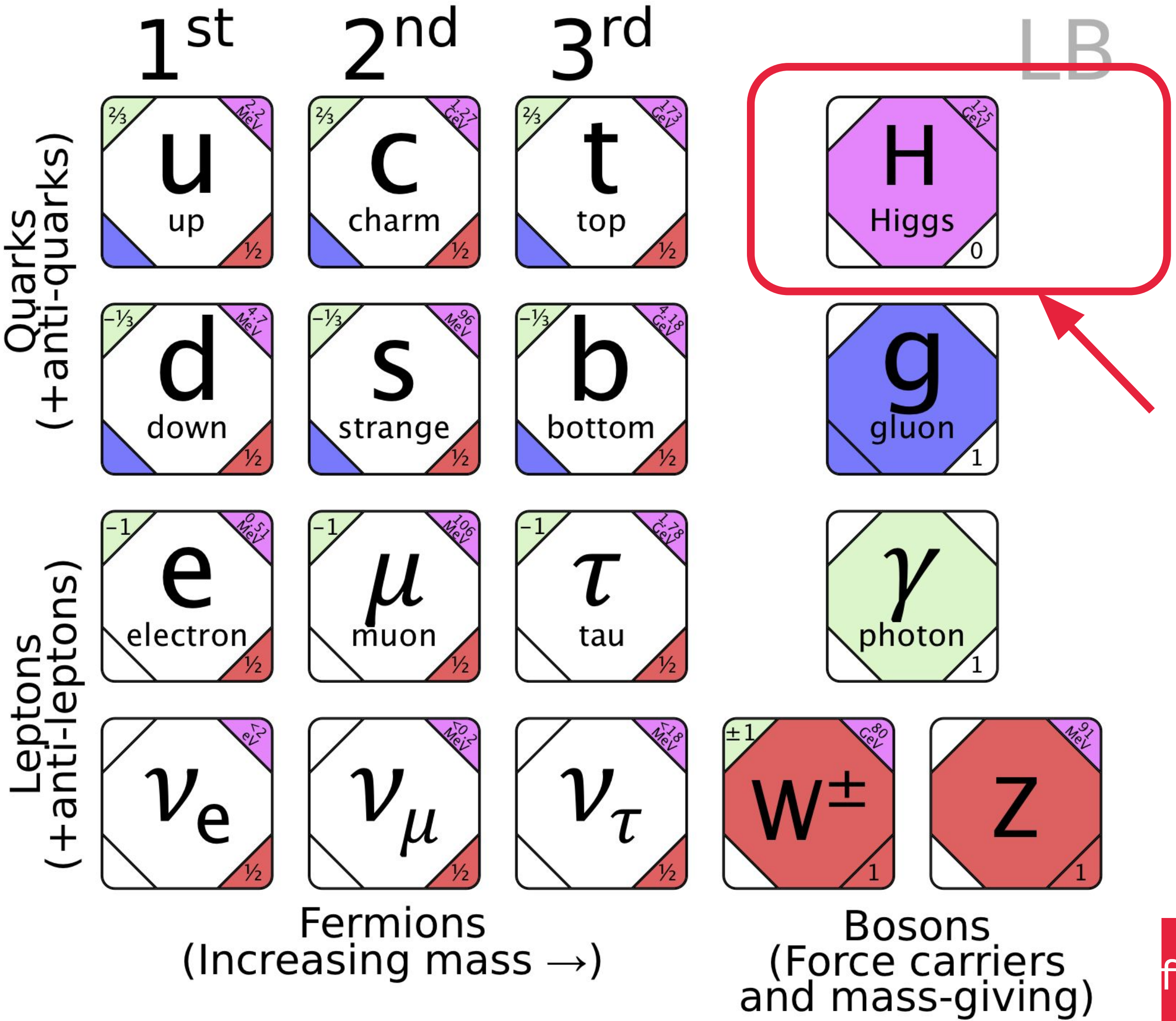
Higgs boson property measurements At the ATLAS and CMS experiments

Lydia Brenner

Introduction

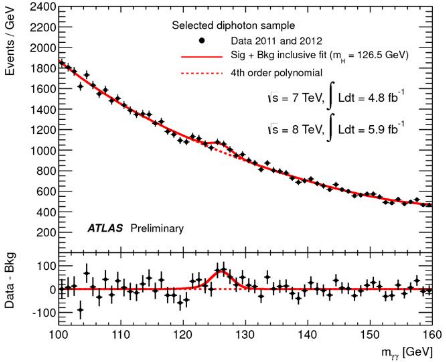
The Higgs boson

- Origin of mass
- Electroweak symmetry breaking
- Potential link to new physics



Higgs timeline at the LHC

Higgs boson observation



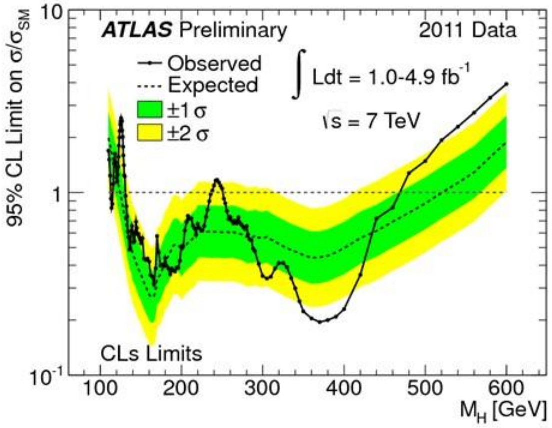
LHC

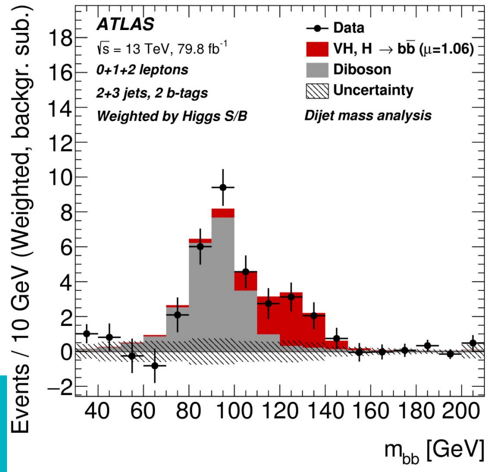
Run 1
7-8 TeV
21 fb^{-1}

Run 2
13 TeV
139 fb^{-1}

High Luminosity LHC

Higgs boson searches

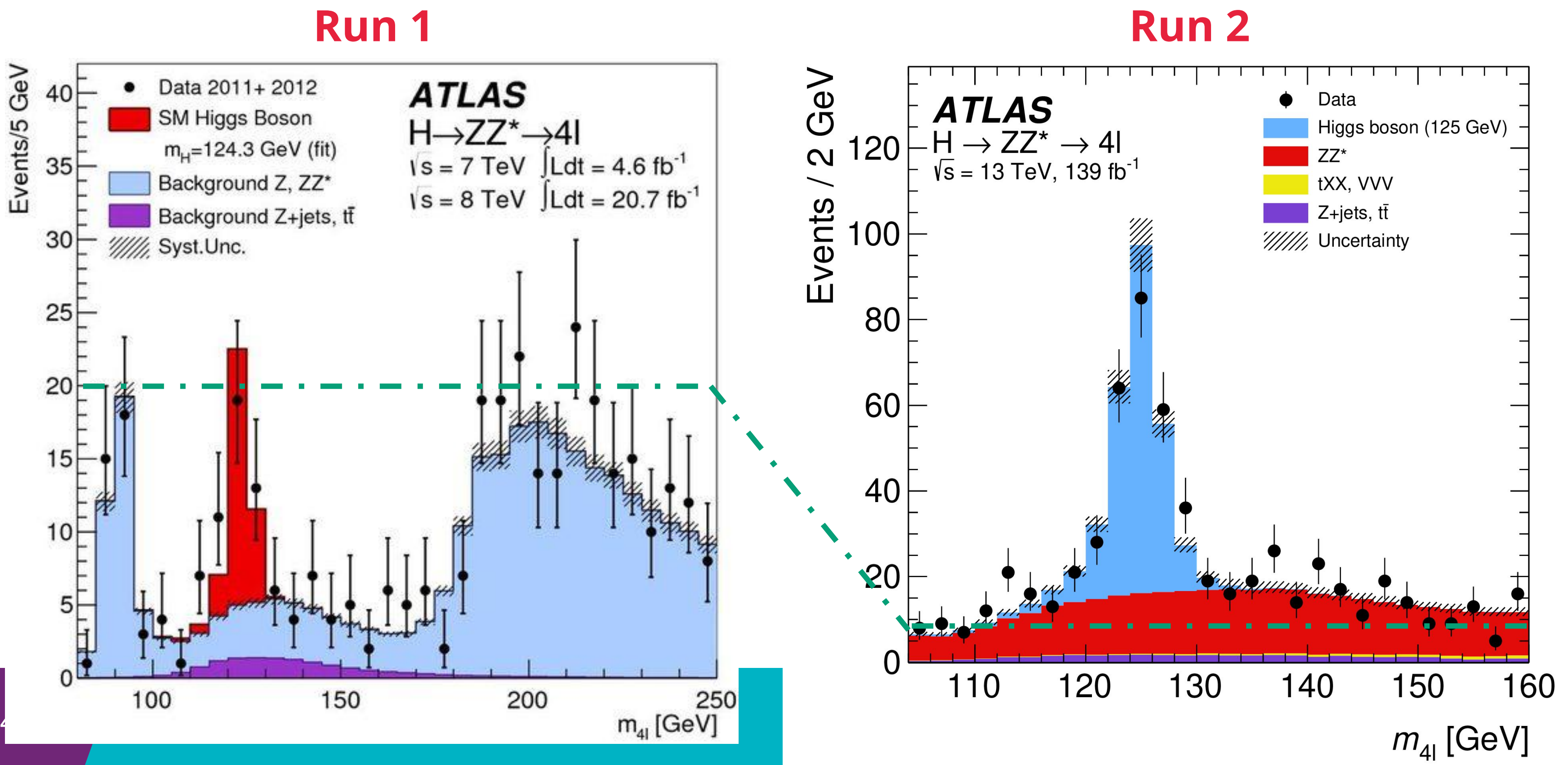




Observation of 3rd generation Yukawa couplings

- H-t, H-b

Towards precision physics



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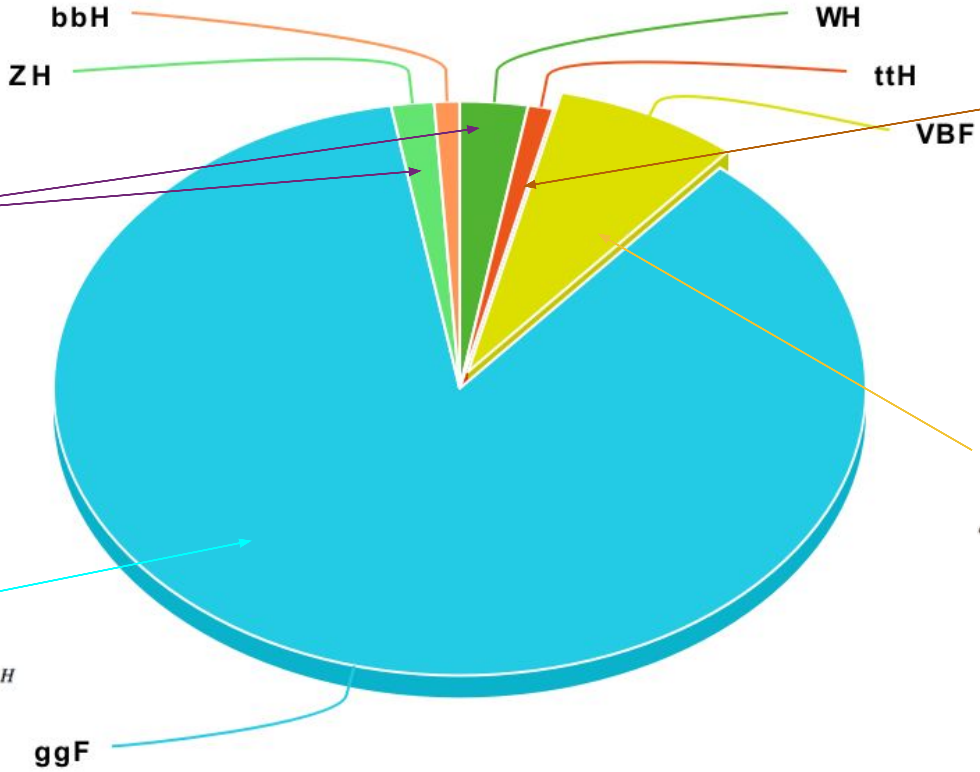
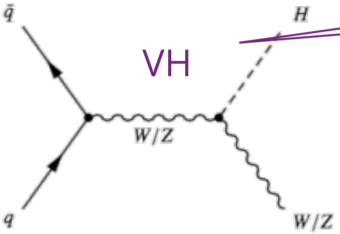
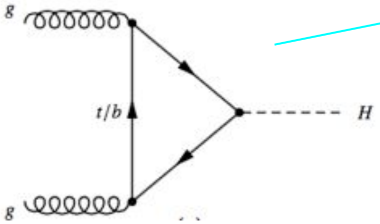


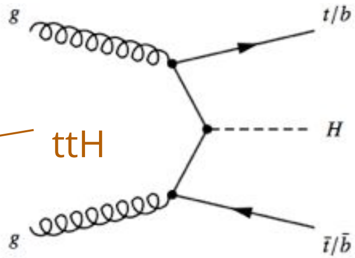
VH



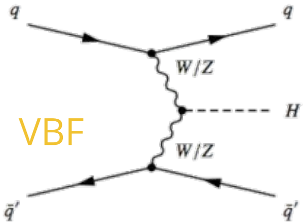
ggF



ttH



VBF



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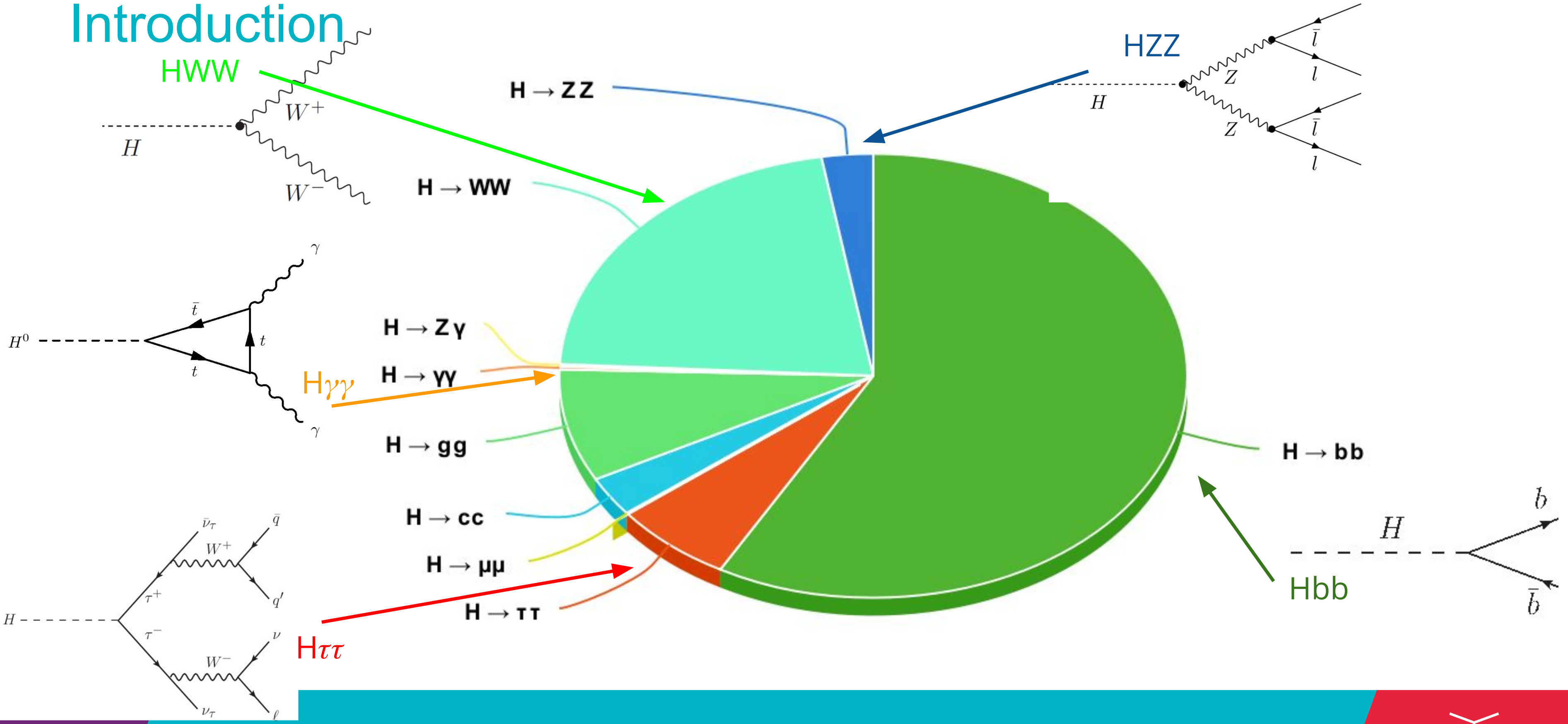


Introduction

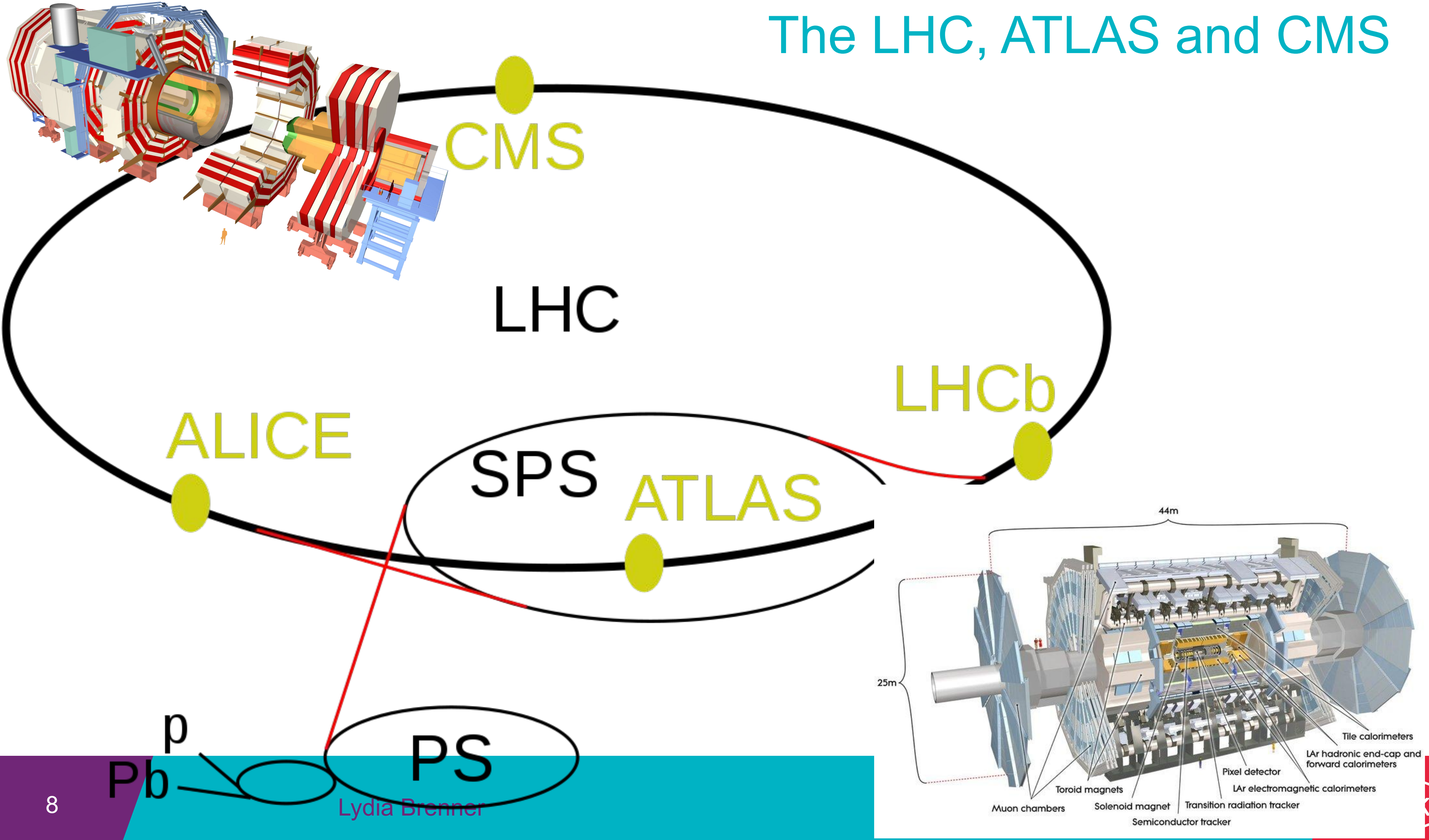
The Higgs boson landscape

- Mass and width
- Coupling properties
    - Fermion interactions New
- Inclusive/differential cross-sections New
- Effective field theory interpretations New

- Quantum numbers
    - Spin/CP
- Self coupling New
    - HH production
- Rare / Exotic / Invisible decays

Particle	Produced in 139 fb^{-1} at $\sqrt{s}$=13 TeV
Higgs Boson	7.7 million
Top quark	275 million
Z Boson	2.8 billion
W Boson	12 billion

The LHC, ATLAS and CMS



Higgs Boson mass

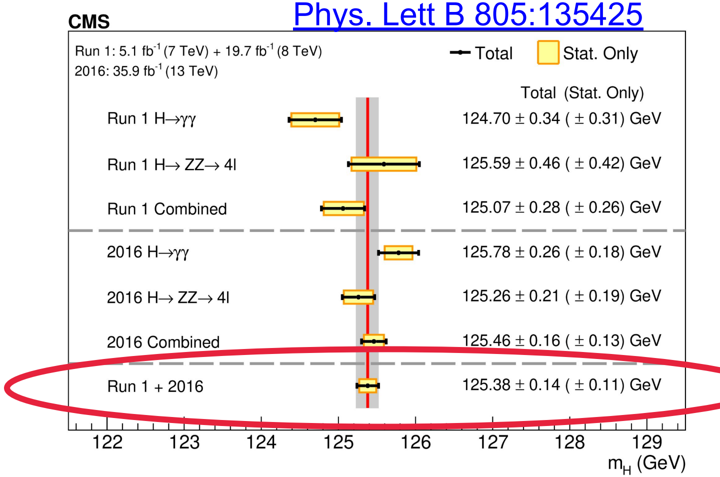
One free parameter in the Standard Model: m_H

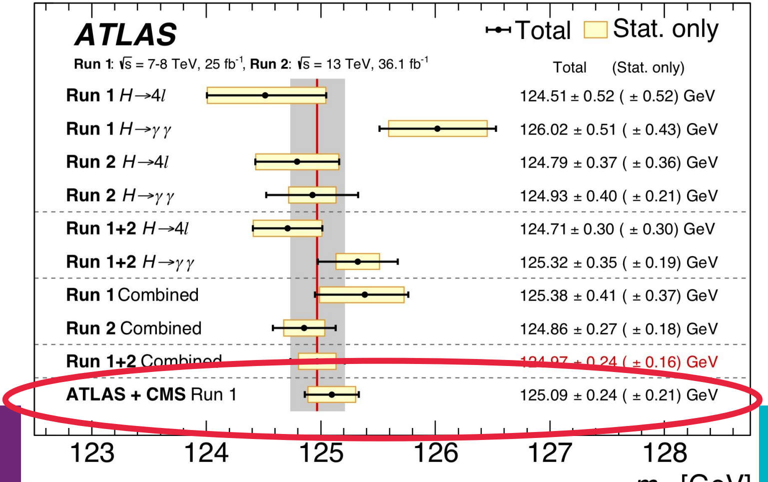
Among the most precise EWK parameters

ATLAS: 124.94 ± 0.17(stat.) ± 0.03(syst.) GeV

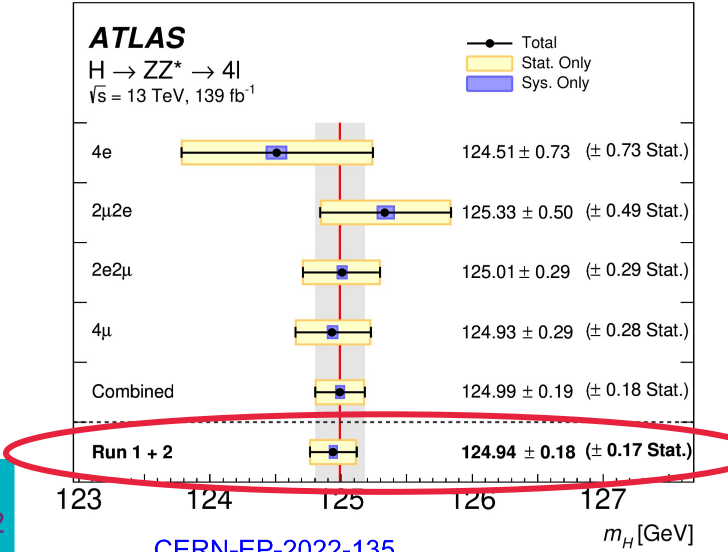
CMS: 125.38 ± 0.11(stat.) ± 0.08(syst.) GeV

Phys. Lett B 805:135425





PLB 784(2018)345

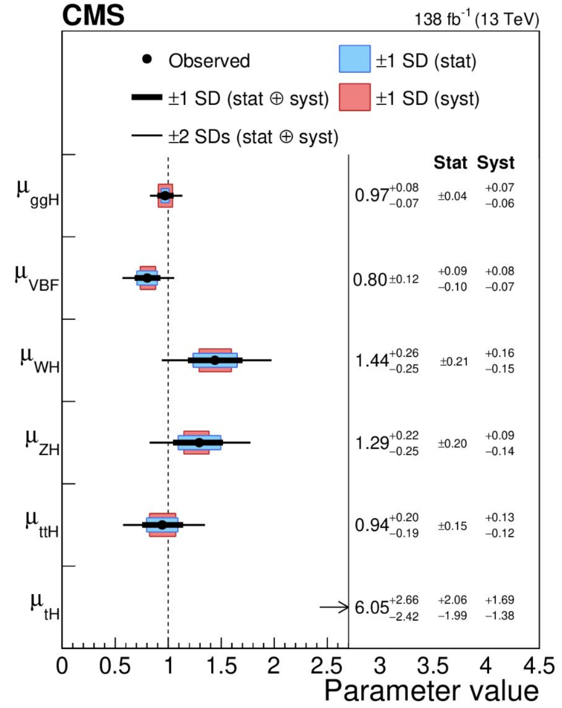


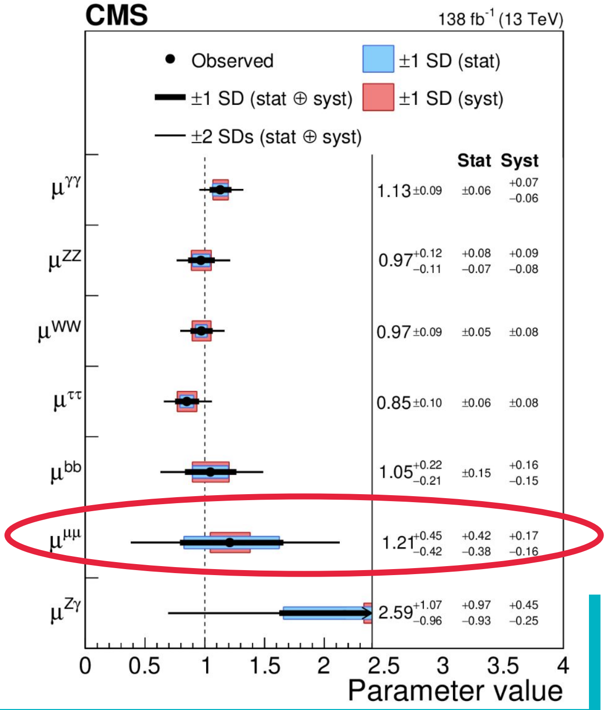
CERN-EP-2022-135

Couplings

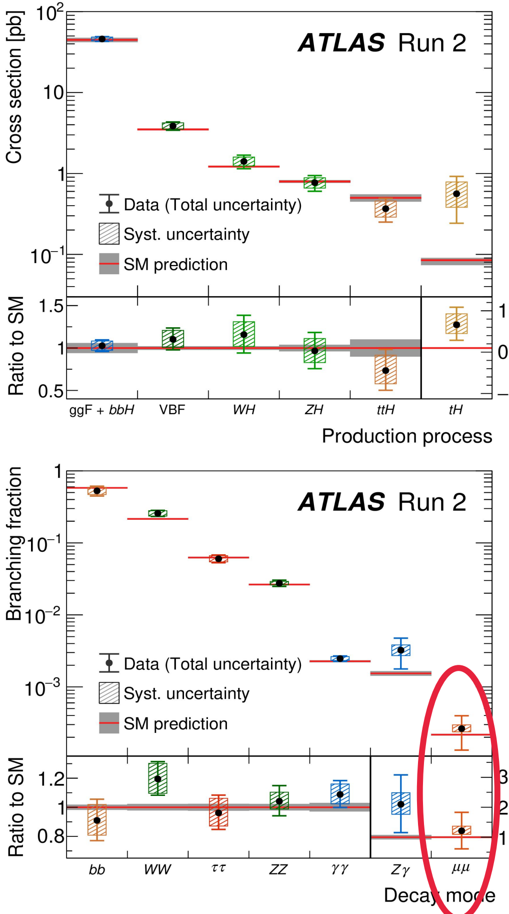
Combining all production and decay channels
Extracting also production information

[Nature 607 (2022) 60-68](#)





[Nature 607, 52–59 (2022)](#)



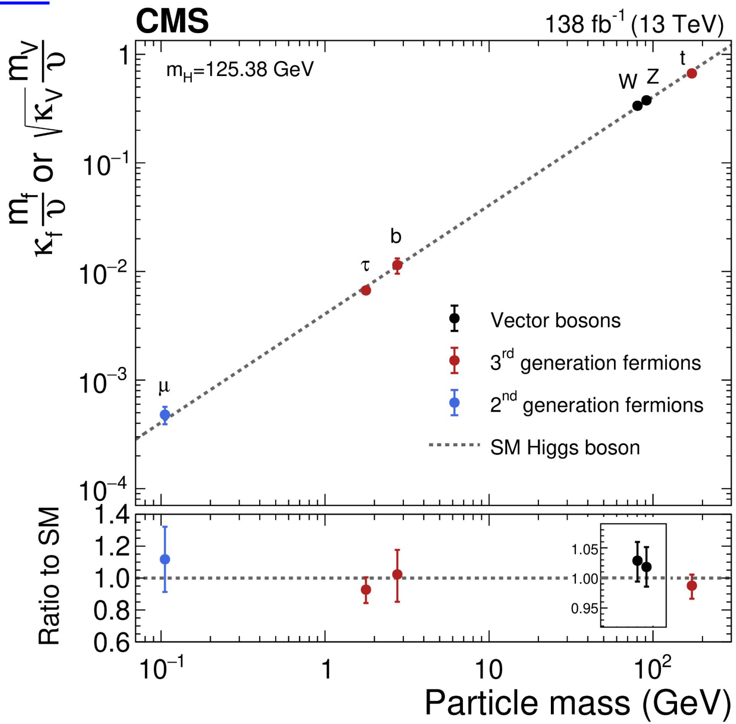
Couplings

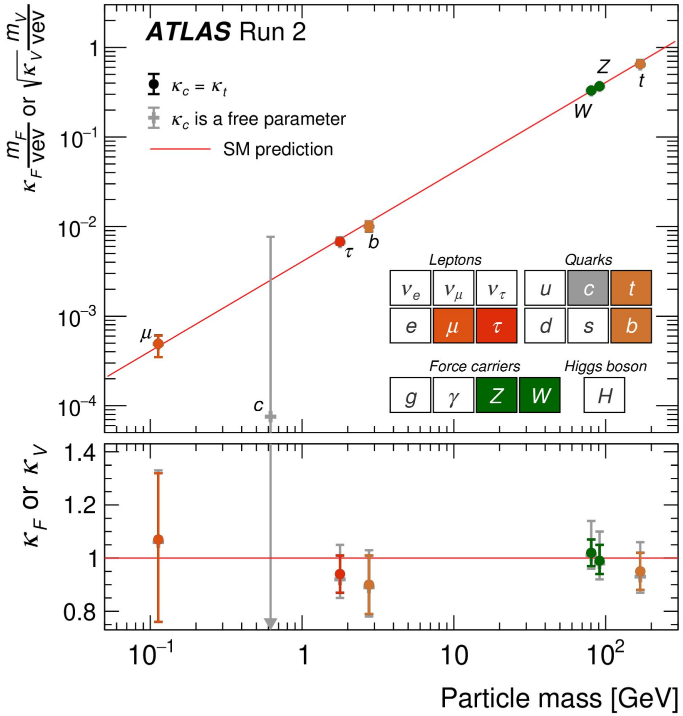
[Nature 607, 52–59 (2022)](#)

Combining all production and decay channels

[Nature 607 (2022) 60-68](#)

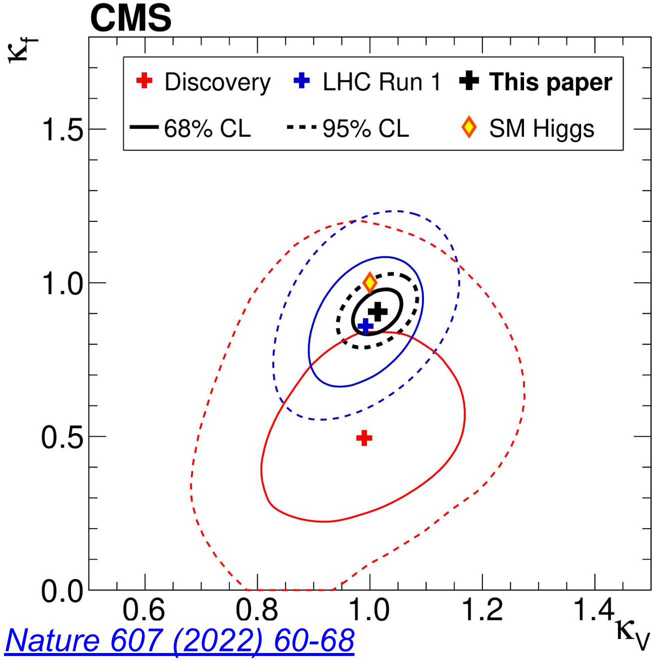
Good agreement with SM predictions





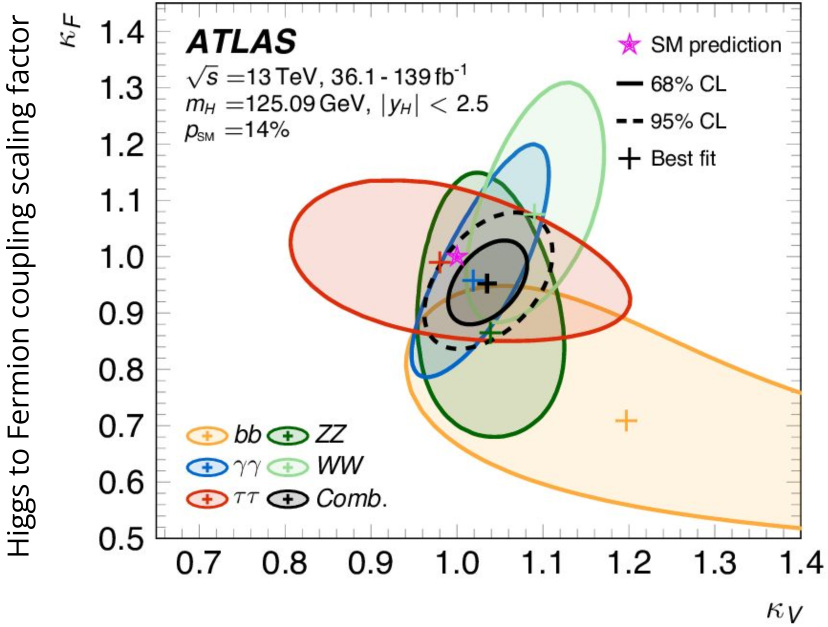
Combination

Extracting more information by combining decay channels



Nature 607 (2022) 60-68

Nature 607, 52–59 (2022)



Higgs to Vector-boson coupling scaling factor

CP - tau tau final state

SM Higgs is even under CP inversion; Observing anything other than CP-even interactions of the Higgs indicates BSM physics.

JHEP 06 (2022) 012

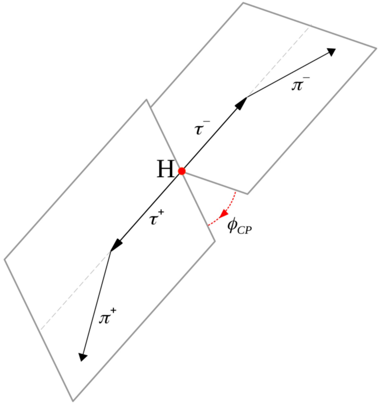
$\varphi_{CP} = -1 \pm 19°$

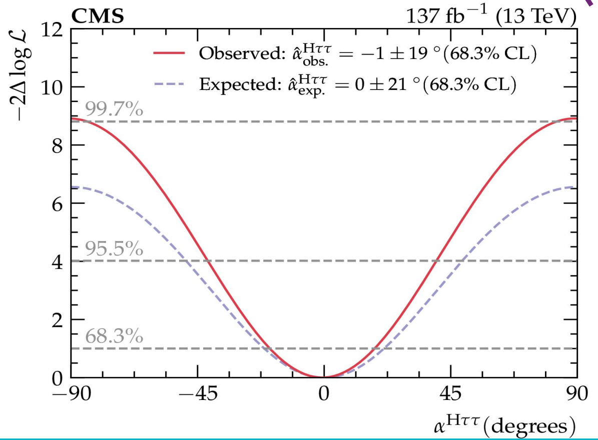
ATLAS-CONF-2022-032

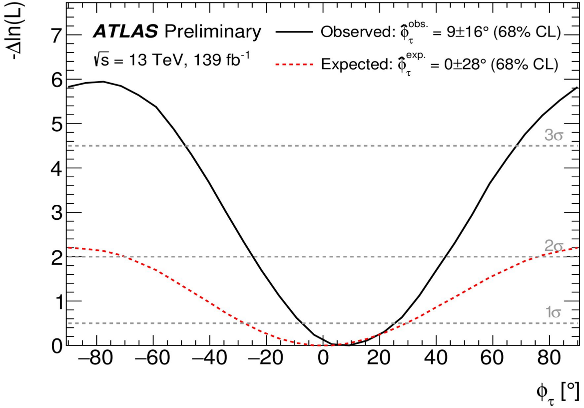
$\varphi_{CP} = 9 \pm 16°$

$H\tau\tau$ coupling

Exclude Pure CP-Odd hypothesis at 3σ 3.4σ







CP - top and boson couplings

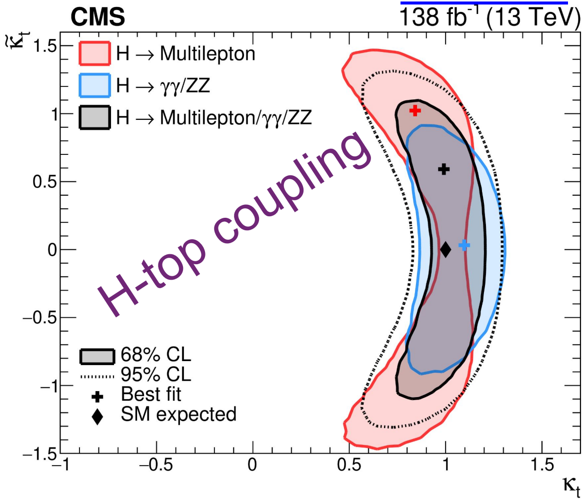
SM Higgs is even under CP inversion Observing anything other than CP-even interactions of the Higgs indicates BSM physics.

Disfavour Pure CP-Odd hypothesis for the H-top coupling at

CMS: 3.2σ

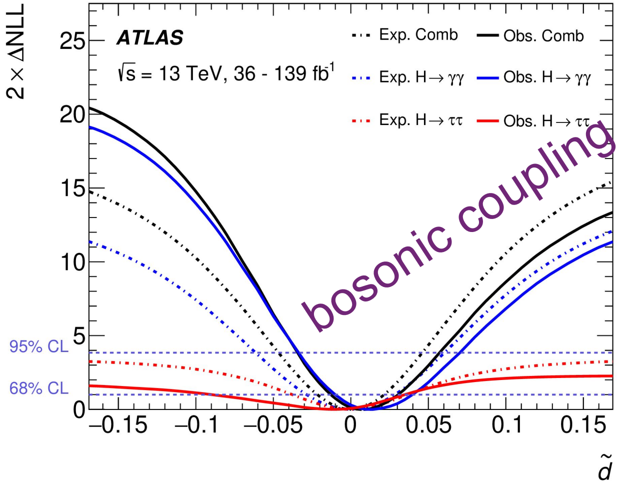
ATLAS: 1.2σ

HIG-21-006



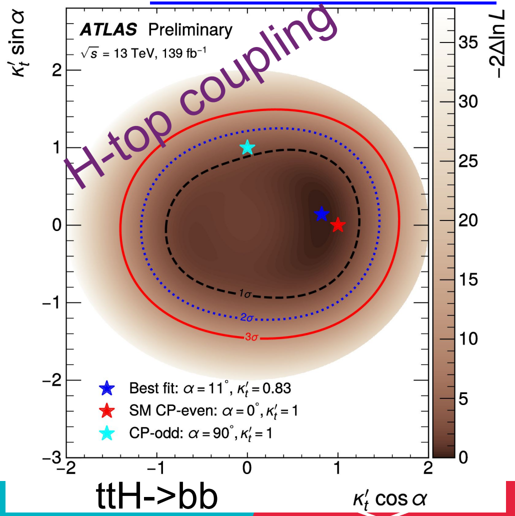
H-top coupling

HIGG-2020-08



bosonic coupling

ATLAS-CONF-2022-016



H-top coupling

ttH->bb

CP - top and boson couplings

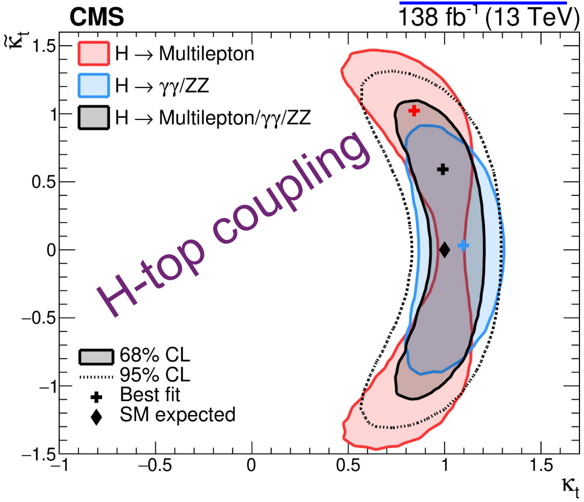
SM Higgs is even under CP inversion Observing anything other than CP-even interactions of the Higgs indicates BSM physics.

Disfavour Pure CP-Odd hypothesis for the H-top coupling at

CMS: 3.2σ

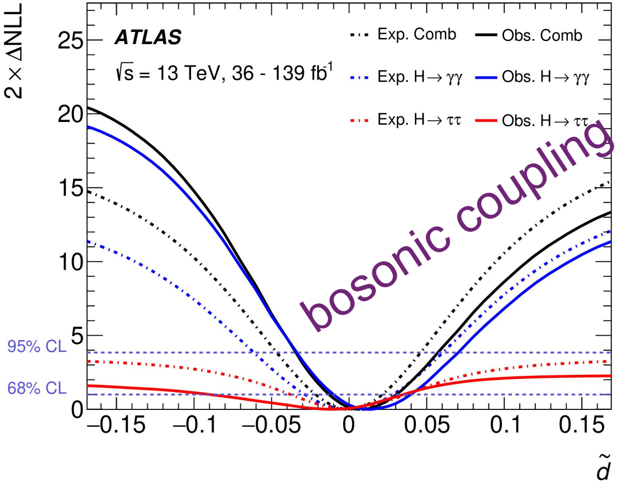
ATLAS: 3.9σ

[HIG-21-006](#)



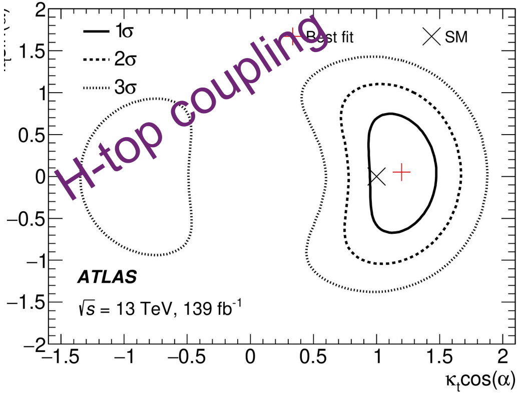
H-top coupling

[HIGG-2020-08](#)



bosonic coupling

[HIGGS-2019-01](#)

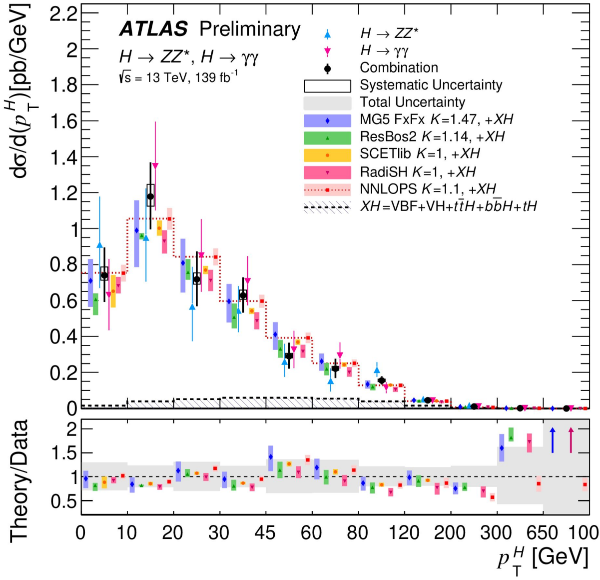


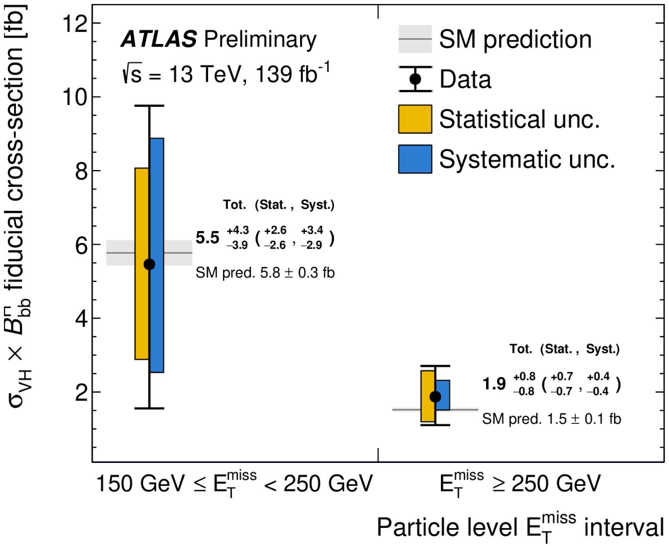
H-top coupling

ttH->yy

Differential cross section measurement

Finer granular measurements for specific observables
Measure a large numbers of distributions and compare with various predictions





ATLAS-CONF-2022-002

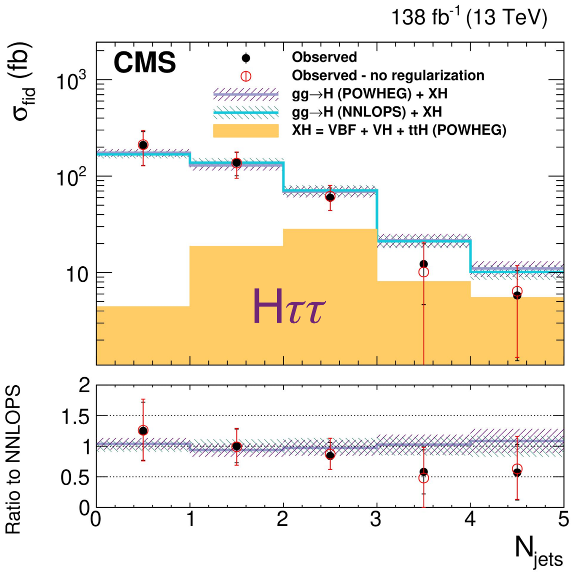
These measurements allow to constrain

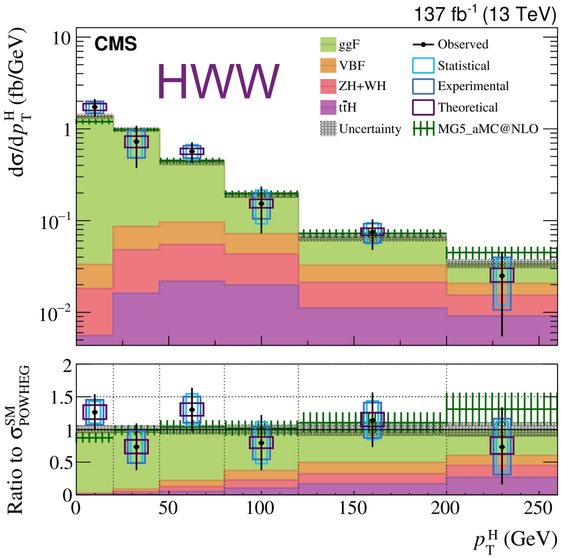
- Couplings not directly accessible (e.g charm-H interaction)
- Wilson coefficients of an effective Lagrangian

Differential cross section measurement

Finer granular measurements for specific observables

Measure a large numbers of distributions and compare with various predictions



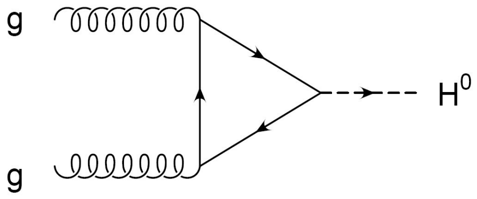


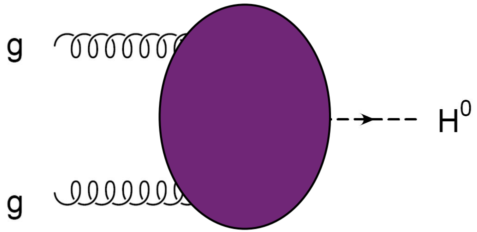
HIG-20-015, HIG-19-002

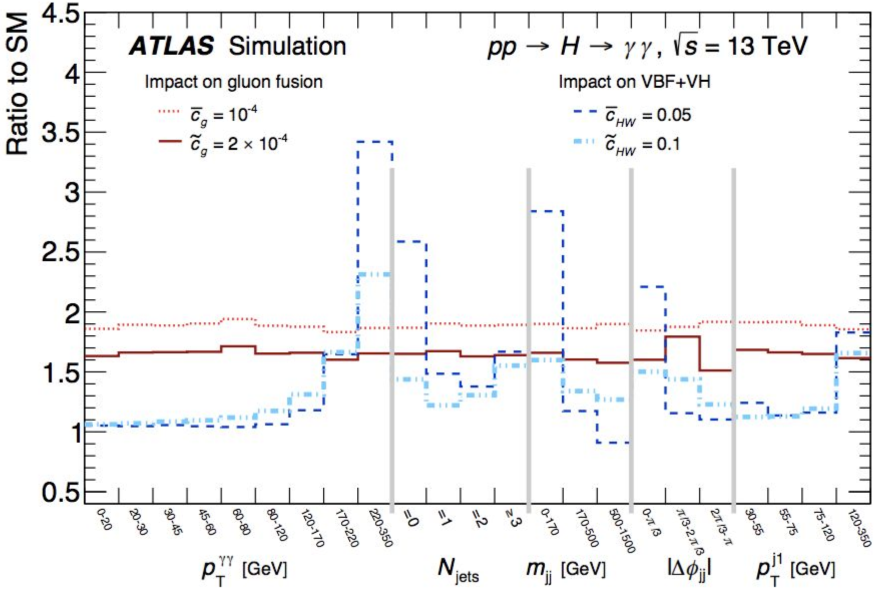
Many possible distributions to measure including $pT_{\gamma\gamma}$, pT_{4l}, $|Y_{\gamma\gamma}|$, N_{jets}, p_T^{j1}, m_{jj}, $\Delta\varphi_{jj}$ and $E_{T,Miss}$

Anomalous interactions search with EFT

Effective couplings





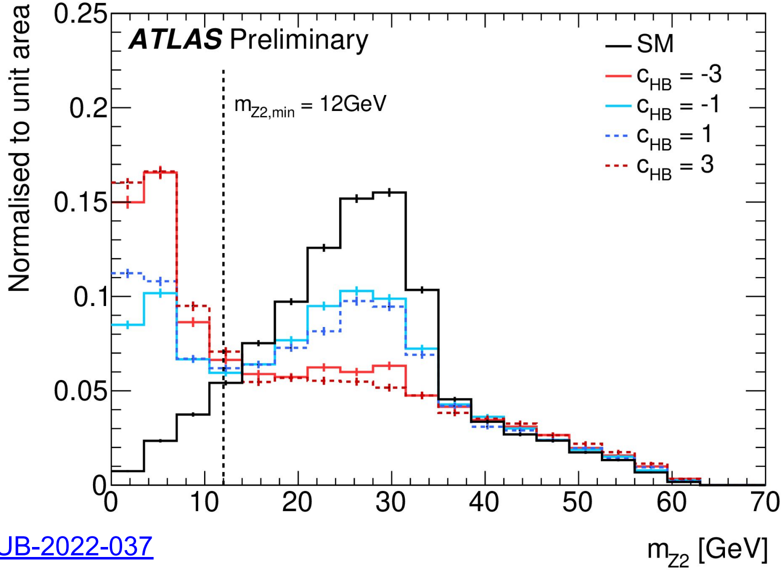


SMEFT is high energy interpretation → Change of Higgs boson properties

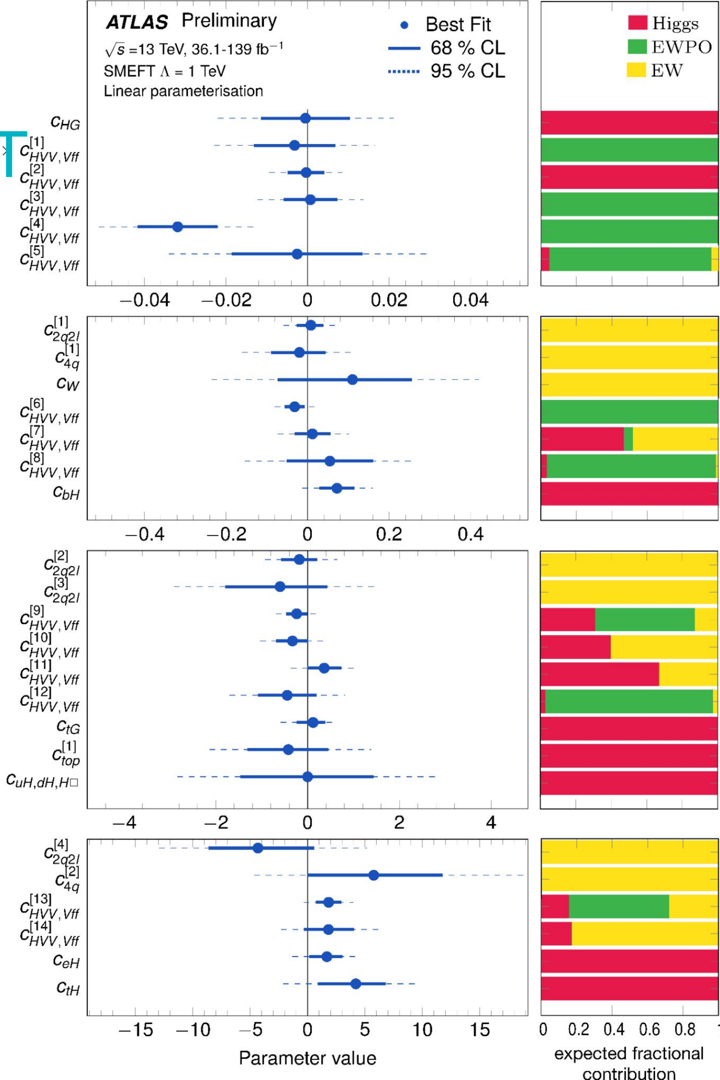
➔ For example applied to the H→$\gamma\gamma$ differential analysis

Anomalous interactions search with EFT

Using combined ATLAS Higgs and EW results and LEP results



ATL-PHYS-PUB-2022-037

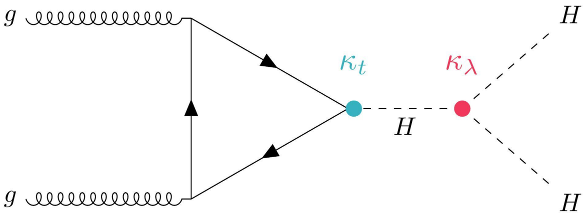


Probing the Higgs self coupling

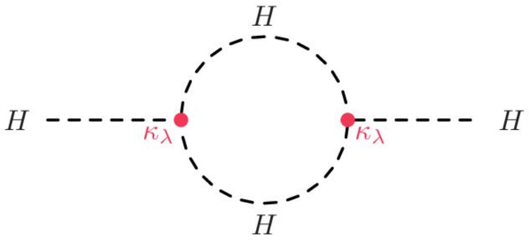
Essential in EWSB, need to measure the Higgs boson trilinear coupling ($\boldsymbol{\lambda}_{HHH}$)

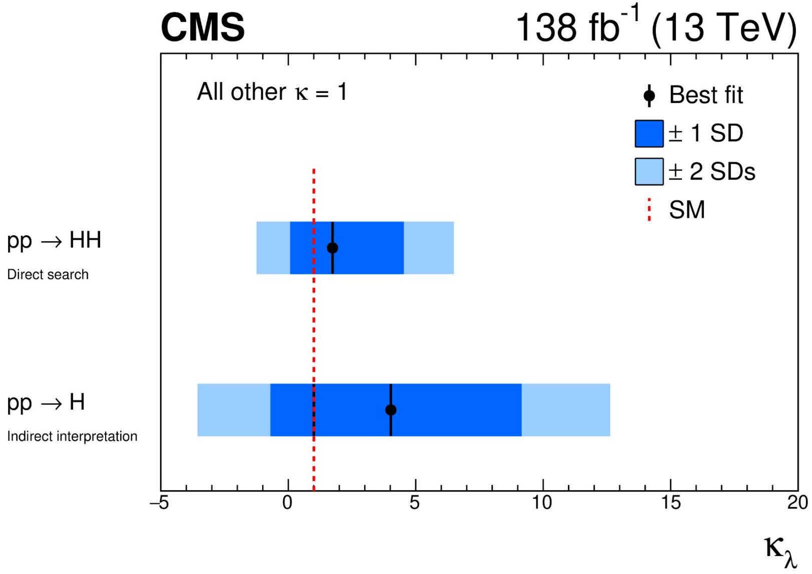
the self-coupling can be probed both using

- di-Higgs production



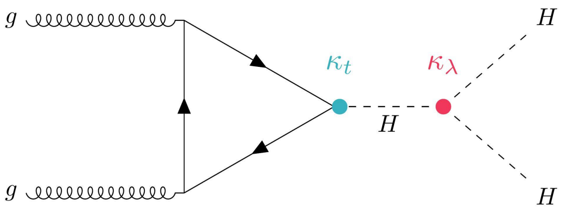
- single Higgs NLO EW effect



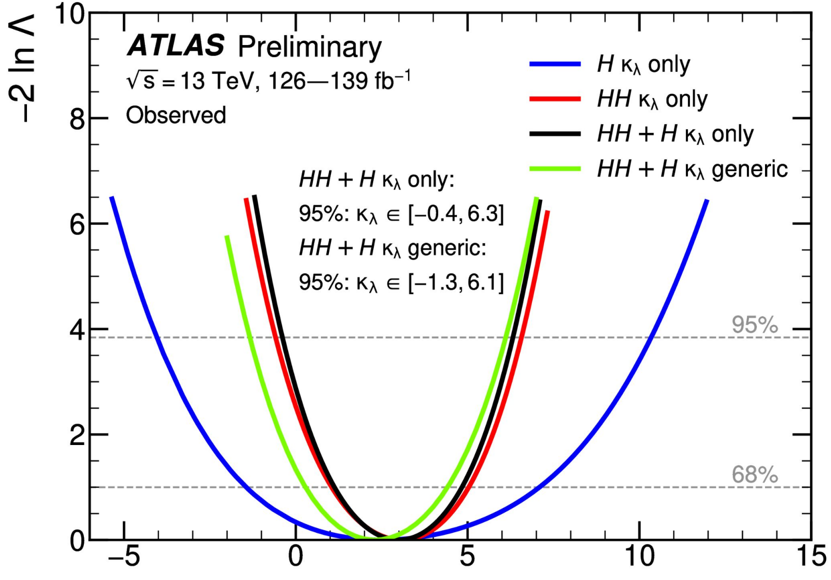


HIG-22-001

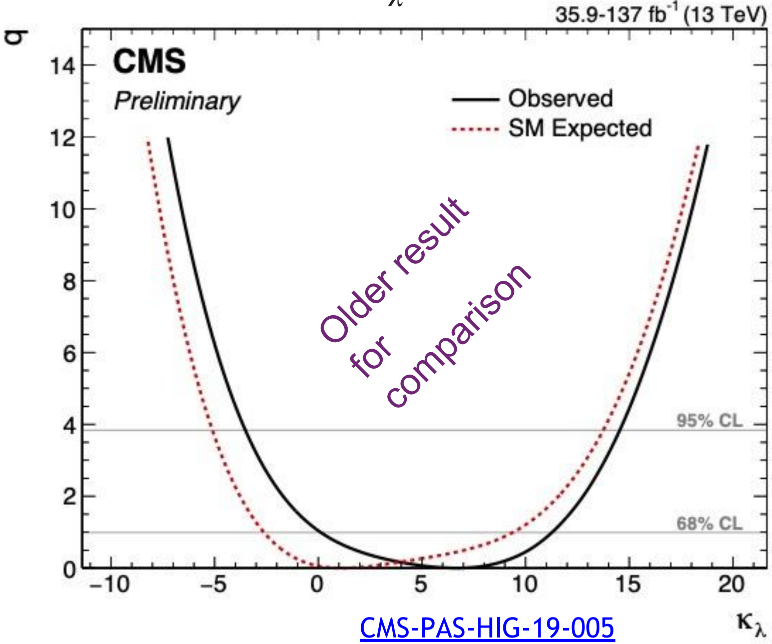
Probing the Higgs self coupling



95%CL obtained by ATLAS -0.4 < κ_λ < 6.3 and CMS −1.24 < κ_λ < 6.49



[ATLAS-CONF-2022-050](https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2022-050/)



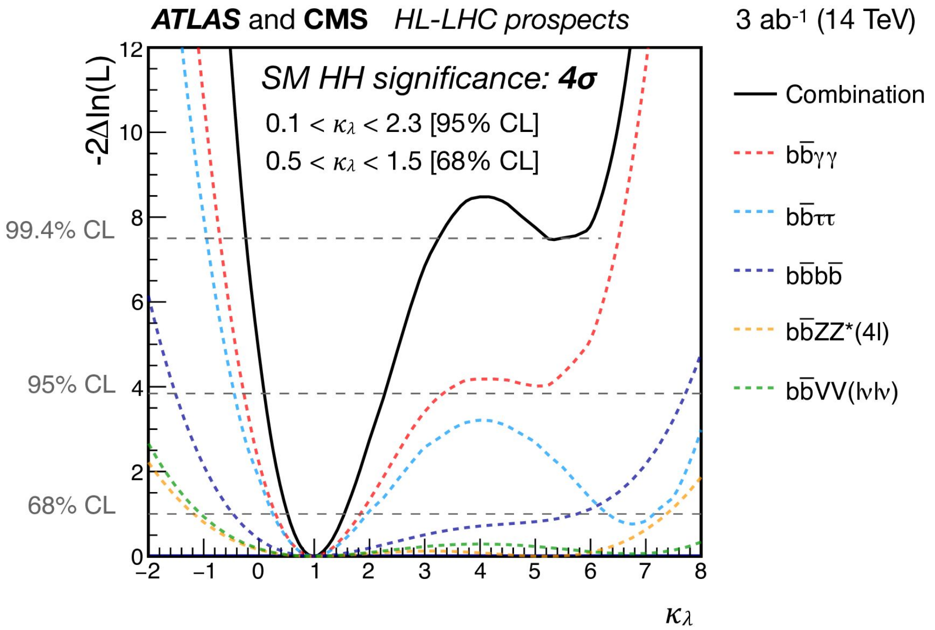
Older result for comparison

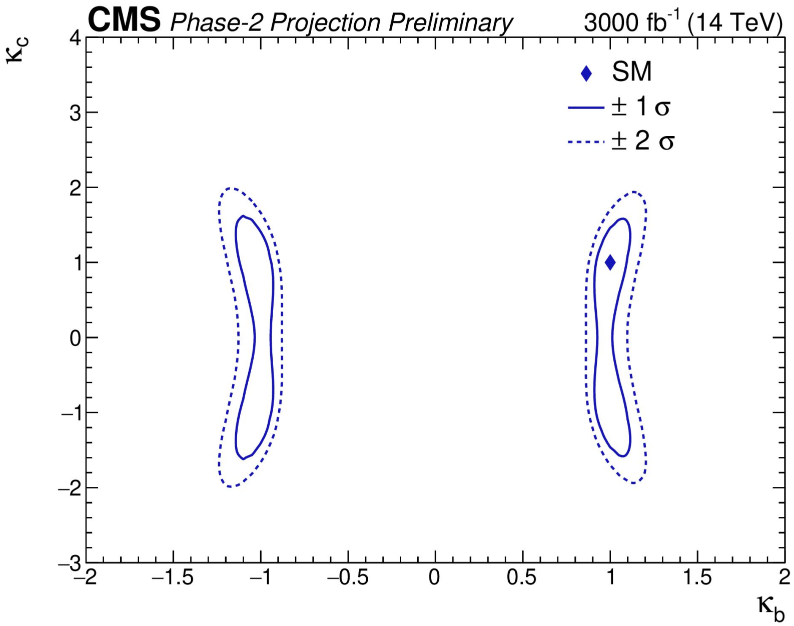
[CMS-PAS-HIG-19-005](https://cds.cern.ch/record/2667190)

Projections for HL-LHC

Projection for HL-LHC for Higgs self coupling and Higgs-charm coupling

ATL-PHYS-PUB-2022-018

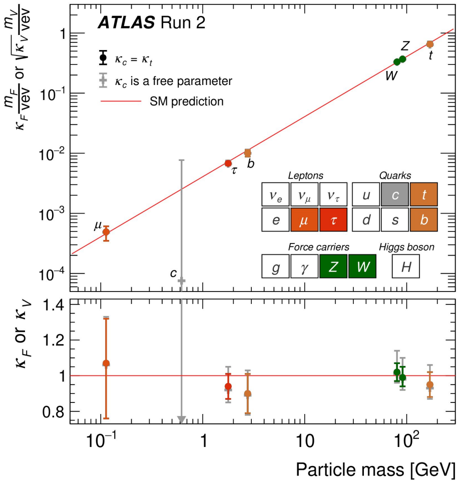




Conclusions

Start of the precision era in the Higgs boson sector towards <10% uncertainties

- Switch from discovery to properties measurements using the 3rd-generation couplings, photon couplings and couplings to W- and Z-bosons
  - Looking at differential and fiducial cross sections
- Focus on rare processes
  - Measurement of 2nd-generation coupling using LHC data
  - Probe charm-H interaction and Higgs self-coupling towards HL-LHC
- Focus on kinematic distributions
- EFT interpretations

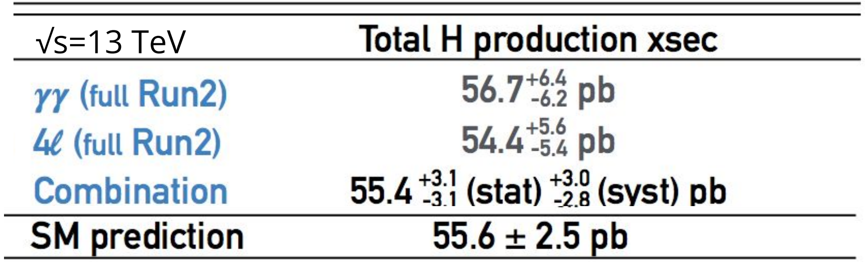


Back up

ATLAS-CONF-2019-032

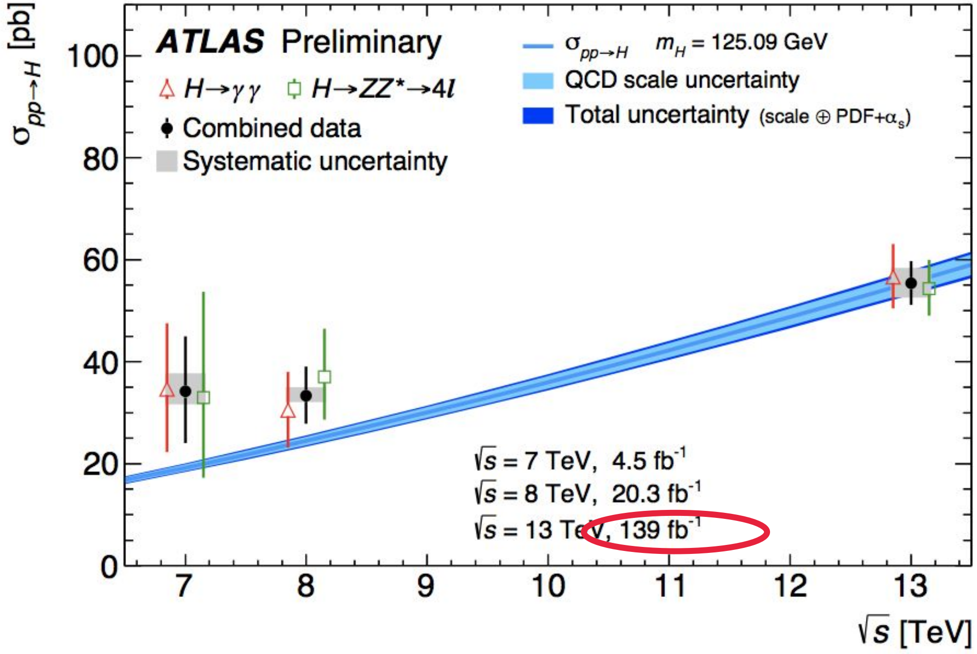
Total cross section measurement

Obtained from H→ZZ→4l, H → $\gamma\gamma$, an



$\sqrt{s}$=13 TeV	Total H production xsec
$\gamma\gamma$ (full Run2)	$56.7^{+6.4}_{-6.2}$ pb
4ℓ (full Run2)	$54.4^{+5.6}_{-5.4}$ pb
Combination	$55.4^{+3.1}_{-3.1}$ (stat) $^{+3.0}_{-2.8}$ (syst) pb
SM prediction	55.6 ± 2.5 pb

Use SM BRs as input

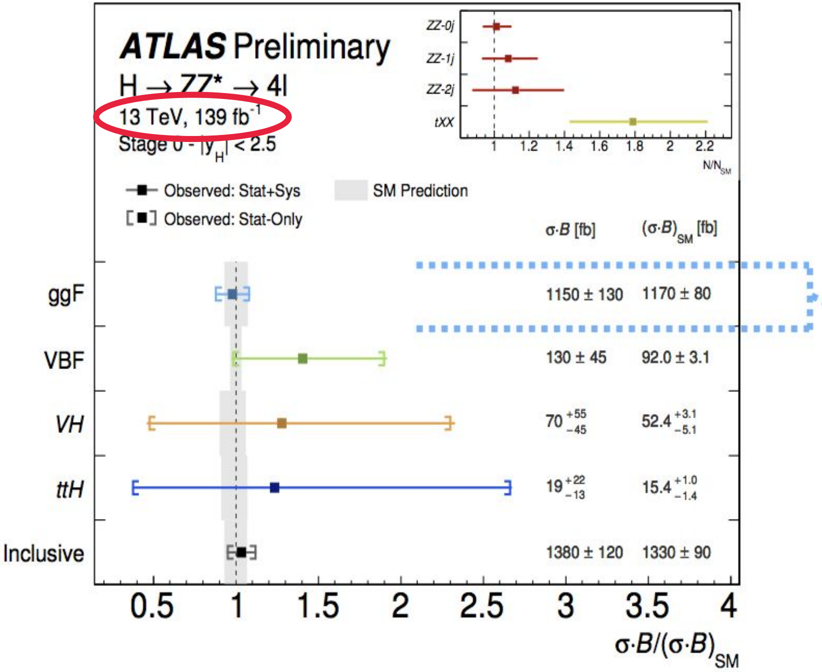


ATLAS-CONF-2019-025

Simplified template cross sections (STXS)

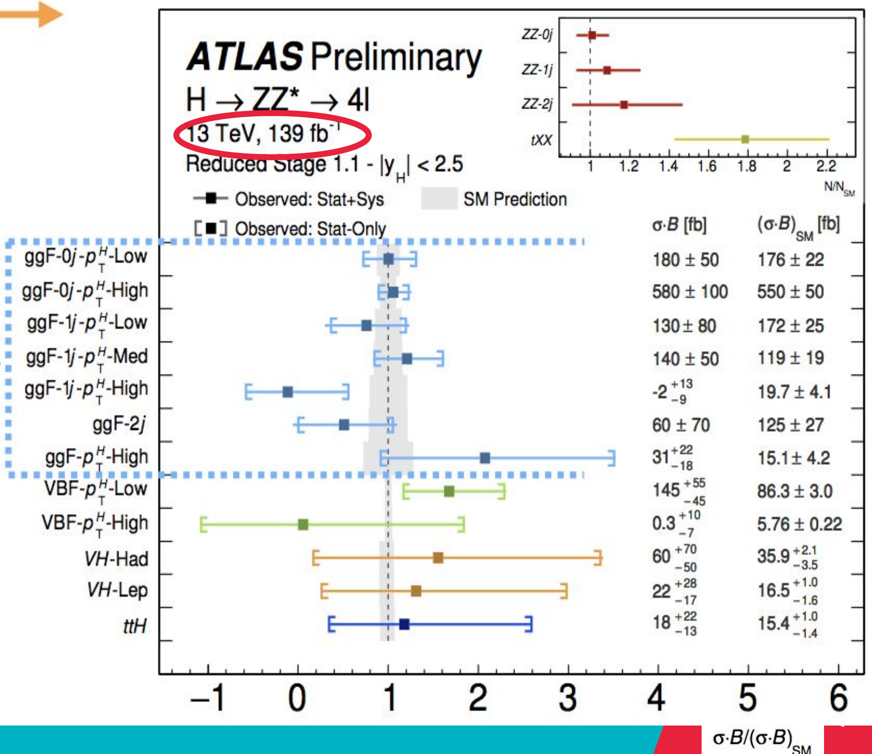
Measure Higgs boson cross sections per production modes and in different regions

Stage-0



	σ·B [fb]	(σ·B)_SM [fb]
ggF	1150 ± 130	1170 ± 80
VBF	130 ± 45	92.0 ± 3.1
VH	70^{+55}_{-45}	$52.4^{+3.1}_{-5.1}$
ttH	19^{+22}_{-13}	$15.4^{+1.0}_{-1.4}$
Inclusive	1380 ± 120	1330 ± 90

Modified Stage-1.1



	σ·B [fb]	(σ·B)_SM [fb]
ggF-0j-p_T^H-Low	180 ± 50	176 ± 22
ggF-0j-p_T^H-High	580 ± 100	550 ± 50
ggF-1j-p_T^H-Low	130 ± 80	172 ± 25
ggF-1j-p_T^H-Med	140 ± 50	119 ± 19
ggF-1j-p_T^H-High	-2^{+13}_{-9}	19.7 ± 4.1
ggF-2j	60 ± 70	125 ± 27
ggF-p_T^H-High	31^{+22}_{-18}	15.1 ± 4.2
VBF-p_T^H-Low	145^{+55}_{-45}	86.3 ± 3.0
VBF-p_T^H-High	0.3^{+10}_{-7}	5.76 ± 0.22
VH-Had	60^{+70}_{-50}	$35.9^{+2.1}_{-3.5}$
VH-Lep	22^{+28}_{-17}	$16.5^{+1.0}_{-1.6}$
ttH	18^{+22}_{-13}	$15.4^{+1.0}_{-1.4}$

ATLAS-CONF-2019-004
PLB 784(2018)173 (ttH)
JHEP 05(2019)141
PLB 786(2018)59 (Hbb)

Third generation fermion couplings

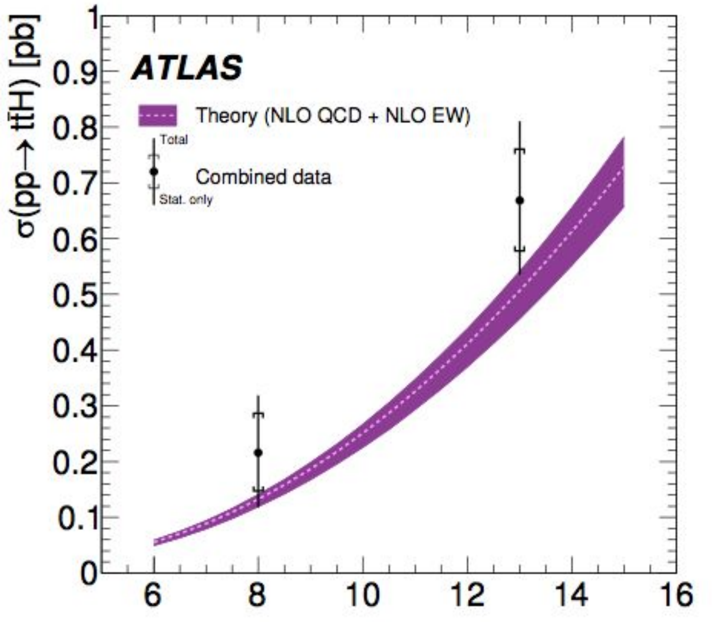
Hbb

Difficult despite large BR (58%) due to large background

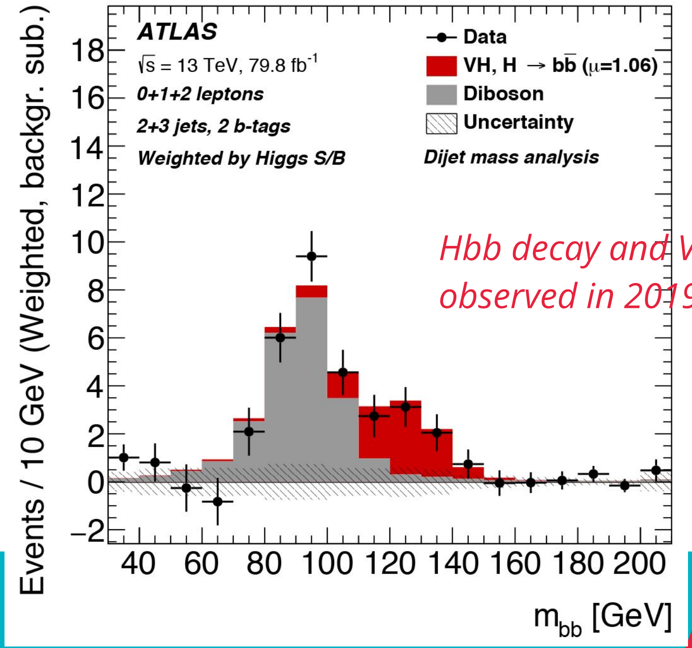
ttH

D

	signal strength
ttH comb (Run1+80/fbRun2)	$1.32^{+0.28}_{-0.26}$



	signal strength
Hbb (Run1+ 80/fb Run2)	1.01±0.20



Hbb decay and VH production observed in 2019!

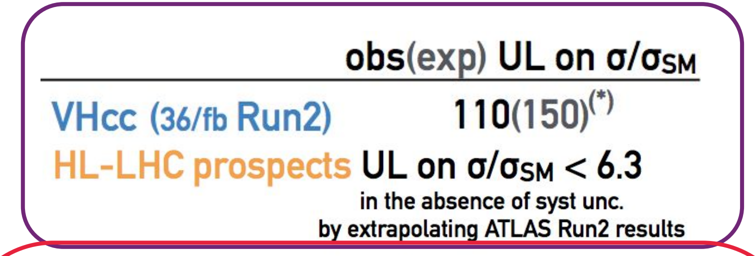
PRL 120(2018)211802
ATL-PHYS-PUB-2018-016
ATLAS-CONF-2019-029

Second generation fermion couplings: H→cc

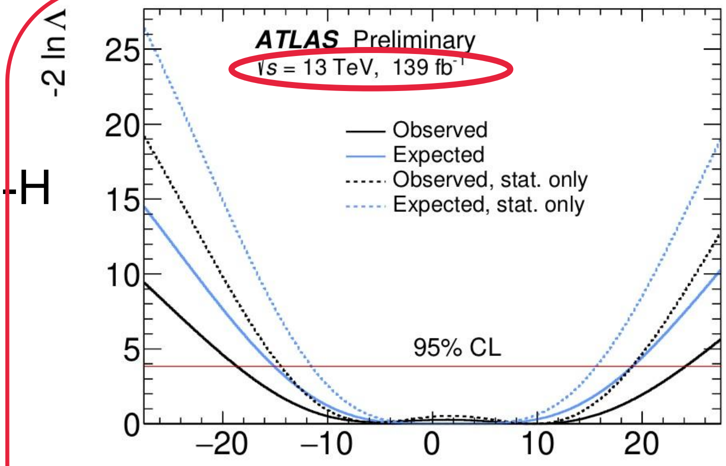
Can probe coupling in different ways

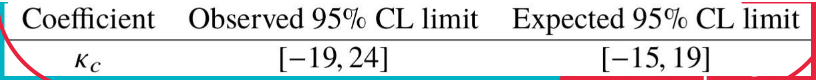
Direct search
- BR(H→cc)~0.05×BR(H→bb)
- H→bb is background
- Large (hadronic) background
- Charm jet ID challenging

Extract constraints from p_T^H kinematics
- c-H interference in ggF-loop with t-H and b-H
- direct ccH production



	obs(exp) UL on σ/σ_{SM}
VHcc (36/fb Run2)	110(150)$^{(*)}$
HL-LHC prospects	UL on $\sigma/\sigma_{SM} < 6.3$ in the absence of syst unc. by extrapolating ATLAS Run2 results





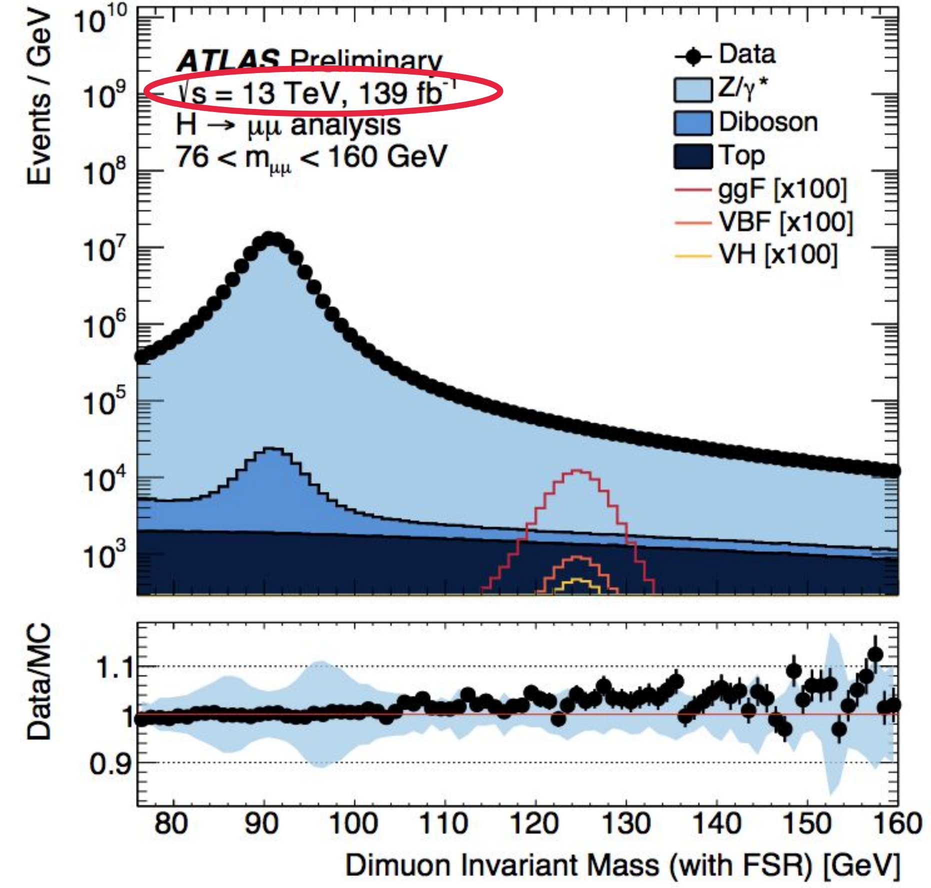
Coefficient	Observed 95% CL limit	Expected 95% CL limit
κ_c	[−19, 24]	[−15, 19]

ATLAS-CONF-2019-028

Second generation fermion cou

Identifying and measuring μ
is not the problem, difficulties are

- Small BR (2×10^{-4})
- Large backgrounds (Z/γ^*, diboson, top)

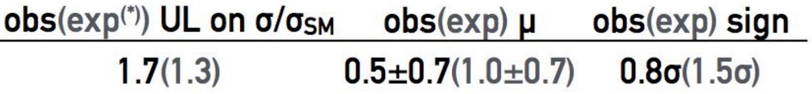


ATLAS-CONF-2019-028

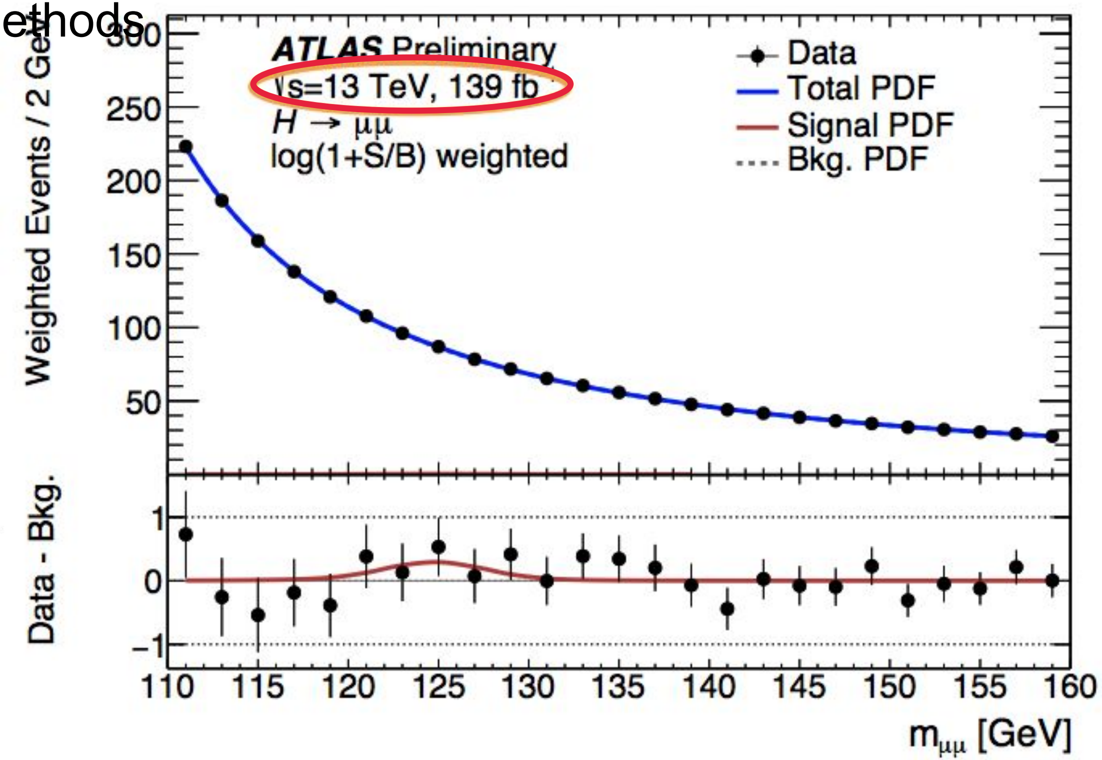
Second generation fermion couplings: H→$\mu\mu$

Difficult analysis using advanced methods

- Low S/B
  - BDT-based event classification
- Large irreducible background
  - Background modelling



obs(exp$^{(*)}$) UL on σ/σ_{SM}	obs(exp) μ	obs(exp) sign
1.7(1.3)	0.5±0.7(1.0±0.7)	0.8σ(1.5σ)



ATLAS-CONF-2019-037

First generation fermion couplings: H→ee

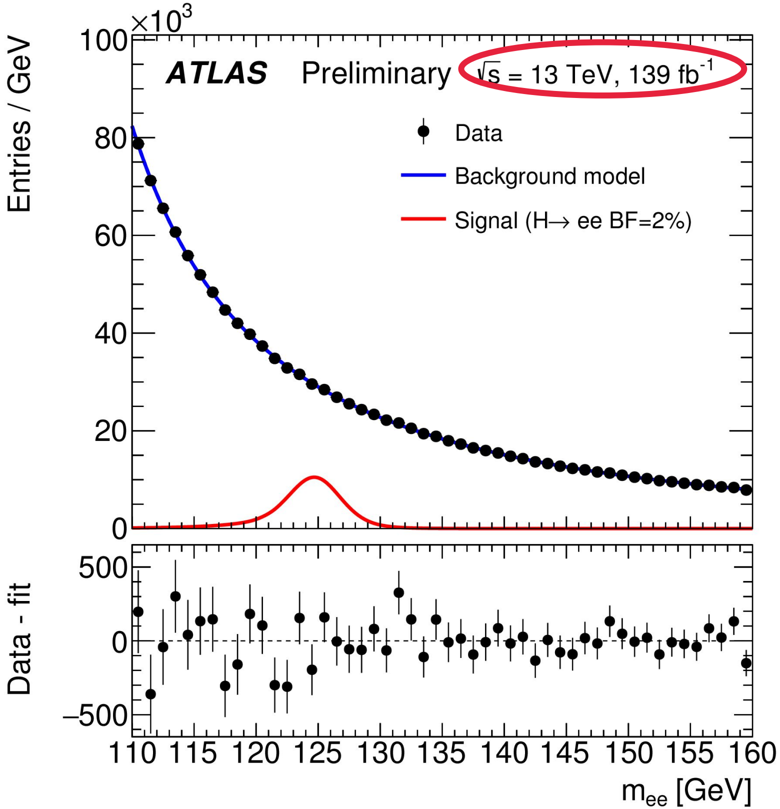
Tested against a background model

Compared with the signal parameterisati 3(H

→ ee) = 2%.

The observed (expected) upper limit at tl g

fraction of H→ee is 3.6×10^{-4} (3.5×10



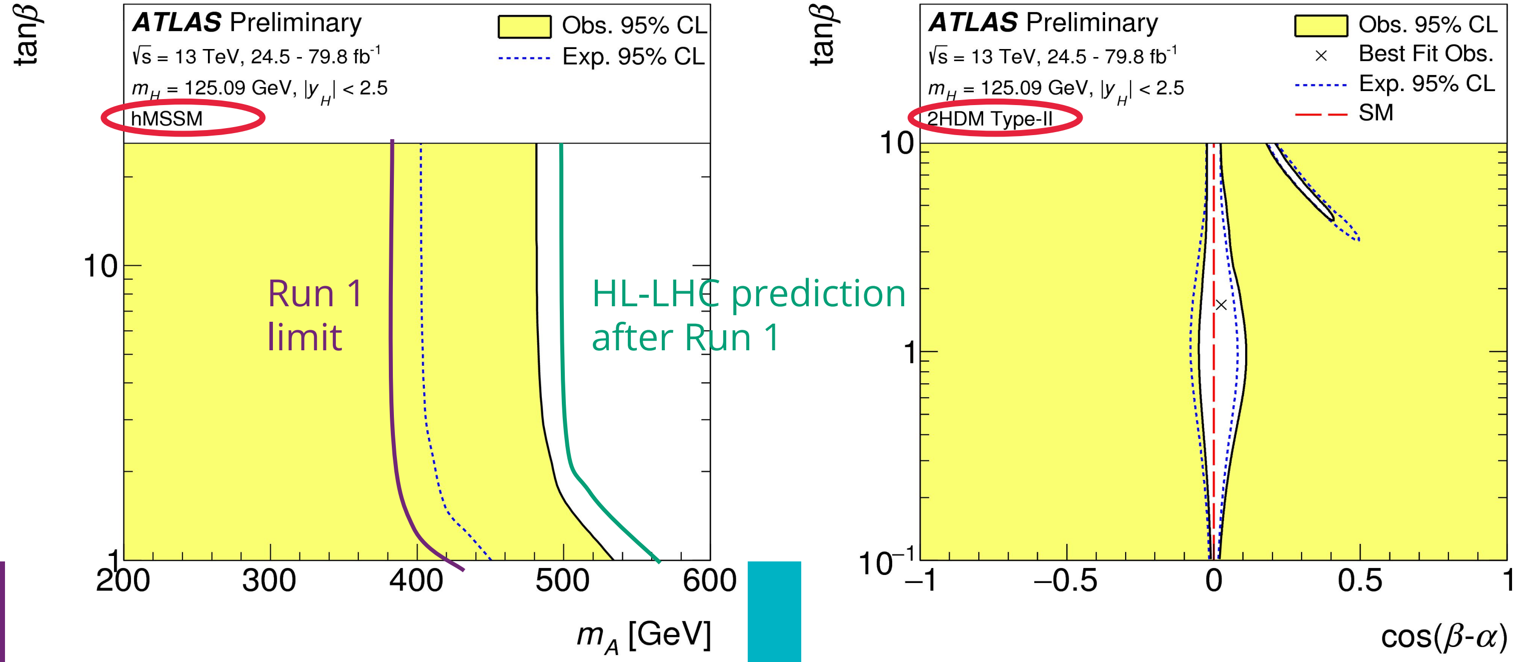
ATLAS-CONF-2019-005

Combination: Reinterpretations

Additional Higgs field
Map couplings to

Coupling	Type I	Type II
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$

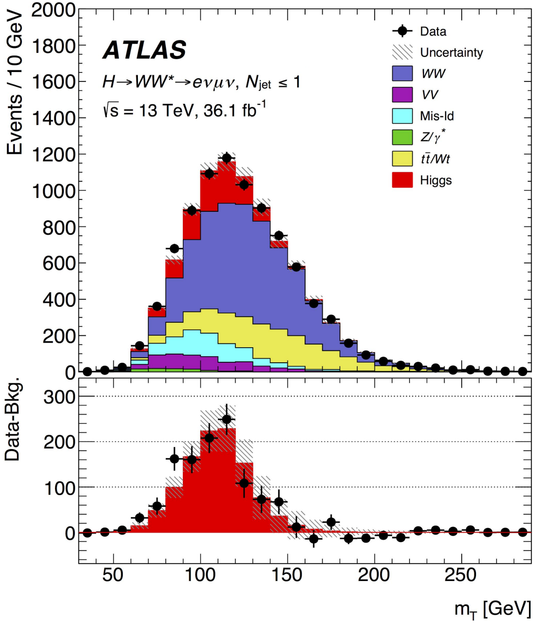
2 New free parameters
- tan **β**: ratio of the two vacuum expectation values
- **α**: mixing angle between two neutral CP even Higgs states



Introduction

How can we measure these things?

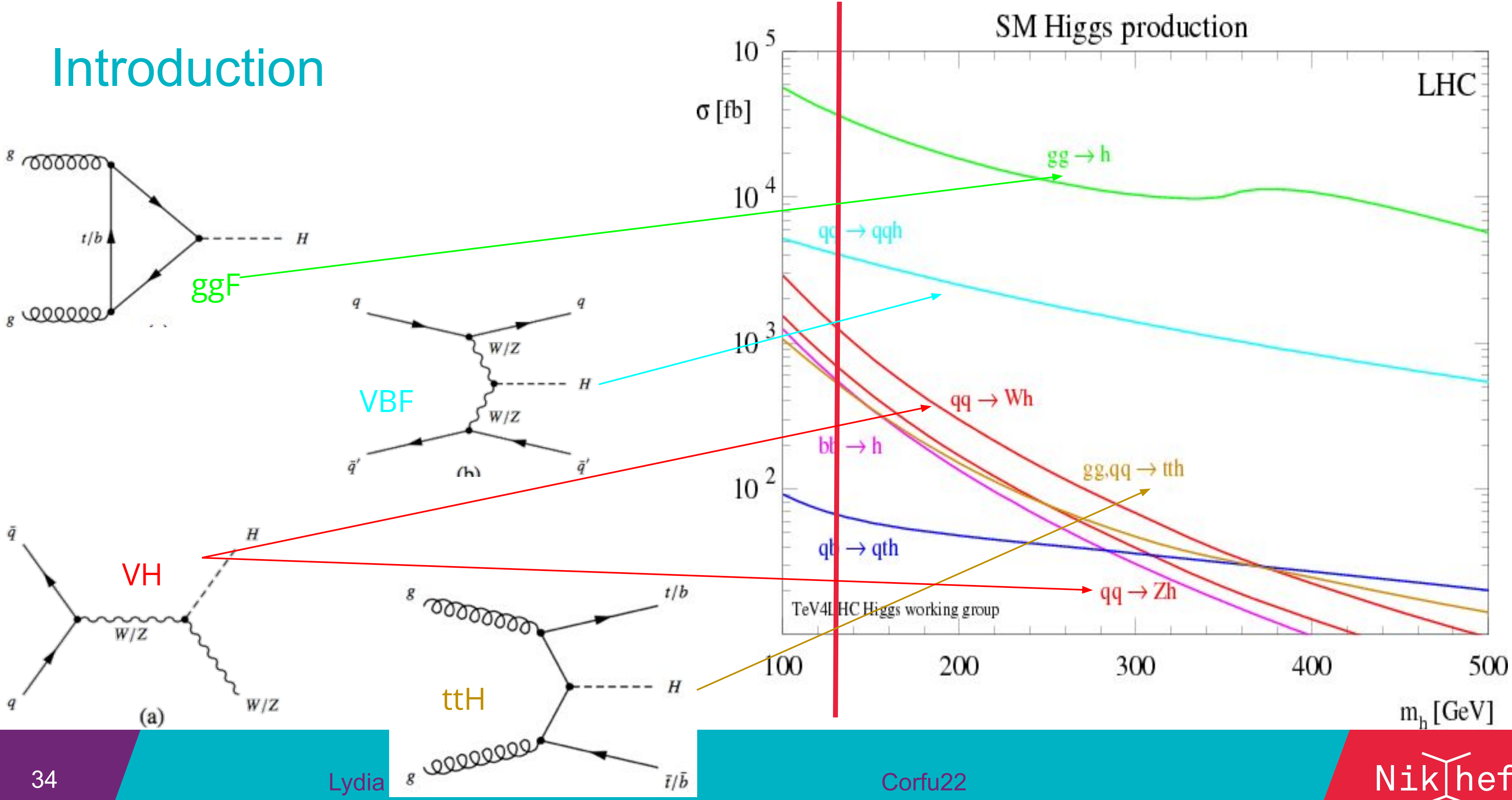
- Compare data to expectations
- Measure free parameter



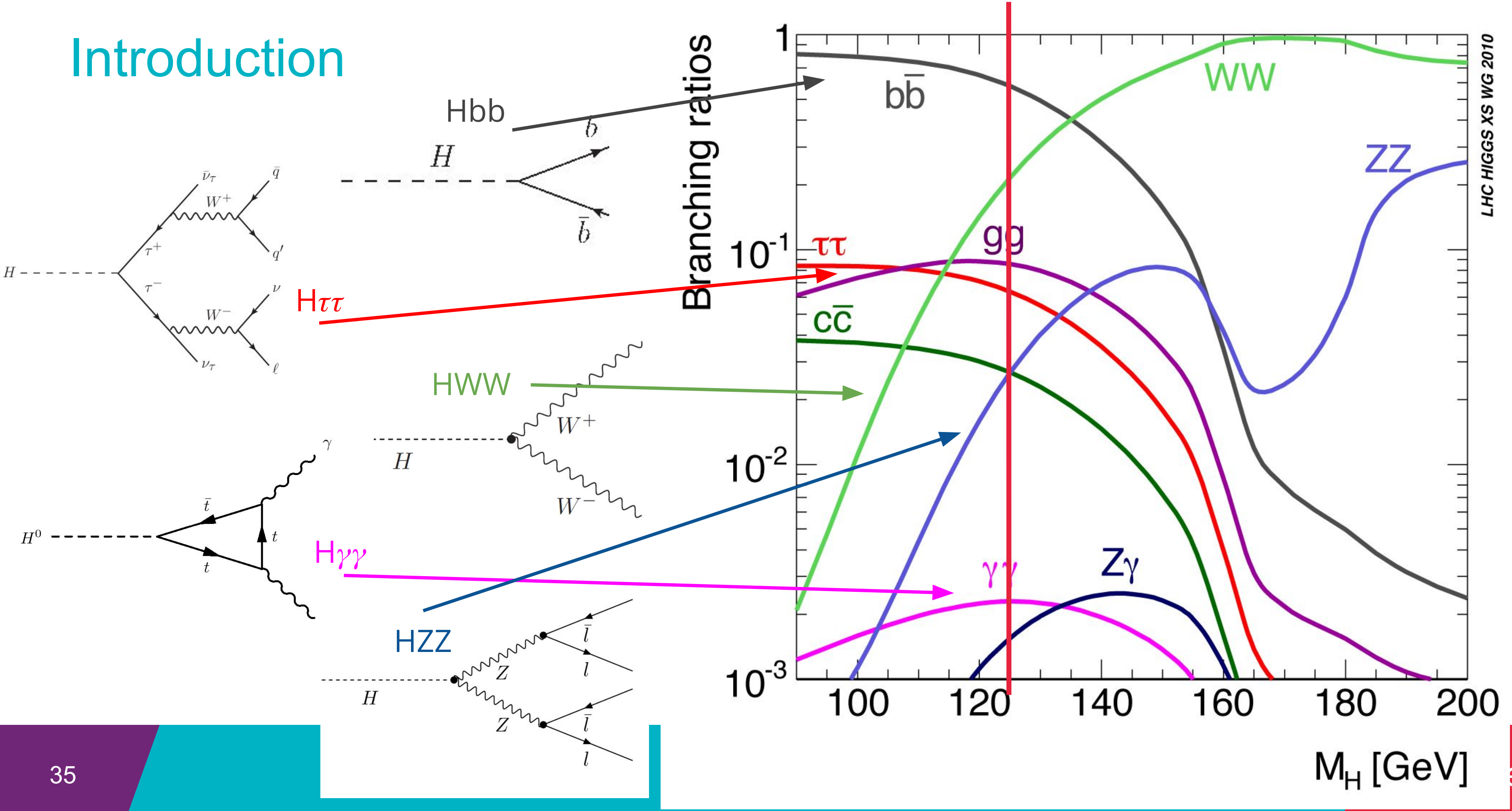
Use Likelihood methods

- Does my data match the prediction?
- What is the most likely value of this parameter?

Introduction

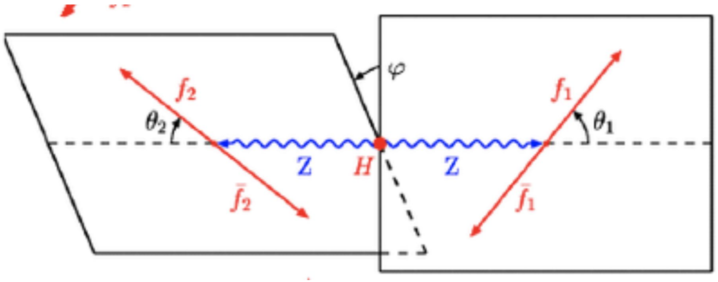


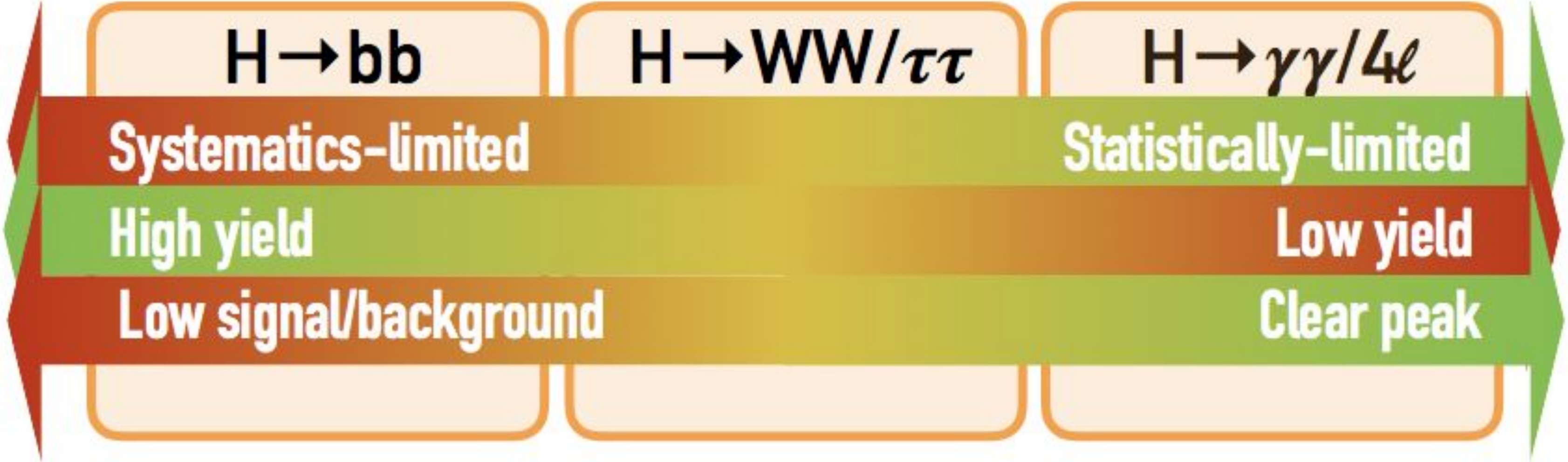
Introduction



extra intro

CP





$H \to bb$

$H \to WW/\tau\tau$

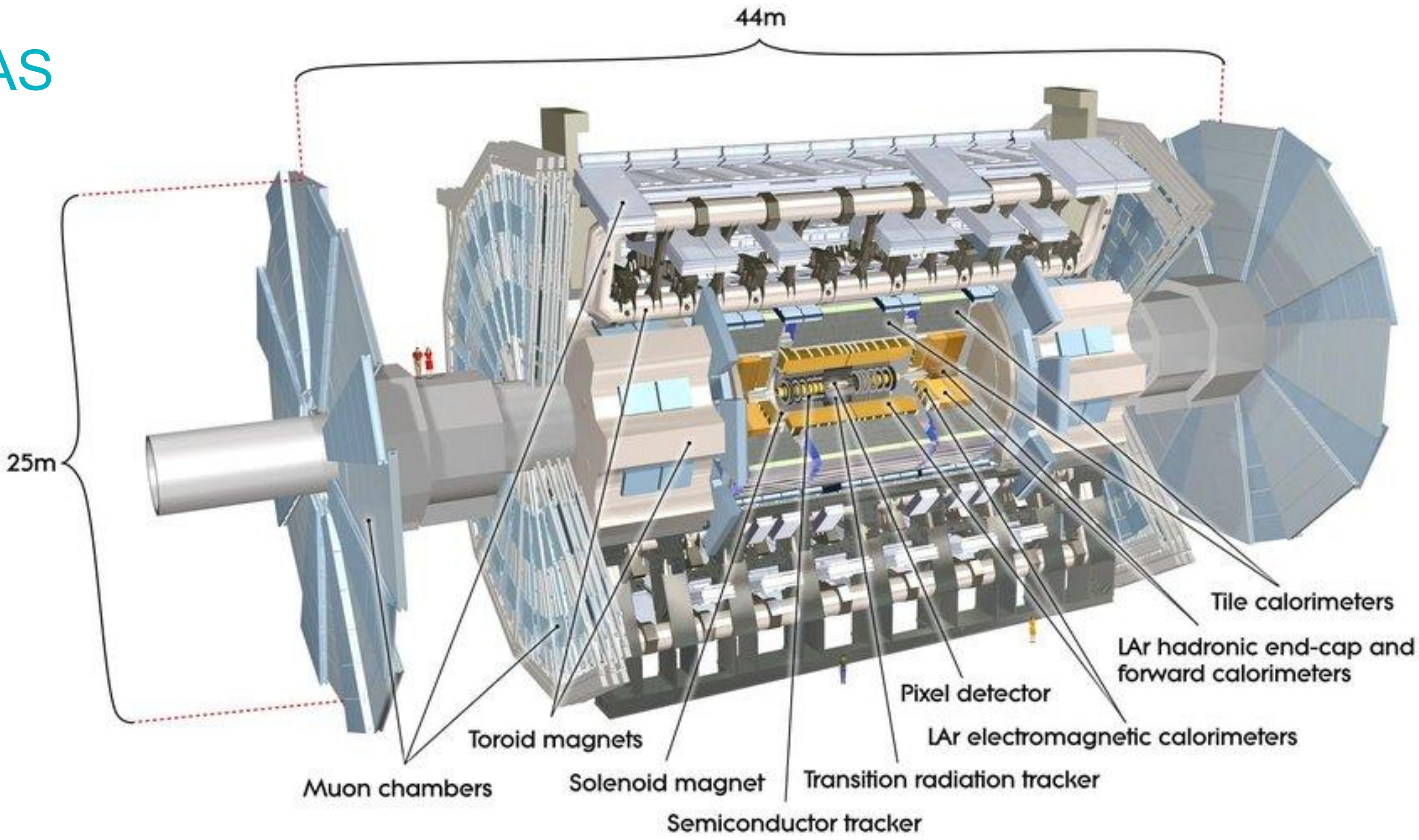
$H \to \gamma\gamma/4\ell$

Systematics-limited ↔ Statistically-limited

High yield ↔ Low yield

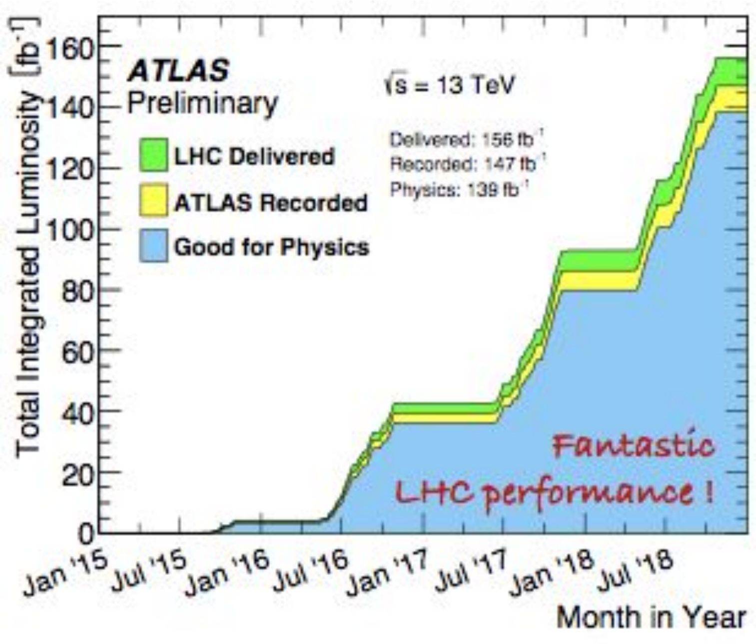
Low signal/background ↔ Clear peak

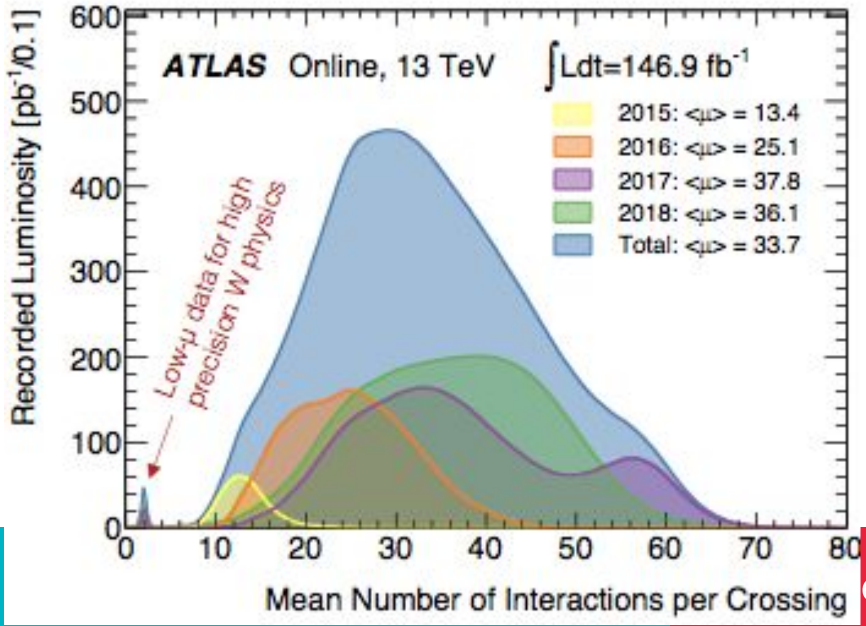
ATLAS


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

Run-2 Luminosity

Integrated pp luminosity during Run-2
Also collected 2.3 nb^{-1} of 5 TeV Pb-Pb data, and p-Pb & Xe-Xe data



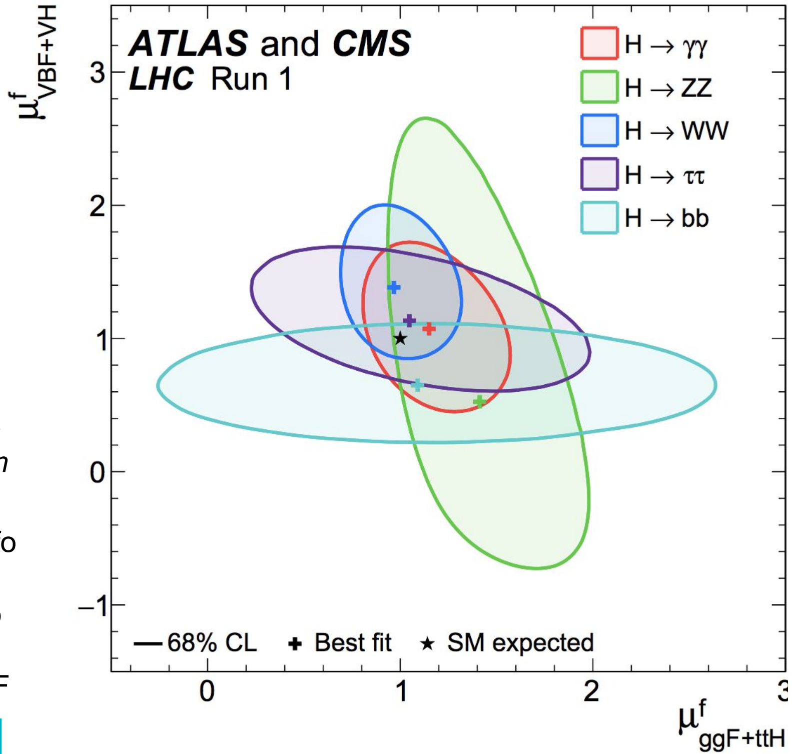


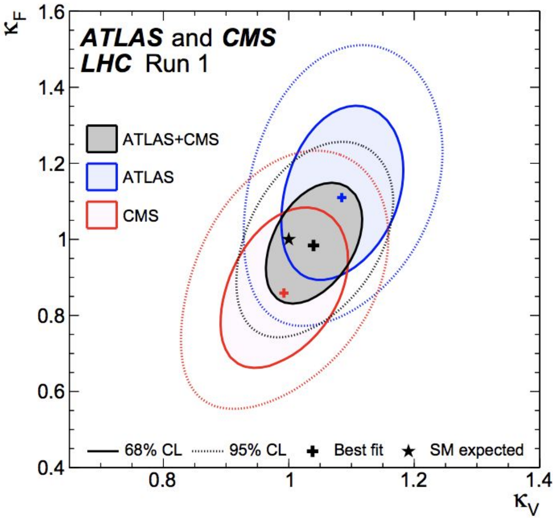
ATLAS + CMS combination Run 1

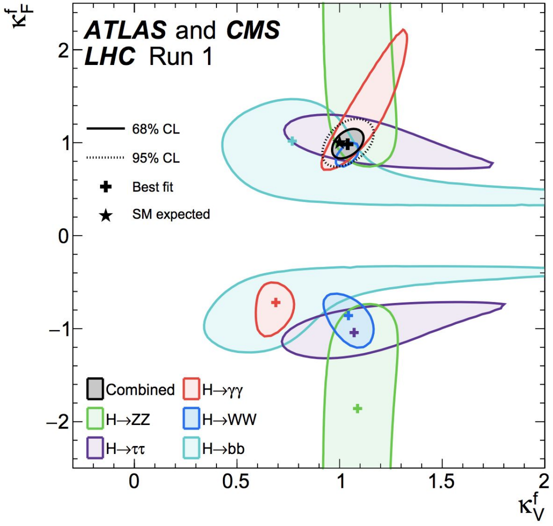
Look at fermion versus boson couplings for indications for new physics

Likelihood contour for negative k_F solution different for channels with interference contributions.

The direction of the elips gives info about sensitivity of that channel; for example lots of WW events so high sensitivity to ggF, HZZ easy to reconstruct, so sensitive to VBF







Interpretations

Minimal Supersymmetric Standard Model

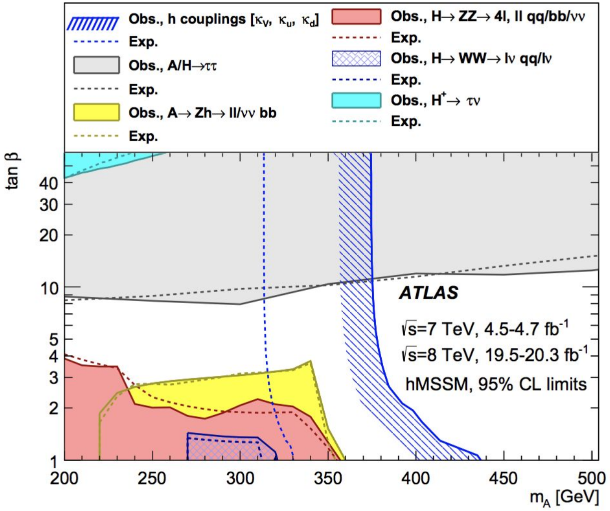
$$\kappa_V = \frac{s_d + \tan\beta s_u}{\sqrt{1+\tan^2\beta}},$$

$$\kappa_u = s_u\frac{\sqrt{1+\tan^2\beta}}{\tan\beta},$$

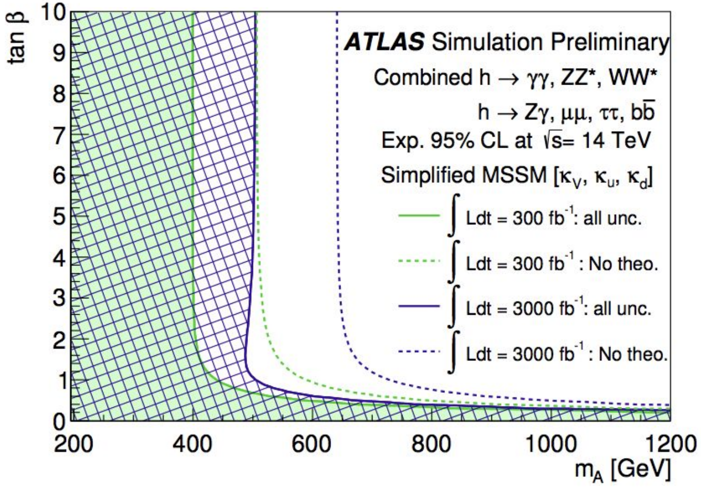
$$\kappa_d = s_d\sqrt{1+\tan^2\beta},$$

$$s_u(m_A, \tan\beta) = \frac{1}{\sqrt{1+\frac{(m_A^2+m_Z^2)^2\tan^2\beta}{(m_Z^2+m_A^2\tan^2\beta-m_h^2(1+\tan^2\beta))^2}}},$$

$$s_d(m_A, \tan\beta) = s_u\frac{(m_A^2+m_Z^2)^2\tan^2\beta}{(m_Z^2+m_A^2\tan^2\beta-m_h^2(1+\tan^2\beta))^2}.$$



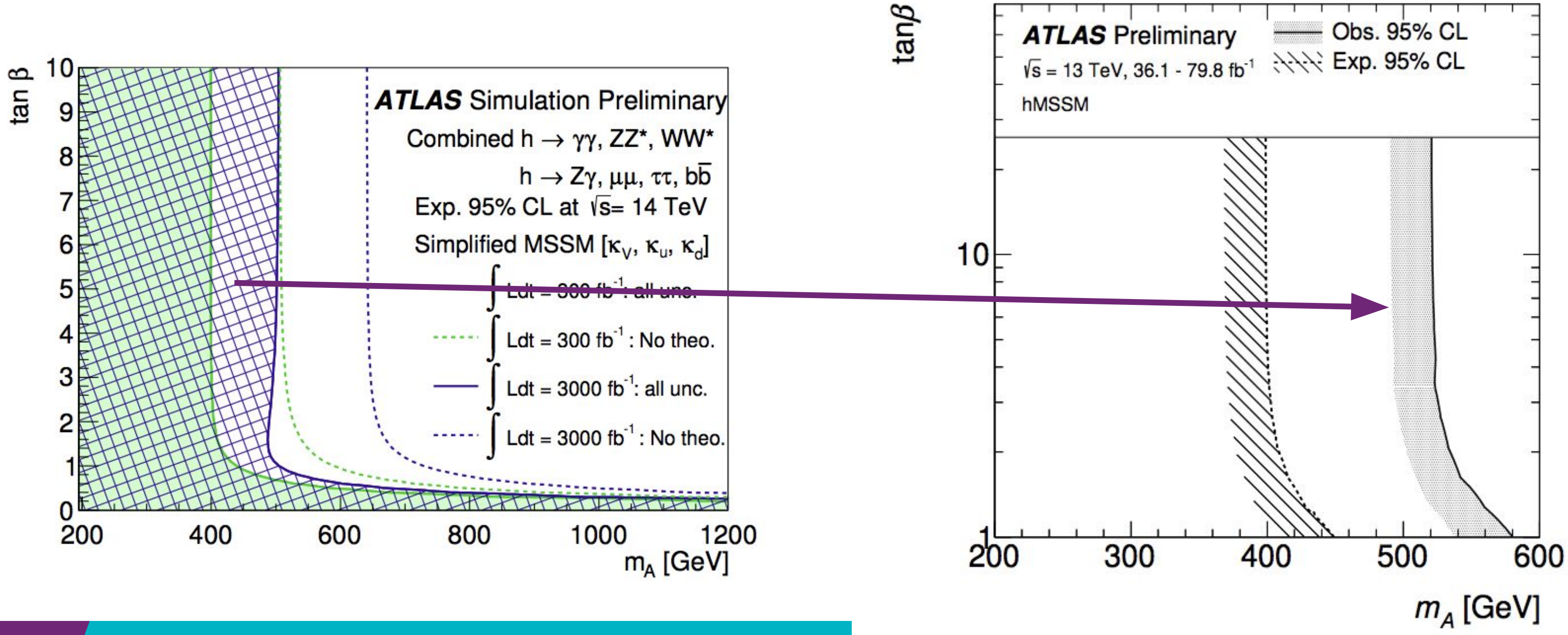
Run 1



HL-LHC

Run 2

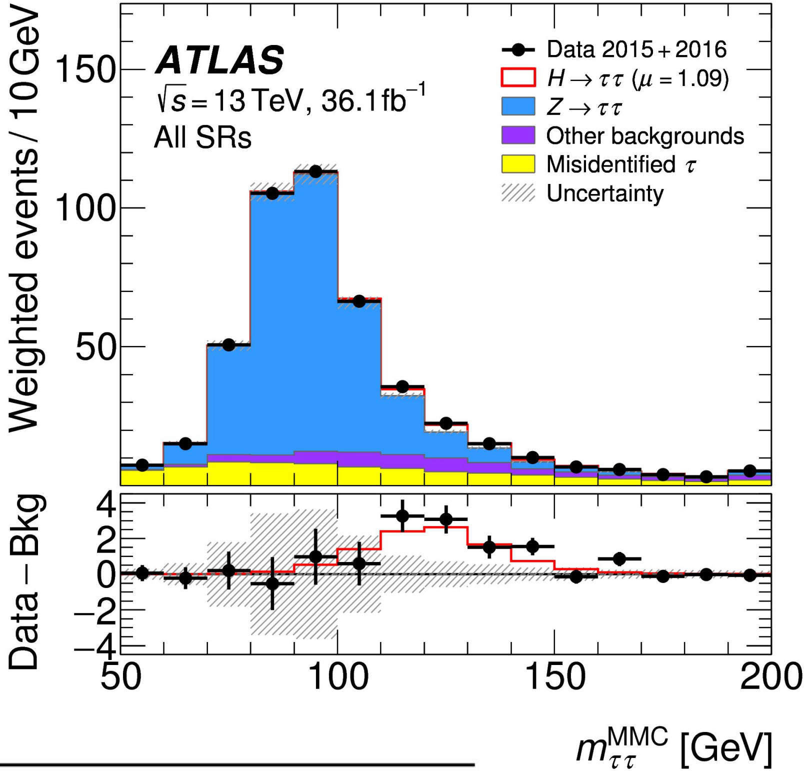
Better than expected!



Phys. Rev. D 99 (2019) 072001

Higgs $\to \tau\tau$ Run1

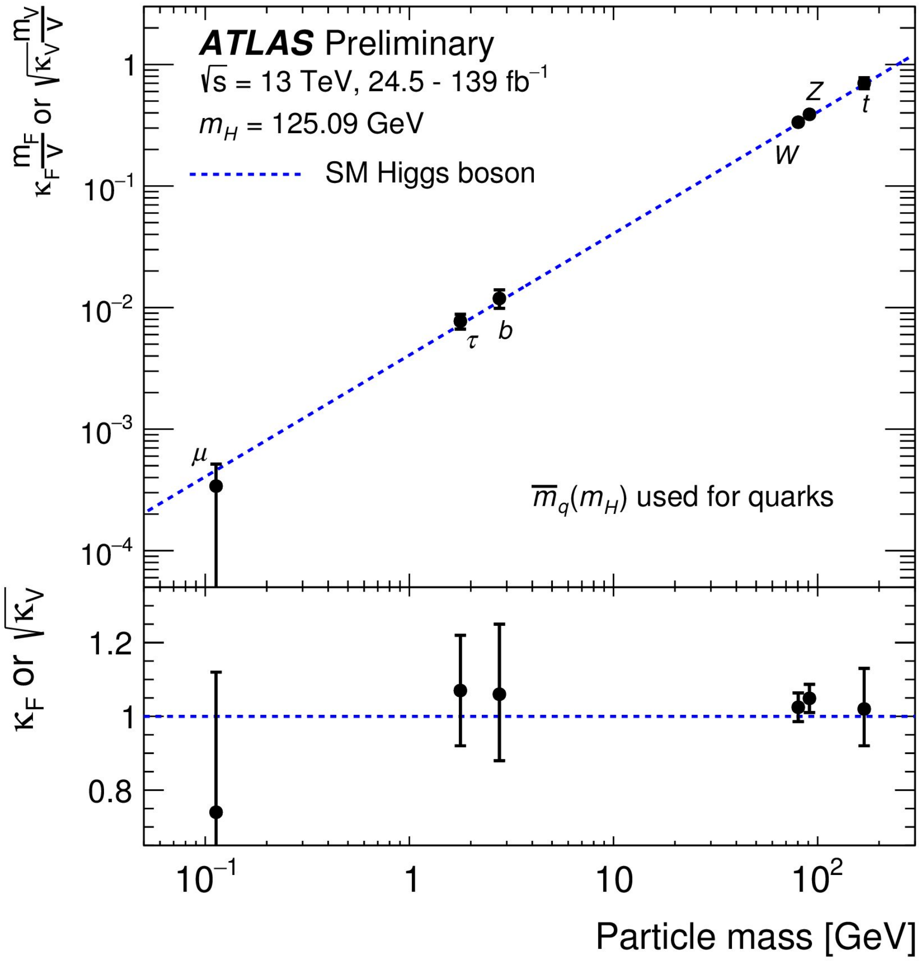
The H→ττ signal over the expected background from other Standard Model processes is established with an observed (expected) significance of 4.4 (4.1) standard deviations. Combined with results obtained using data taken at 7 and 8 TeV center-of-mass energies, the observed (expected) significance amounts to 6.4 (5.4) standard deviations and constitutes an observation of H→ττ decays.



Process	Particle-level selection	σ [pb]	σ^{SM} [pb]
ggF	$N_{\text{jets}} \geq 1$, $60 < p_{\text{T}}^{H} < 120\,\text{GeV}$, $\lvert y_H \rvert < 2.5$	$1.79 \pm 0.53\,(\text{stat.}) \pm 0.74\,(\text{syst.})$	0.40 ± 0.05
ggF	$N_{\text{jets}} \geq 1$, $p_{\text{T}}^{H} > 120\,\text{GeV}$, $\lvert y_H \rvert < 2.5$	$0.12 \pm 0.05\,(\text{stat.}) \pm 0.05\,(\text{syst.})$	0.14 ± 0.03
VBF	$\lvert y_H \rvert < 2.5$	$0.25 \pm 0.08\,(\text{stat.}) \pm 0.08\,(\text{syst.})$	0.22 ± 0.01

Coupling vs Mass

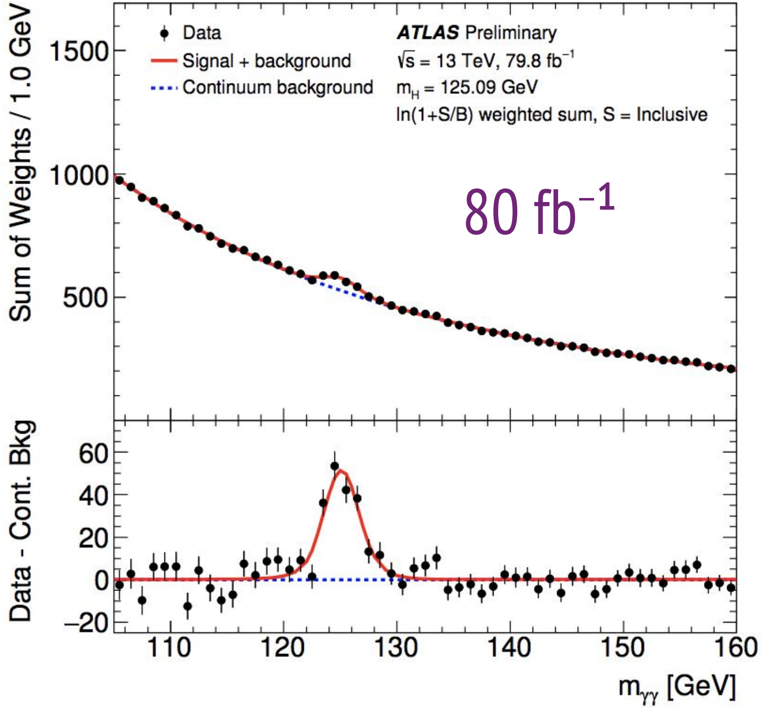
Hmumu limit is much lower than the measured Htautau. Thus, non-universal coupling.



Higgs → $\gamma\gamma$

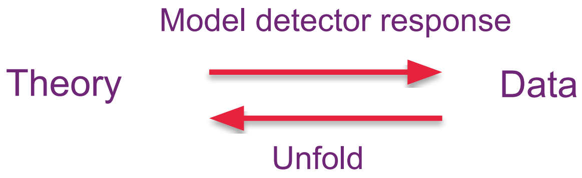
Fiducial and Differential analysis

- New physics likely at high energy → high pT
- New physics more visible at particle level
    - rather than detector phase space



80 fb^{-1}

Unfolding



Model detector response

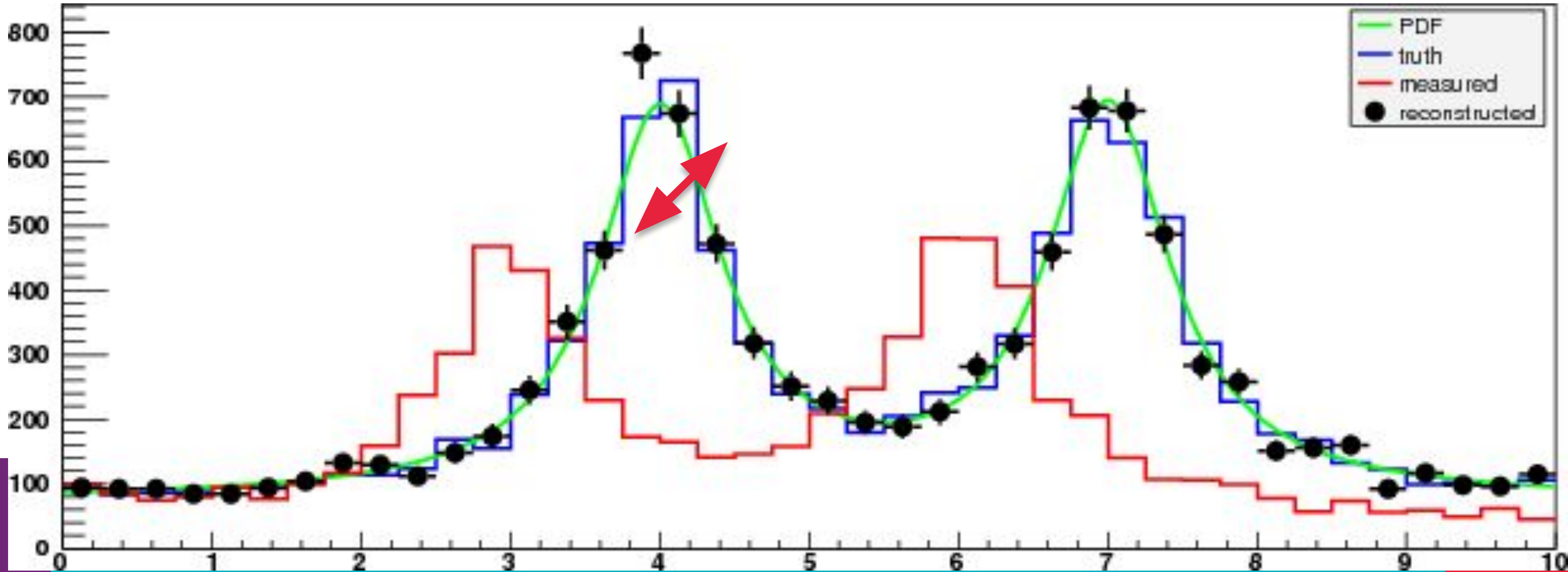
Theory

Data

Unfold

Modelling detector response versus unfolding

You want to know the underlying physics, not only if it matches with predictions

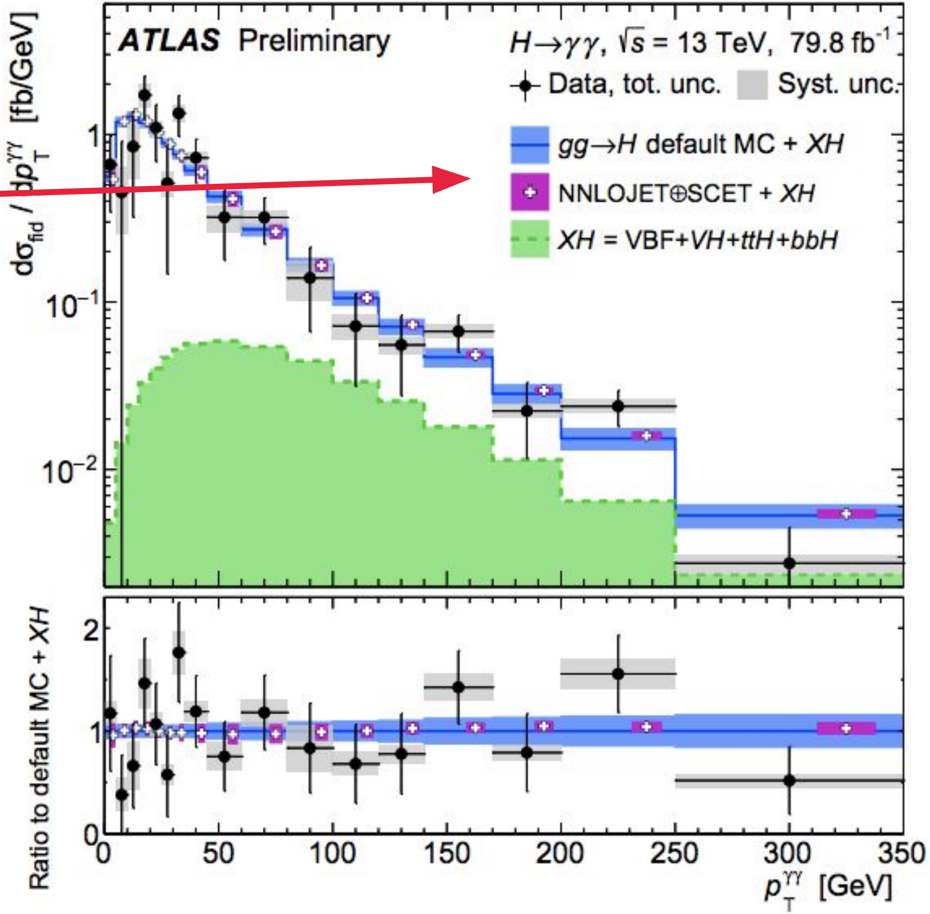


Higgs $\rightarrow \gamma\gamma$

Compare with different predictions

Also look at other distributions

- Jet distributions
  - Number of jets
  - Mass of dijet system
  - pT
- Rapidity



Higgs → $\gamma\gamma$ light yukawa

140 fb^{-1} Full Run 2 - Includes Interpretations

quarks in the loop
dominated by top-quark