Phi^\dagger \Phi G^a_{\mu\nu} G^{a\mu\nu}$	
c_{HB}	$\Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu}$	
c_{HW}	$\Phi^\dagger \Phi W^I_{\mu\nu} W^{I\mu\nu}$	
c_{HWB}	$\Phi^\dagger \Phi W^I_{\mu\nu} B^{I\mu\nu}$	
c_{Hq1}	$(i\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\bar{q}\gamma^\mu q)$	
c_{Hl1}	$(i\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\bar{\ell}\gamma^\mu \ell)$	

Warsaw basis



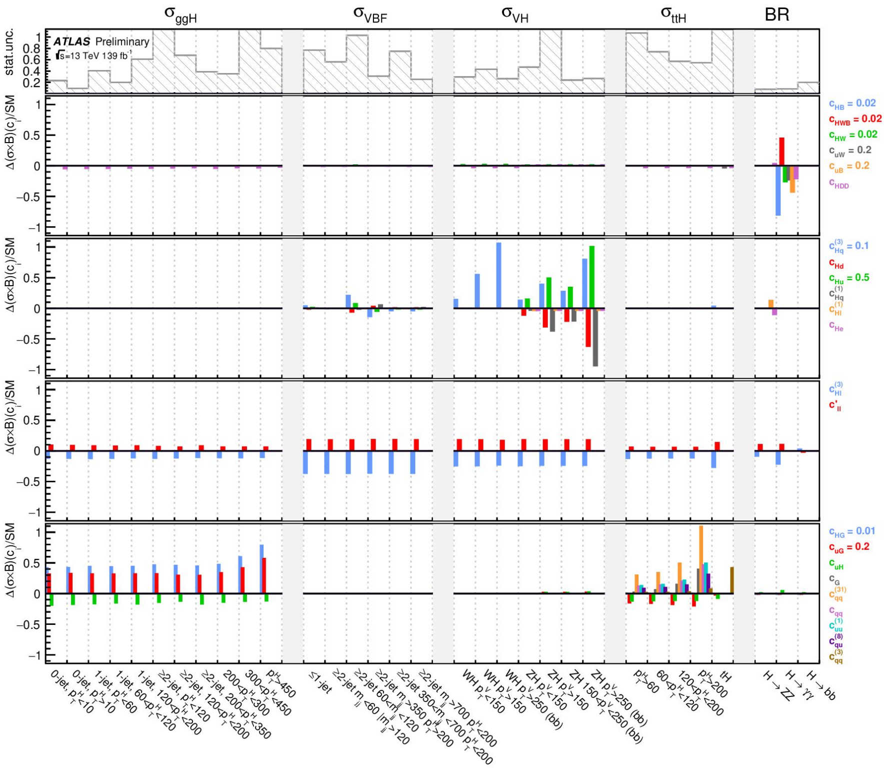
J. Ellis et al, JHEP 04 (2021) 279

Measuring EFT

EFT effects largest at high Q²: use of differential distributions

- Reinterpret the STXS measurements
  - For individual channels or for their combination
  - Parameterize the cross-section in each STXS category in terms of EFT operators

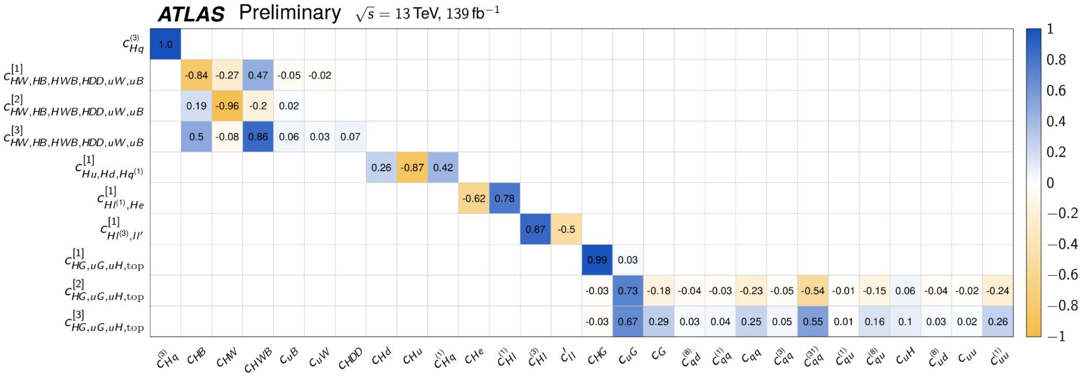
$ggF(\geq 1-jet, p_T^H > 200GeV)$	$15.6 \cdot c_{HG}$
$qq \to Hqq(non-VH)$	$0.1213 \cdot c_{Hbox} - 0.0107 \cdot c_{HDD} - 0.008 \cdot c_{HW} + 0.0313 \cdot c_{HWB} - 0.364 \cdot c_{Hl3} + 0.0043 \cdot c_{Hq1} - 0.212 \cdot c_{Hq3} - 0.0108 \cdot c_{Hu} + 0.0038 \cdot c_{Hd} + 0.182 \cdot c_{ll1}$
$qq \to Hqq(VH)$	$0.120 \cdot c_{Hbox} - 0.0071 \cdot c_{HDD} + 0.623 \cdot c_{HW} + 0.0215 \cdot c_{HB} + 0.098 \cdot c_{HWB} - 0.360 \cdot c_{Hl3} - 0.026 \cdot c_{Hq1} + 1.86 \cdot c_{Hq3} + 0.135 \cdot c_{Hu} - 0.0506 \cdot c_{Hd} + 0.181 \cdot c_{ll1}$
$qq \to Hqq(p_T^{j1} > 200GeV)$	$0.122 \cdot c_{Hbox} - 0.0073 \cdot c_{HDD} - 0.25 \cdot c_{HW} + 0.0024 \cdot c_{HB} + 0.045 \cdot c_{HWB} - 0.367 \cdot c_{Hl3} + 0.030 \cdot c_{Hq1} - 0.47 \cdot c_{Hq3} - 0.030 \cdot c_{Hu} + 0.0087 \cdot c_{Hd} + 0.180 \cdot c_{ll1}$
$qq \to Hl\nu(p_T^V < 250GeV)$	$0.1212 \cdot c_{Hbox} - 0.0304 \cdot c_{HDD} + 0.874 \cdot c_{HW} - 0.242 \cdot c_{Hl3} + 1.710 \cdot c_{Hq3} + 0.182 \cdot c_{ll1}$

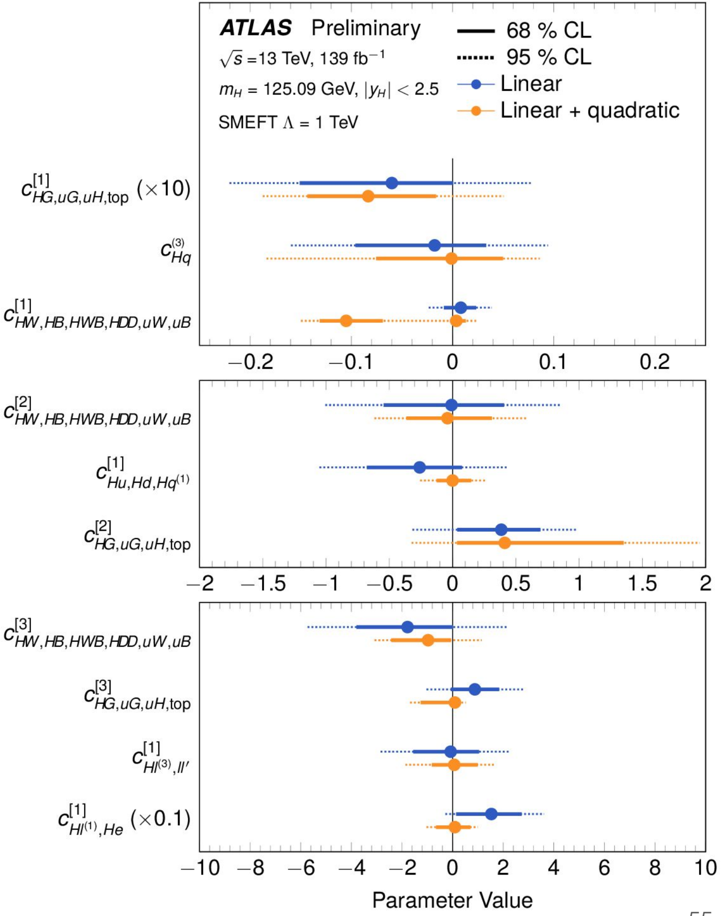


- More operators than numbers of measurements
  - Scan operators one by one
  - Fix some operators at 0
  - Do PCA (diagonalization) and constrain linear combinations of operators

EFT in the Higgs sector: results

- Include either linear or linear + quadratic terms
  - When results disagree, questions robustness of EFT as perturbative method

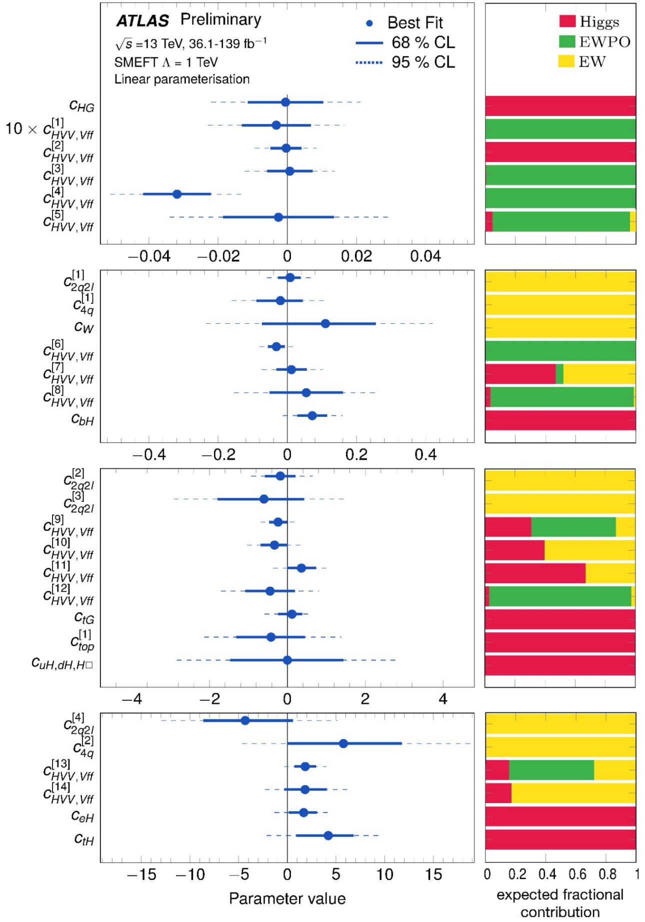




EFT potential: making use of all SM measurements

Unique possibility to look for BSM simultaneously in all SM measurements

- First "global" EFT combinations start to appear
  - Higgs measurements
  - Electroweak processes
  - Precision electroweak observables from LEP
- Very active field of research
  - Many open questions: EFT validity, uncertainties, higher order terms…
  - More channels to be included in global combinations in next years



Conclusions

- Higgs discovery has been a major shift in particle physics
  - Whole new sector of SM Lagrangian to explore
- 10 years after discovery, Higgs boson is a well-known particle
  - Mass, spin, CP properties
  - Couplings to SM particles
  - No sign of deviations from SM so far
- A powerful way to look for BSM
  - No more free parameter in SM: each measurement is a SM consistency test
  - Direct searches for BSM
  - Indirect searches for BSM by looking for deviations in couplings or distributions

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- Individual papers from ATLAS and CMS