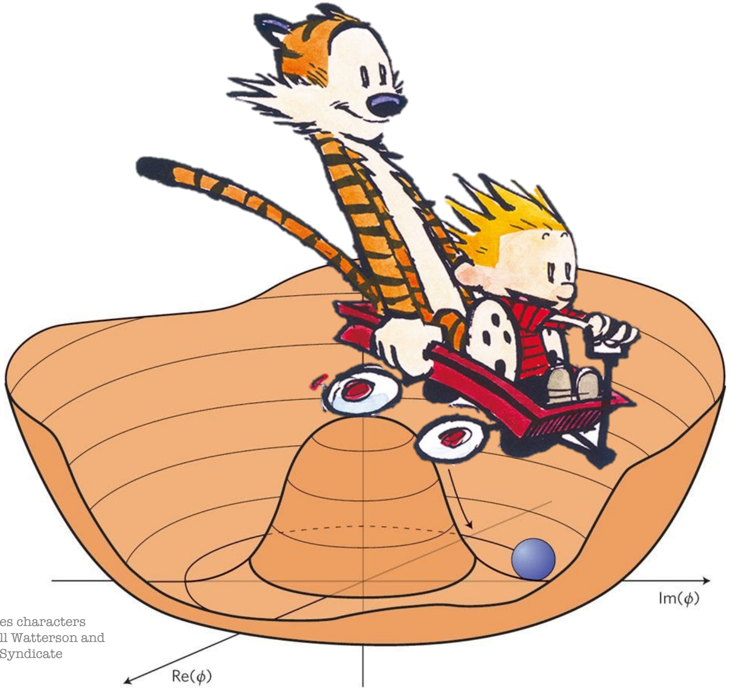
Living with a *pre-teen* Higgs boson

(12 years with the Higgs boson, and the next 12 years)

A tale in 12 chapters



Calvin and Hobbes characters
copyright by Bill Watterson and
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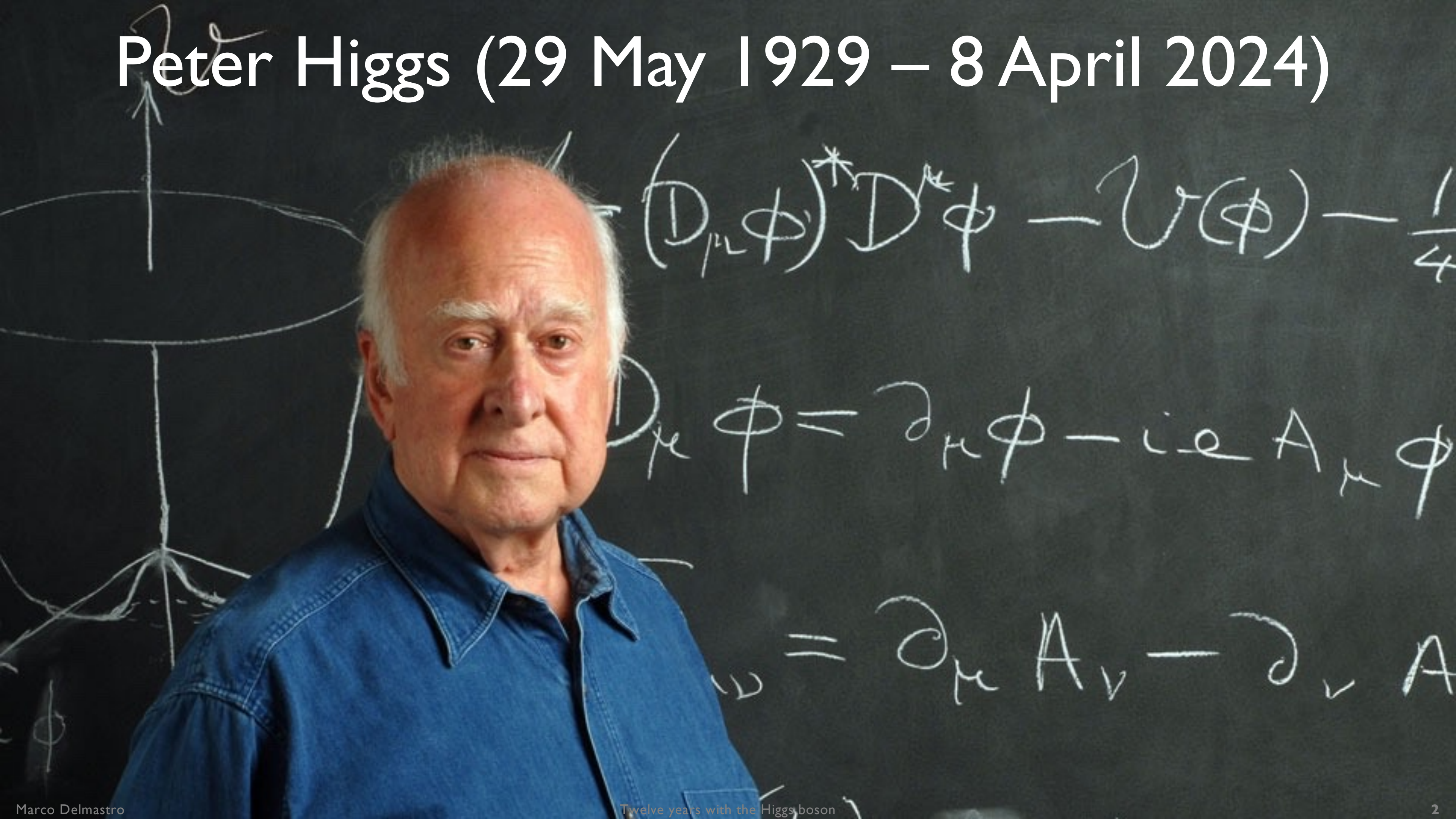
Marco Delmastro

LAPP
Laboratoire d'Annecy de Physique des Particules

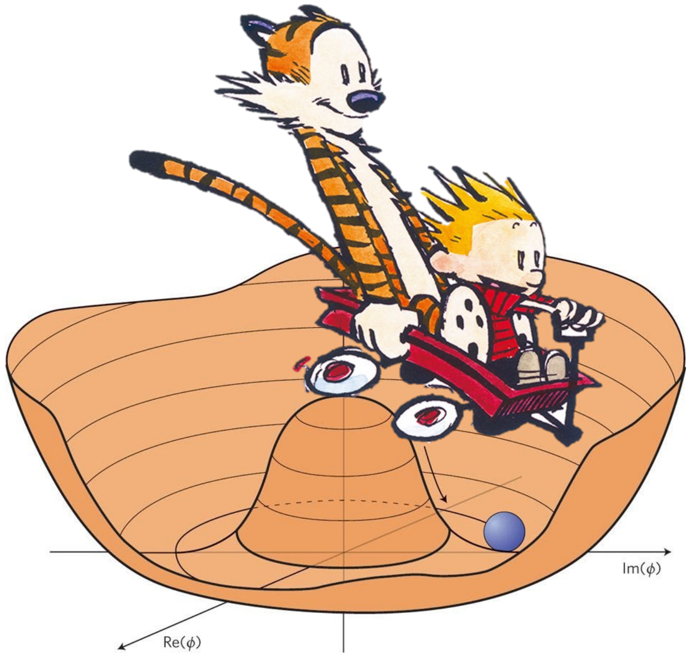
Université de Genève, 8/5/2024

Peter Higgs (29 May 1929 – 8 April 2024)



1.

Why the Higgs boson?



A fundamental question

How do elementary particles get mass?

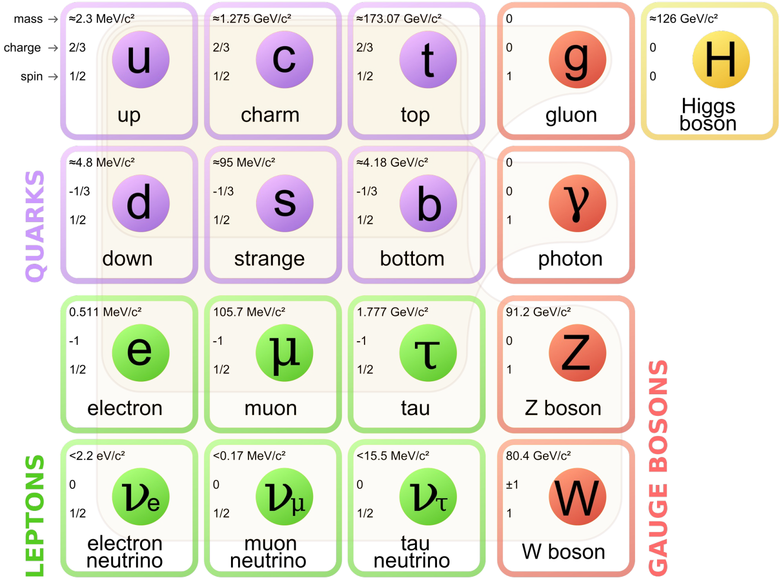
This is not a QFT lecture…

All microscopic phenomena seems to be well described by a remarkably simple *theory*
(that we continue to call "model" only for historical reasons...)

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}}(\psi_i, A_a) + \mathcal{L}_{\text{Higgs}}(H, A_a, \psi_i)$$

massless particles interact by exchanges of forces carried by massless gauge bosons. QFT describes free fields, interactions generated by gauge symmetries (thus renormalizable)

mass terms cannot be directly added without breaking theory gauge invariance
(i.e. mass is not a fundamental property, rather an emerging phenomenon)



Theory would not make sense without a Higgs field (or something similar) responsible for spontaneous symmetry breaking and mass generation…

2.

An idea from 1964

What's hot in in physics in 1964?

Quark model

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING
II *)

G. Zweig **)
CERN—Geneva

ABSTRACT

Both mesons an
three fundamental part
into an isospin double
number 1/3 and is fr
Eightfold Way) is ado
interactions. The bre
universal, being due
Extensive space-time
predicted for both me
ting experimental inf
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definitively classif
interaction theory b
to predict rates for
experimental search

*) Version I is
**) This work wa
of Scie
of Scie

8419/TH.412
21 February 1964

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that th
...

...r all known baryons and
...ing example of such a
...iplet has spin $\frac{1}{2}$ and
...icles d^-, s^-, u^0 and b^0
...ptons.
...nt scheme can be
...ntegral values for the
...tirely with the basic
...iplet t the following
...d baryon number $\frac{1}{3}$.
$u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of
...d the members of the
...Baryons can now be
...ing the combinations
...esons are made out
...ming that the lowest
...s just the represen-
...en observed, while
...$q\bar{q}$) similarly gives
...based on field
...rks exactly as for
...r example 3)
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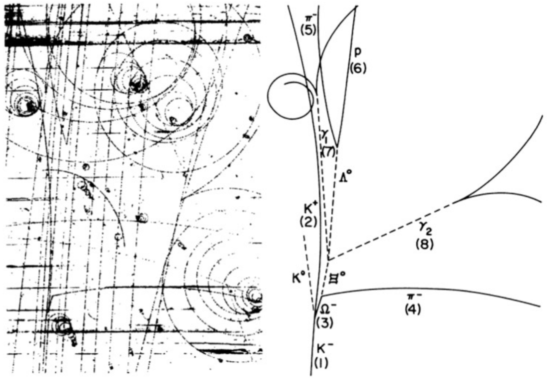
VOLUME 12, NUMBER 8 PHYSICAL REVIEW LETTERS 24 FEBRUARY 1964

OBSERVATION OF A HYPERON WITH STRANGENESS MINUS THREE*

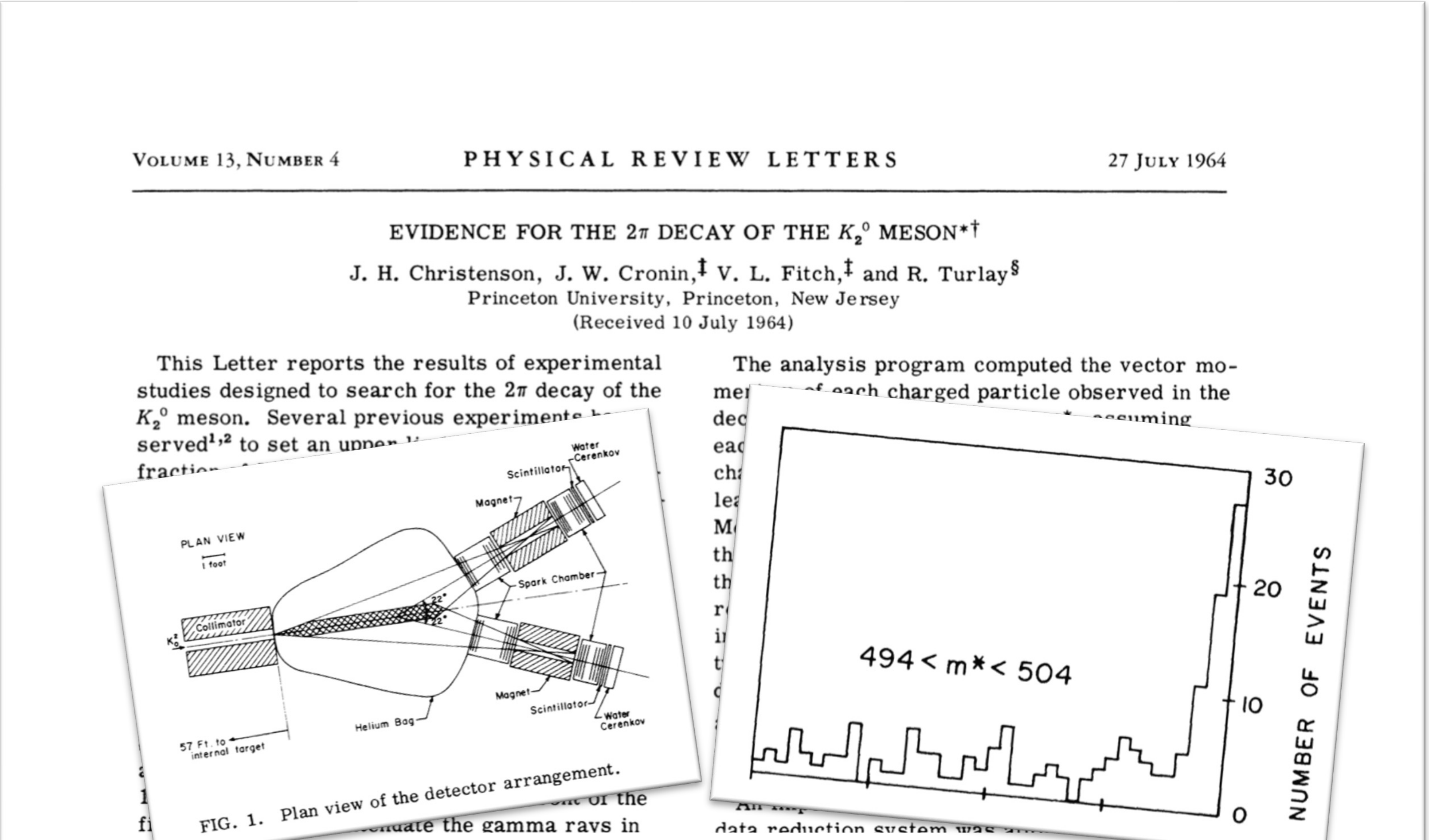


$$K^- + p \to \Omega^- + K^+ + K^0$$
$$\Omega^- \to \Xi^0 + \pi^-$$
$$\Xi^0 \to \Lambda^0 + \pi^0$$
$$\pi^0 \to \gamma_1 + \gamma_2, \quad \gamma_1 \to e^+ + e^-, \quad \gamma_2 \to e^+ + e^-$$
$$\Lambda^0 \to \pi^- + p.$$

FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

What's hot in in physics in 1964?

Observation of CP-violation


VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments h… served[1,2] to set an upper li… fractio…

The analysis program computed the vector mo- men… of each charged particle observed in the dec… … assuming …

FIG. 1. Plan view of the detector arrangement.

The Brout-Englert-Higgs mechanism is also proposed…

… and barely noticed!

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

14 citations in the first 5 years

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland
Received 27 July 1964

18 citations in the first 5 years

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)

11 citations in the first 5 years

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

23 citations in the first 5 years

It would take 10 more years to become "mainstream"…

1967

PHYSICAL REVIEW VOLUME 155, NUMBER 5 25 MARCH 1967

Symmetry Breaking in Non-Abelian Gauge Theories*

T. W. B. KIBBLE
Department of Physics, Imperial College, London, England
(Received 24 October 1966)

Photon remains massless

1967

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

A. Salam, "Weak And Electromagnetic Interactions," Originally printed in "N. Svartholm: Elementary Particle Theory, Proceedings of The Nobel Symposium Held 1968 at Lerum, Sweden" 367-377 (1968).

Electroweak Symmetry Breaking incorporated into Standard Model

RENORMALIZABLE LAGRANGIANS FOR MASSIVE YANG-MILLS FIELDS

G.'t HOOFT
Institute for Theoretical Physics, University of Utrecht

Received 13 July 1971

REGULARIZATION AND RENORMALIZATION OF GAUGE FIELDS

G. 't HOOFT and M. VELTMAN
*Institute for Theoretical Physics *, University of Utrecht*

Received 21 February 1972

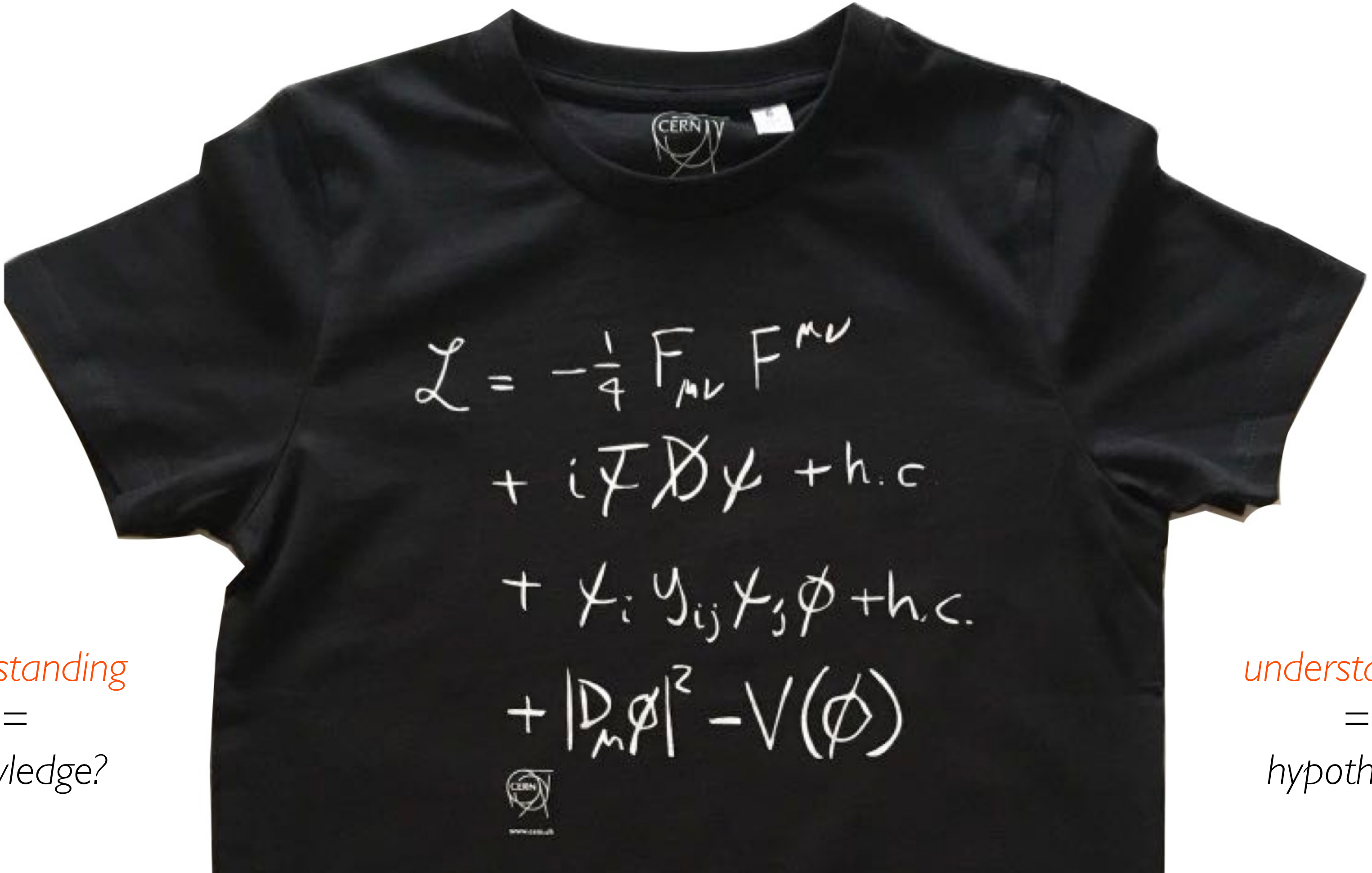
1971-72

Standard Model is renormalizable

3.

A closer look to the SM Lagrangian

"This equation neatly sums up our current understanding of fundamental particles and forces"



understanding

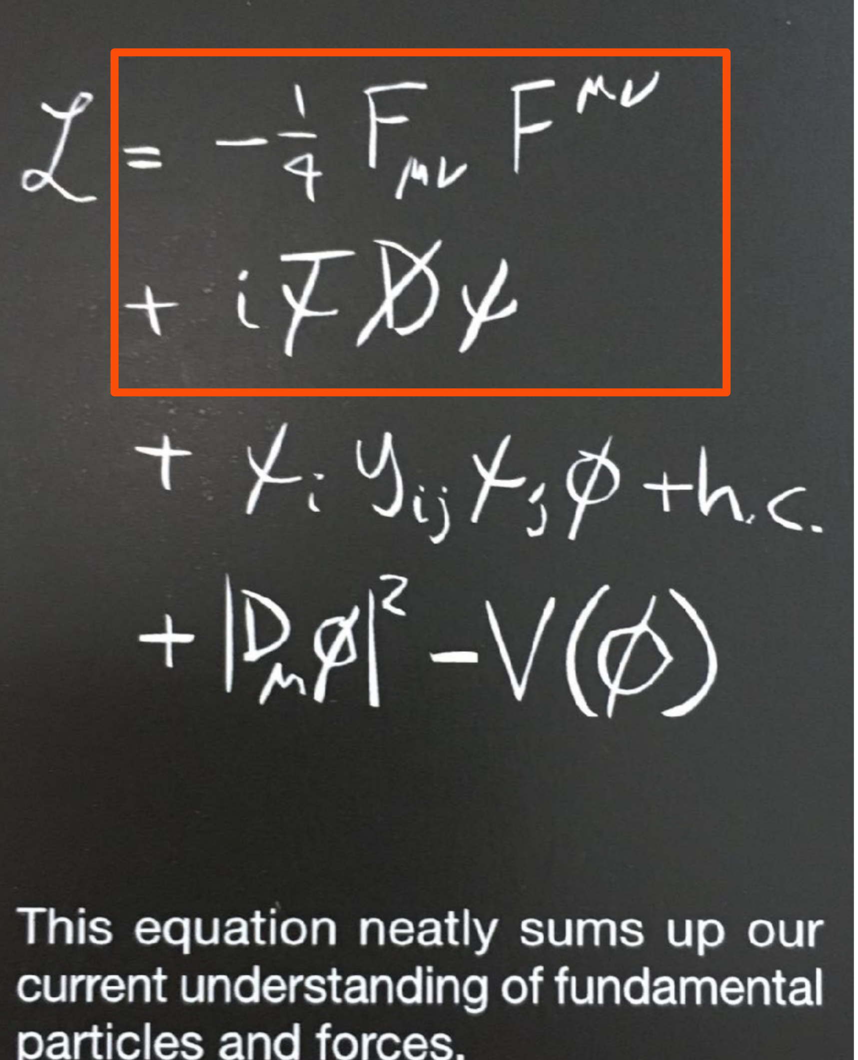
=

knowledge?

understanding

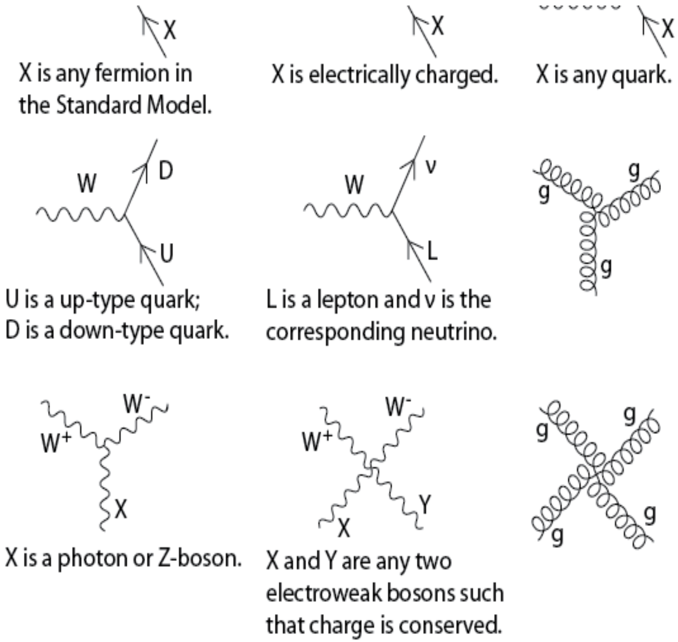
=

hypothesis?

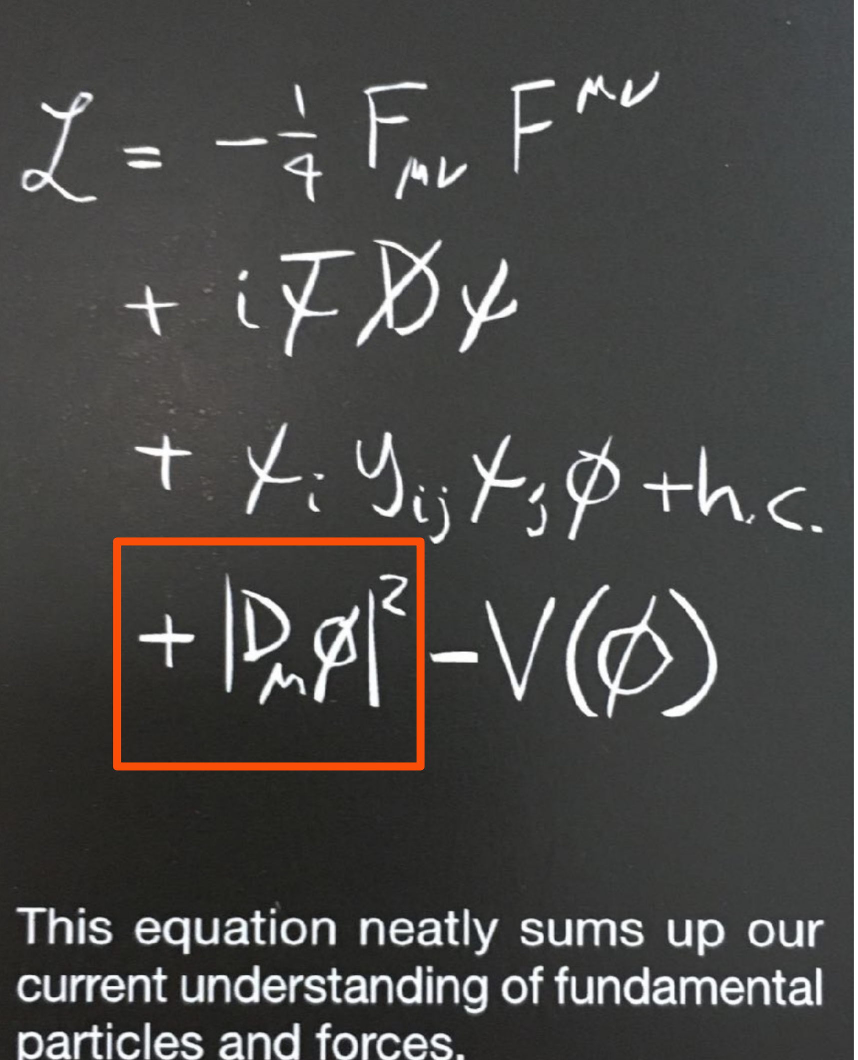


Gauge sector

This part is very well known (one could even say since the discovery of Maxwell equations in 1880), elegant and very well experimentally verified!



understanding = knowledge

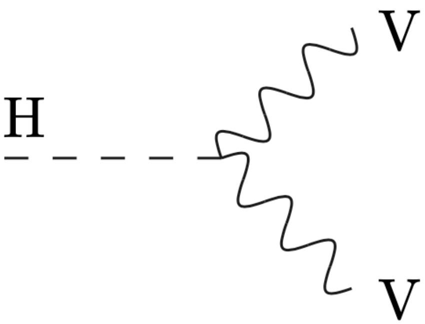


Electro-weak symmetry breaking

Still a gauge interaction (nothing new, one might be tempted to say…), only this time between bosons and a scalar field!

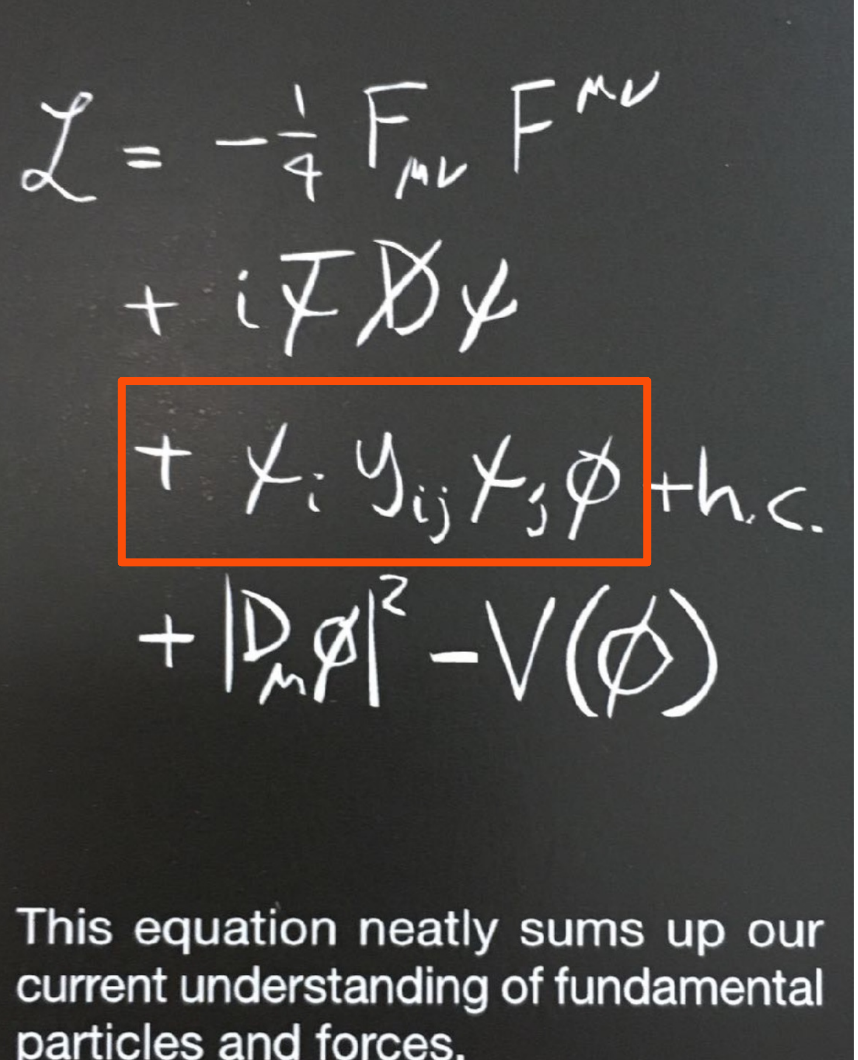
Nothing like this directly observed before 2012 (but tested before by precision electroweak interactions)

Experimentally observed in 2012 with Higgs boson discovery…



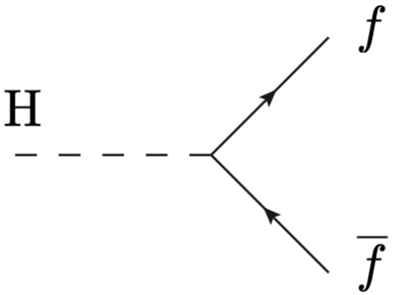
$$\frac{2m_V^2}{v}$$

…this term could not exist without a v.e.v.



Fermion masses via Yukawa interaction

Before 2012 this term was almost a conjecture… and even after the discovery in 2012, it remains an "anomalous" term (it's not a gauge interaction, and no interaction with this structure has ever been observed in nature)

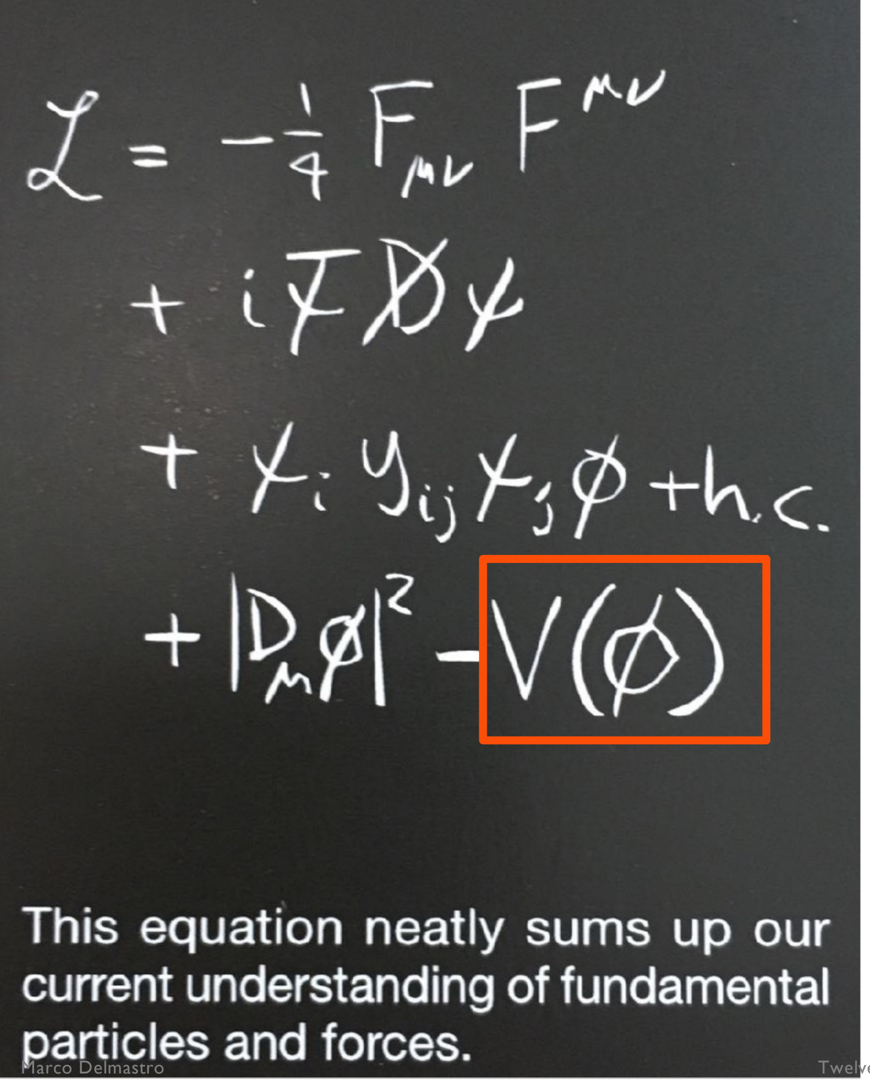


$$\frac{m_f}{v}$$

Is the Higgs boson responsible for the EW symmetry breaking also responsible for the masses of fermions?

Is the Higgs boson responsible for the masses of all fermions?

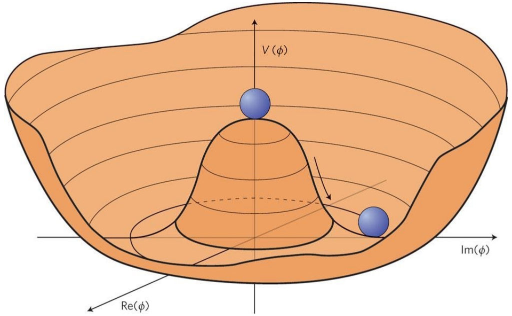
understanding = hypothesis



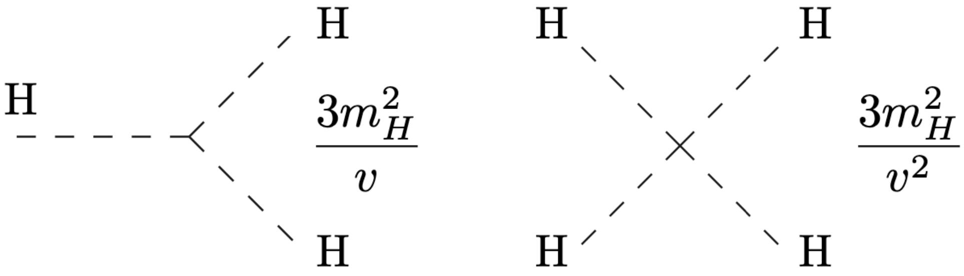
Higgs potential

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

It defines all characteristics of Higgs field and defines Higgs self-interaction properties. Nothing like this has ever been observed in nature



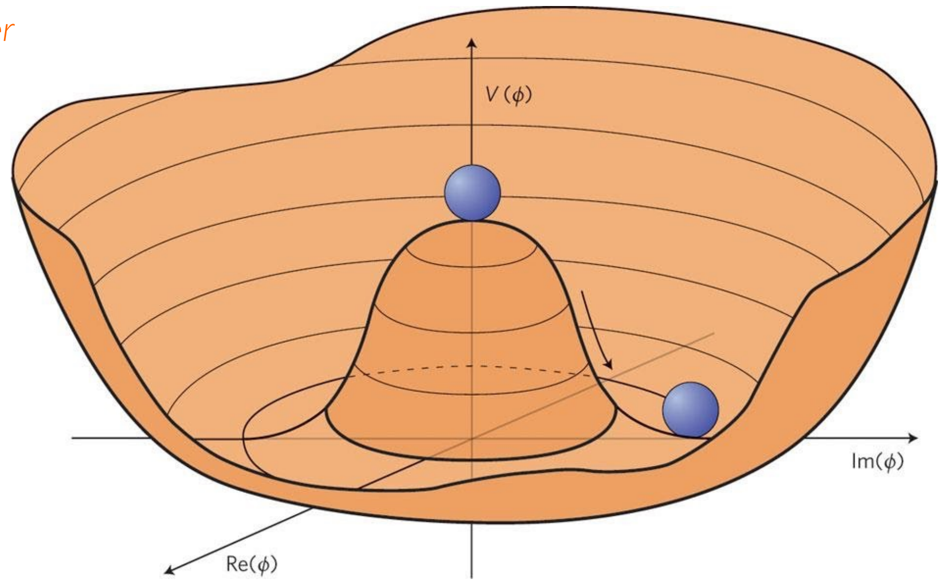
Is the shape of the Higgs potential that postulated by the Standard Model?



A couple of things about the Higgs potential…

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

The potential is symmetric under rotations in Φ space



$$\mu^2 < 0$$

$$\lambda > 0$$

It has a minimum which is not at <Φ>=0 known as the vacuum expectation value (vev) v that defines the electroweak scale

The mass of the Higgs boson is not predicted by the theory!

$$\nu = \frac{\mu}{\sqrt{\lambda}} = \frac{m_W}{g} = 246\text{GeV}$$

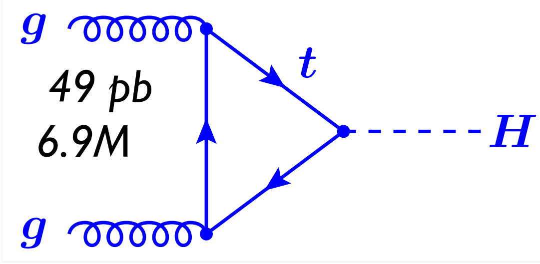
$$m_H = \sqrt{2}\mu = \sqrt{2\lambda}\nu$$

4.

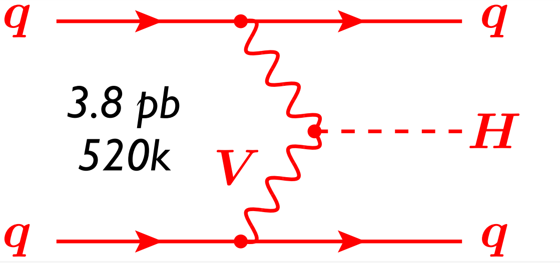
A textbook discovery

The Large Hadron Collider

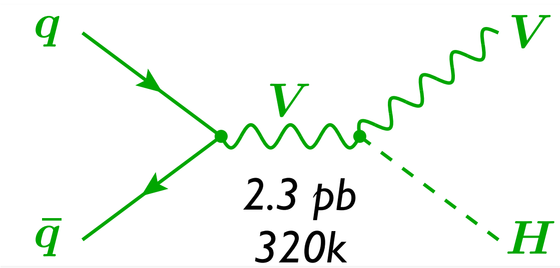
Higgs boson production at the LHC



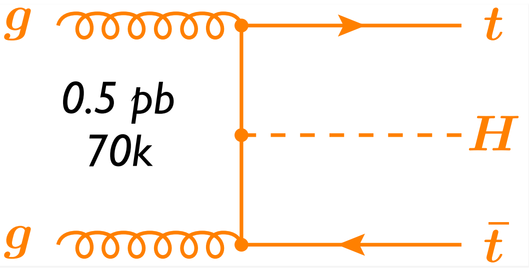
gluon-gluon fusion:
main production mode at
LHC



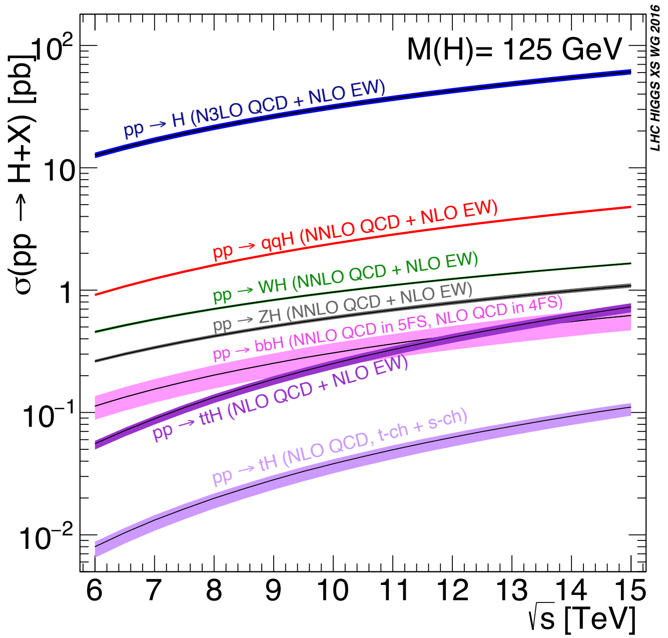
Vector Boson Fusion
2 well-separated forward
jets



VH
tag W and Z
boson decays

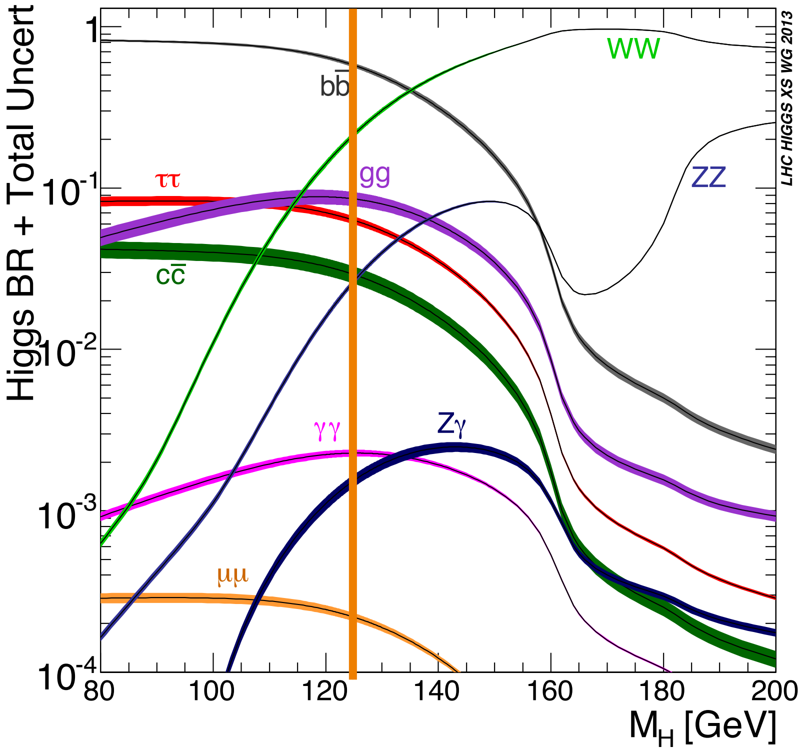


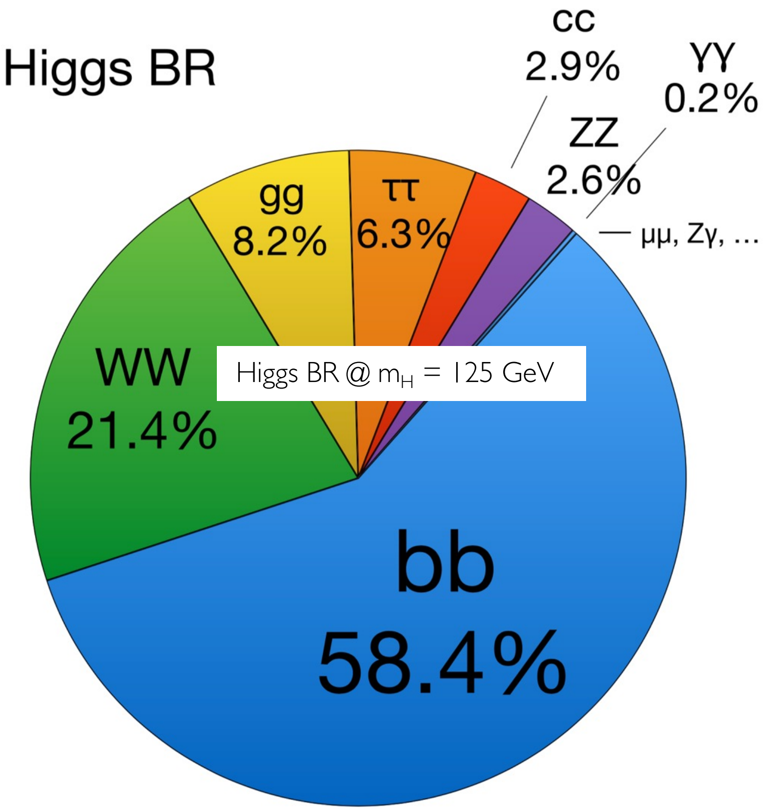
ttH
tag 2 top quarks



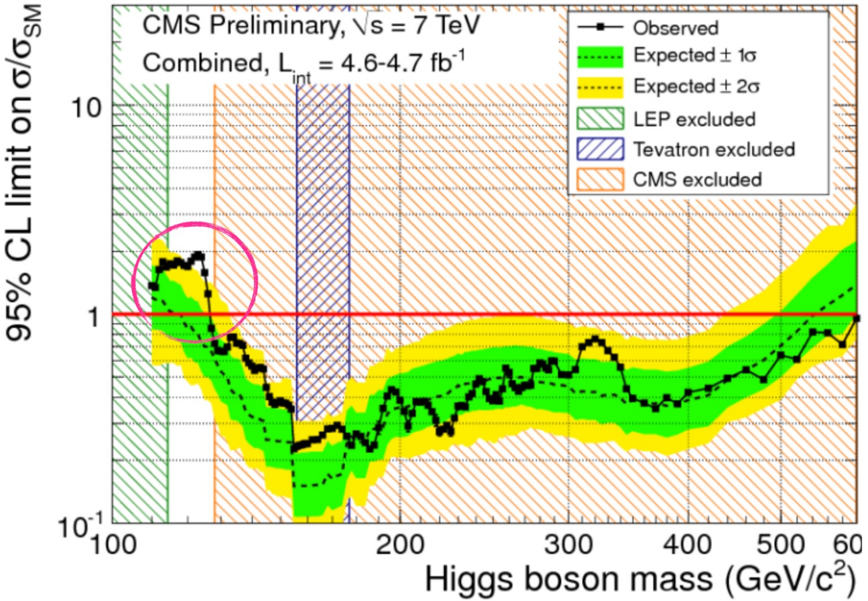
σ[pb] @ 13 TeV
 # Higgs produced in 140 fb^{-1} in one experiment

The Higgs boson is an unstable particle

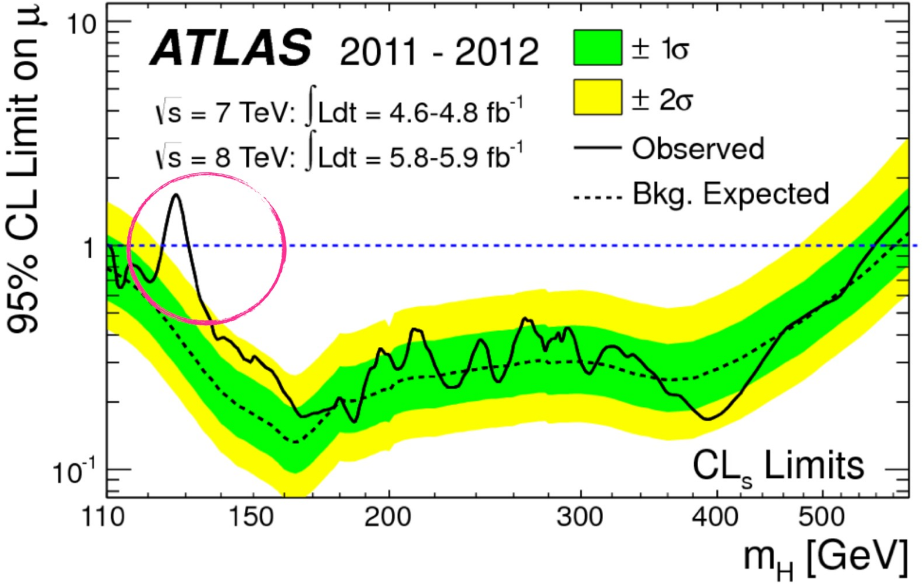




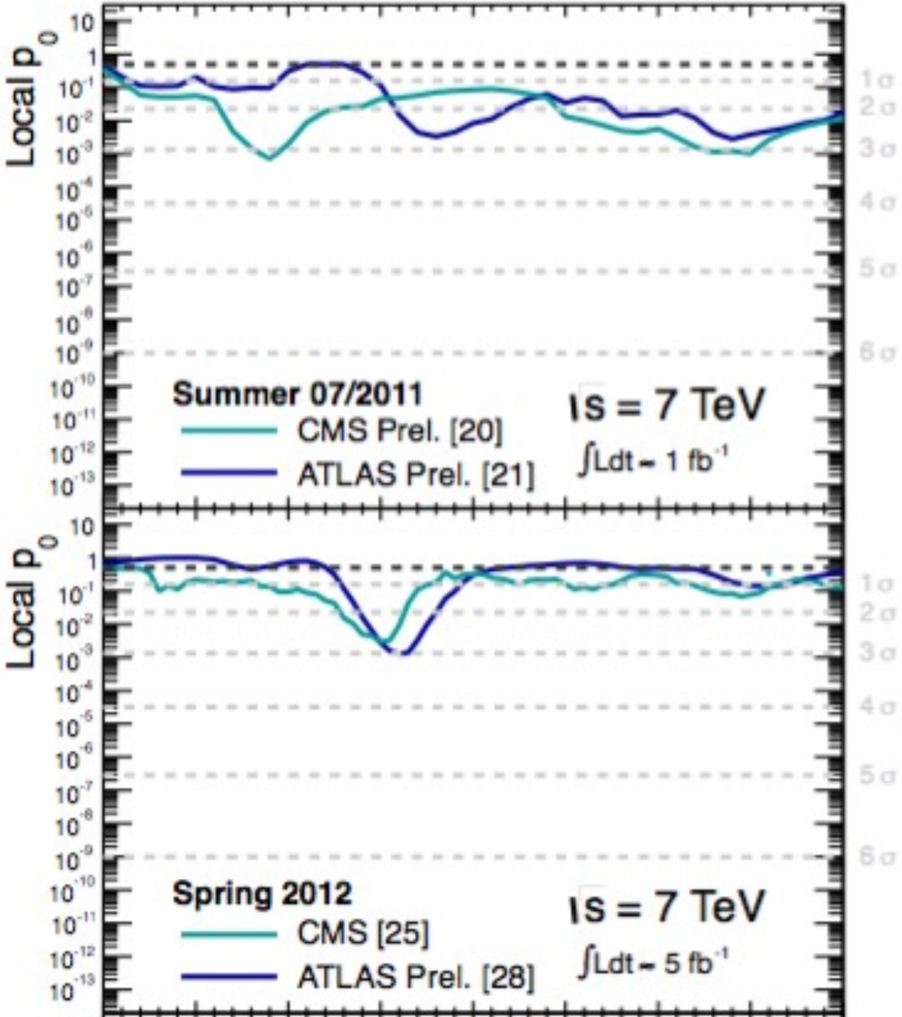
Almost exactly 12 years ago…



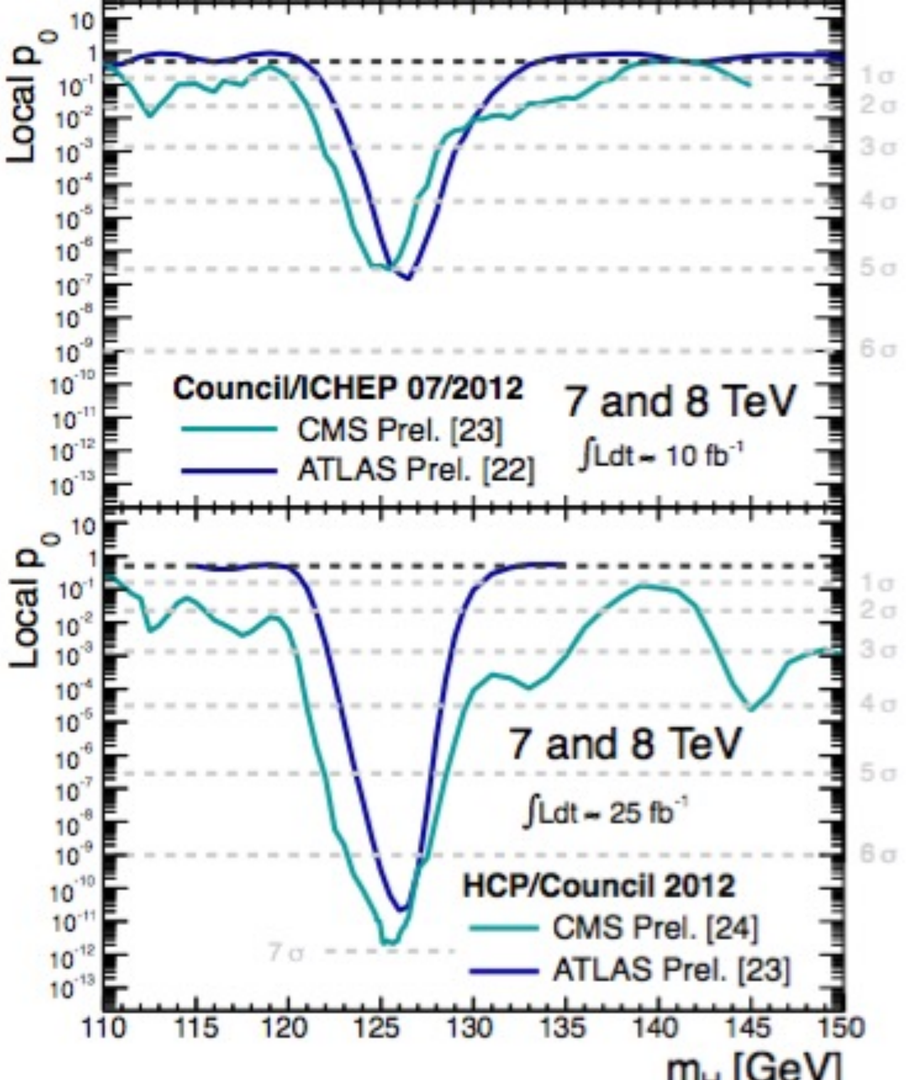
End of 2011…



… June 2012…



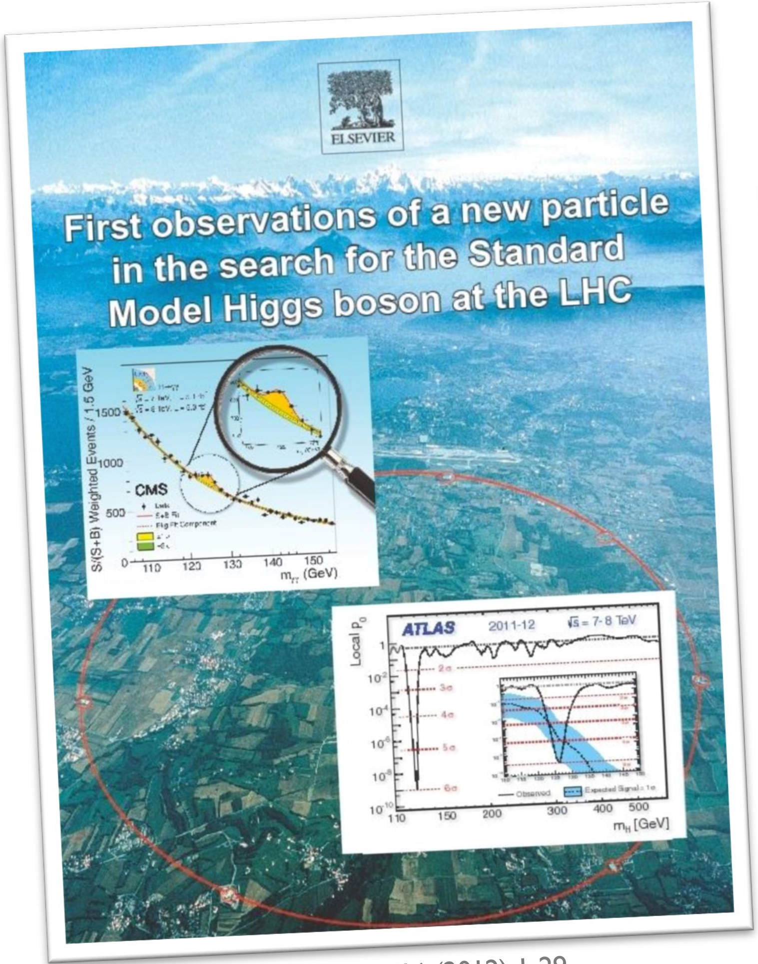
Local p_0
Summer 07/2011
CMS Prel. [20]
ATLAS Prel. [21]
√s = 7 TeV
∫Ldt ~ 1 fb⁻¹
1σ
2σ
3σ
4σ
5σ
6σ
Local p_0
Spring 2012
CMS [25]
ATLAS Prel. [28]
√s = 7 TeV
∫Ldt ~ 5 fb⁻¹


Local p_0
1σ
2σ
3σ
4σ
5σ
6σ
Council/ICHEP 07/2012
CMS Prel. [23]
ATLAS Prel. [22]
7 and 8 TeV
∫Ldt ~ 10 fb^{-1}
Local p_0
7 and 8 TeV
∫Ldt ~ 25 fb^{-1}
7σ
HCP/Council 2012
CMS Prel. [24]
ATLAS Prel. [23]
110 115 120 125 130 135 140 145 150
m_H [GeV]

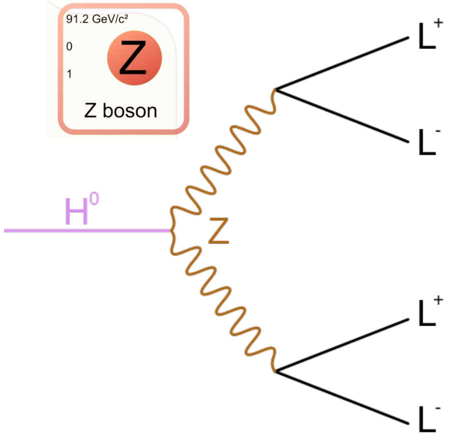
5 σ!

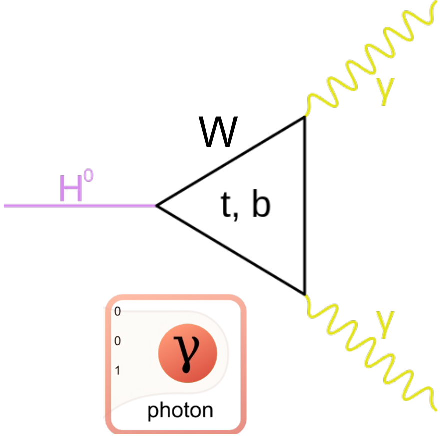
Fabiola Gianotti revealing the combined significance of the ATLAS Higgs searches on on July 4 2012

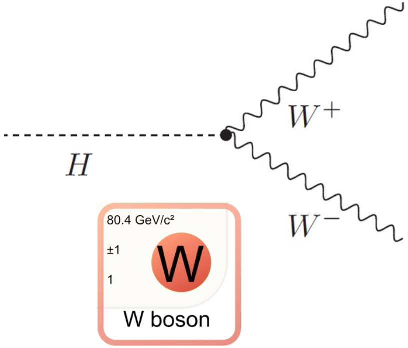
Higgs boson discovery channels



ATLAS: PLB 716 (2012) 1-29
CMS: PLB 716 (2012) 30







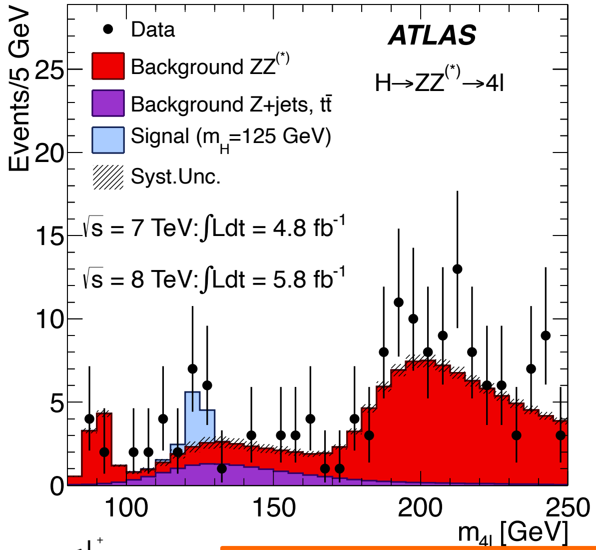
5.

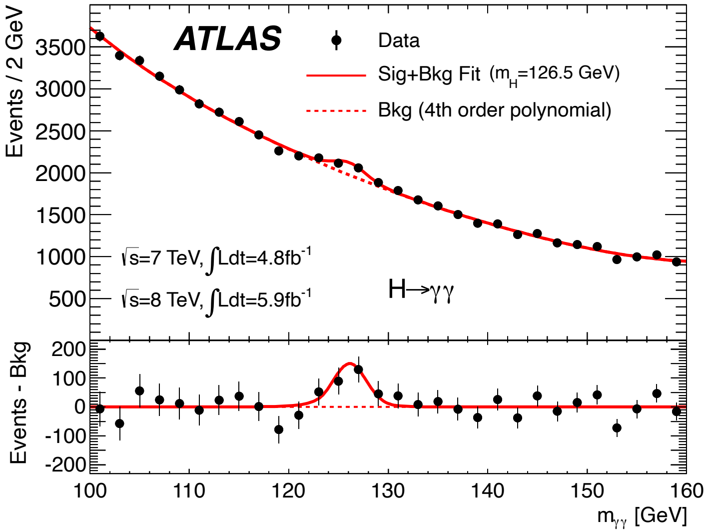
12 years of Higgs measurements

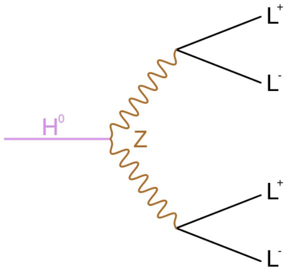
A long way since the discovery…

2012

Phys Lett B 716 (1) 1-29 2012





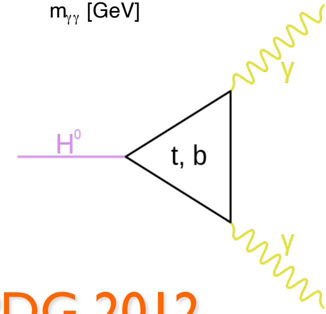


H^0 DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$W W^*$	seen	–
$Z Z^*$	seen	–
$\gamma\gamma$	seen	–
$b\bar{b}$	possibly seen	–
$\tau^+\tau^-$	possibly seen	–

Mass Limits for the Standard Model Higgs

Mass $m > 122$ and none 127–600 GeV, CL = 95%

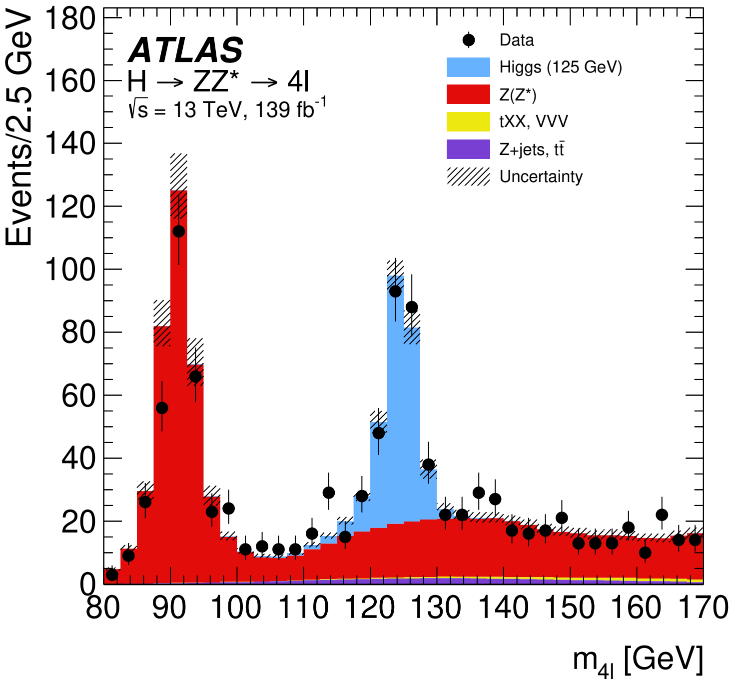
J. Beringer *et al.* (Particle Data Group), PR **D86**, 010001 (2012)

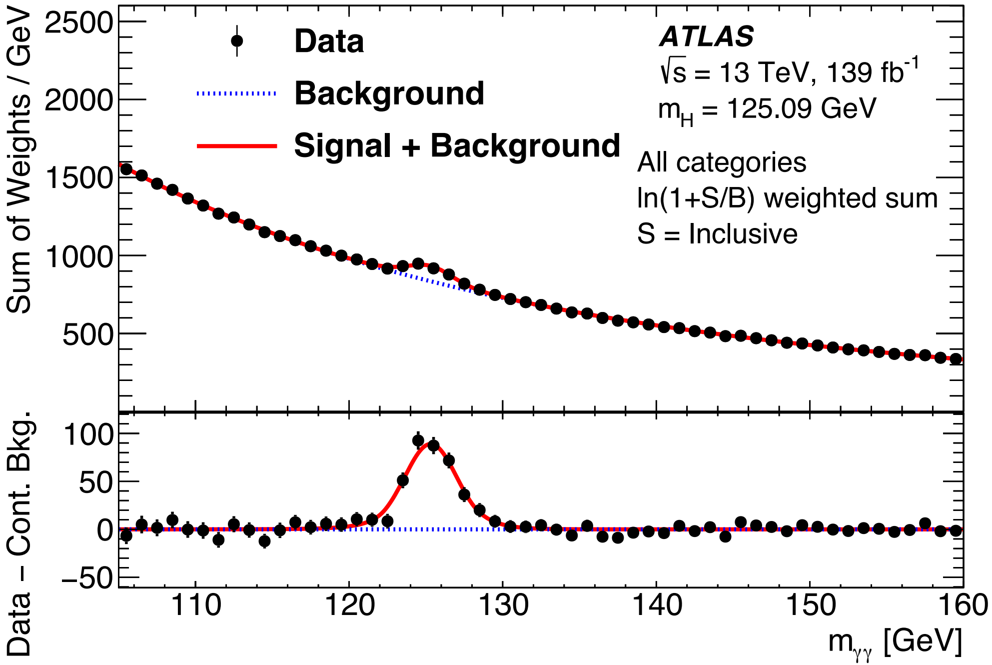


PDG 2012

A long way since the discovery…

YESTERDAY





Eur. Phys. J. C 80 (2020) 942

JHEP 07 (2023) 088

A long way since the discovery…

PDG 2022

H^0

$J = 0$

Mass $m = 125.25 \pm 0.17$ GeV (S = 1.5)
Full width $\Gamma = 3.2^{+2.8}_{-2.2}$ MeV (assumes equal on-shell and off-shell effective couplings)

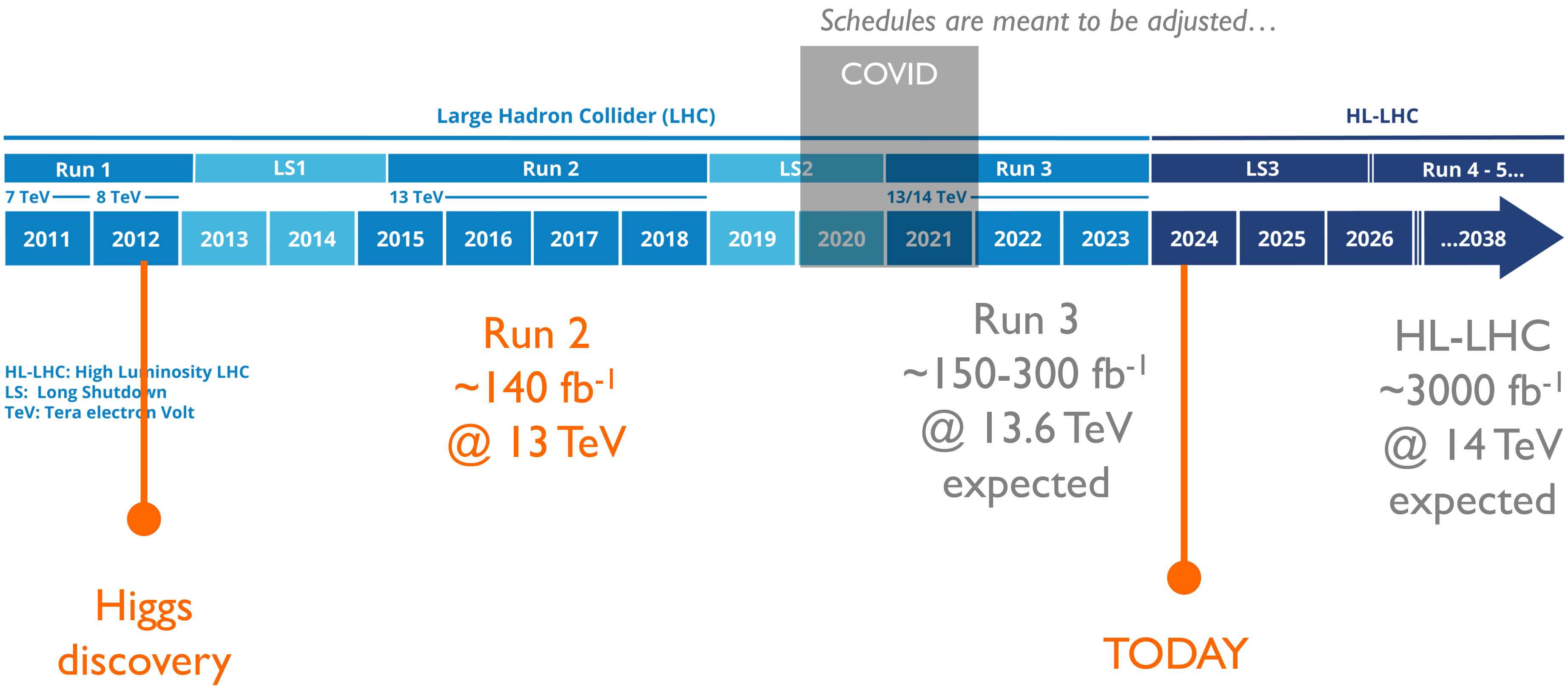
H^0 Signal Strengths in Different Channels

Combined Final States = 1.13 ± 0.06
$W W^* = 1.19 \pm 0.12$
$Z Z^* = 1.01 \pm 0.07$
$\gamma\gamma = 1.10 \pm 0.07$
$c\overline{c}$ Final State = 37 ± 20
$b\overline{b} = 0.98 \pm 0.12$
$\mu^+\mu^- = 1.19 \pm 0.34$
$\tau^+\tau^- = 1.15^{+0.16}_{-0.15}$
$Z\gamma < 3.6$, CL = 95%
$\gamma^*\gamma$ Final State = 1.5 ± 0.5
$t\overline{t}H^0$ Production = 1.10 ± 0.18
tH^0 production = 6 ± 4
H^0 Production Cross Section in pp Collisions at $\sqrt{s} = 13$ TeV = 56 ± 4 pb

H^0 DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
e^+e^-		$< 3.6 \times 10^{-4}$	95%	62625
$Z\rho(770)$		< 1.21 %	95%	29423
$Z\phi(1020)$		$< 3.6 \times 10^{-3}$	95%	29417
$J/\psi\gamma$		$< 3.5 \times 10^{-4}$	95%	62587
$J/\psi J/\psi$		$< 1.8 \times 10^{-3}$	95%	62548
$\psi(2S)\gamma$		$< 2.0 \times 10^{-3}$	95%	62571
$\Upsilon(1S)\gamma$		$< 4.9 \times 10^{-4}$	95%	62268
$\Upsilon(2S)\gamma$		$< 5.9 \times 10^{-4}$	95%	62224
$\Upsilon(3S)\gamma$		$< 5.7 \times 10^{-4}$	95%	62197
Υ(nS) Υ(mS)		$< 1.4 \times 10^{-3}$	95%	–
$\rho(770)\gamma$		$< 8.8 \times 10^{-4}$	95%	62623
$\phi(1020)\gamma$		$< 4.8 \times 10^{-4}$	95%	62621
$e\mu$	LF	$< 6.1 \times 10^{-5}$	95%	62625
$e\tau$	LF	$< 2.2 \times 10^{-3}$	95%	62612
$\mu\tau$	LF	$< 1.5 \times 10^{-3}$	95%	62612
invisible		<19 %	95%	–

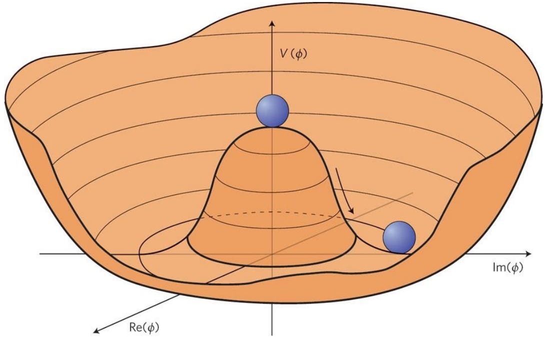
R.L. Workman *et al* (PDG), Prog. Theor. Exp. Phys. **2022**, 083C01 (2022)

12 years with the Higgs boson, and the next 12+ years…



6. How well do we know the "basic" Higgs properties?

Higgs boson mass and width



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

$$\nu = \frac{\mu}{\sqrt{\lambda}}$$

$$V(\Phi) = V_0 + \frac{1}{2}m_H^2 H^2 + \lambda\nu H^3 + \frac{1}{4}\lambda H^4$$

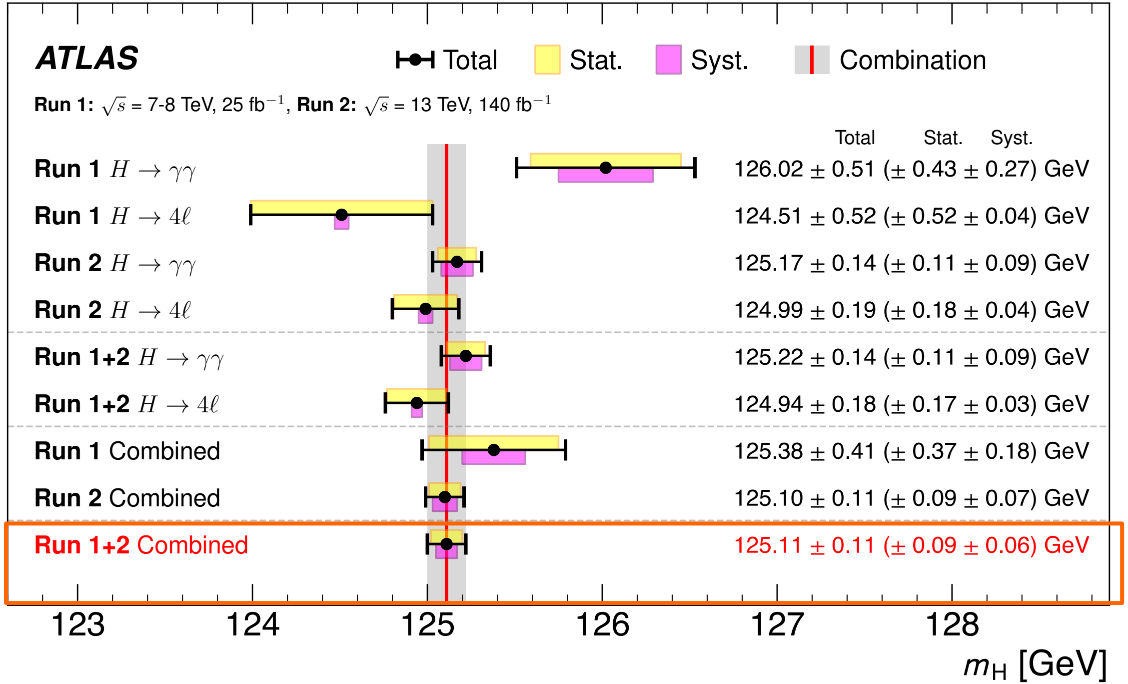
$$m_H = \sqrt{2}\mu = \sqrt{2\lambda}\nu$$

How well do we know the Higgs mass?

$$m_H = \sqrt{2}\mu$$

- m_H Not predicted by theory
- All Higgs coupling properties depend on m_H
- Excellent measurements by ATLAS and CMS
  - ✓ Precision depends on energy (photons, electrons) and momentum (muons) calibration

Phys. Rev. Lett. 131 (2023) 251802



110 MeV
(0.09%)

Higgs width: a problem difficult to tackle directly!

Total Higgs natural width in SM is small!

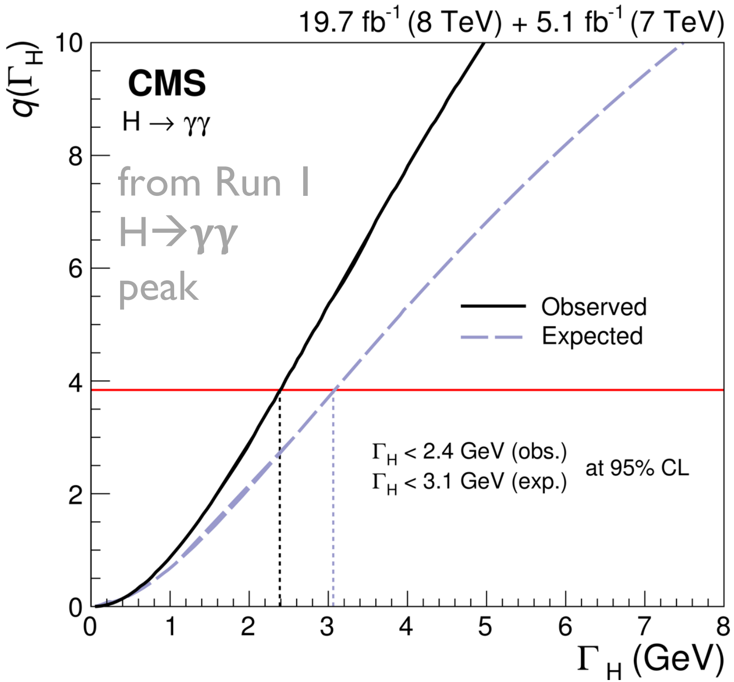
- ✓ Too small to be accessed experimentally at LHC from resonance line-shape in analysis where peak can be reconstructed…

Γ_H^{SM} dominated by

$$\Gamma(H \to b\bar{b}) \approx \frac{N_c g_w^2 m_b^2 m_H}{32\pi m_W^2}$$

$\Gamma_H^{SM} = 4.07$ MeV

Direct measurement severely limited by detector resolution! One (old) example:

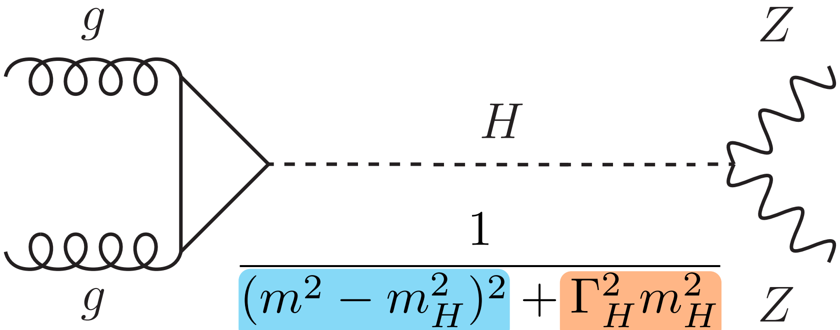


Eur. Phys. J. C 74 (2014) 3076

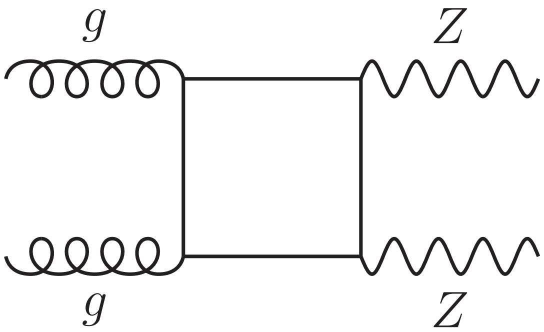
$\Gamma_H < 2.4$ (3.1) GeV obs. (exp.)

The Higgs boson as propagator: width from off-shell Higgs

ggF as an example



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



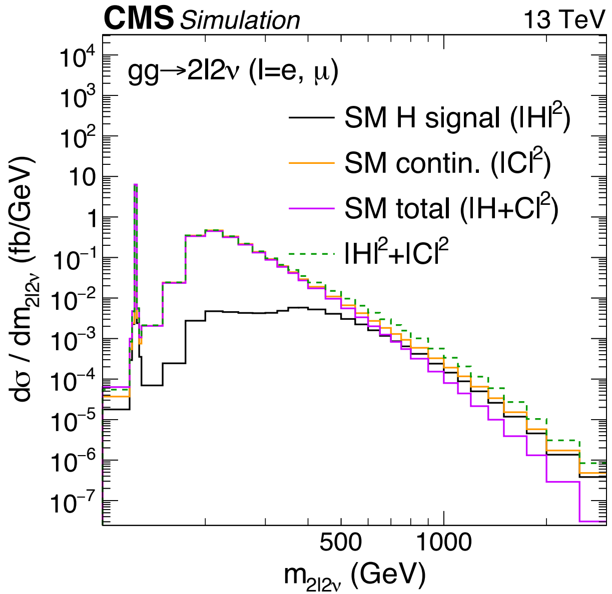
- Interference impacts both total cross section and m(VV) line-shape
- Assuming on-shell and off-shell couplings are equal:

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

$vv = gg$

$vv = WW, ZZ, Z\gamma, \gamma\gamma$

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

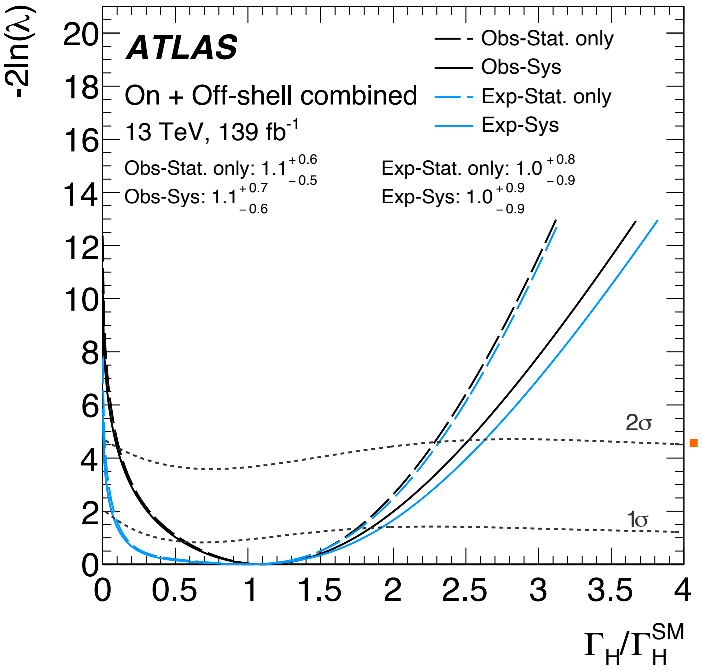


arXiv:2202.06923

Measurements of the Higgs width from off-shell production

Measurements in 4l and 2l2ν final states and for different production modes

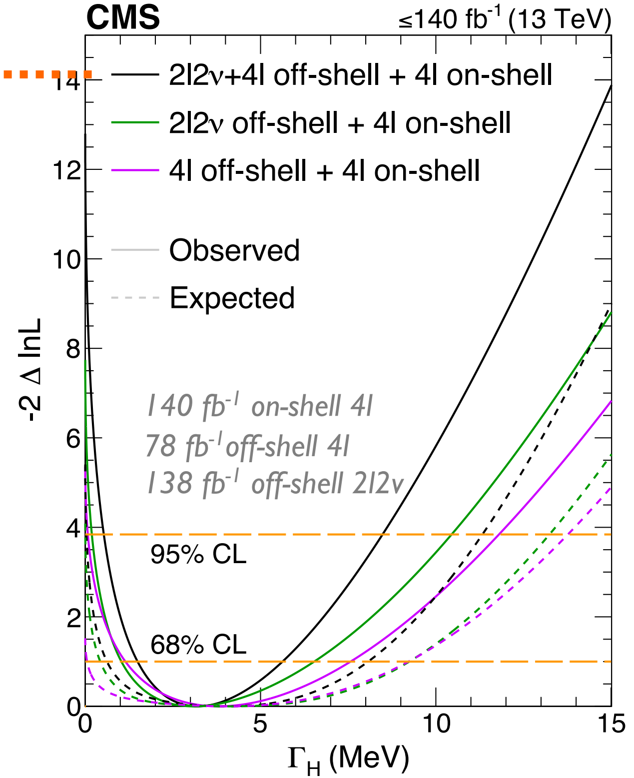
Phys. Lett. B 846 (2023) 138223



CMS
$\Gamma_H = 3.2^{+2.5}_{-1.7}$ MeV

~3 σ evidence for off-shell H production

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

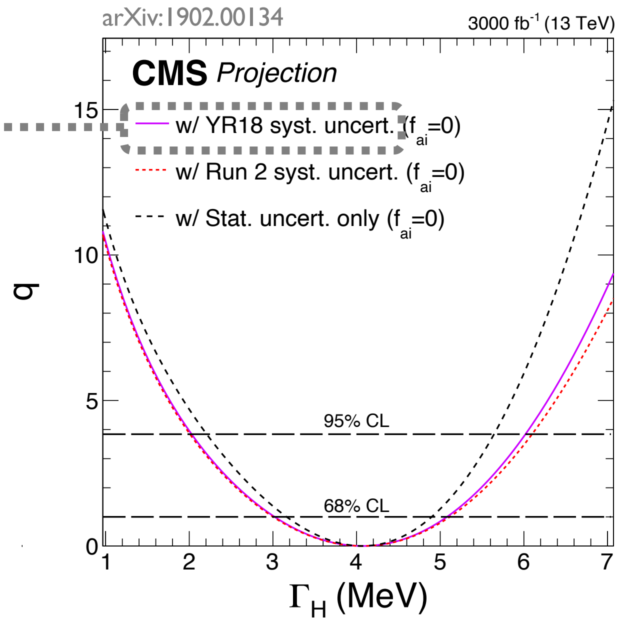


arXiv:2202.06923

How well *will* we know the Higgs width?

- Combined ATLAS + CMS width sensitivity with 3000 fb^{-1}, based on the off-shell measurement
  - ✓ $\Gamma_H = 4.1 \pm$ 0.8 MeV
    - More conservative assumptions on theoretical uncertainties than Run 2 results
      - i.e. signal and background k-factors

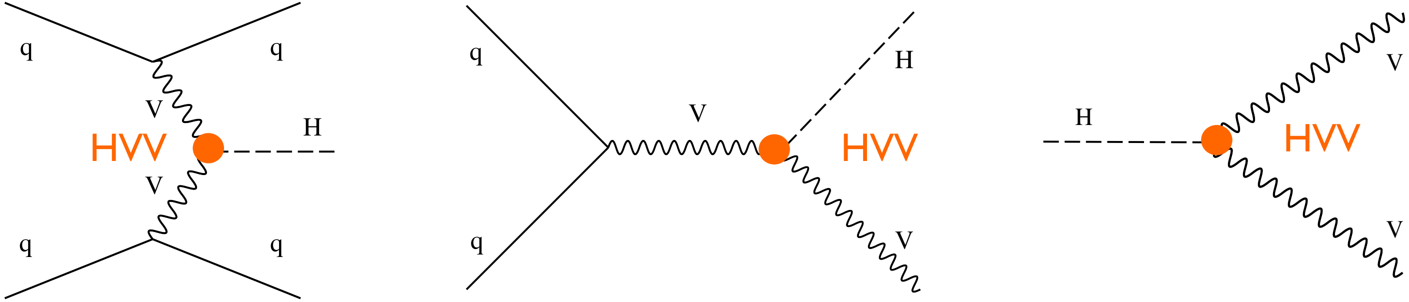
"YR18" systematics: uncertainties reduced wrt Run 2 according to the improvements expected to be reached at the end of HL-LHC e.g. theory uncertainties generally halved. See https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCCommonSystematics



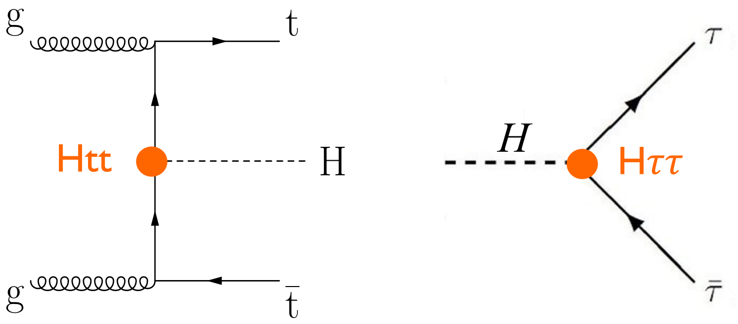
Studies of the Higgs CP properties

Spin is property of the particle, CP of the coupling…

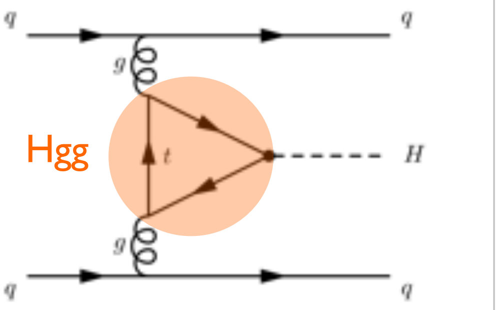
coupling to EW vector bosons



coupling to fermions



coupling to gluons

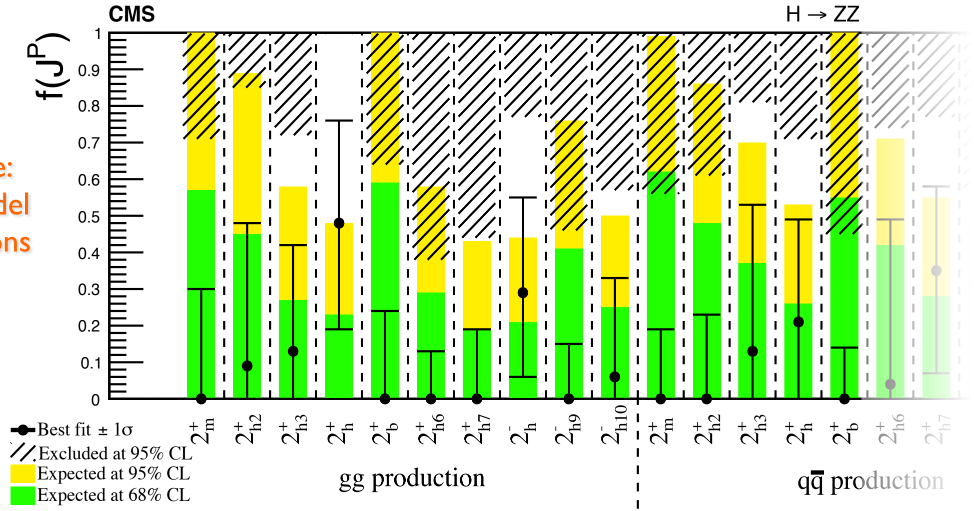


SM Higgs spin and CP properties

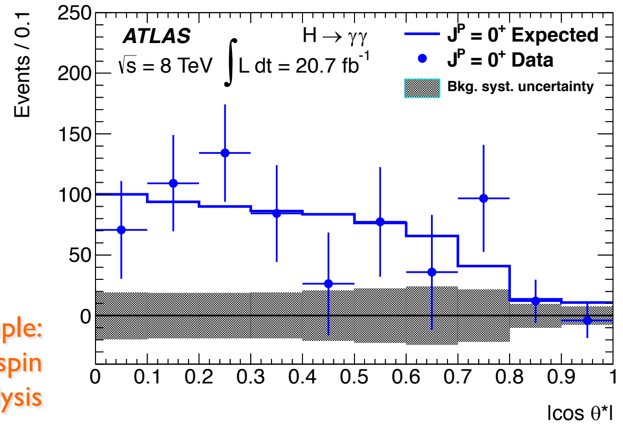
- SM Higgs has spin 0 and positive (even) parity (J^{CP} = 0++)
- At the end of Run 1 we knew Higgs had spin 0…
  - ✓ Spin 1 and 2 hypotheses excluded at > 99.9% CL using H→γγ, H→ZZ* and H→WW*

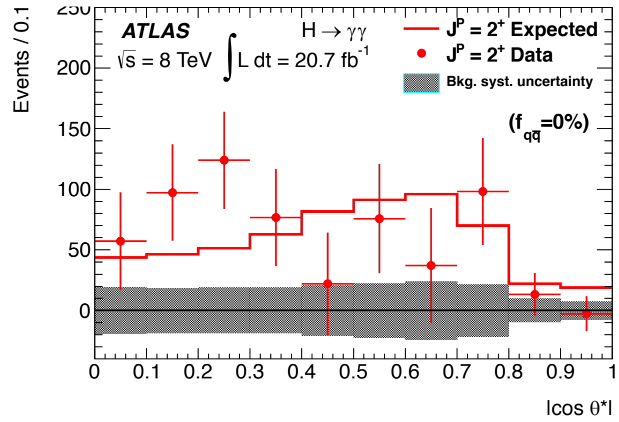
Example: J=2 model exclusions with H→ZZ

Phys. Rev. D 92 (2015) 012004



Example: H→γγ spin analysis



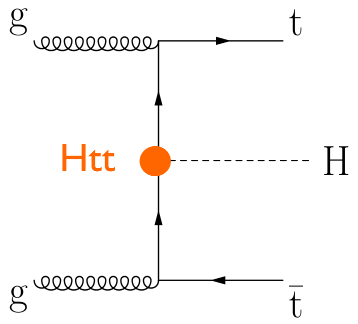


Phys. Lett. B 726 (2013) 120

$$\cos\theta^* = \frac{\sinh(\eta_{\gamma 1} - \eta_{\gamma 2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma 1} p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

γγ polar angle ϑ with respect to Z-axis in Collins-Soper frame*

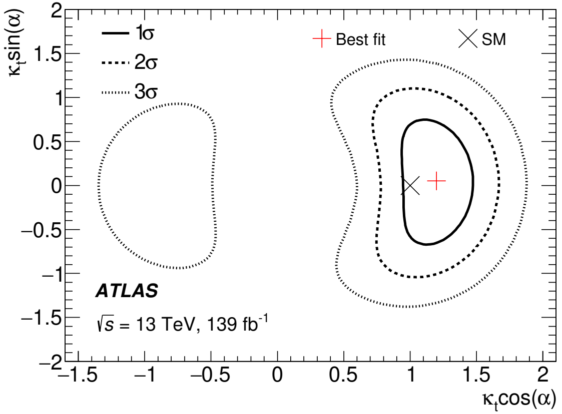
CP properties of Higgs-top coupling with ttH



Effective Lagrangian for Yukawa coupling to top quarks parameterized by CP-Even and CP-odd components

$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

Phys. Rev. Lett. 125 (2020) 061802



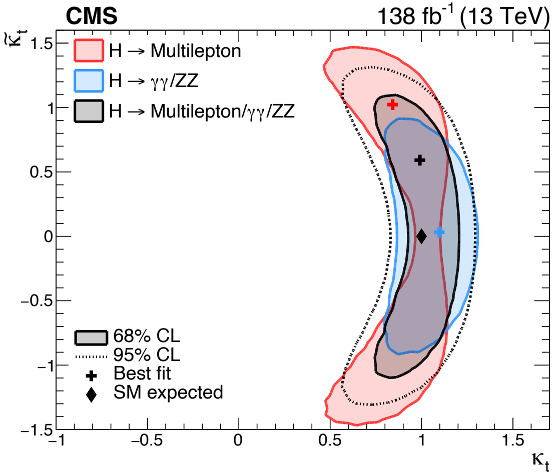
Two examples:

ATLAS ttH
H→γγ

pure CP-odd coupling excluded at 3.9σ

CMS ttH
H→ML
+ H→γγ
+H→ZZ

pure CP-odd coupling excluded at 3.7σ



JHEP 07 (2023) 092

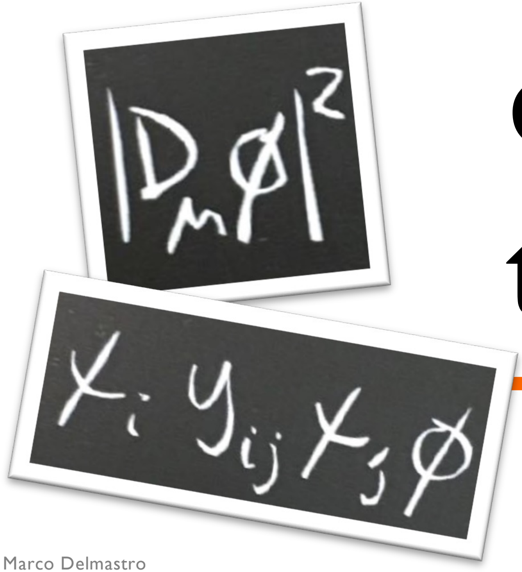
|α| > 43 deg excluded @ 95% CL.

$$f_{CP}^{Htt} = \frac{\tilde{\kappa}_t^2}{\tilde{\kappa}_t^2 + \kappa_t^2} \quad \mathcal{A}(Hff) = \frac{m_f}{v}\bar{\psi}_f(\kappa_t + i\tilde{\kappa}_t\gamma_5)\psi_f$$

$|f_{Htt}| = (\sin\alpha)^2$ $\quad$ $|f_{Htt}| = 0.28$ (< 0.55 at 1σ)

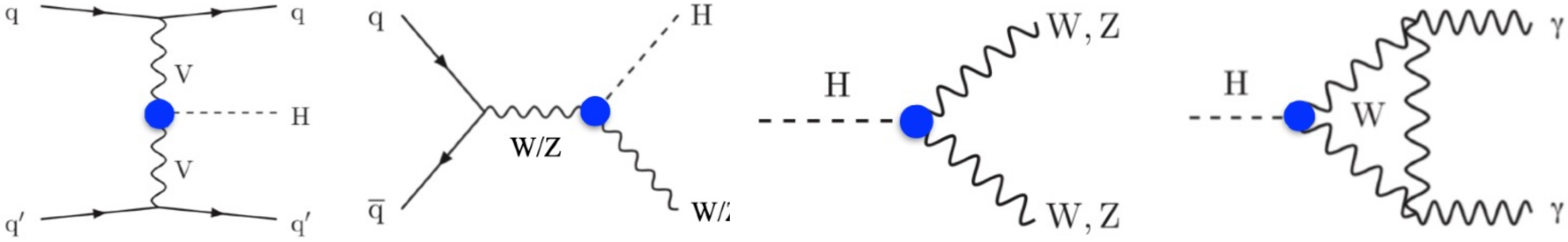
7.

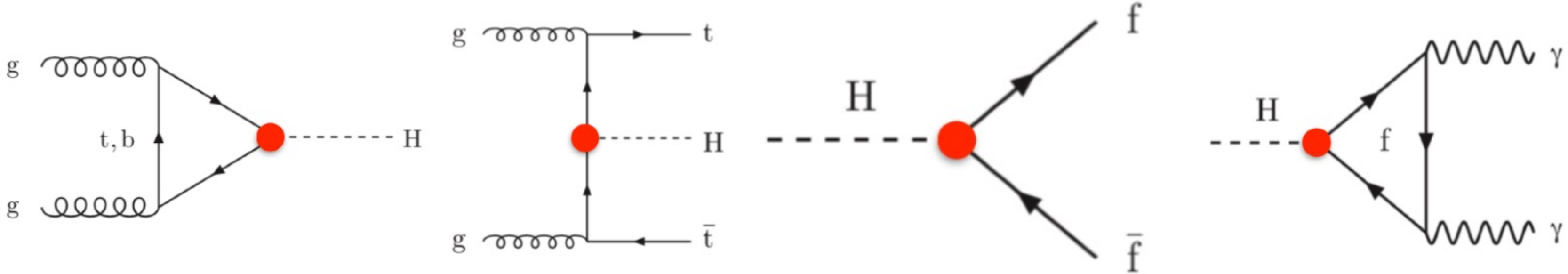
How well do we know the Higgs couplings?



Couplings to…

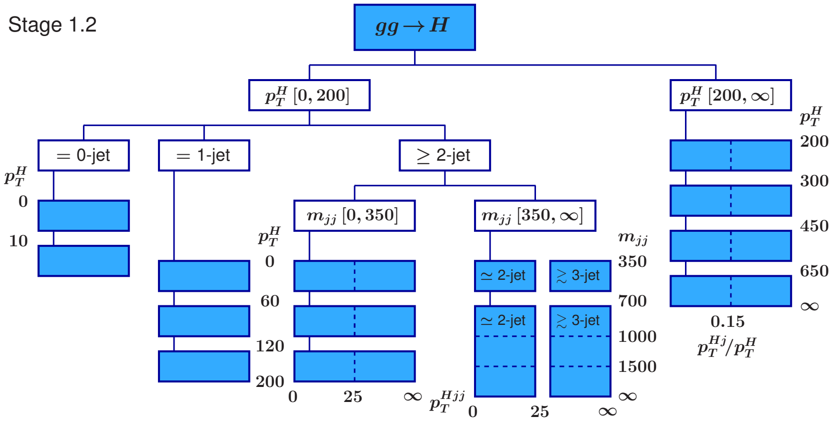
… gauge bosons

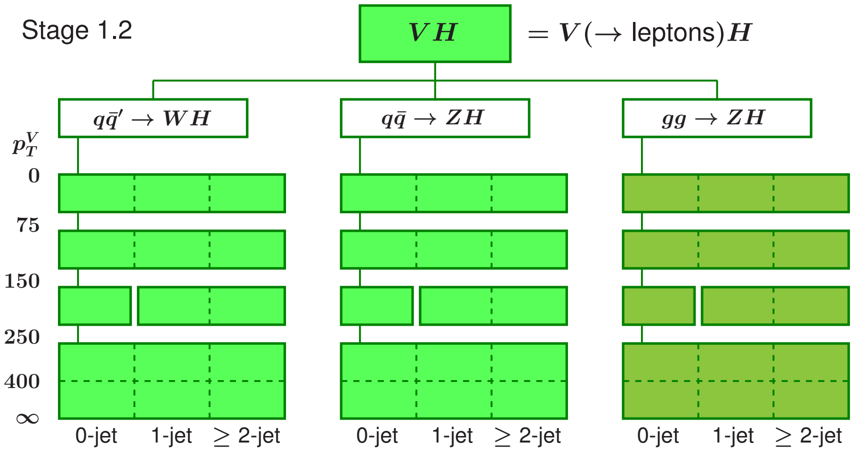


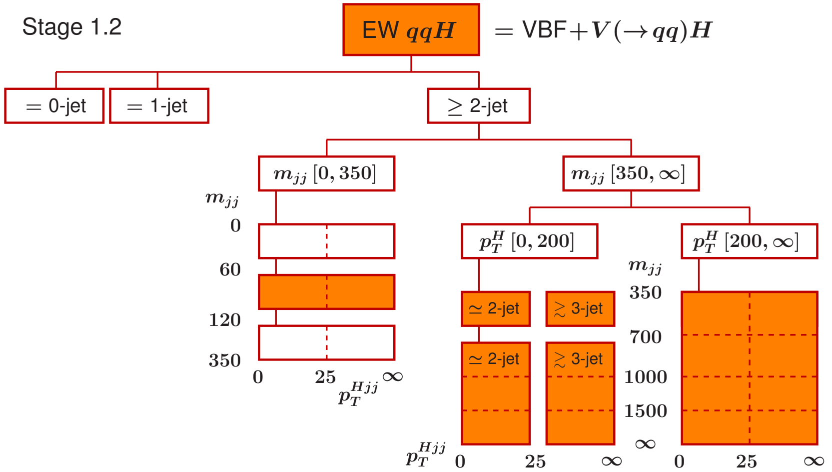


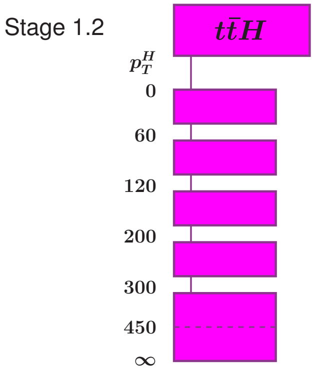
… fermions

STXS: Simplified Template Cross Sections



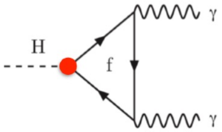




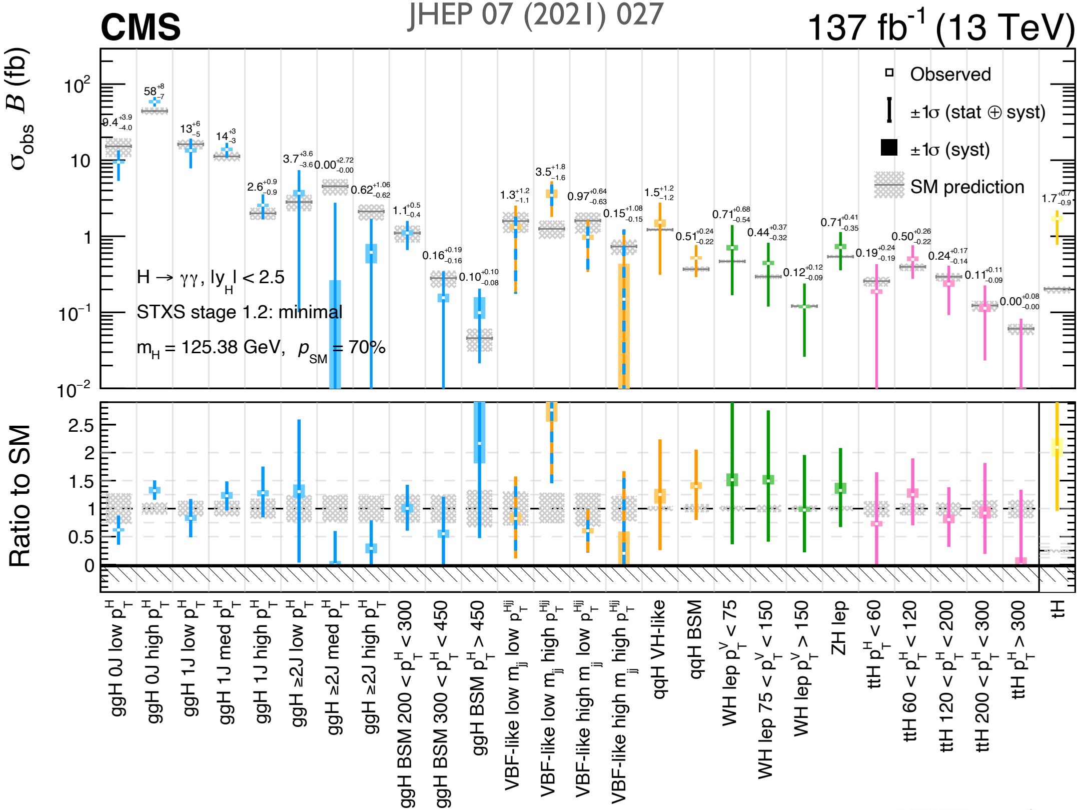


- Cross sections per production mode in different regions of phase space
  - ✓ Reduce dependency on theory
  - ✓ Allow MVA analysis
  - ✓ Exploit sensitivity of each channel specific region of phase space (designed for combination)
  - ✓ Inclusive in decays (for now)
  - ✓ Binning defined to allow better estimate of theoretical uncertainties, and easier merging when insufficient experimental sensitivity
  - ✓ Largely model-independent approach to test for BSM deviations in kinematic distributions

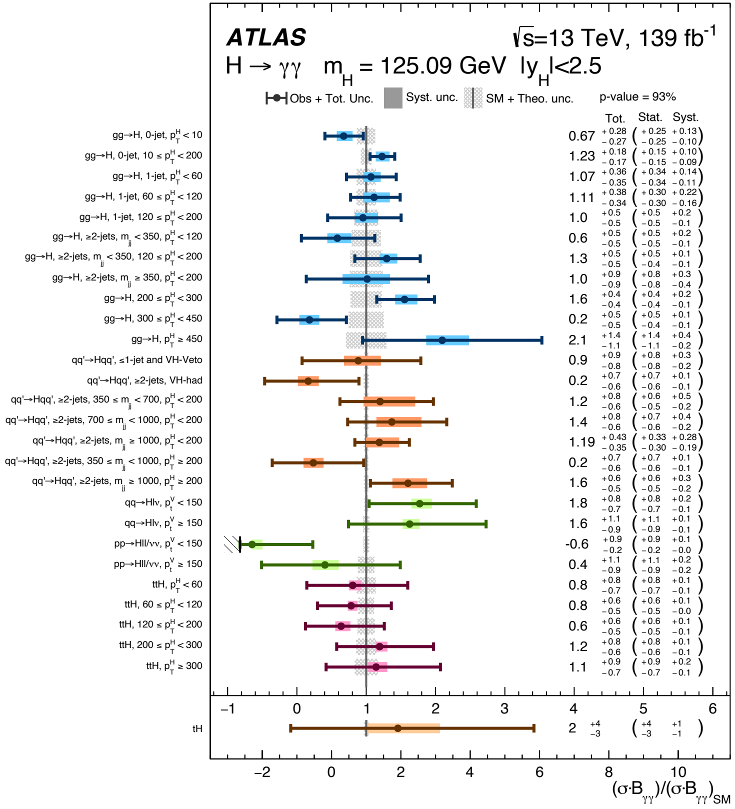
STXS at work: H → $\gamma\gamma$

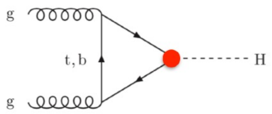


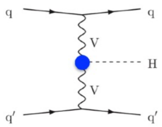
JHEP 07 (2021) 027

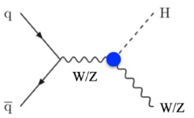


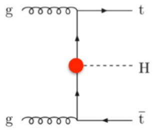
JHEP 07 (2023) 088





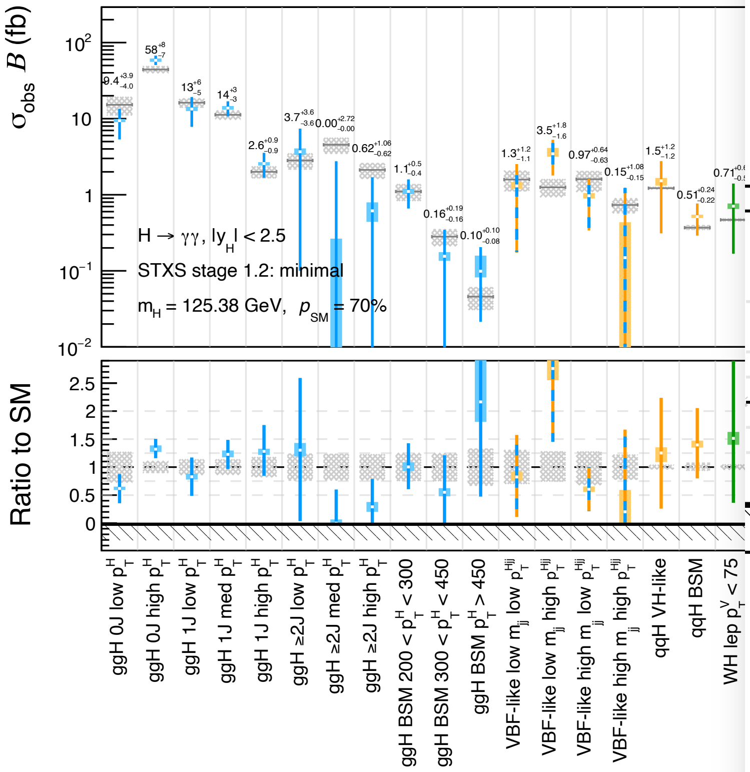


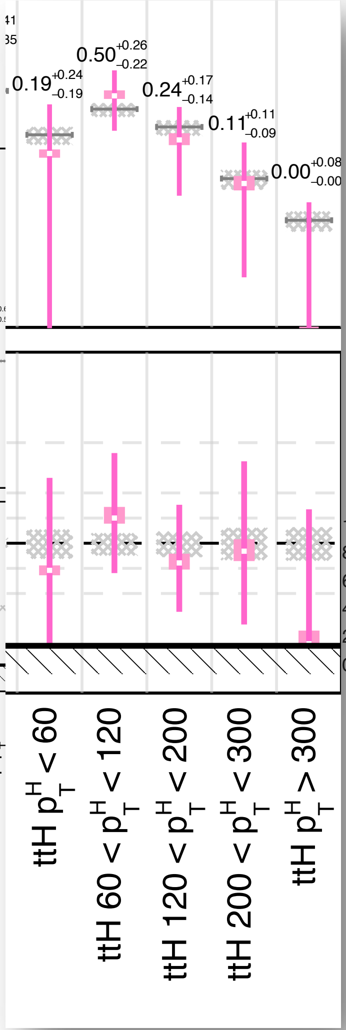


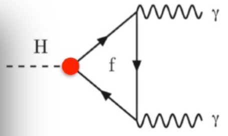


STXS at work: H → $\gamma\gamma$

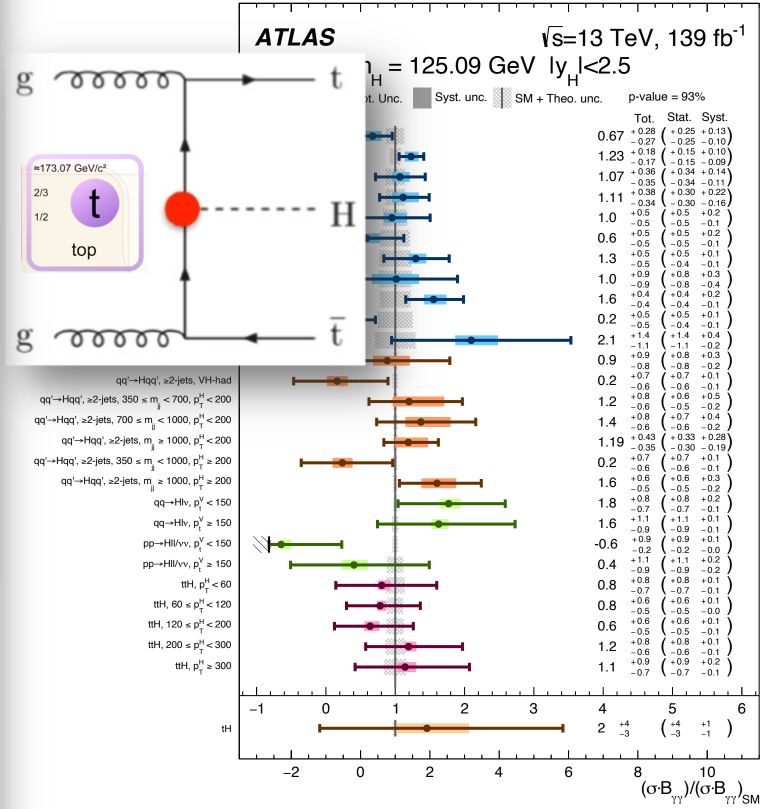
JHEP 07 (2021) 027





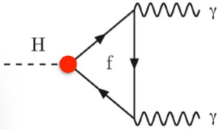


arXiv:2207.00348

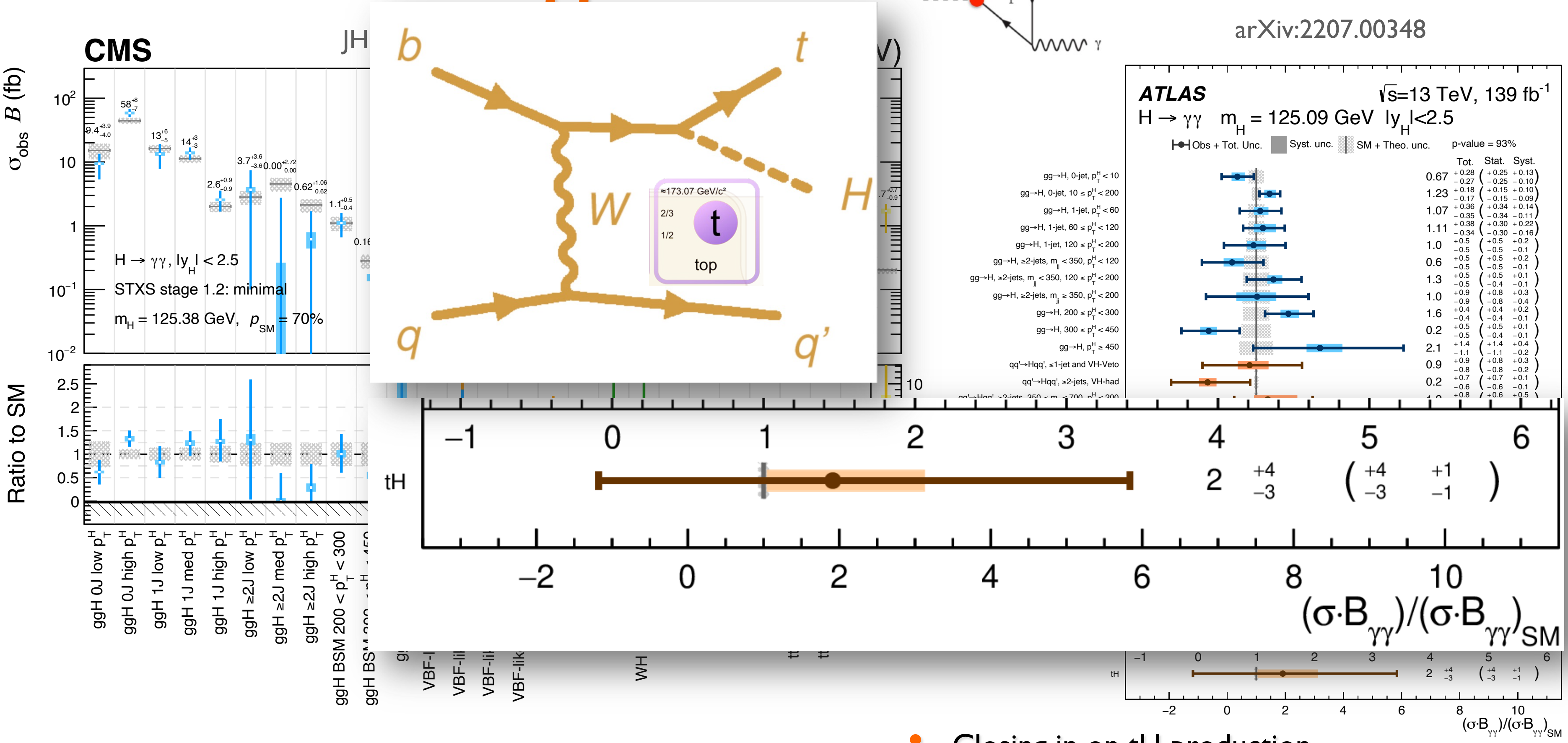


- Differential measurement of p_T^H in ttH

STXS at work: H → $\gamma\gamma$



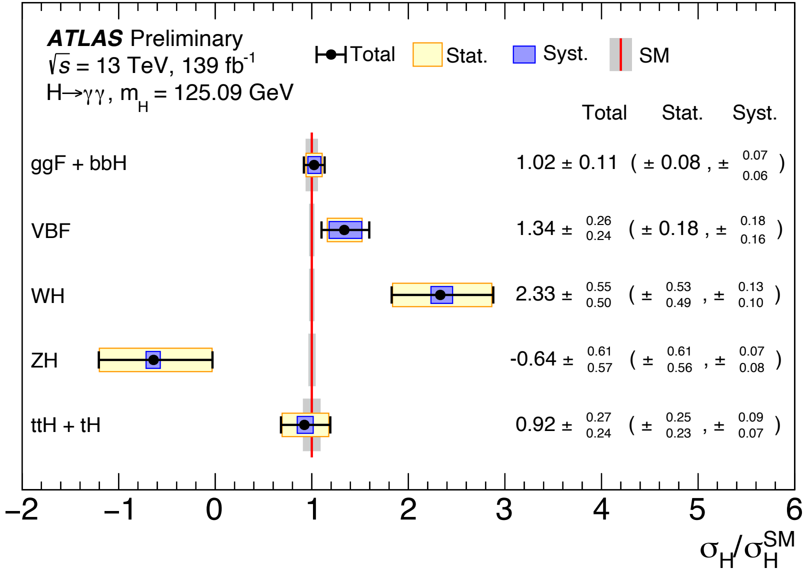
arXiv:2207.00348



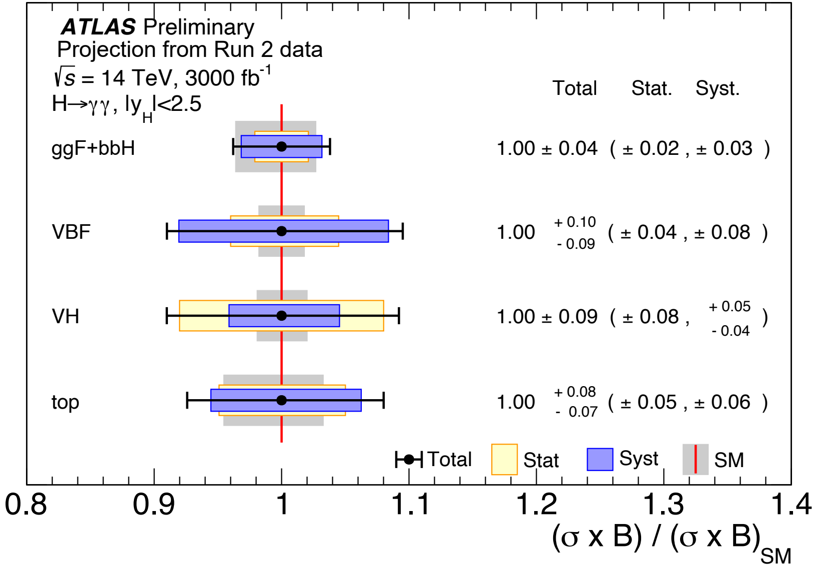
- Closing in on tH production
  - ✓ ~10 × σ_{tH}^{SM} excluded at 95% CL

H → γγ as an example: Run 2 vs HL-LHC

- While STXS measurement remains main current goal, traditional "production-mode" results (a.k.a. "Stage 0" STXS) still measured by more powerful decay channels and in combination
- Already at Run 2 some measurement limited by systematics: more and more true in the future!



ATLAS-CONF-2020-026



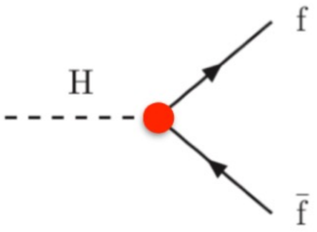
arXiv:1902.00134

8.

zoom on Higgs coupling to fermions

PDG 2012

$b b$	possibly seen
$\tau^+ \tau^-$	possibly seen



PDG 2022

$c\overline{c}$ Final State $= 37 \pm 20$
$b\overline{b} = 0.98 \pm 0.12$
$\mu^+ \mu^- = 1.19 \pm 0.34$
$\tau^+ \tau^- = 1.15^{+0.16}_{-0.15}$
$Z\gamma <$ 3.6, CL $= 95\%$
$\gamma^* \gamma$ Final State $= 1.5 \pm 0.5$
$t\overline{t}H^0$ Production $= 1.10 \pm 0.18$

Why is Yukawa interaction important?

In SM Yukawa interaction between Higgs and fermions gives fermions their mass…

$$m_i = -\frac{y_i \nu}{\sqrt{2}} \qquad \nu = \frac{\mu}{\sqrt{\lambda}}$$

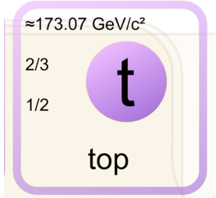
- **Why is *elementary* mass important? Two ideas…**
  - ✓ Mass of quark u and d is responsible for difference of mass between neutron and proton, thus of proton stability, thus of existence of hydrogen atoms…

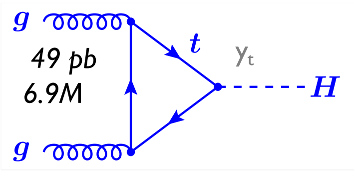
proton (up+up+down): 2.2 + 2.2 + 4.7 + … = 938.3 MeV
neutron (up+down+down): 2.2 + 4.7 + 4.7 + … = 939.6 MeV

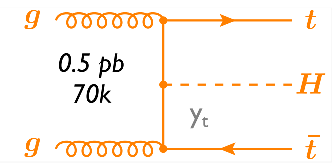
  - ✓ Mass of electron determines Bohr radius, thus dimensions of atoms, thus all chemistry

$$a_0 = \frac{4\pi\varepsilon_0 \hbar^2}{m_e e^2} = \frac{\hbar}{m_e\, c\, \alpha}$$

Coupling to top quark: direct observation of ttH in 2018!

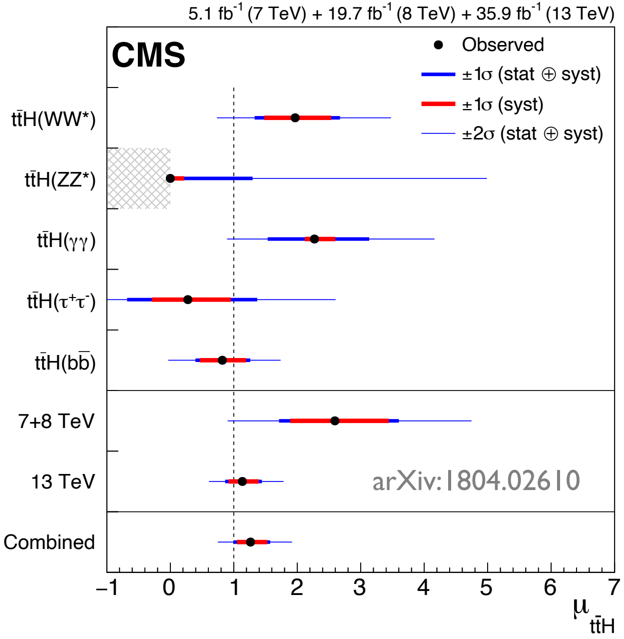


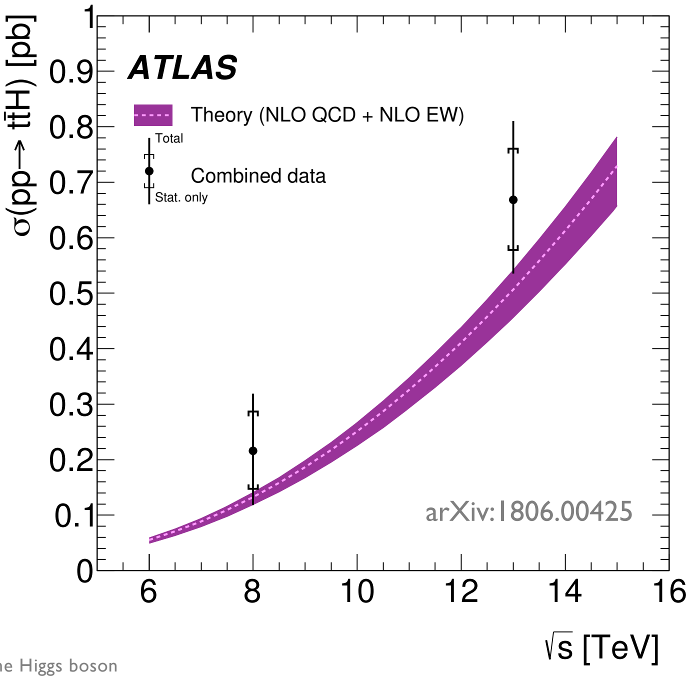


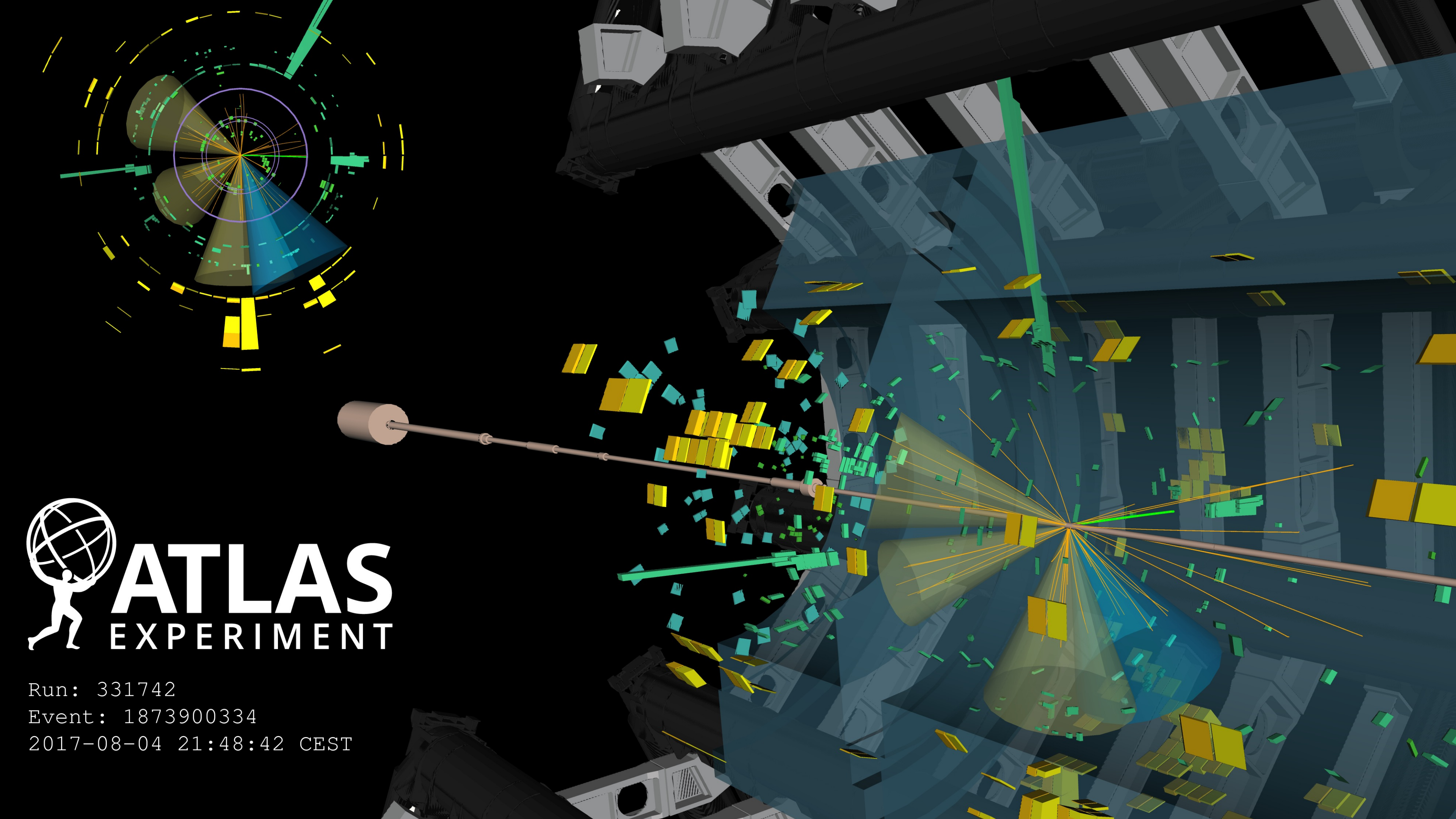


CMS (Run 1 + 36 fb^{-1} Run 2): 5.2 σ (4.2 σ exp)

ATLAS: (Run 1 + 36-80 fb-1 Run 2): 6.3 σ (5.1 σ exp)



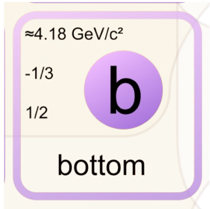


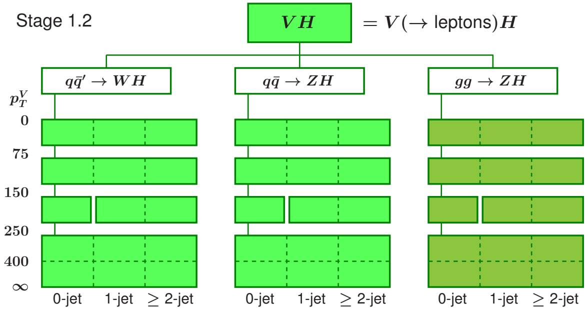

ATLAS
EXPERIMENT
Run: 331742
Event: 1873900334
2017-08-04 21:48:42 CEST

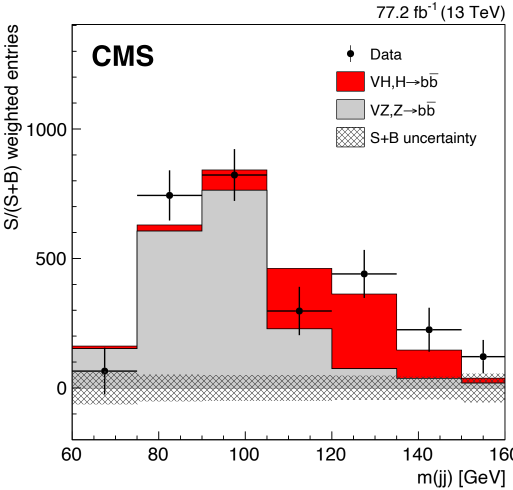
Coupling to bottom quark: observation of VH/H→bb in 2018!

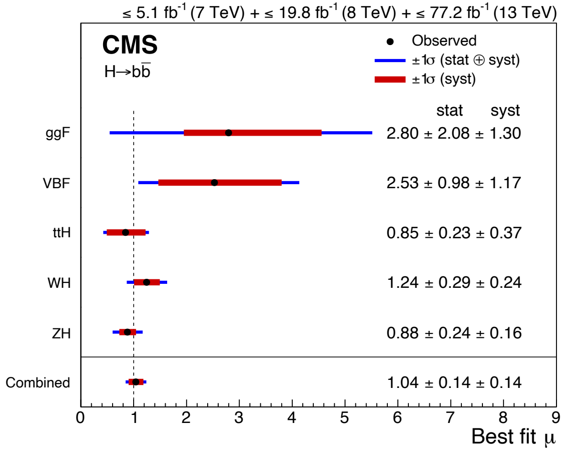
- Difficult channel despite large BR(58%) due to large backgrounds
  - ✓ VH production most sensitive → Observation in 2018!
    - ATLAS: 5.4σ (5.5σ)
    - CMS: 5.5σ (5.6σ)

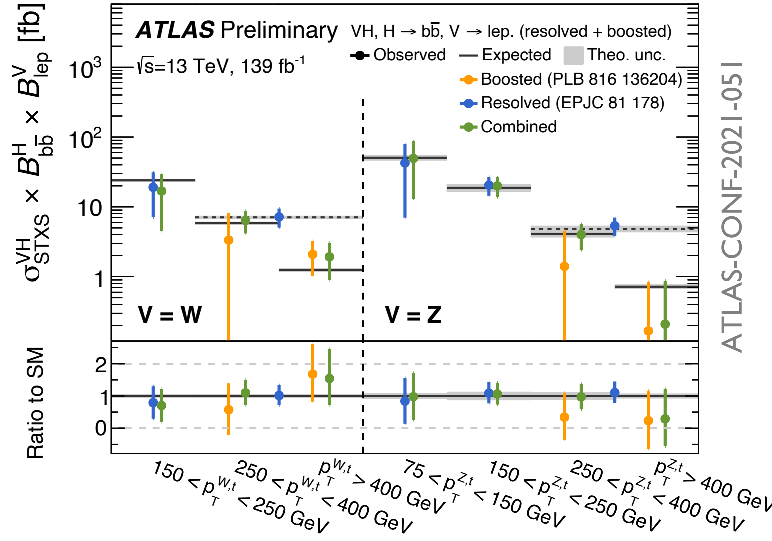
ATLAS: arXiv:1808.08238
CMS: arXiv:1808.08242







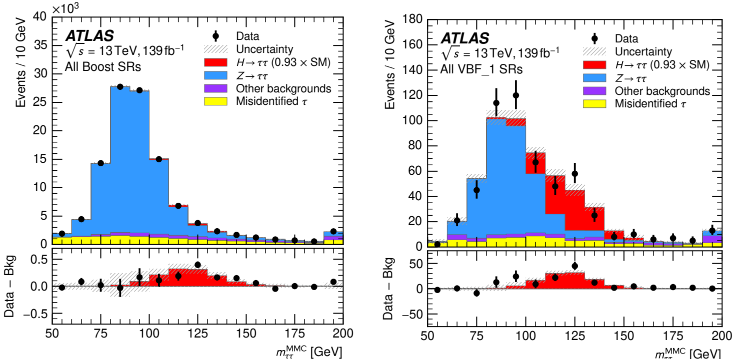




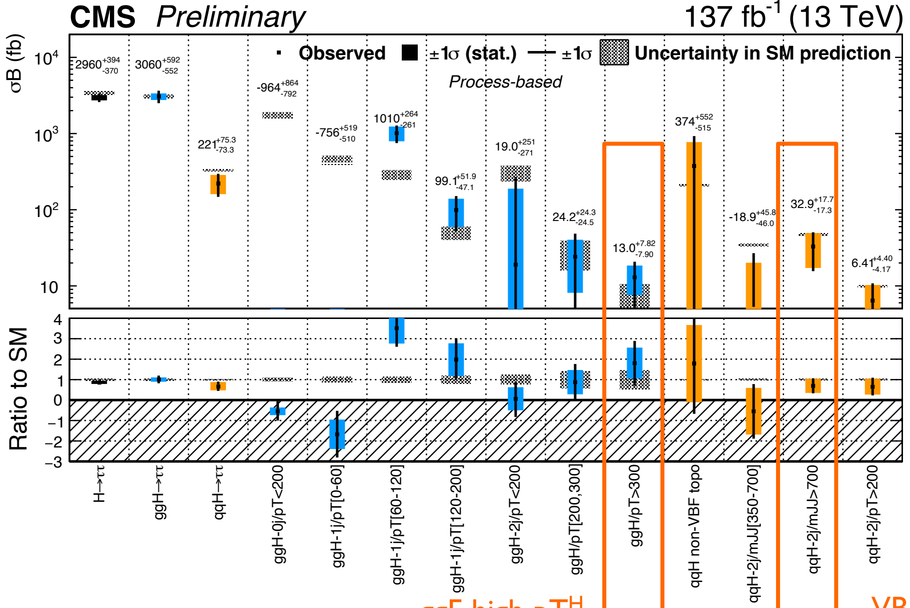
Coupling to 3rd generation leptons: H→ττ

JHEP 08 (2022) 175

- Observation already in Run 1 ATLAS+CMS coupling combination
- Now more precise measurements, bringing sensitivity to regions of the phase space less well measured by e.g. $H \to \gamma\gamma$ and $H \to 4l$
  - ✓ i.e. ggF high p_T^H and especially VBF

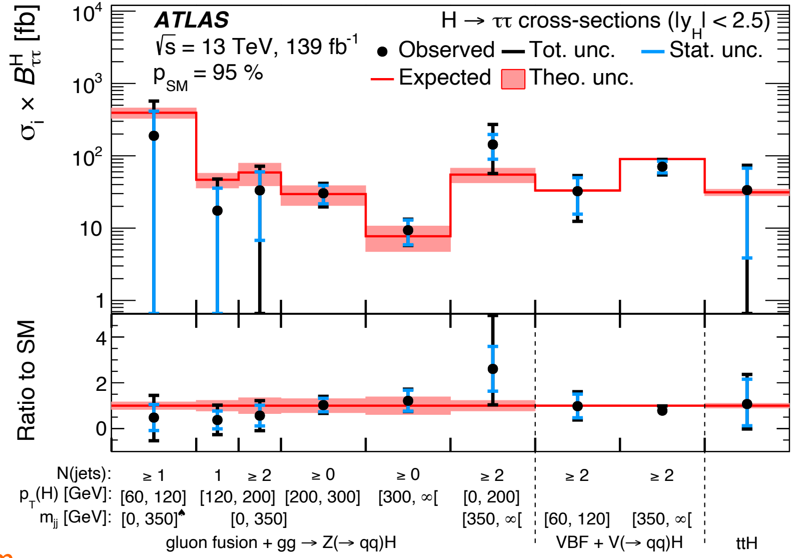


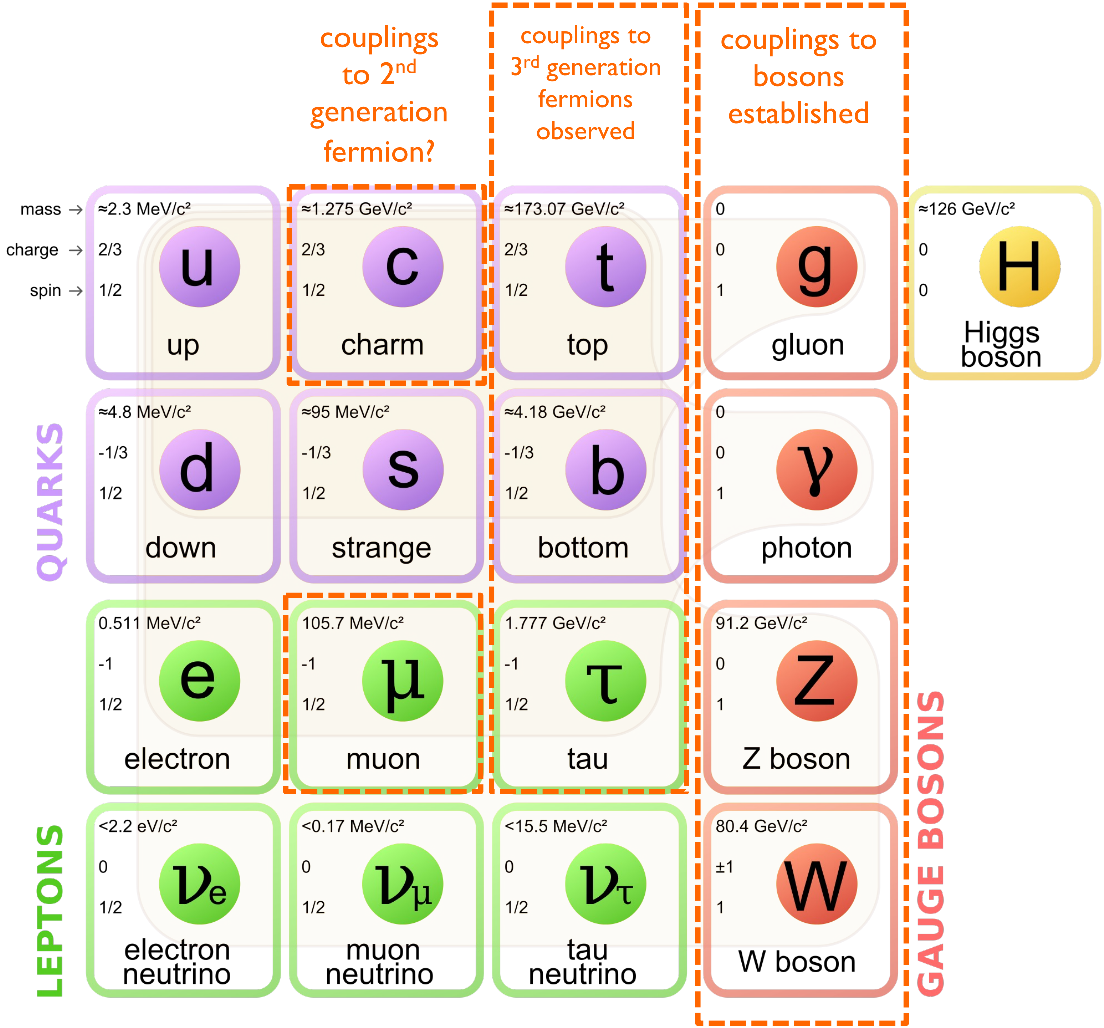
CMS-PAS-HIG-19-010



ggF high p_T^H

VBF high m_{jj}



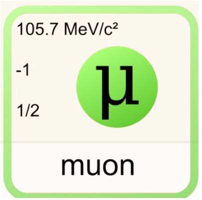


Is the Higgs boson responsible for the EW symmetry breaking also responsible for the masses of fermions?

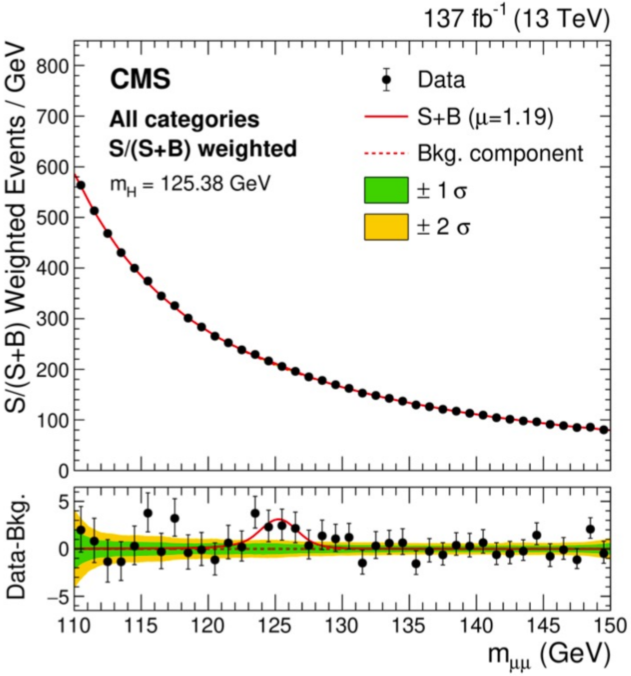
Is the Higgs boson responsible for the masses of all fermions?

Coupling to 2nd generation leptons: H→μμ evidence in 2020!

- H→μμ very rare (BR ~ 2 10^{-4}) with large resonant background from DY→ μμ (S/B ~ 0.1%)



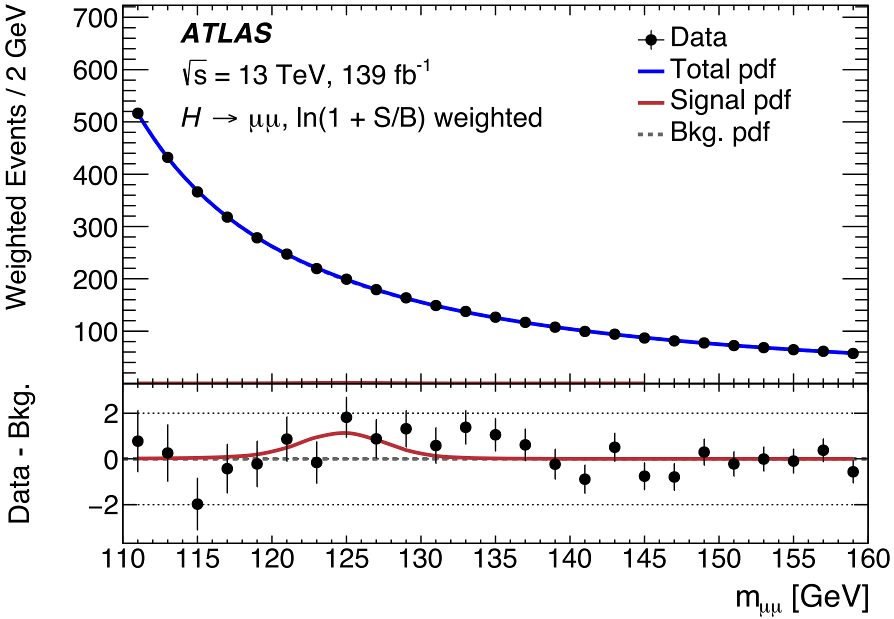
JHEP 01 (2021) 148



μ = 1.2 ± 0.2

Significance: 3.0 σ (2.5 expected)

PLB 812(2021) 135980



μ = 1.2 ± 0.6

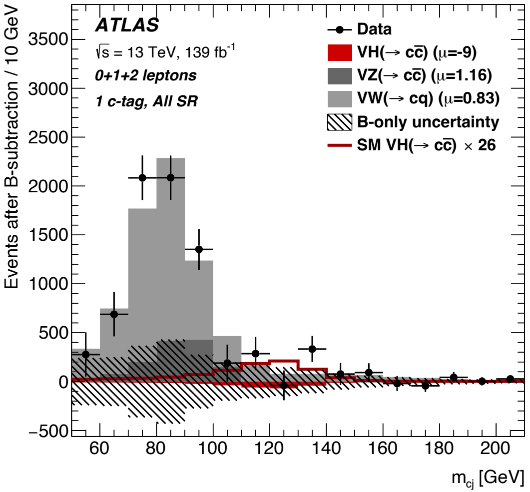
Significance: 2.0 σ (1.7 expected)

The next frontier: coupling to 2nd generation quarks H→cc

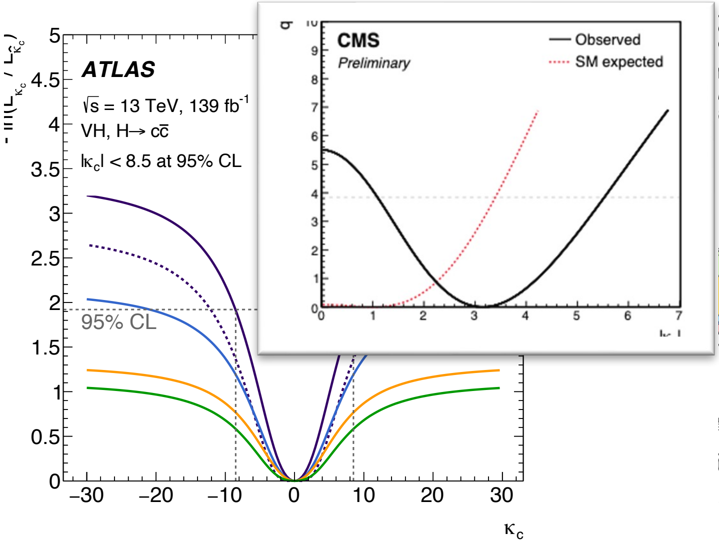
- Very challenging channel: large backgrounds from multi-jets
  - ✓ c-tagging needed to discriminate H → bb

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

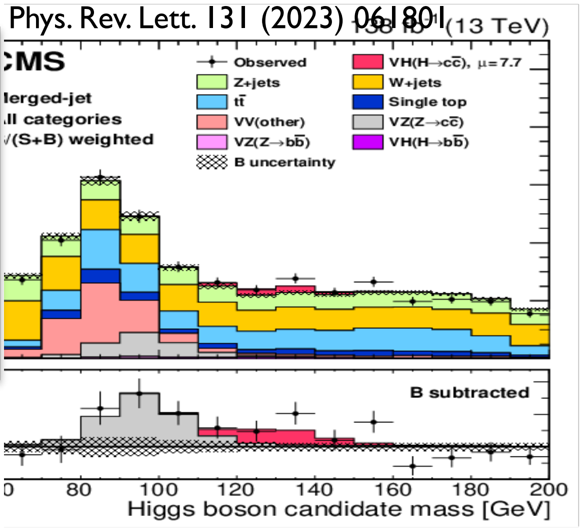
Eur. Phys. J. C 82 (2022) 717



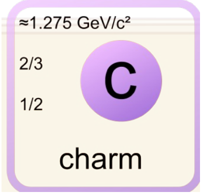
VZ,VW: 3.8 σ for VW(→cq)



Phys. Rev. Lett. 131 (2023) 061801



Z→cc: 5.7 σ

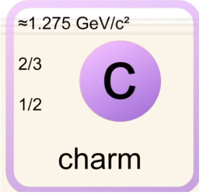


limits on κ_c coupling

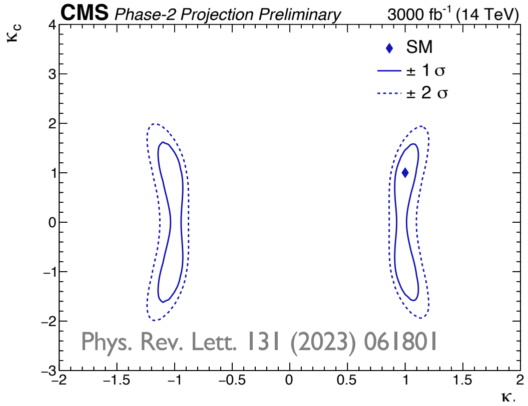
ATLAS: $\kappa_c = \sigma/\sigma_{SM} < 8.5$ (12.4 exp.)

CMS: $1.1 < \kappa_c < 5.5$ (< 3.4 exp.)

Will we observe H→cc in the future?



- Extrapolations to HL-LHC luminosity
  - ✓ Sensitivity to k_c (and k_b) from ATLAS VH/H→cc and VH/H→bb analyses Sensitivity to k_c and k_b from CMS p_T^H differential measurements



Phys. Rev. Lett. 131 (2023) 061801

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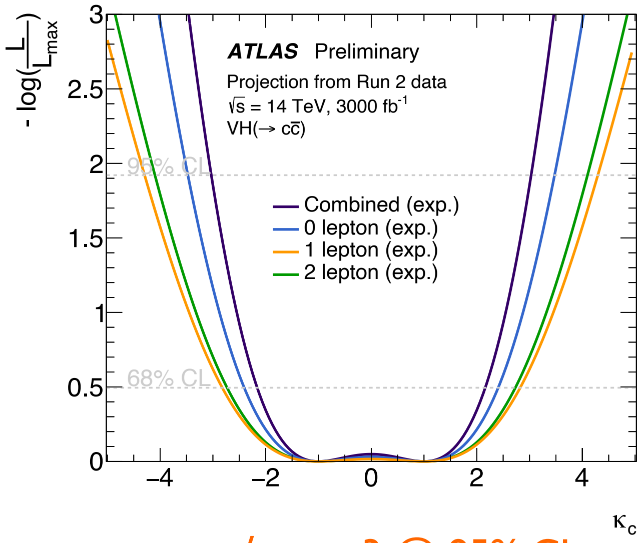
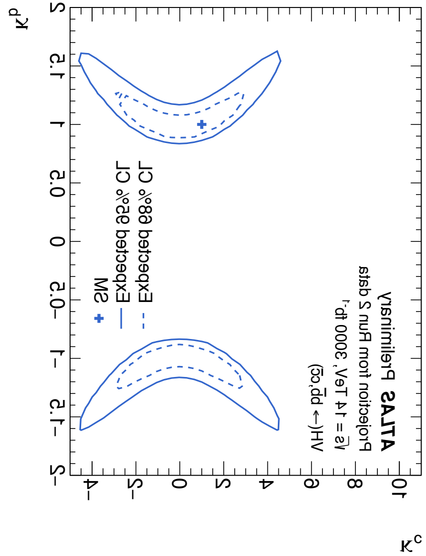
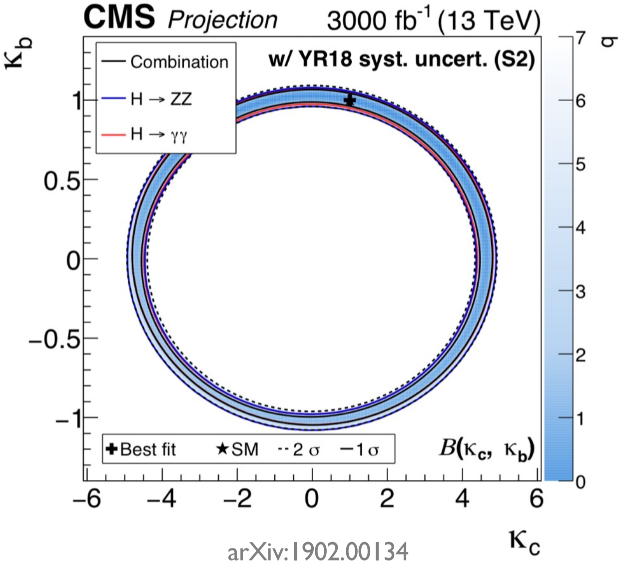


$\kappa_c = \sigma/\sigma_{SM} < 3$ @ 95% CL





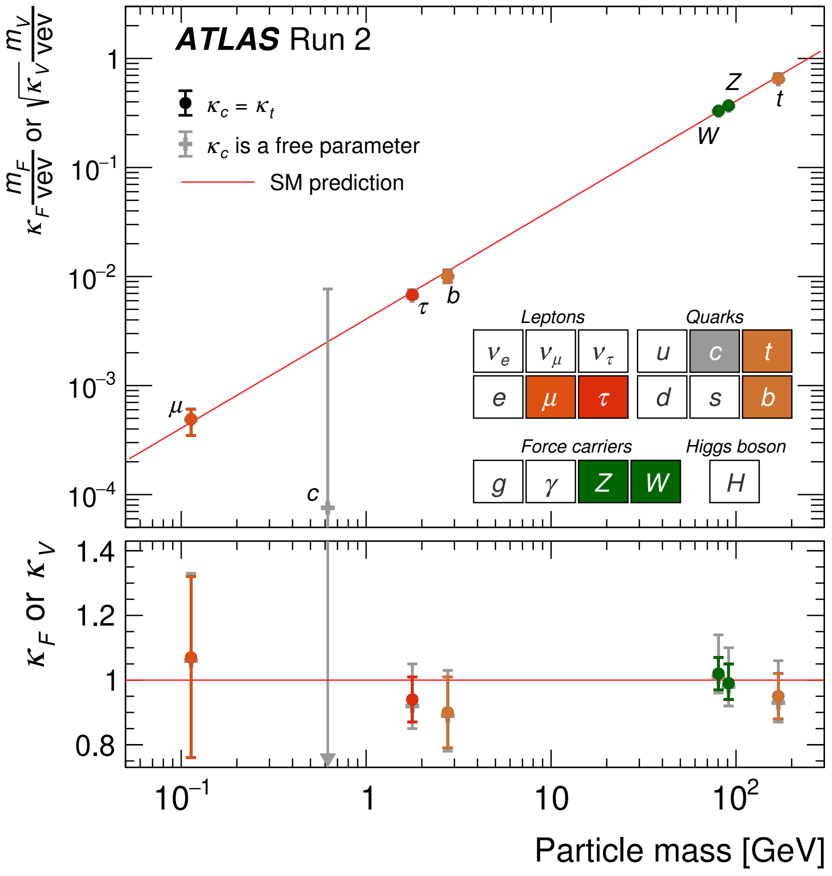
arXiv:1902.00134

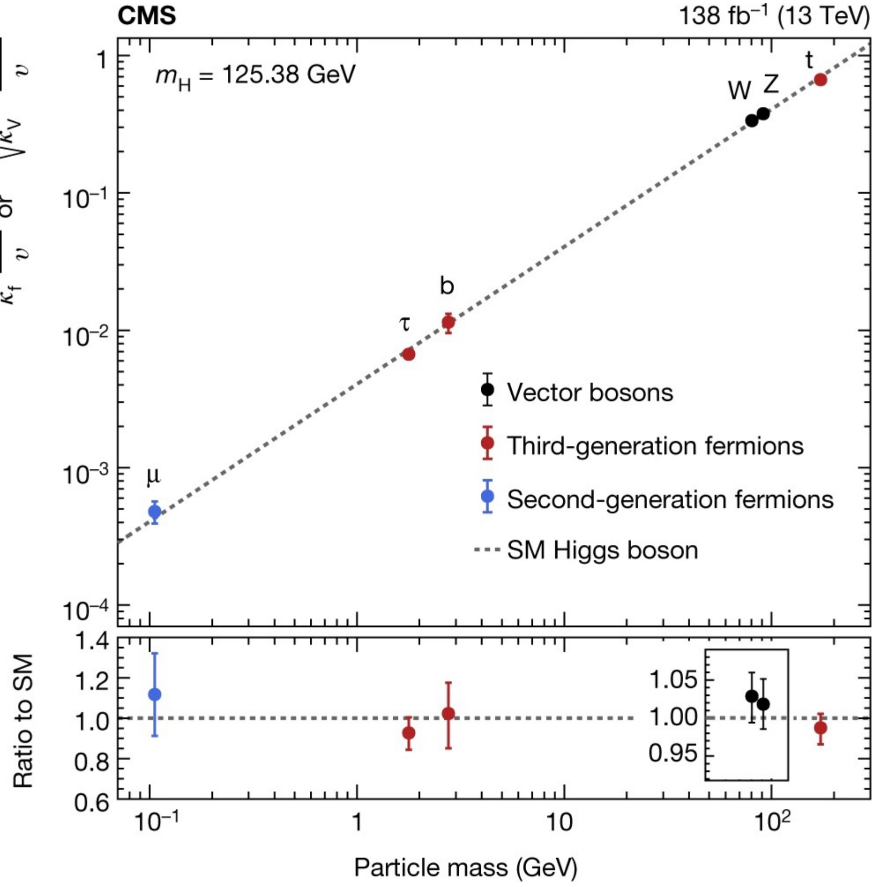
9.

One for all,
all for one!

The Standard Model rules (over 3 order of magnitudes)!

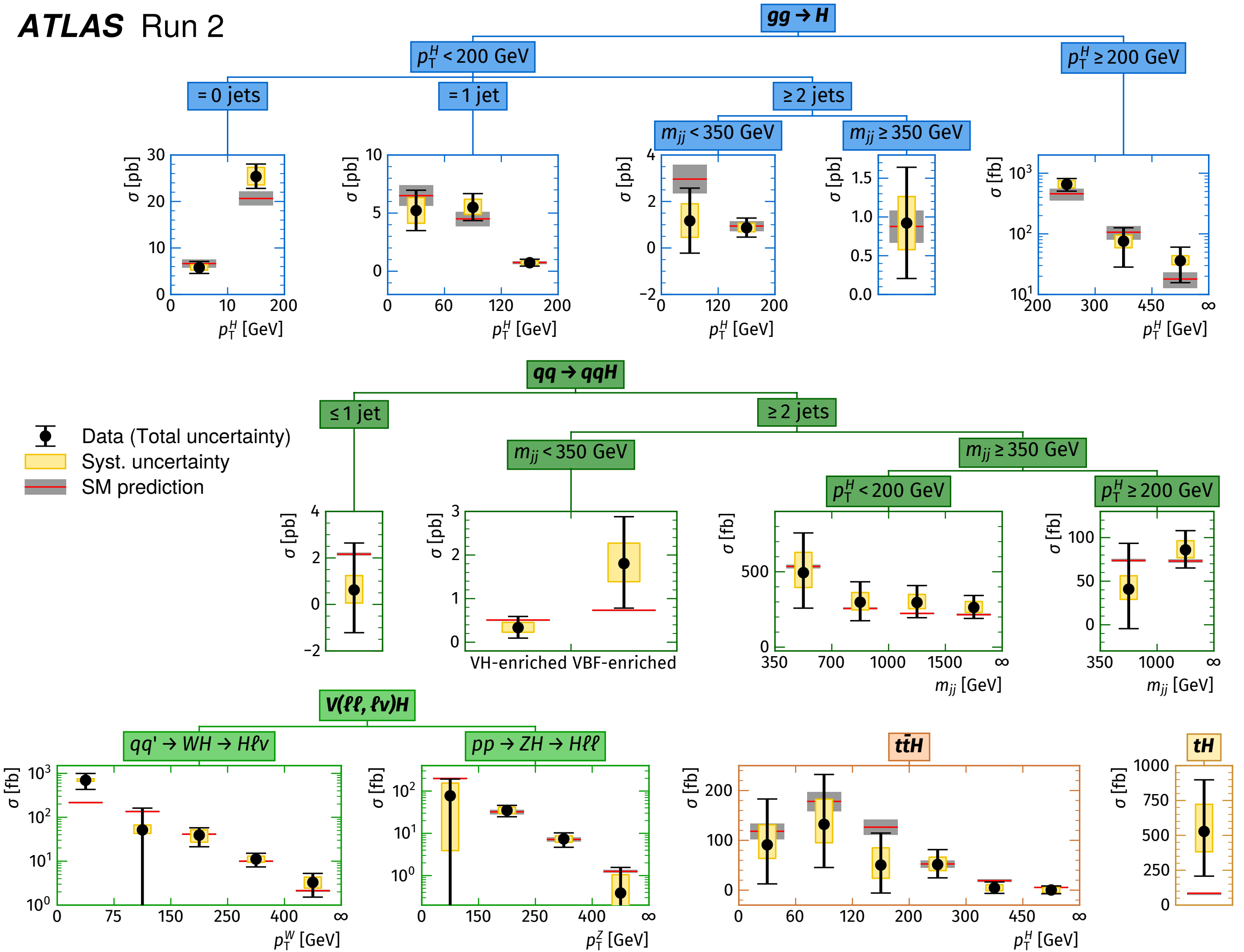
Nature 607 (2022) 52





Nature 607 (2022) 60

Nature 607 (2022) 52

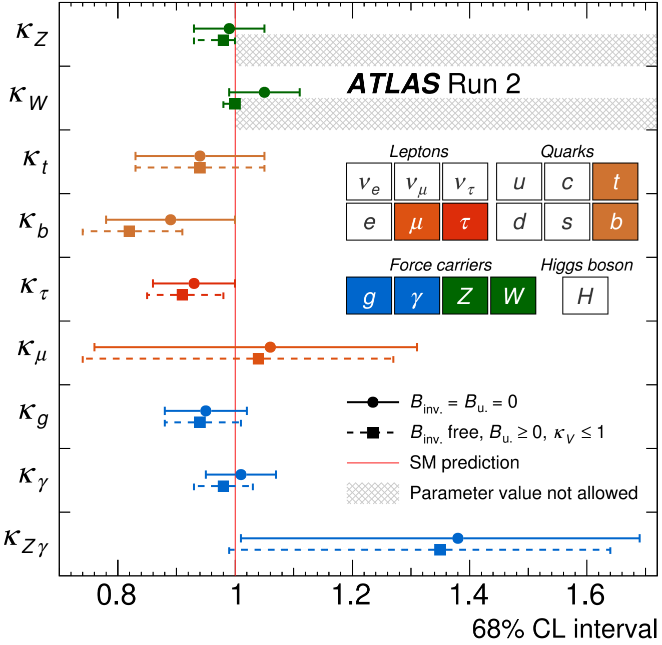


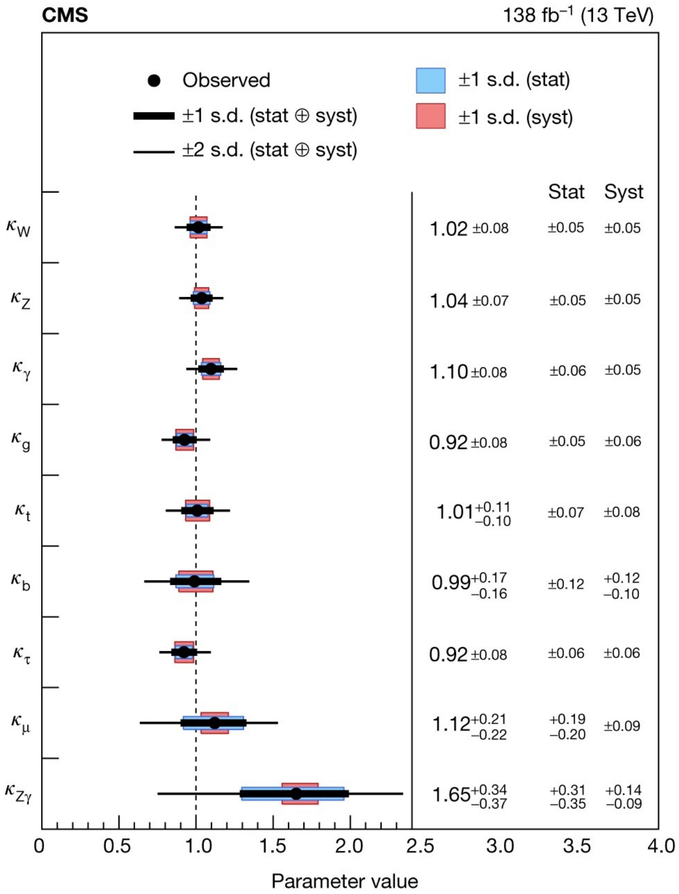
How well do we know the Higgs couplings?

- **Higgs couplings known to ~6-15%**
  - ✓ Some channel not included yet, or with partial statistics
  - ✓ Expect more improvements in next ~2 years, also from ATLAS+CMS combination

$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}}$$

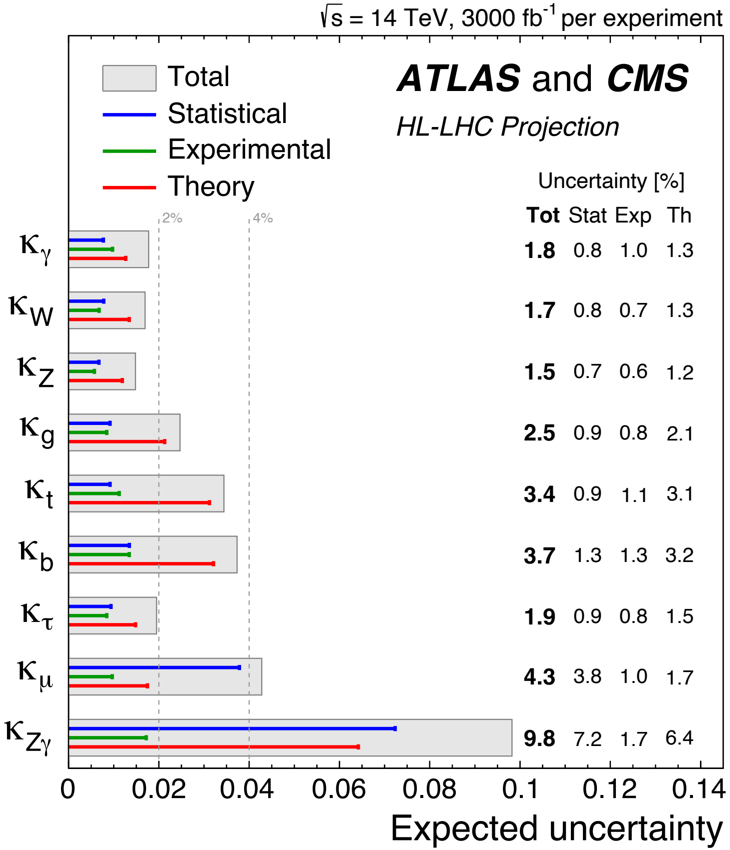
$$\kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}$$





How well *will* we know the Higgs couplings?

- **2-4% precision** expected with 2 x 3000 fb^{-1}



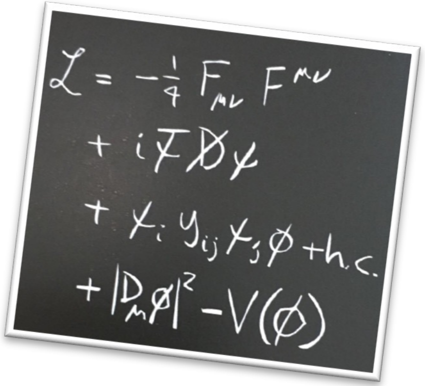
arXiv:1902.00134

10.

Can the Higgs boson tell us something about new phenomena?

Can Higgs properties constrain BSM phenomena *today*?

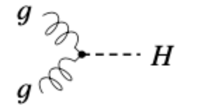
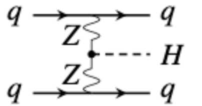
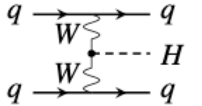
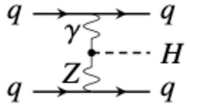
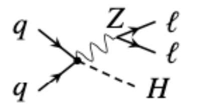
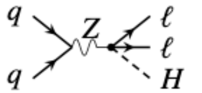
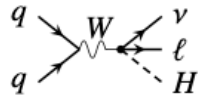
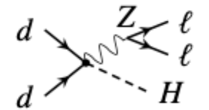
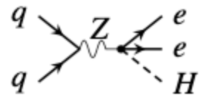
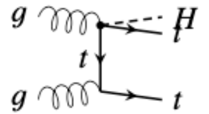
- Most recent approach: Effective Field Theory (EFT) interpretation



$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_i}{\Lambda^4} O_i^{(8)} + \ldots,$$

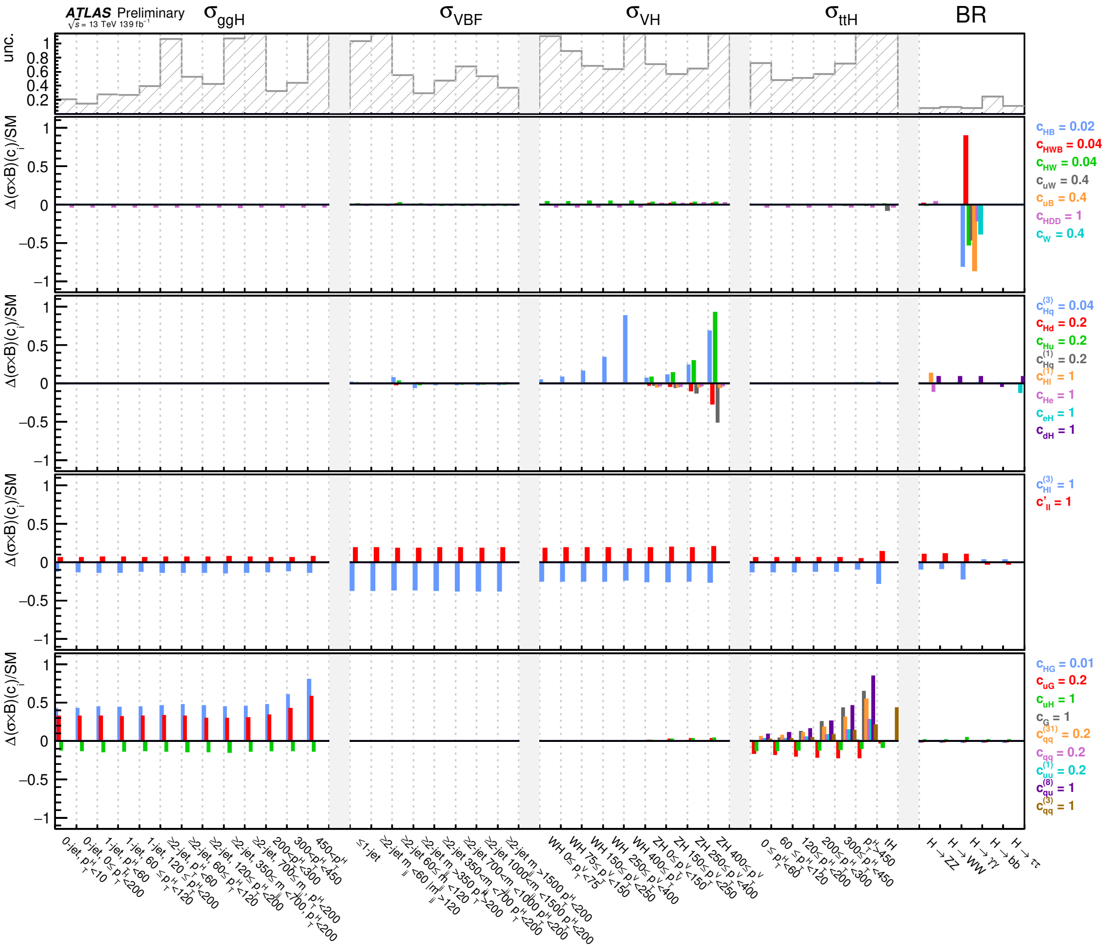
- $O_i^{(n)}$ affect rates and kinematics
- STXS measurements and Higgs BR reparametrized in terms of dimension-six Wilson coefficients c_i in Warsaw basis
  - ✓ Correction for modified acceptance in $H \rightarrow 4l$ and $H \rightarrow l\nu l\nu$
  - ✓ U(3)5 flavor symmetry assumed, linearized in Wilson coefficients contribution (linear contribution $\propto \Lambda^{-2}$, expected to be leading)

Can Higgs properties constrain BSM phenomena today?

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}	$(i\Phi^\dagger\overleftrightarrow{D}_\mu\Phi)(\bar{\ell}\gamma^\mu \ell)$	
c_{Hq3}	$(i\Phi^\dagger\overleftrightarrow{D}^I_\mu\Phi)(\bar{q}\sigma^I\gamma^\mu q)$	
c_{Hl3}	$(i\Phi^\dagger\overleftrightarrow{D}^I_\mu\Phi)(\bar{\ell}\sigma^I\gamma^\mu \ell)$	
c_{Hu}	$(i\Phi^\dagger\overleftrightarrow{D}^I_\mu\Phi)(\bar{u}\gamma^\mu u)$	
c_{Hd}	$(i\Phi^\dagger\overleftrightarrow{D}^I_\mu\Phi)(\bar{d}\gamma^\mu d)$	
c_{He}	$(i\Phi^\dagger\overleftrightarrow{D}_\mu\Phi)(\bar{e}\gamma^\mu e)$	
$\lvert c_{uG}\rvert$	$(\bar{q}\sigma^{\mu\nu}T^a\tilde{\Phi}u)G^a_{\mu\nu}$	
$\lvert c_{eH}\rvert$	$(\Phi^\dagger\Phi)(\bar{\ell}e\Phi)$	
$\lvert c_{dH}\rvert$	$(\Phi^\dagger\Phi)(\bar{q}d\Phi)$	

EFT interpretation of Higgs couplings: c_i impact

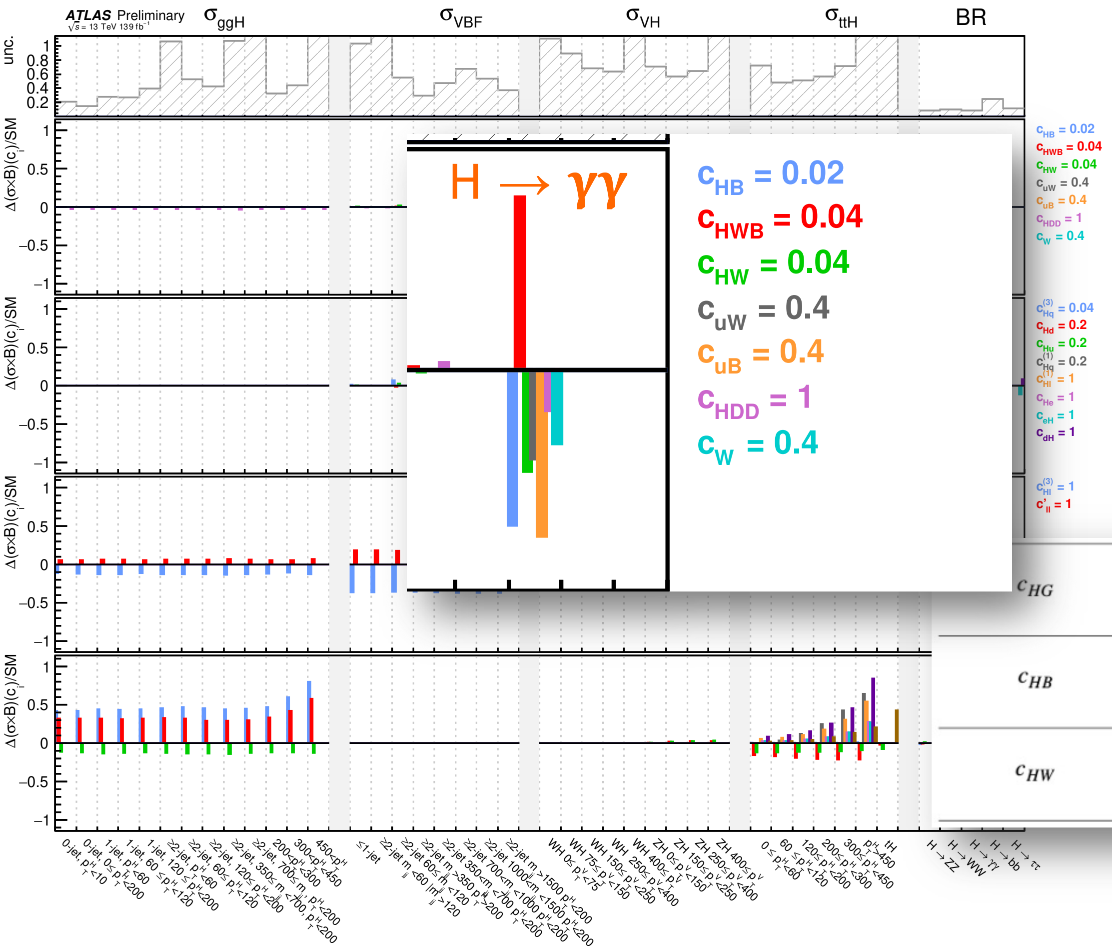
Measurement uncertainty in STXS bin / decay channel



Relative effect of relevant operators

EFT interpretation of Higgs couplings: c_i impact

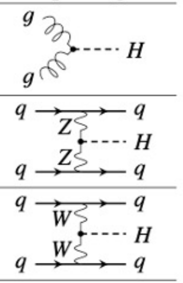
Measurement uncertainty in STXS bin / decay channel



Relative effect of relevant operators

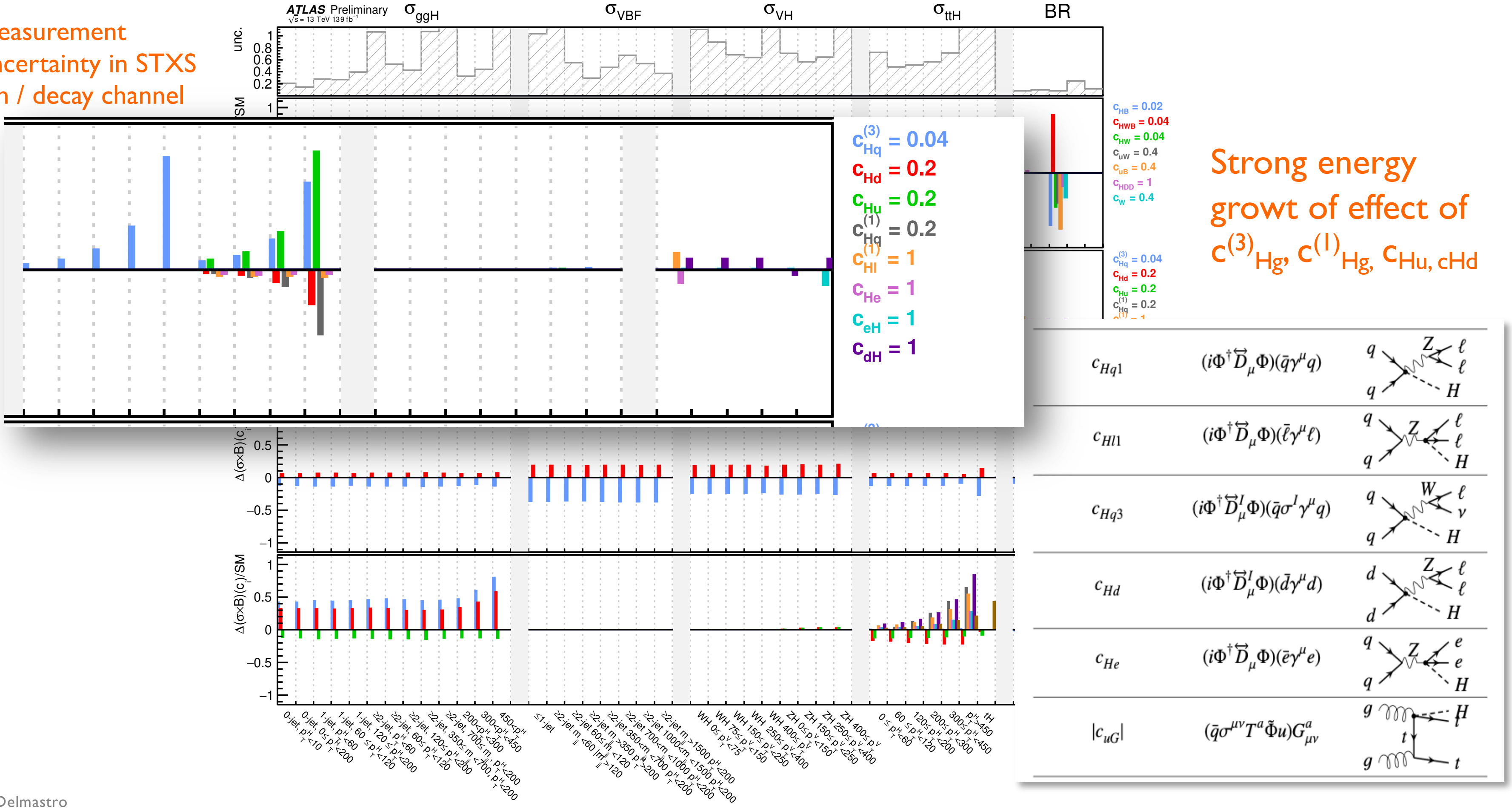
O(1) effects for small values of c_{HB}, c_{HW}, c_{HWB} (tree level $H \to \gamma\gamma$)

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}	$\Phi^\dagger\Phi W^I_{\mu\nu}W^{I\mu\nu}$	



EFT interpretation of Higgs couplings: c_i impact

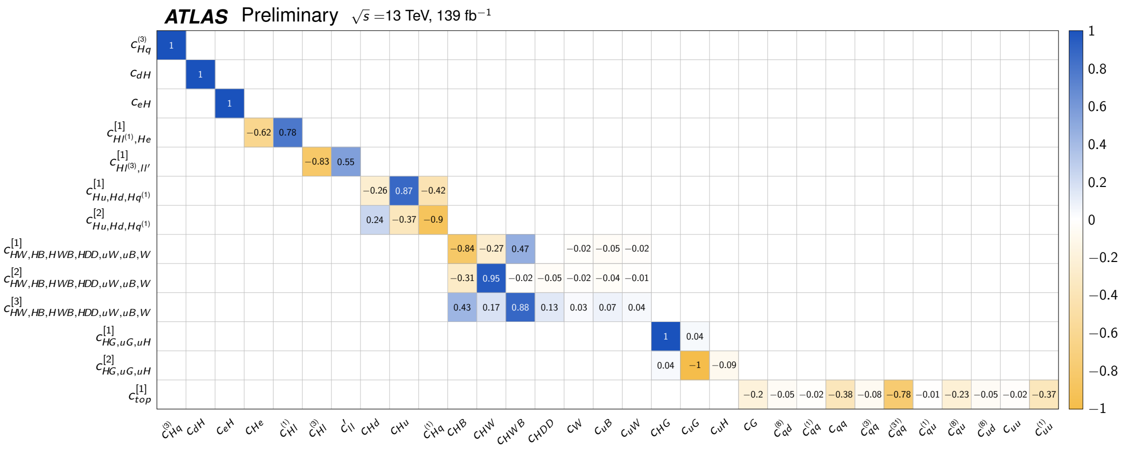
Measurement uncertainty in STXS bin / decay channel

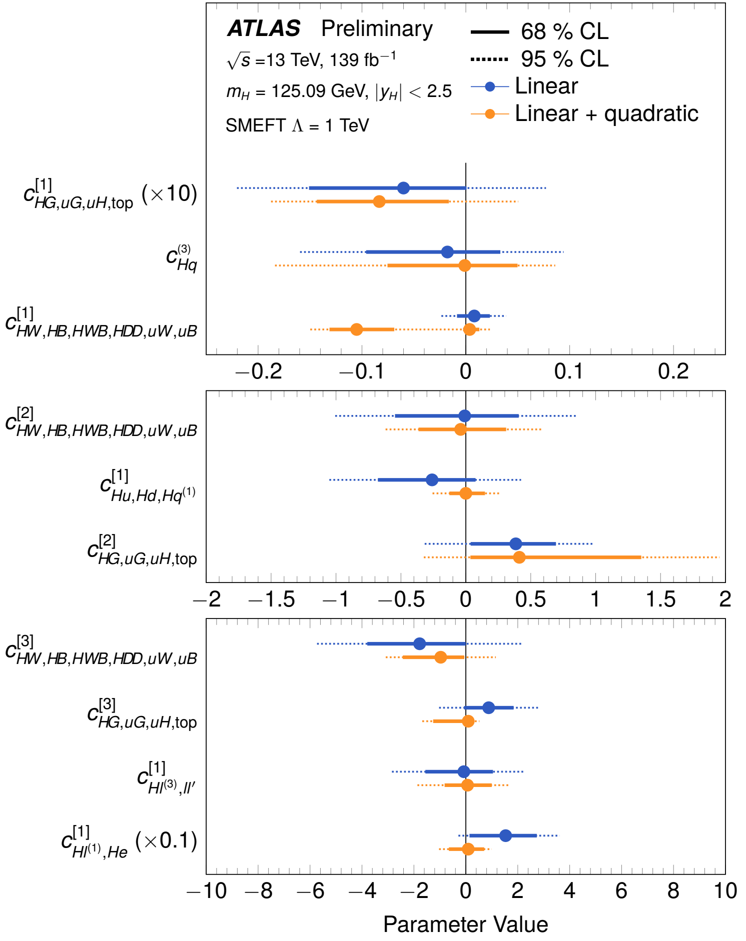


Strong energy growt of effect of $c^{(3)}_{Hg}$, $c^{(1)}_{Hg}$, c_{Hu}, c_{Hd}

EFT interpretation of Higgs couplings

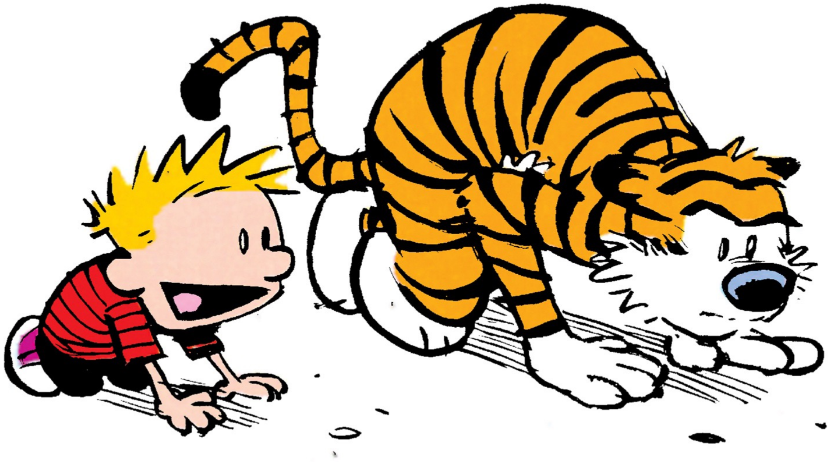
- Simultaneously constraining all coefficients impossible
- Fit performed in *sensitive directions*
  - ✓ linear combinations informed by principal component analysis
- Examples
  - ✓ $c^{[1]}_{HG,uG,uH}$: linear comb. with strong impact on $gg \to H$
  - ✓ $c^{[1]}_{HW,HB,HWB,HDD,uW,uB,W}$: strong impact on $H \to \gamma\gamma$
  - ✓ $c^{(3)}_{Hq}$: unique impact on VH

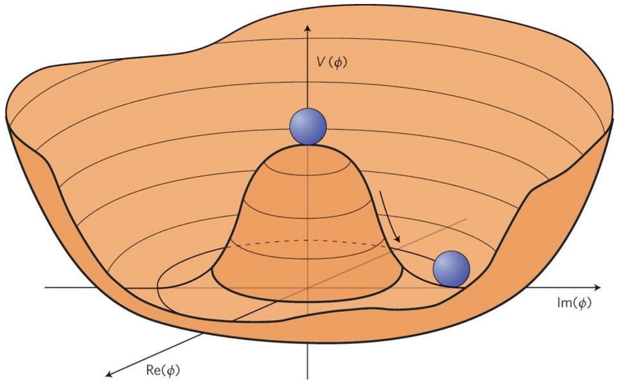




11

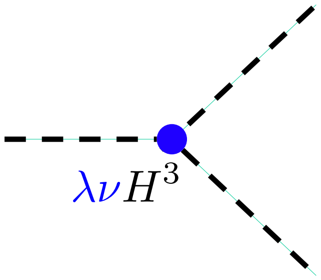
The SM missing piece

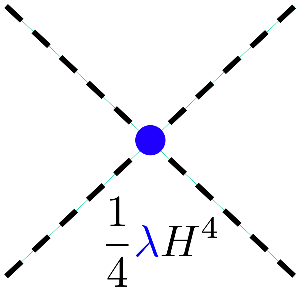




$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

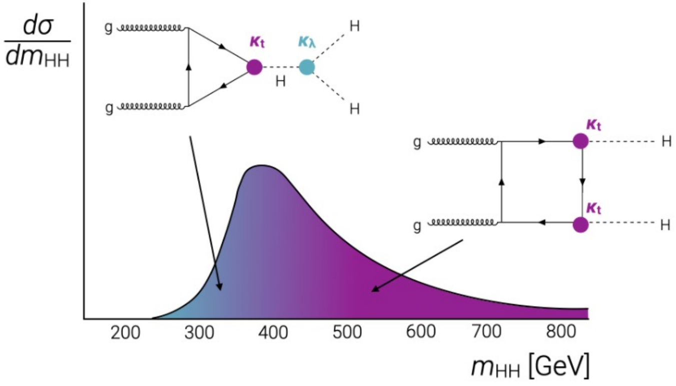
$$V(\Phi) = V_0 + \frac{1}{2} m_H^2 H^2 + \lambda \nu H^3 + \frac{1}{4} \lambda H^4$$





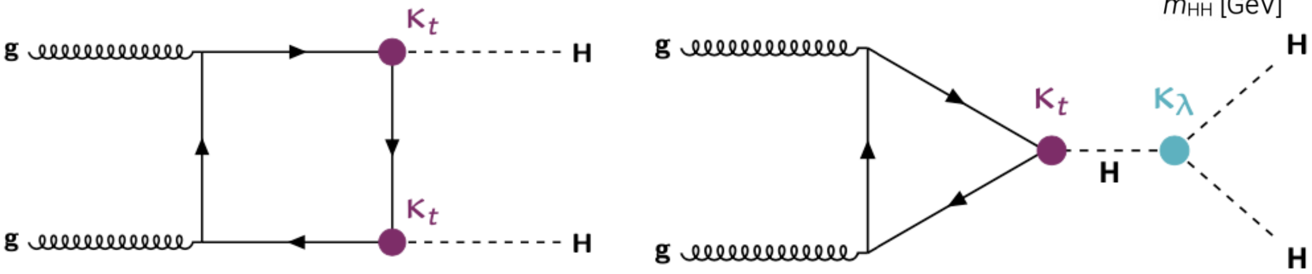
Can we access the Higgs self-coupling at the LHC?

- Main avenues toward self-coupling measurement at LHC
  - ✓ Direct: HH production
  - ✓ Indirect: constraints from single Higgs measurements
- HH production
  - ✓ Very low cross-section (~1000x smaller than single Higgs!)
  - ✓ Destructive interference between gg→HH processes



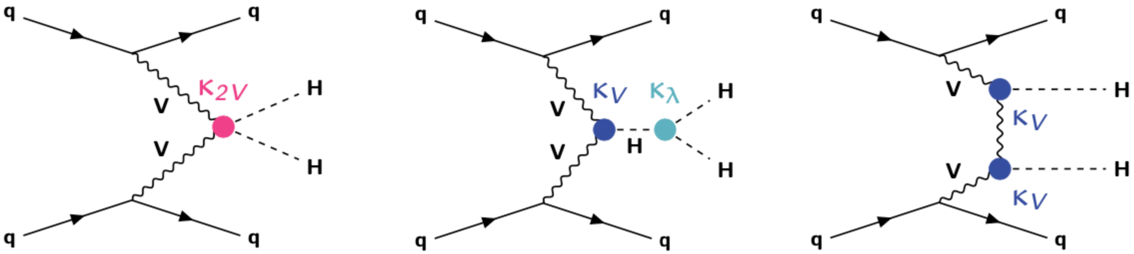
gluon-fusion

$\sigma_{ggF}(pp \to HH) = 31.05$ fb



VBF

$\sigma_{VBF}(pp \to HH) = 1.726$ fb

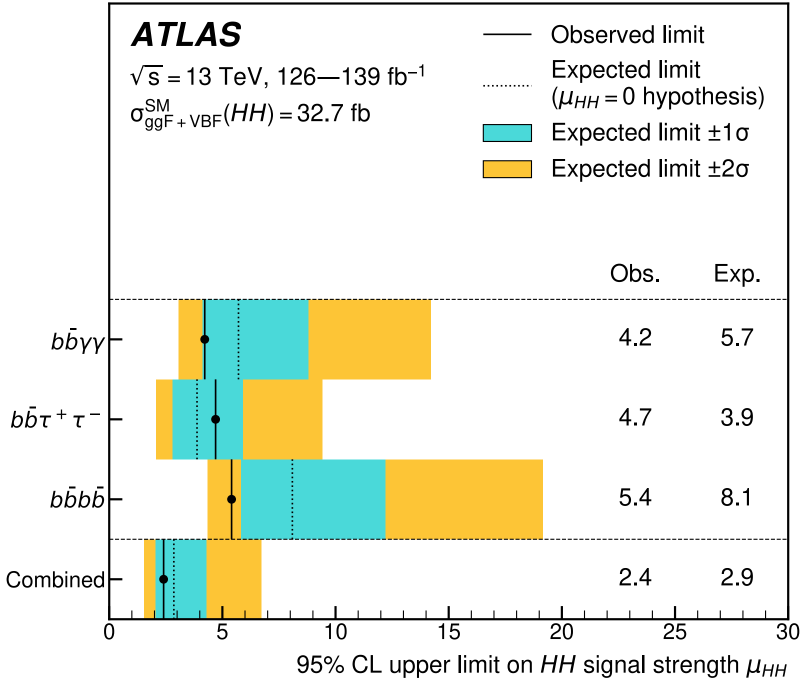


How to measure di-Higgs production?

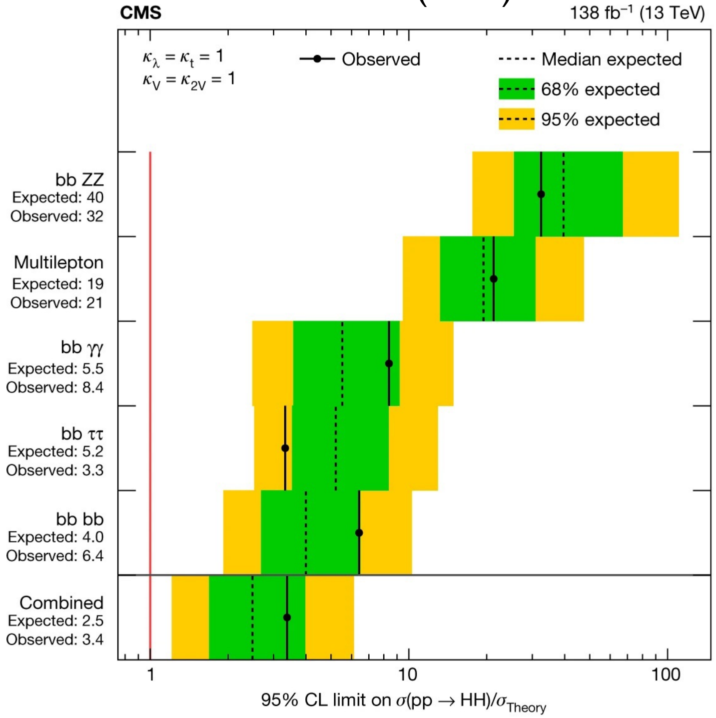
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Closing in on di-Higgs production!

Phys. Lett. B 843 (2024) 137745



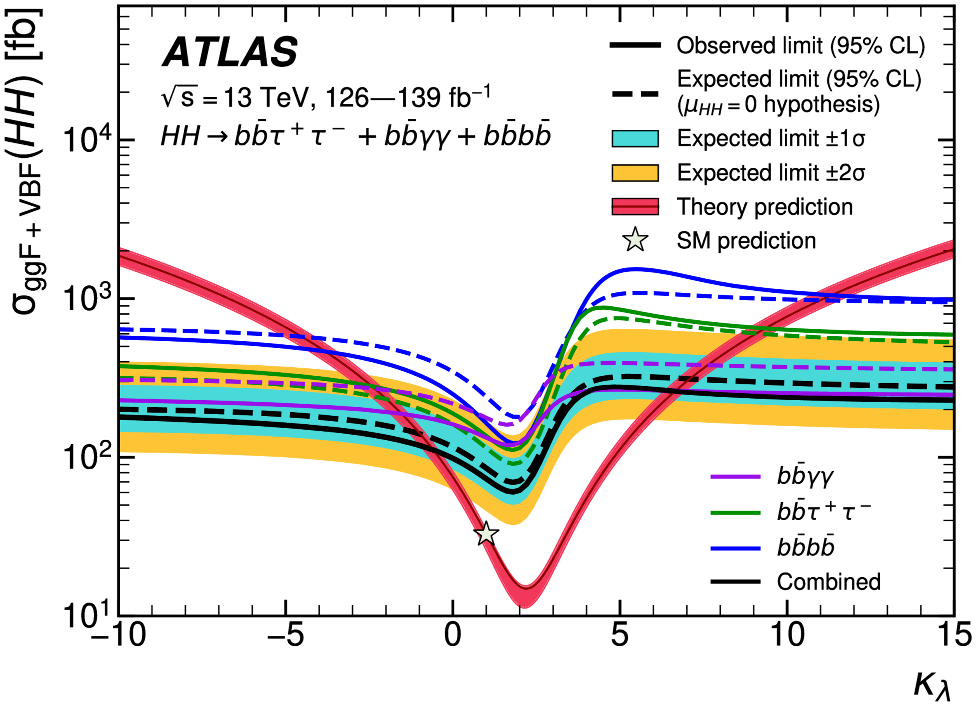
Nature 607 (2022) 60



- Limits on k_λ are improving dramatically, and there is more to be exploited (VBF production, combination of all channels and between ATLAS and CMS, …)
- Di-Higgs studies will be a central aspect of the Run 3 (and of course HL-LHC)!

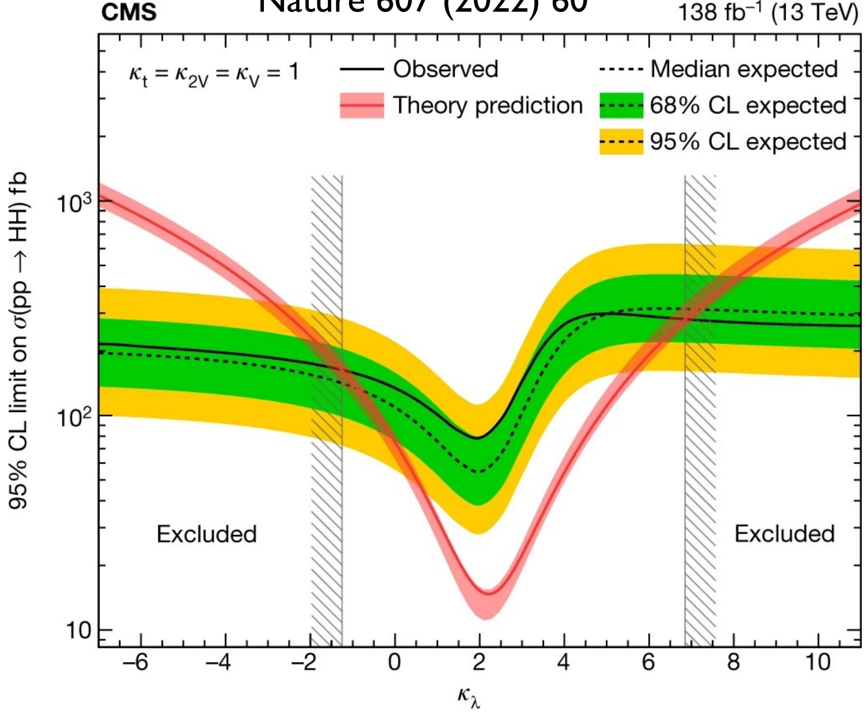
Closing in on di-Higgs production!

arXiv:2211.01216



$-0.4 < \kappa_\lambda < 6.3$ @ 95% CL

Nature 607 (2022) 60



$-1.24 < \kappa_\lambda < 6.49$ @ 95% CL

- Di-Higgs studies will be a central aspect of the Run 3 (and of course HL-LHC)!

When will we finding the missing piece of the SM?

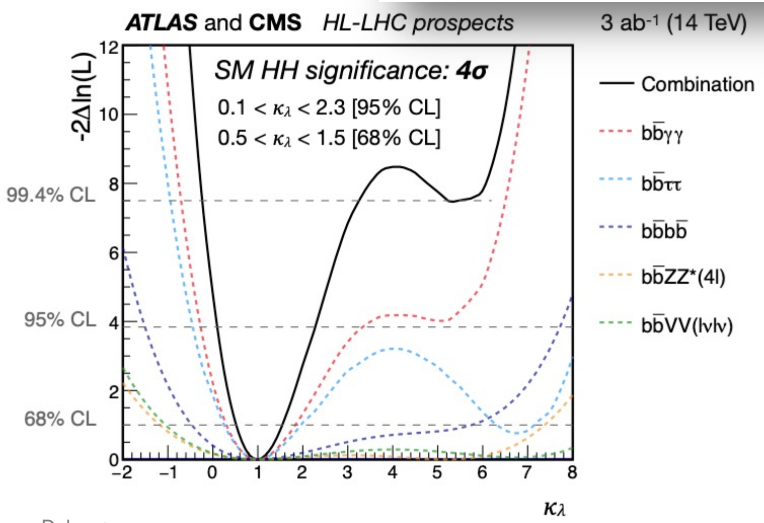
	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6

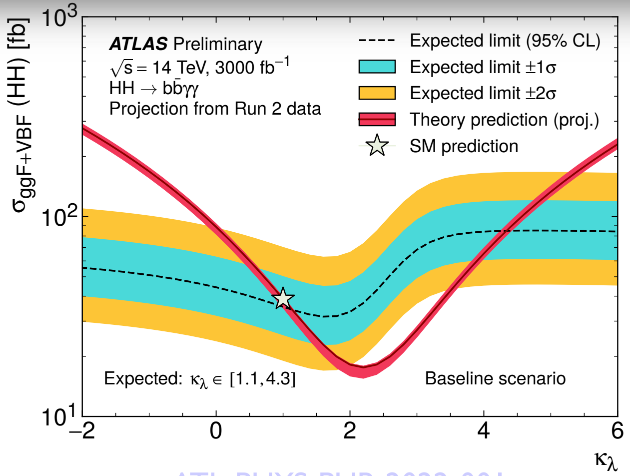
	Combined	Combined
	4.5	4.0

arXiv:1902.00134

A word of hope…

We often do better than our projections!



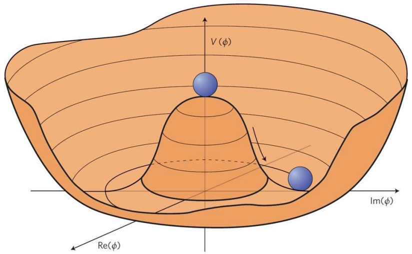


ATL-PHYS-PUB-2022-001

… and one of caution

Sometimes projection are optimistic, and HL-LHC will present formidable challenges!

12.

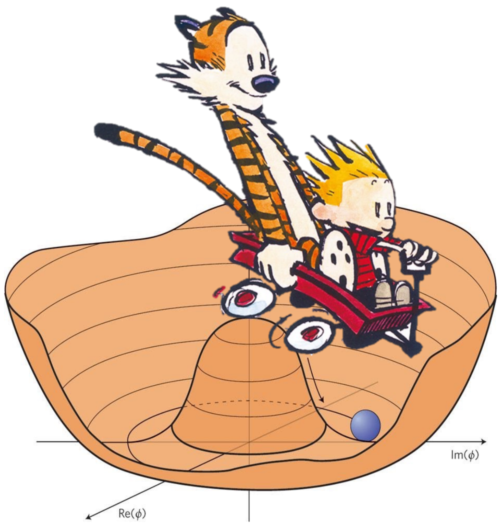


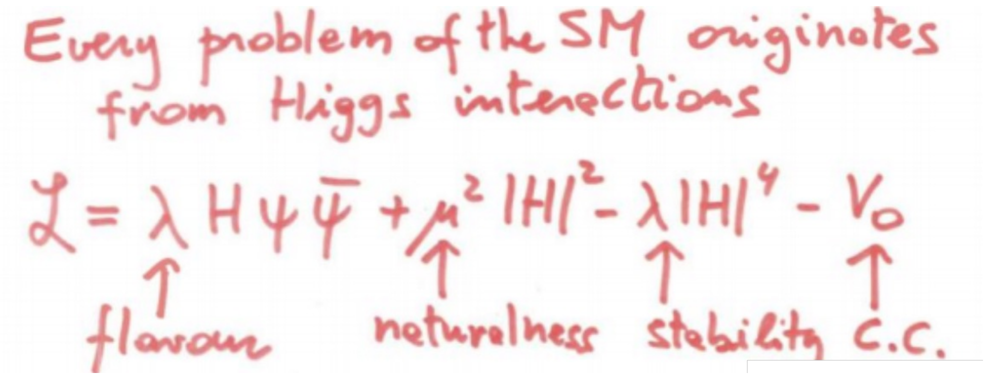
The road ahead

We have a formidable tool to understand particle physics…

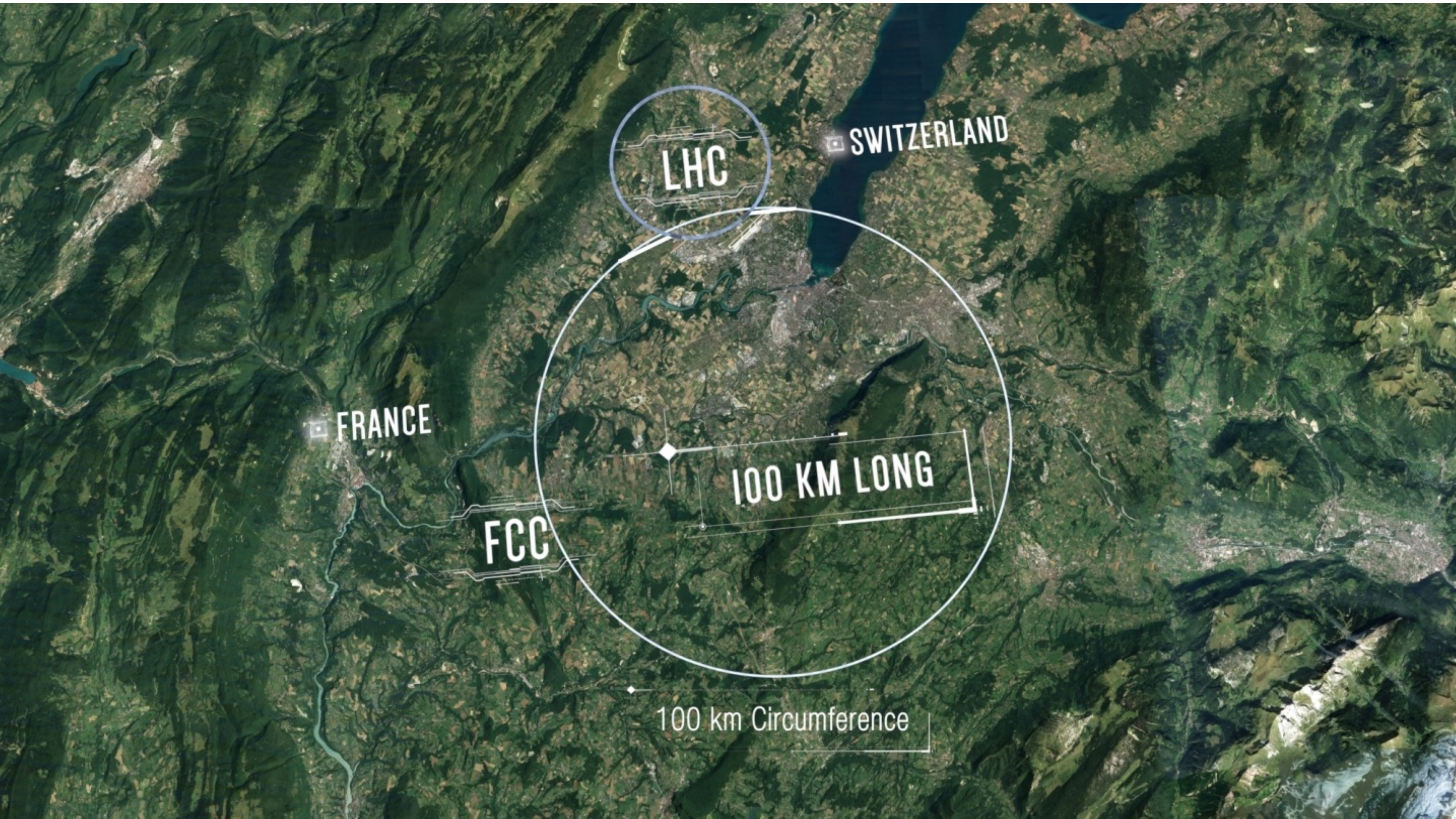
- **In 12 years we have measured with great precision many Higgs boson properties**
  - ✓ Mass, width, CP properties…
  - ✓ Coupling properties and differential distributions…
  - ✓ Closing in on coupling to 2nd generation, rare decays, self-interaction…
  - ✓ Higgs as a tool to constrain New Physics...

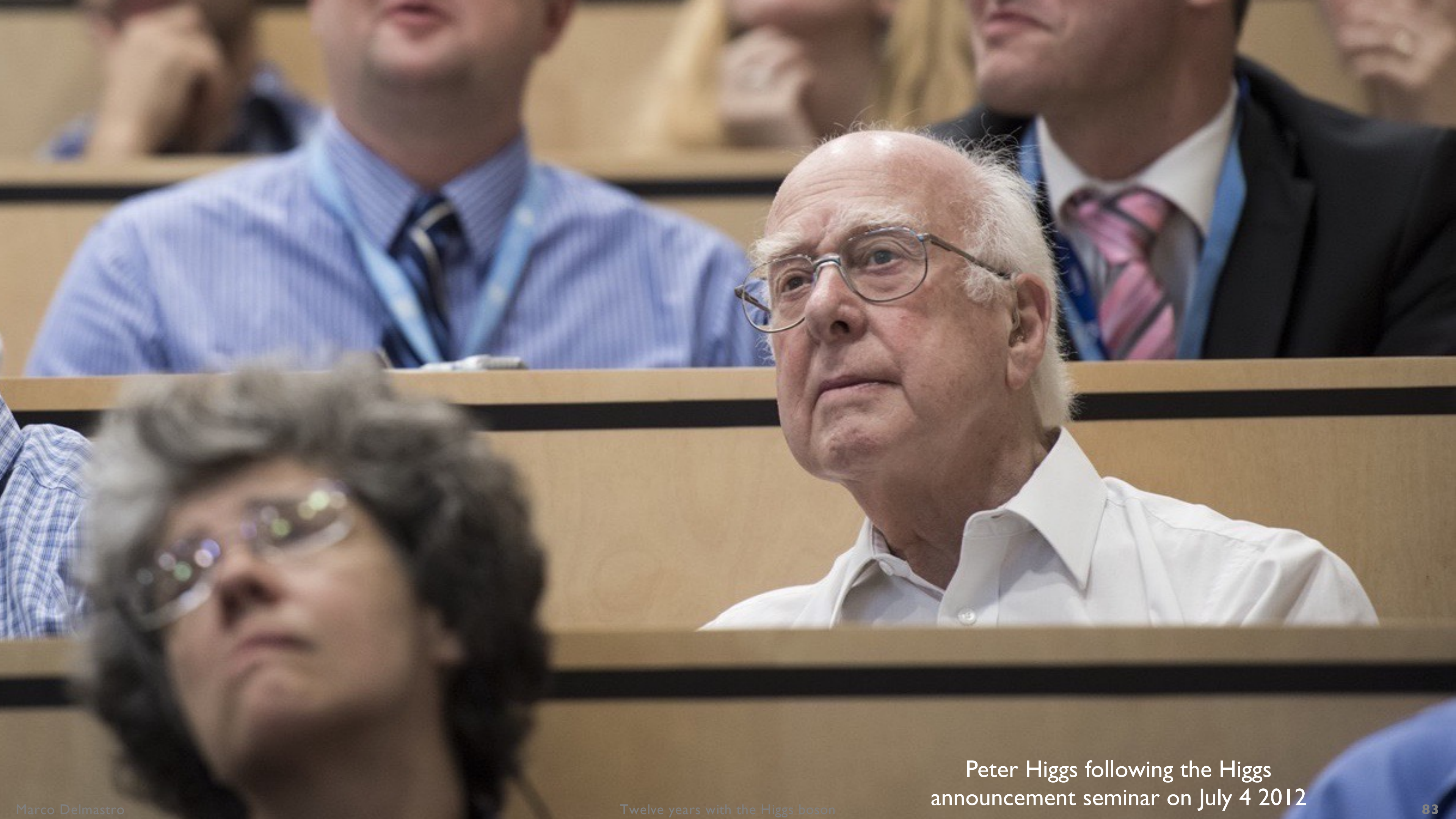
- **The LHC has restarted in 2022 for its Run 3 and will operate for a long time…**
  - ✓ A unique opportunity to continue characterizing the Higgs sector!





G. Giudice
via F. Gianotti

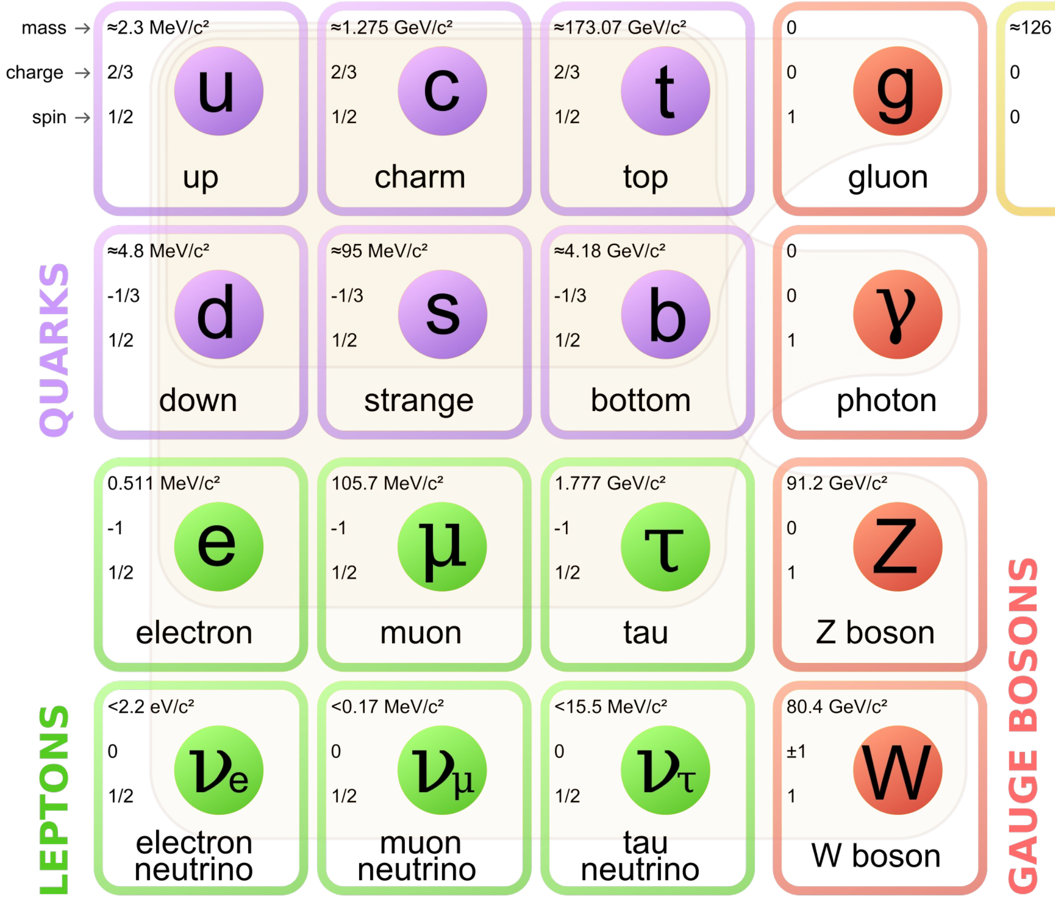

LHC
SWITZERLAND
FRANCE
100 KM LONG
FCC
100 km Circumference



Peter Higgs following the Higgs announcement seminar on July 4 2012

More material

The Standard Model



Higgs boson

Why is the electroweak interaction so much stronger than gravity?

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs boson with the *W* and *Z* bosons?

Why is there more matter than antimatter in the Universe?

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-Universe electroweak phase transition?
- Are there multiple Higgs sectors?

What is dark matter?

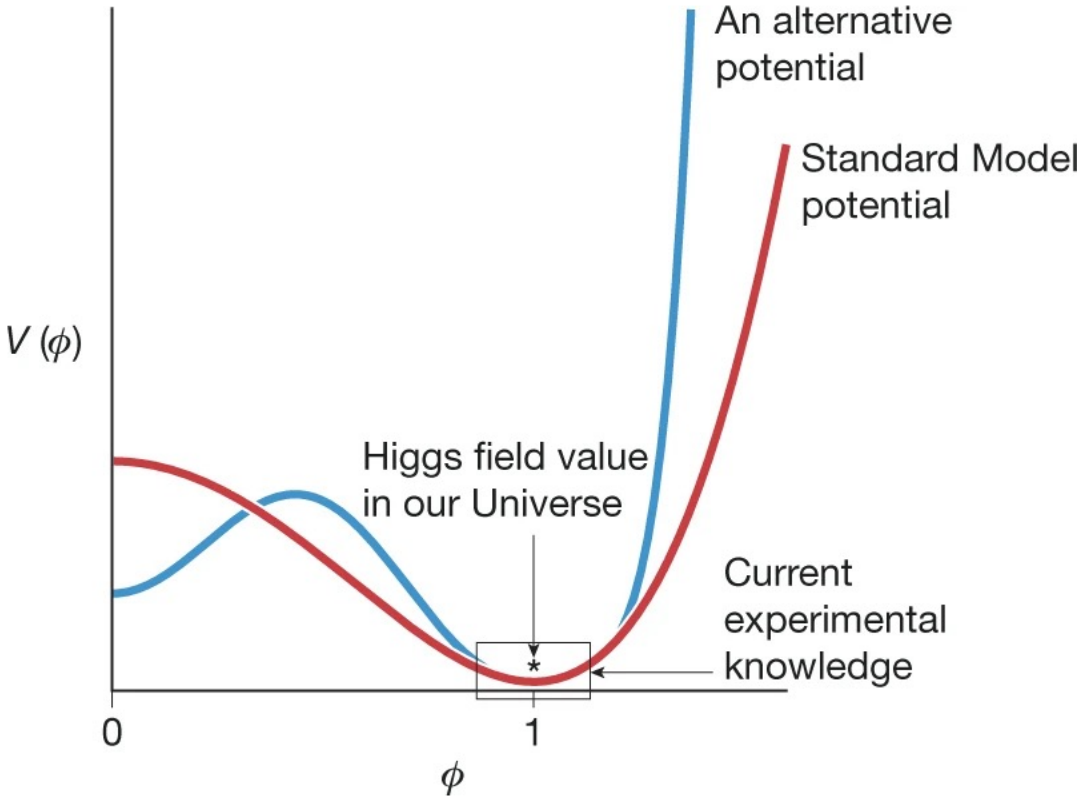
- Can the Higgs boson provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs boson?

What is the origin of the vast range of quark and lepton masses in the Standard Model?

- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs boson decay into pairs of quarks or leptons with distinct flavours (for example, $H \to \mu^+ \tau^-$)?

What is the origin of the early Universe inflation?

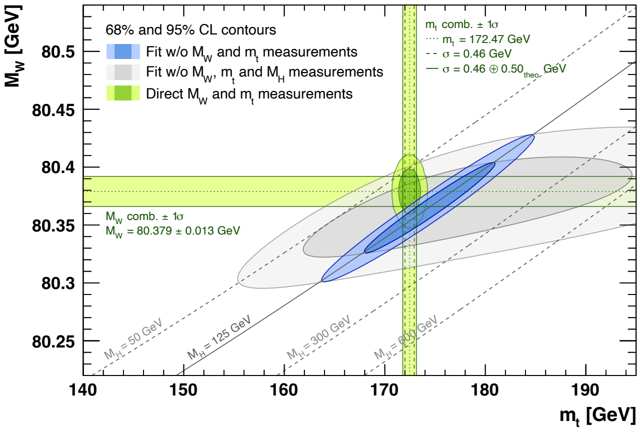
- Any imprint in cosmological observations?

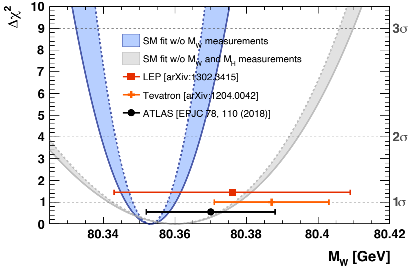


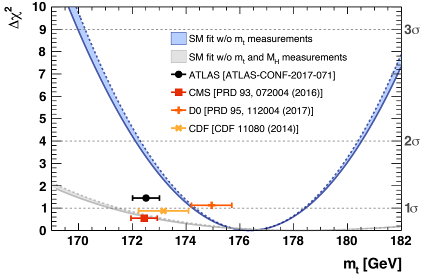
Knowing the Higgs mass values…

… allows to make precision predictions

Eur. Phys. J. C78, 675 (2018)







… but current m_H precision has little impact

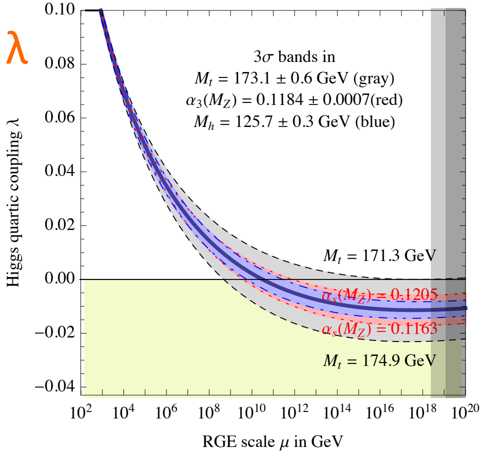
… questions us on vacuum (meta) stability

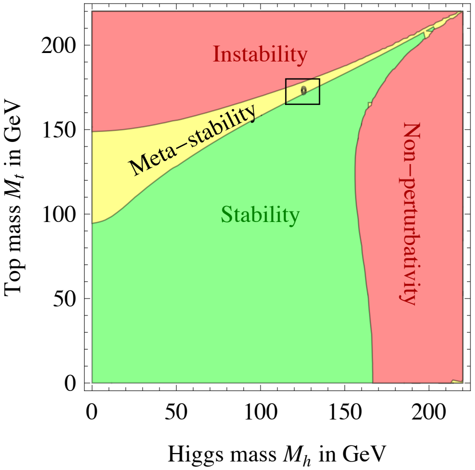
$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

$$m_H = \sqrt{2\lambda}\nu$$

Running of the Higgs self coupling,
assuming SM only at high scale

λ



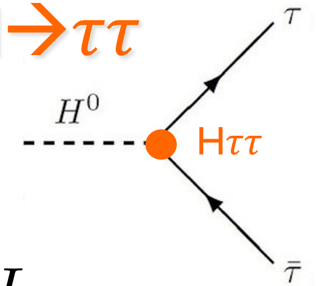


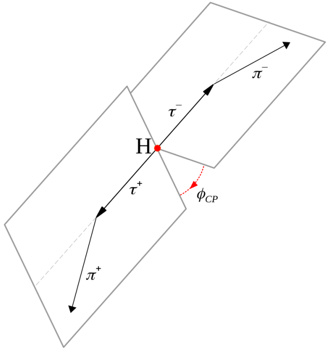
arXiv:1205.6497

Vanishing quartic coupling at the Planck scale? Potential not bounded?
… but interpretation more sensitive to precision on top quark mass

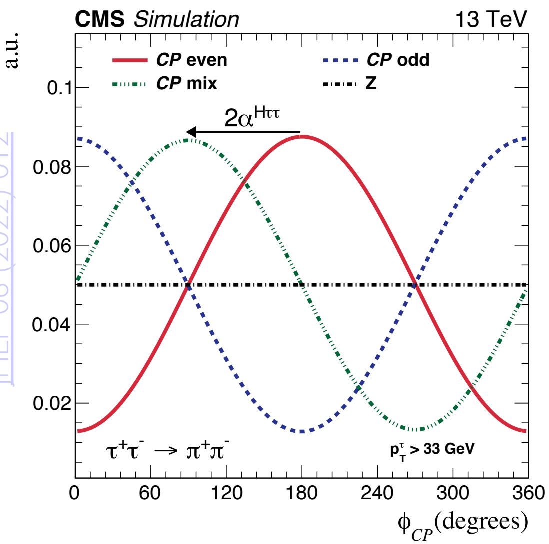
CP properties of Higgs-τ coupling with H→ττ

Effective Lagrangian for Yukawa coupling to tau leptons parameterized by CP-Even and CP-odd components



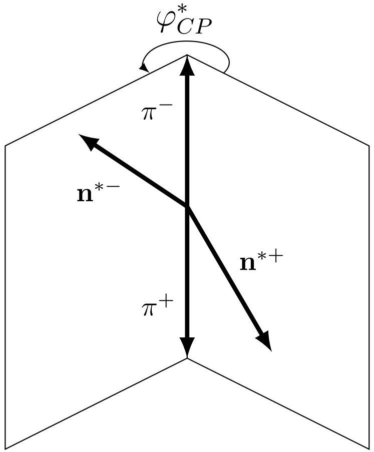


$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{\nu}\kappa_\tau \left(\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i\gamma_5 \tau\right) H$$



$\alpha^{H\tau\tau}$(CMS) = ϕ_τ (ATLAS)

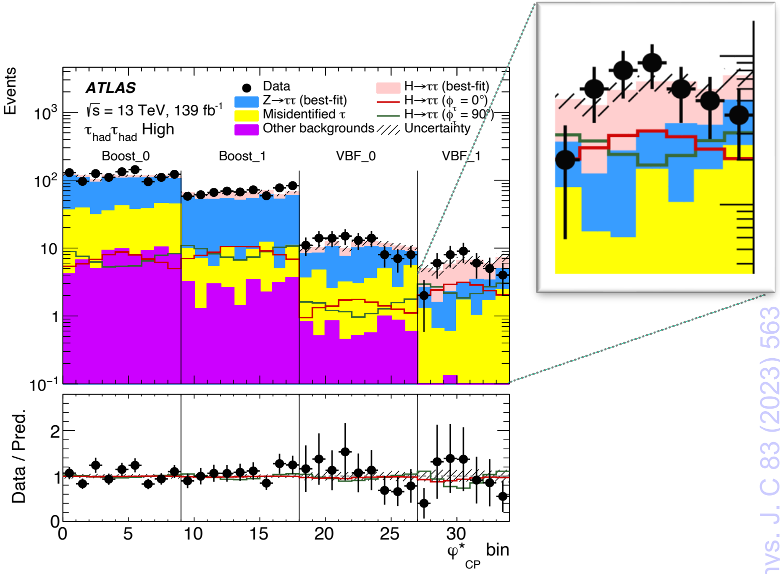
JHEP 06 (2022) 012



$$H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$$

$$\varphi^* = \arccos(\hat{\mathbf{n}}^{*+}_\perp \cdot \hat{\mathbf{n}}^{*-}_\perp)$$

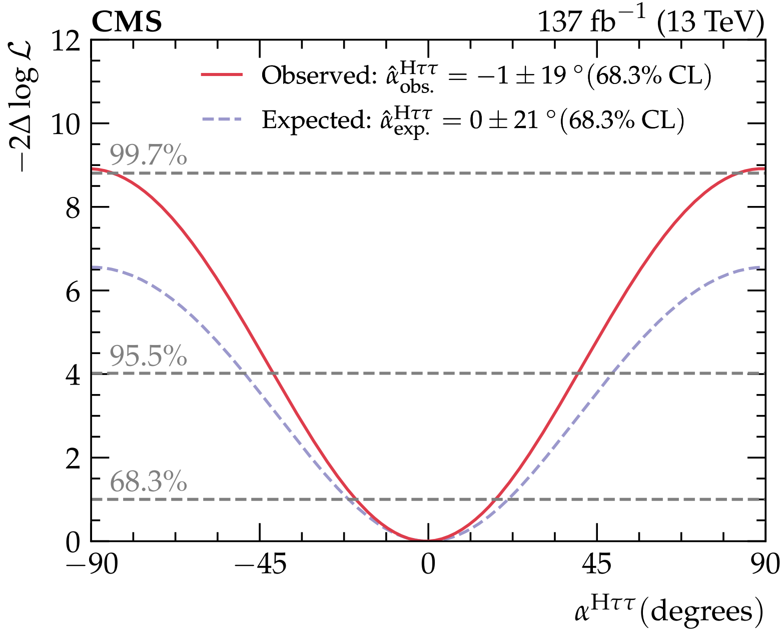
Uses either the impact parameter direction for single-prong taus ([illegible]±) or [illegible] momentum for τ → [illegible]± [illegible] ρ ν_τ (also for 3-prong decays with ρ → [illegible])

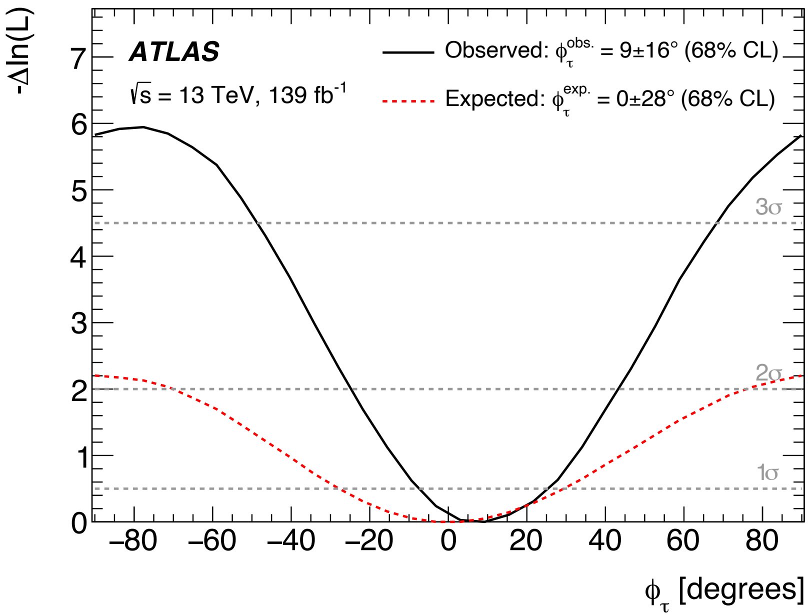


Eur. Phys. J. C 83 (2023) 563

CP properties of Higgs-τ coupling with H→ττ

JHEP 06 (2022) 012





Eur. Phys. J. C 83 (2023) 563

ϕ_τ = -1 ± 19° (21° exp)

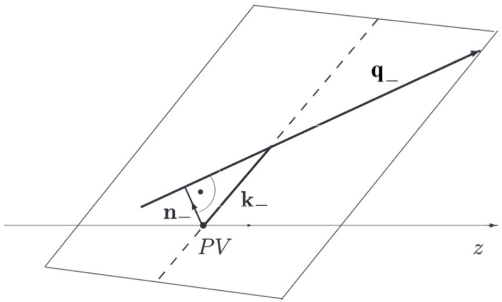
$\alpha^{H\tau\tau}$(CMS) = ϕ_τ (ATLAS)

ϕ_τ = 9 ± 16° (28° exp)

pure CP-odd coupling excluded at 3 σ

pure CP-odd coupling excluded at 3.4 σ

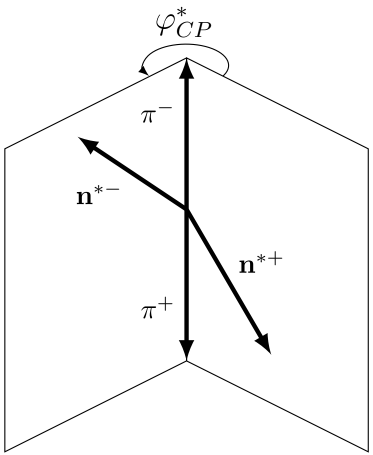
H→ττ decay CP

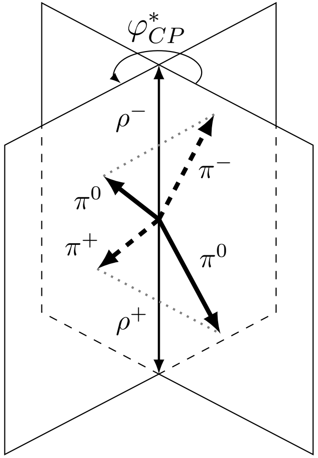


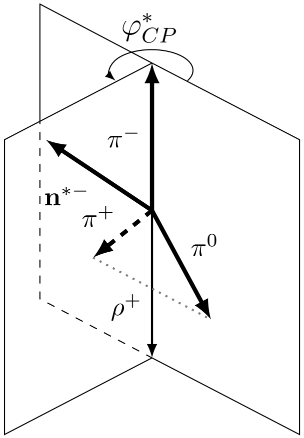
Impact parameter

directional distance of closest approach of charged particle's track to reconstructed PV of the event

4-vectors boosted to the rest frame of visible di-τ Zero Momentum Frame (e.g. two decay charged particles)







$$H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$$

impact parameter

$$\varphi^* = \arccos(\hat{\mathbf{n}}^{*+}_\perp \cdot \hat{\mathbf{n}}^{*-}_\perp)$$

$$\mathcal{O}^*_{CP} = \hat{\mathbf{q}}^{*-} \cdot (\hat{\mathbf{n}}^{*+}_\perp \times \hat{\mathbf{n}}^{*-}_\perp)$$

$$\varphi^*_{CP} = \begin{cases} \varphi^* & \text{if } \mathcal{O}^*_{CP} \geq 0 \\ 360° - \varphi^* & \text{if } \mathcal{O}^*_{CP} < 0 \end{cases}$$

$$H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\pi^0\nu$$

ρ decay plane

$$\varphi^* = \arccos(\hat{\mathbf{q}}^{*0+}_\perp \cdot \hat{\mathbf{q}}^{*0-}_\perp)$$

$$\mathcal{O}^*_{CP} = \hat{\mathbf{q}}^{*-} \cdot (\hat{\mathbf{q}}^{*0+}_\perp \times \hat{\mathbf{q}}^{*0-}_\perp)$$

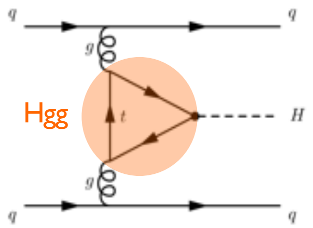
$$\varphi^{*\prime} = \begin{cases} \varphi^* & \text{if } \mathcal{O}^*_{CP} \geq 0 \\ 360° - \varphi^* & \text{if } \mathcal{O}^*_{CP} < 0 \end{cases} \quad \varphi^*_{CP} = \begin{cases} \varphi^{*\prime} & \text{if } y^\rho_+ y^\rho_- \geq 0 \\ \varphi^{*\prime} + 180° & \text{if } y^\rho_+ y^\rho_- < 0 \end{cases} \quad y^\rho_\pm = \frac{E_{\pi^\pm} - E_{\pi^0}}{E_{\pi^\pm} + E_{\pi^0}}$$

$$H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\nu$$

impact parameter +
ρ decay plane

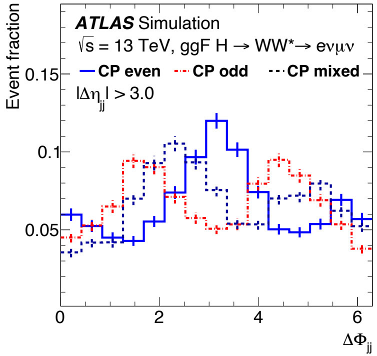
CP properties of Higgs-gluon coupling with ggF+VBF

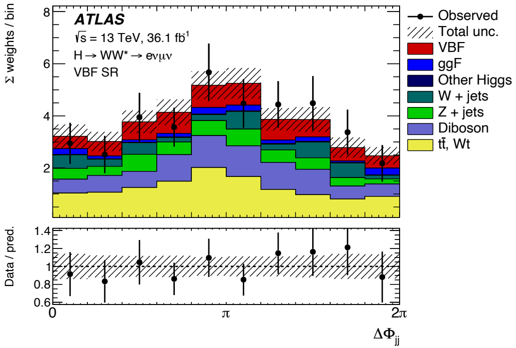
Study ggF+2 jets events: jet kinematics sensitive to Hgg coupling CP properties



ATLAS: $\Delta\Phi_{jj}$ ggF+VBF $H\rightarrow WW^*$

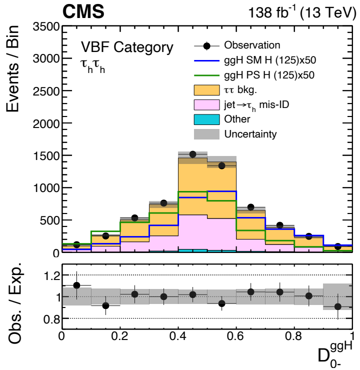
arXiv:2109.13808





CMS: $\Delta\Phi_{jj}$ or MELA discriminant ggF+VBF $H\rightarrow\tau\tau$

arXiv:2205.05120

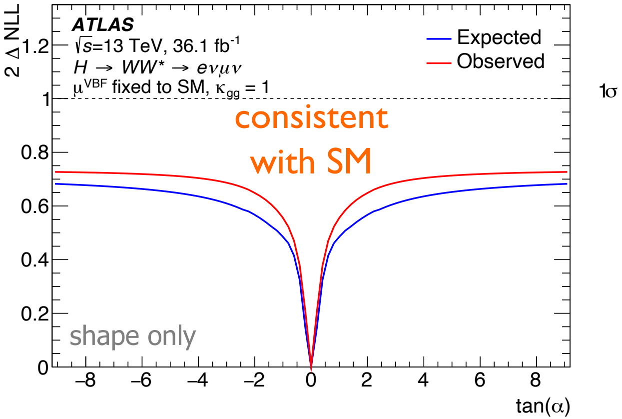


$$\mathcal{D}_{2jet}^{VBF} = \frac{\mathcal{P}_{SM}^{ggH}+\mathcal{P}_{0-}^{ggH}}{\mathcal{P}_{SM}^{ggH}+\mathcal{P}_{0-}^{ggH}+\mathcal{P}_{SM}^{VBF}}$$ ggF vs VBF

$$\mathcal{D}_{CP}^{ggH} = \frac{\mathcal{P}_{SM-0-}^{ggH}}{\mathcal{P}_{SM}^{ggH}+\mathcal{P}_{0-}^{ggH}}$$ ggF CP-even vs ggF CP-odd

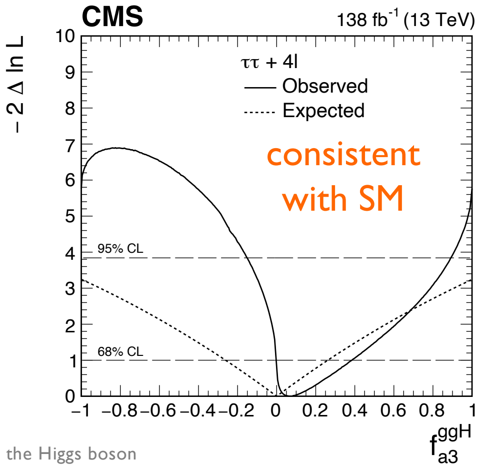
$$\mathcal{D}_{0-}^{ggH} = \frac{\mathcal{P}_{SM}^{ggH}}{\mathcal{P}_{SM}^{ggH}+\mathcal{P}_{0-}^{ggH}}$$ CP-even CP-odd interference

$H\rightarrow WW^*$



α parameterizes CP-even/CP-odd mixture on Hgg coupling

$H\rightarrow\tau\tau$ (combined with $H\rightarrow 4l$)



f_{a3}^{ggH} parameterizes fraction of CP-odd BSM point-like Hgg coupling

CP properties of HVV coupling (mult. prod. + H→4l)

HVV couplings parameterized by tensor structures in scattering amplitude

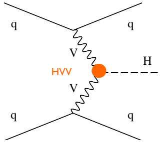
Multiple analyses constraining HVV couplings with ggH, VBF, VH, ttH, tH production and H→ττ, H→4l, H→γγ decay

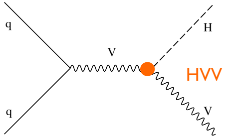
$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

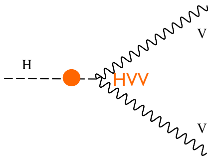
$$f_{a3} = \frac{|a_3|^2 \sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + |\kappa_1|^2\sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2 \sigma_{\Lambda 1}^{Z\gamma}} \, \mathrm{sgn}\left(\frac{a_3}{a_1}\right)$$

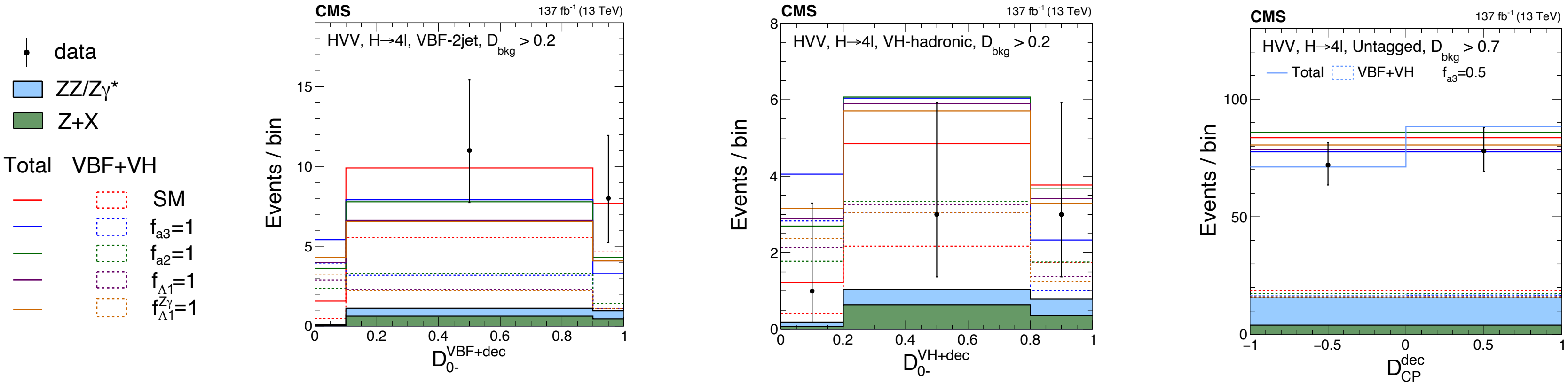
f_{a3} parameterizes fractional contribution of CP-odd HZZ coupling

Phys. Rev. D 104, 052004 (2021)

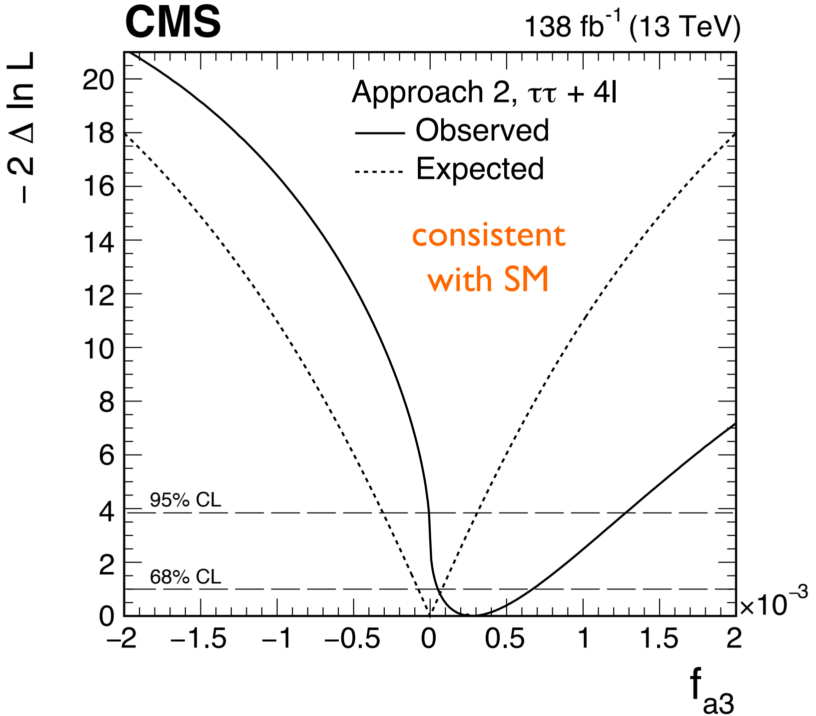








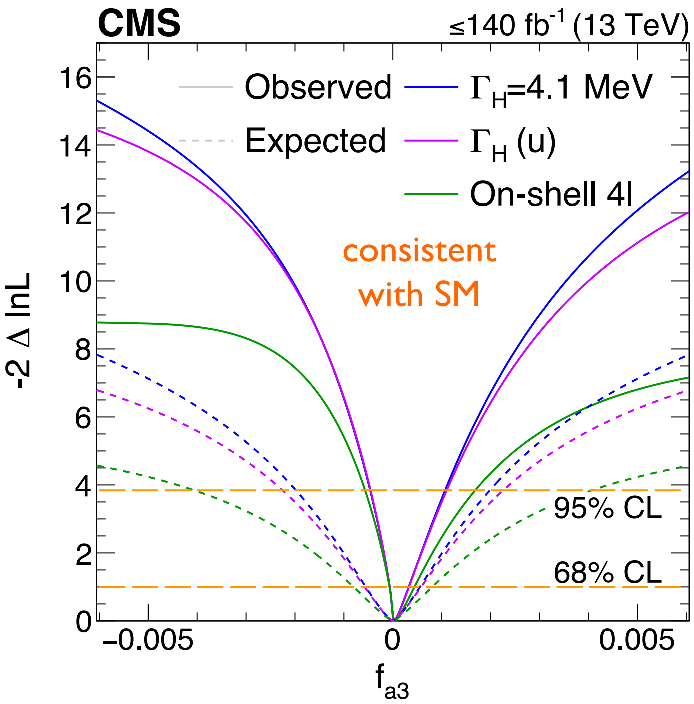
CP properties of HVV coupling (mult. prod. + H→4l; offshell)



Constraint from combined analyses

Other anomalous HVV fixed to 0

$$f_{a3} = 0.20^{+0.26}_{-0.16} \times 10^{-3}$$



Constraints from H→4l onshell + off-shell

Other anomalous couplings floated in fits

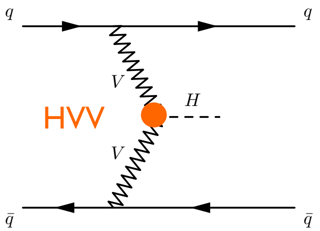
$$f_{a3} = 0.024^{+0.32}_{-0.064} \times 10^{-3}$$

Phys. Rev. D 104, 052004 (2021)

arXiv:2202.06923

CP properties of HVV coupling with VBF

SM Lagrangian augmented with CP-odd dim-6 operators involving Higgs and EW gauge fields in EFT formalism



$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + \tilde{d} \cdot 2Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd}) + \tilde{d}^2 \cdot |\mathcal{M}_{CP-odd}|^2$$

Approach pursued with various decay modes, here most recent ATLAS H→γγ, then combined with 36 fb^{-1} H→ττ

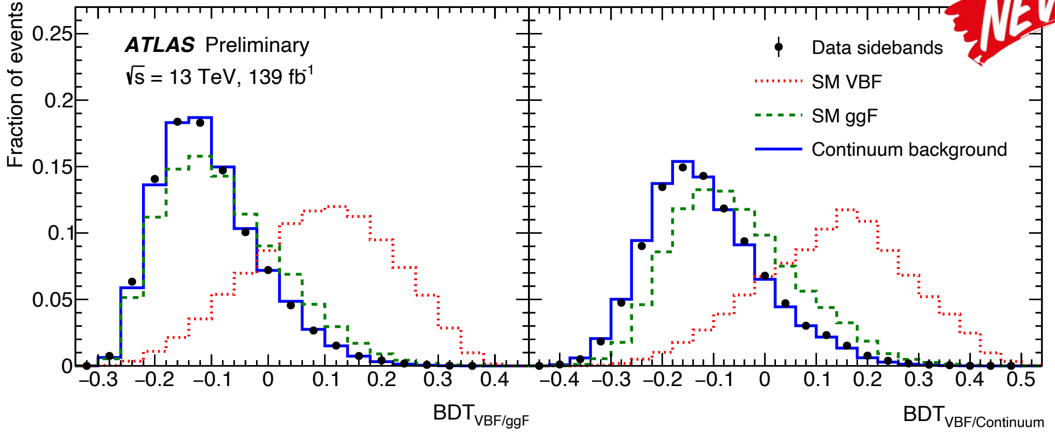
$$c_{H\tilde{W}} = c_{H\tilde{B}}$$
$$c_{HW\tilde{B}} = 0$$

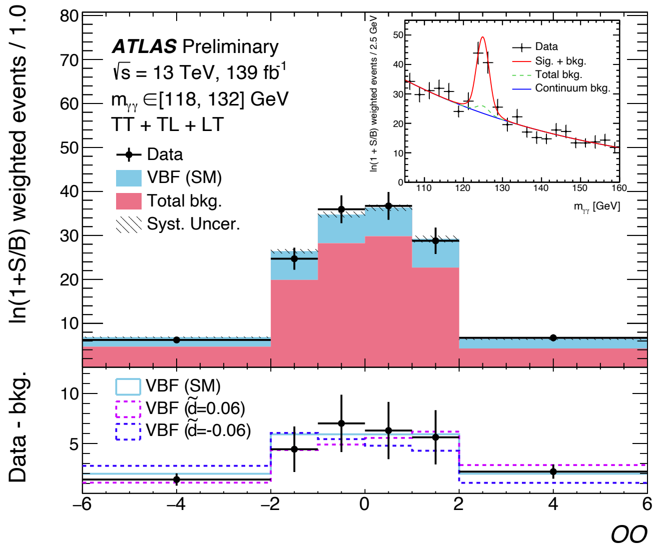
$$\tilde{d} = \frac{\nu^2}{\Lambda^2} c_{H\tilde{W}}$$

$$OO = \frac{2Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$$

2 dedicated BDT's (VBF vs ggF, VBF vs yy)

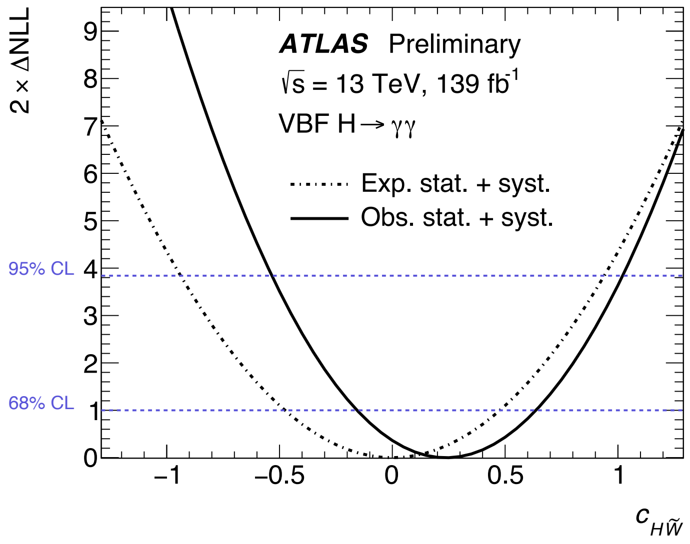
NEW

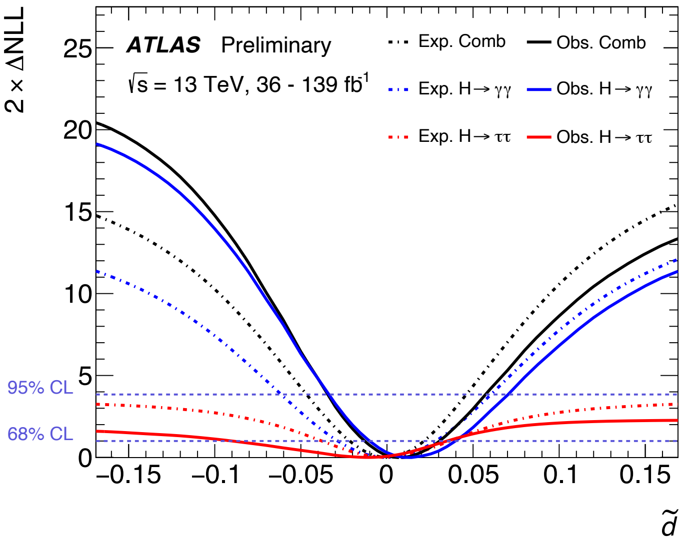




CERN-EP-2022-134

CP properties of HVV coupling with VBF





$$\tilde{d} = \frac{\nu^2}{\Lambda^2} c_{H\tilde{W}}$$

	68% (exp.)	95% (exp.)	68% (obs.)	95% (obs.)
$\tilde{d}$ (inter. only)	[-0.027, 0.027]	[-0.055, 0.055]	[-0.011, 0.036]	[-0.032, 0.059]
$\tilde{d}$ (inter.+quad.)	[-0.028, 0.028]	[-0.061, 0.060]	[-0.010, 0.040]	[-0.034, 0.071]
$\tilde{d}$ from $H \to \tau\tau$	[-0.038, 0.036]	-	[-0.090, 0.035]	-
Combined $\tilde{d}$	[-0.022, 0.021]	[-0.046, 0.045]	[-0.012, 0.030]	[-0.034, 0.057]
$c_{H\tilde{W}}$ (inter. only)	[-0.48, 0.48]	[-0.94, 0.94]	[-0.16, 0.64]	[-0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[-0.48, 0.48]	[-0.95, 0.95]	[-0.15, 0.67]	[-0.55, 1.07]

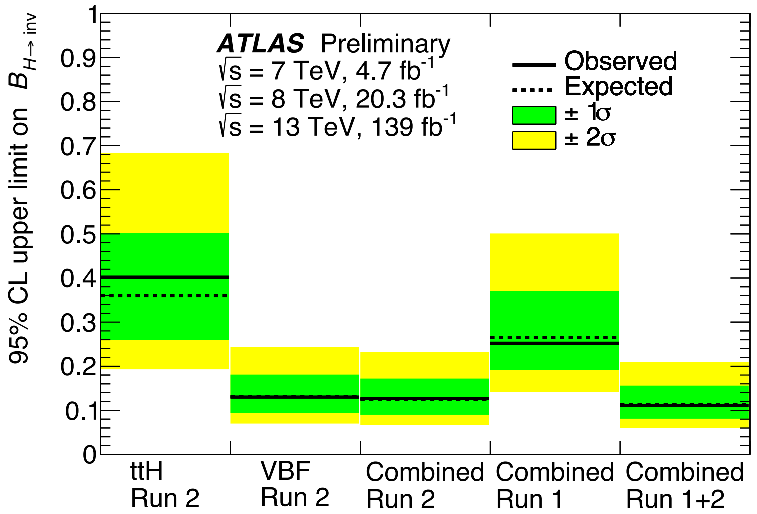
most stringent constraints on CP-properties of HVV coupling to date

CERN-EP-2022-134

Other information about the Higgs width?

- Part of Higgs width could be due to decays to undetectable particles (H→invisible)
  - ✓ Limits from direct searches in H→ invisible, explicitly requiring MET in the event

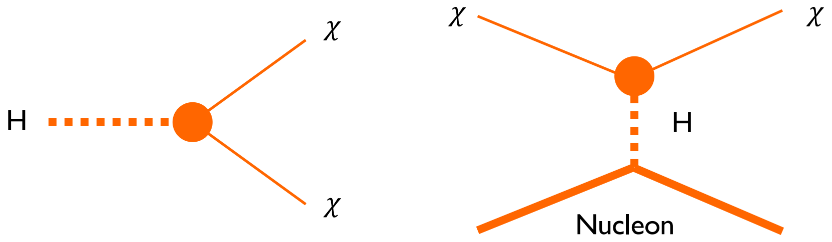
ATLAS-CONF-2020-052



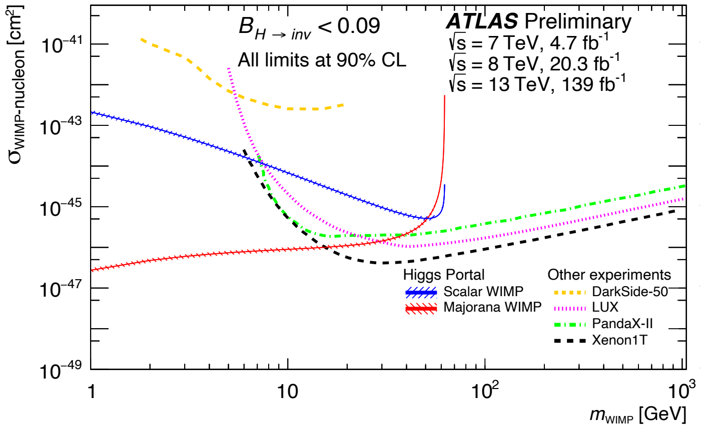
ATLAS: BR(H → inv) < 0.11 (exp. 0.11) @ 95% CL

CMS: BR(H → inv) < 0.17 (exp. 0.11) @ 95% CL

CMS-PAS-HIG-20-003

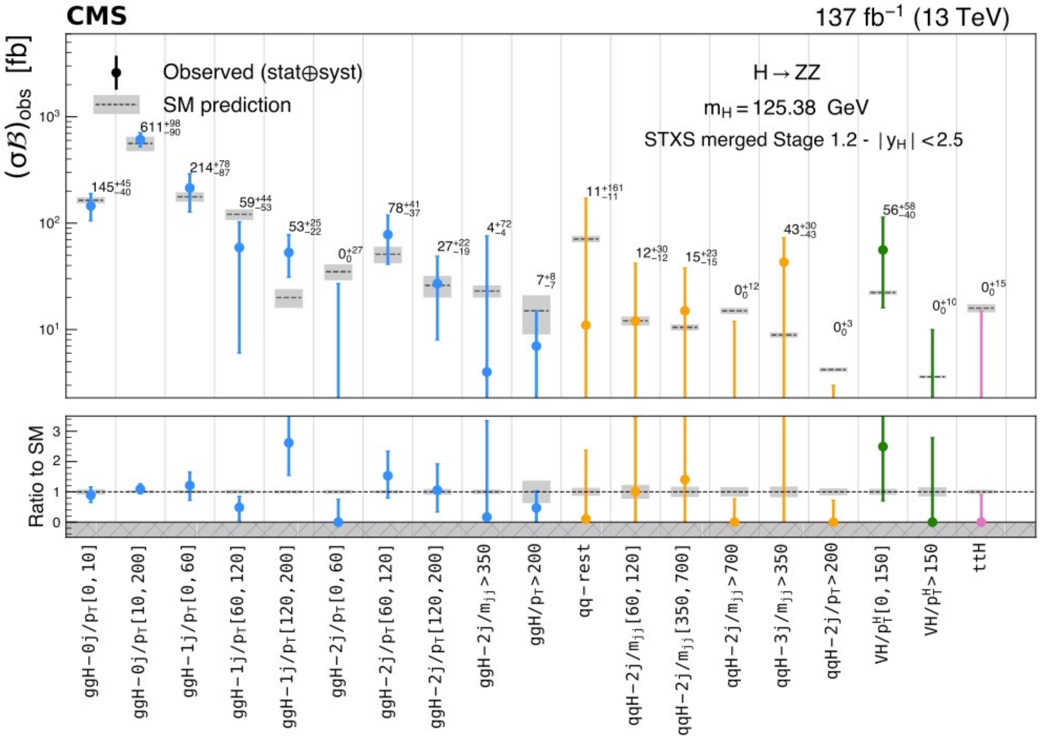


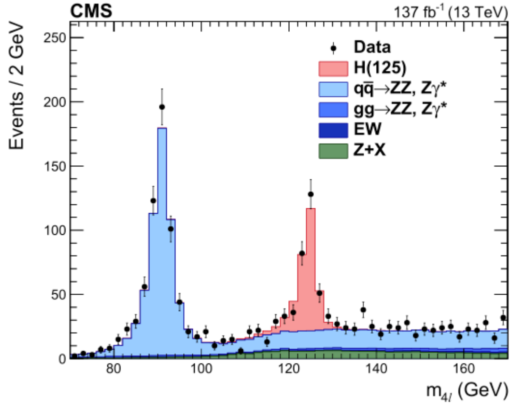
Limits on BR(H->inv) can be recast in term of limit on Dark Matter production

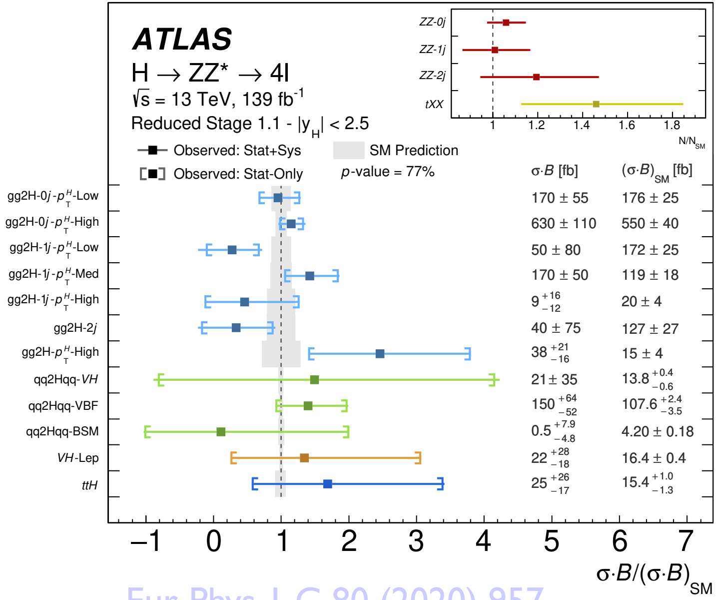


STXS at work: H → ZZ*

Eur. Phys. J. C 81 (2021) 488

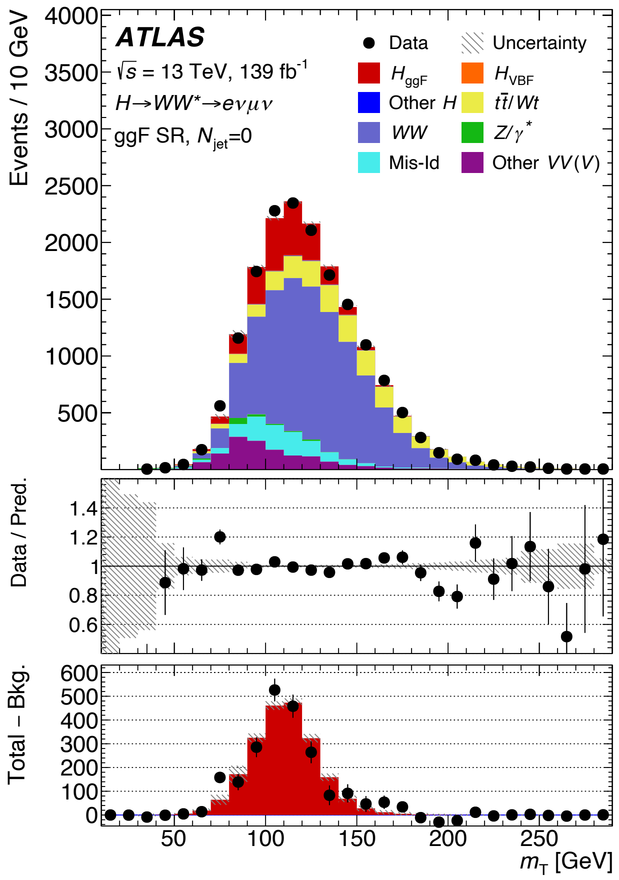




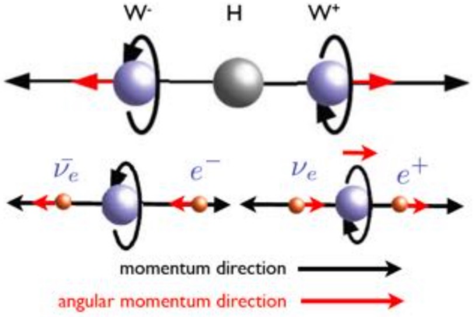


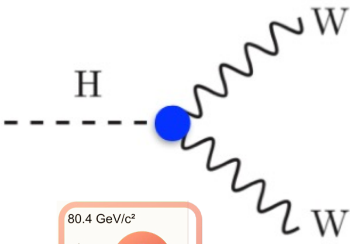
Eur. Phys. J. C 80 (2020) 957

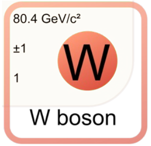
STXS at work: H → WW*



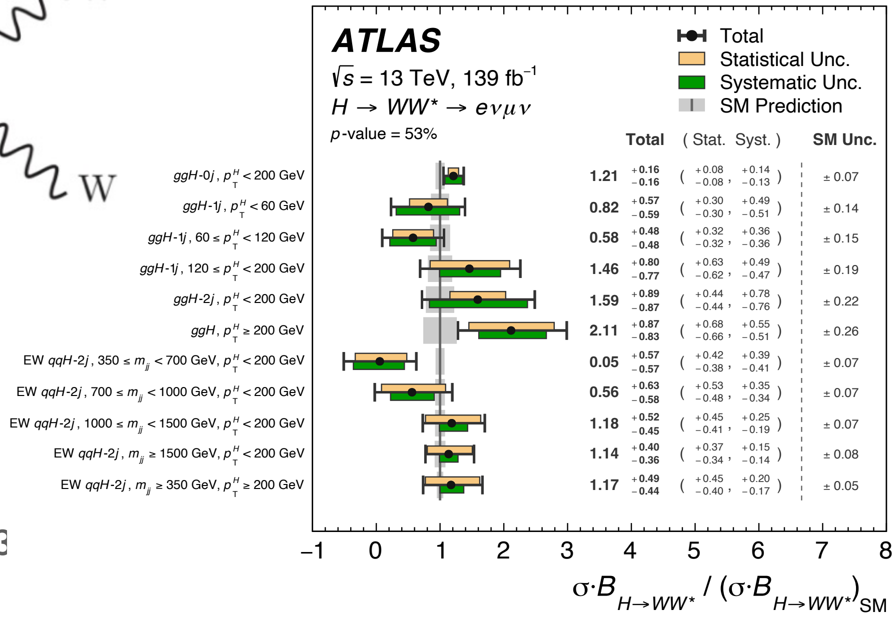
- Precision measurements have become a possible also for those channels where reconstructing the final state is not possible, e.g. H→WW* (neutrinos, missing transverse energy)!



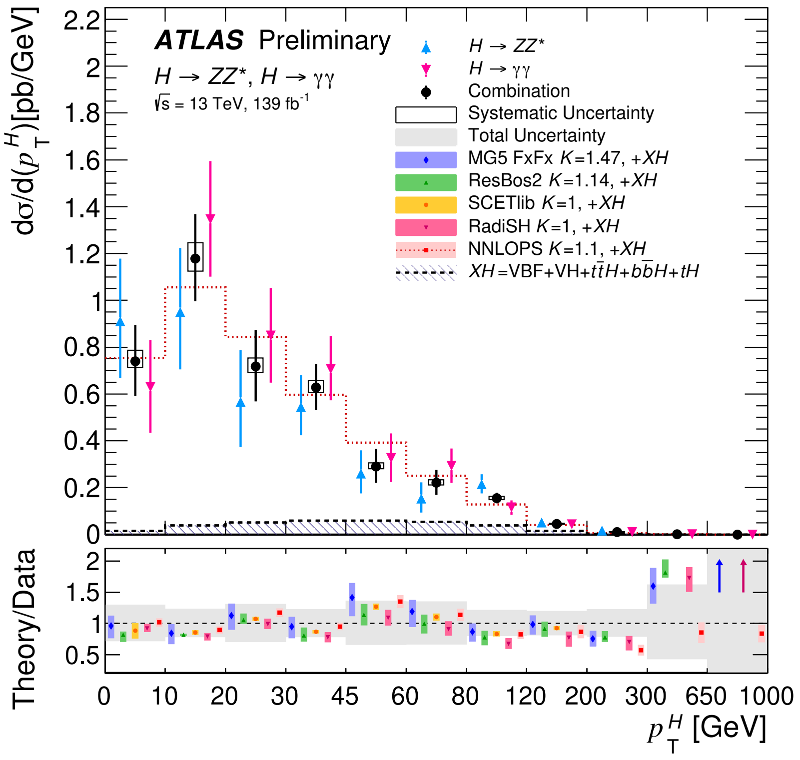


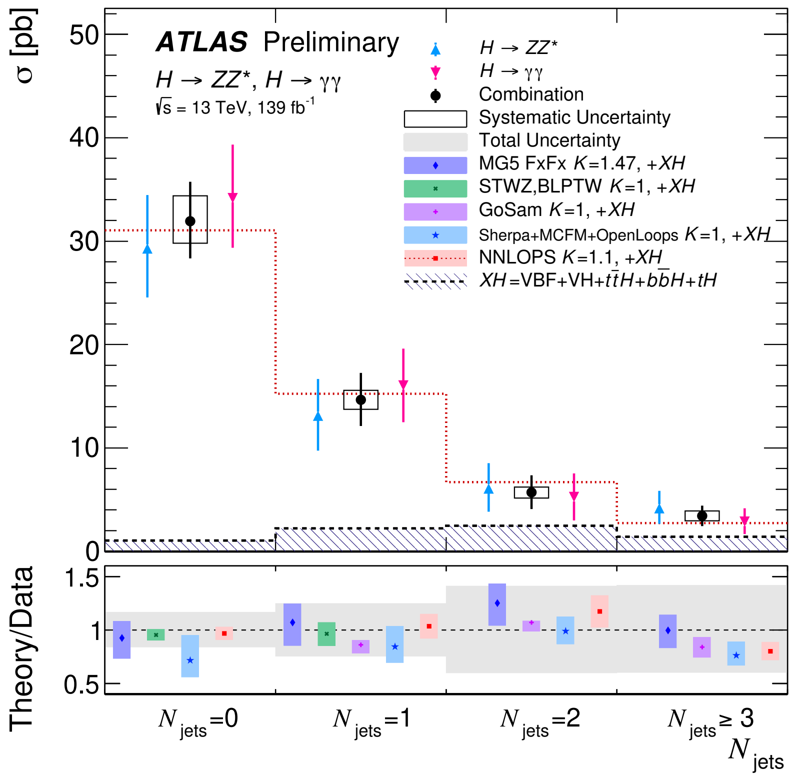


arXiv:2207.0033



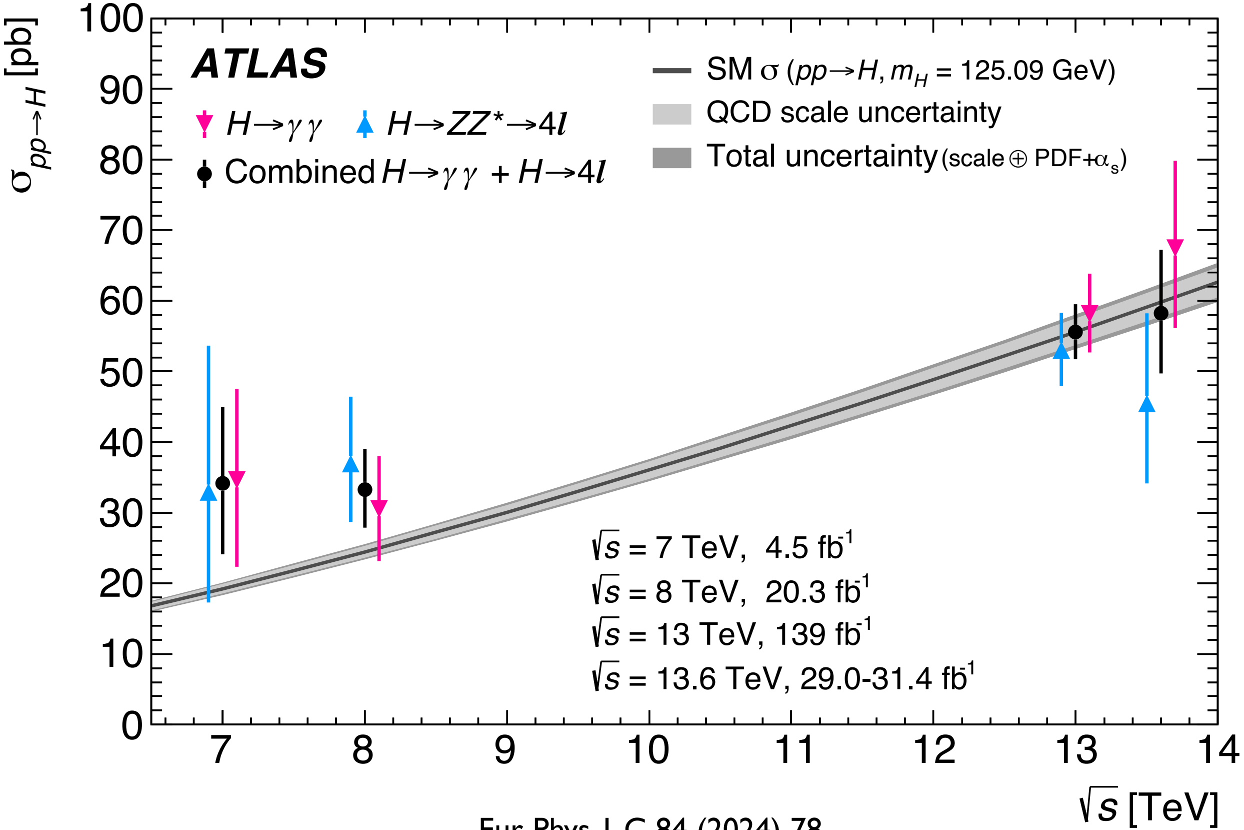
H → γγ and H → ZZ*: differential and fiducial cross-sections





ATLAS-CONF-2022-002

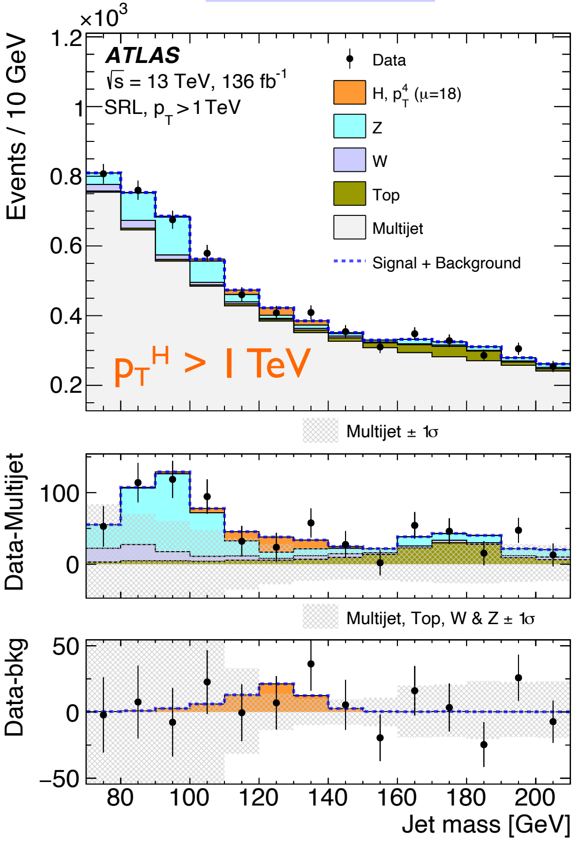
H → γγ and H → ZZ*: inclusive cross-sections



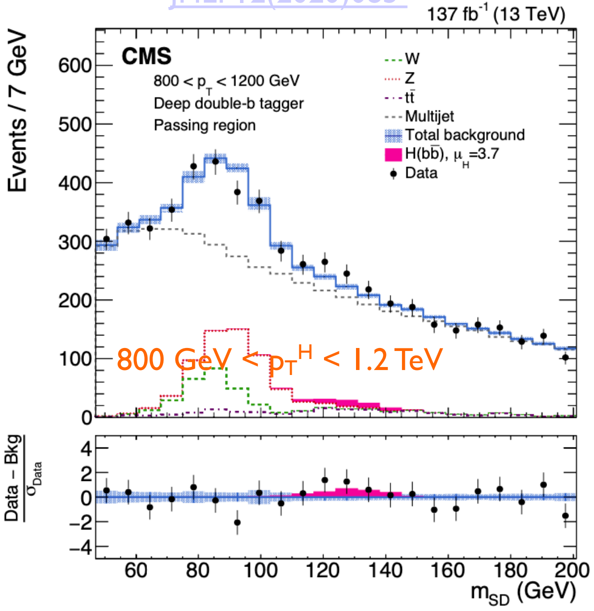
Eur. Phys. J. C 84 (2024) 78

Reaching the highest p_T^H with H→bb

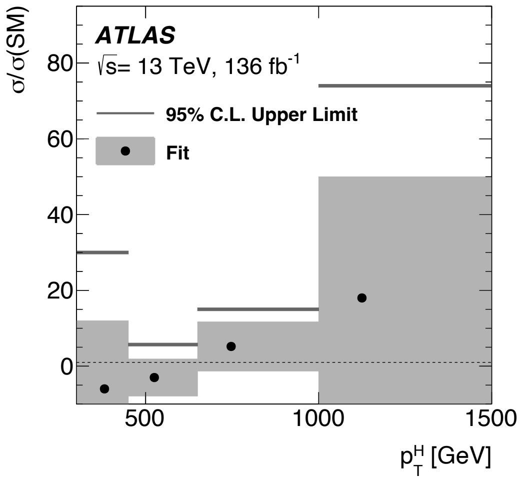
arXiv:2111.08340

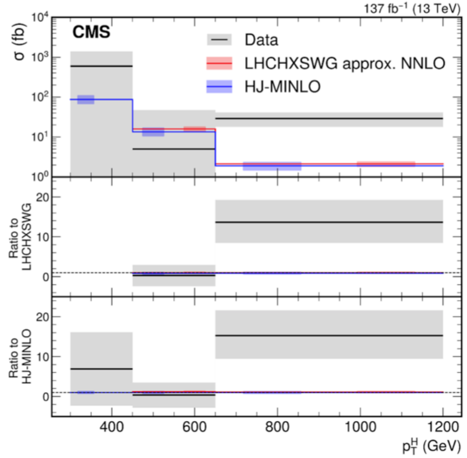


JHEP12(2020)085



- Jets substructure with 1 or 2 b-tags
- Fiducial cross-section (mostly ggF)
- Can be recasted as STXS
- Highest p_T^H most sensitive to BSM effects





Other rare Higgs decays within reach?

evd. = evidence

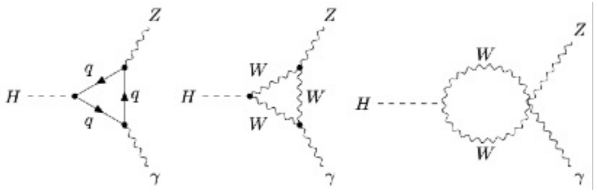
Analysis	Final states	13 TeV $\mathcal{L}$ [fb^{-1}]	BR (SM)	$\sigma_H \times$ BR(H decays)	ATLAS/CMS references
$c\bar{c}$		139, 35.9	2.9%	26 × SM, 70 × SM	**ATLAS-CONF-2021-021**, JHEP 03 (2020) 131
invisible		139, 35.9	~10^{-3}		ATLAS-CONF-2020-052, PLB 793 (2019) 520
$Z\gamma$	ee/μμ+γ	139, 35.9	~10^{-3}	**evd. μ = 1.5**, 3.9 × SM	**arXiv:2103.10322 (PLB 2021)**, JHEP 11 (2018) 152
$\mu^+\mu^-$		139, 137	~10^{-4}	2.2 × SM, **evd. μ = 1.19**	**PLB 812 (2021) 135980**, **JHEP 01 (2021) 148**
				BR(H decays)	
$\rho\gamma$	$\pi^+\pi^-\gamma$	35.6	~10^{-5}	8.8×10^{-4}	JHEP 07 (2018) 127
$\phi\gamma$	$K^+K^-\gamma$		~10^{-6}	4.8×10^{-4}	
$Z\rho$	ee/μμ + $\pi^+\pi^-$	137	~10^{-5}	$(1.04–1.31) \times 10^{-2}$	JHEP 11 (2020) 039
$Z\phi$	ee/μμ + K^+K^-	137	~10^{-6}	$(3–4) \times 10^{-3}$	
$Z\eta_c$	ee/μμ + had	139	~10^{-5}	(σ × BR =110 pb)	PRL 125 (2020) 221802
ZJ/ψ			~10^{-6}	(σ × BR =100 pb)	
$J/\psi\ \gamma$	$\mu^+\mu^-\gamma$	36.1, 35.9	~10^{-6}	3.5×10^{-4}, 7.6×10^{-4}	PLB 786 (2018) 134, EPJ C 79 (2019) 94
$\psi(2S)\gamma$		36.1	~10^{-6}	2.0×10^{-3}	PLB 786 (2018) 134
$\Upsilon(nS)\gamma$ (n=1,2,3)		36.1	~10^{-9}	$(4.9, 5.9, 5.7) \times 10^{-4}$	
$\Upsilon\Upsilon$	4μ	37.5	~10^{-9}	1.4×10^{-3}	PLB 797 (2019) 134811
$J/\psi\ J/\psi$			~10^{-10}	1.8×10^{-3}	
e^+e^-		139	~10^{-9}–10^{-10}	3.6×10^{-4}	PLB 801 (2020) 135148

BR (SM): + (top) to − (bottom)

Imma Riu @ LHCP 2021

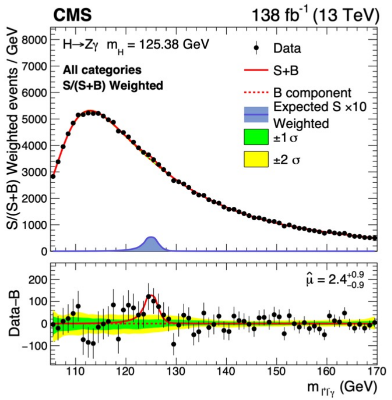
Other rare Higgs decays within reach?

- $SU(2)_L$ symmetry relates the HWW, HZZ, Hγγ and HZγ interactions
  - ✓ If New Physics respects $SU(2)_L$, effect correlated in all four channels
  - ✓ Important to observed and measure also H→Zγ

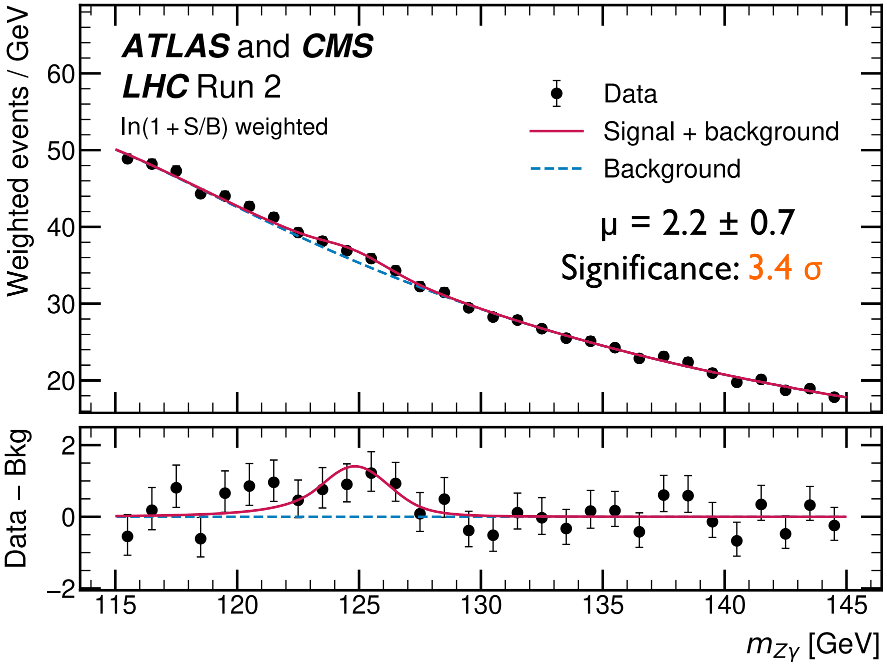


Phys. Rev. Lett. 132 (2024) 021803

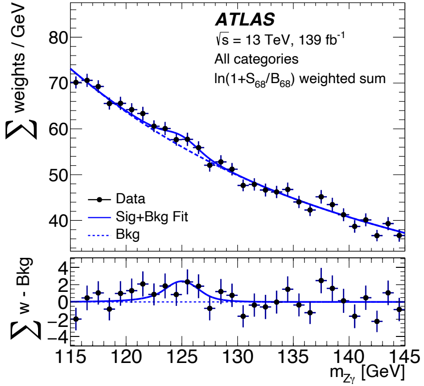
JHEP 05 (2023) 233



μ = 2.4 ± 0.9
Significance: 2.7 σ
(1.2 expected)



Phys. Lett. B 809 (2020) 135754



μ = 2.0 ± 0.9
Significance: 2.2 σ
(1.2 expected)

How well *should* we know the Higgs couplings?

SMALL CORRECTIONS EXPECTED IN MANY BSM MODELS

If new physics is at 1 TeV:

	$\delta\kappa_V$	$\delta\kappa_b$	$\delta\kappa_\gamma$
Singlet	<6%	<6%	<6%
2HDM (large t_β)	~1%	~10%	~1%
MSSM	~.001%	~1.6%	~-.4%
Composite	~-3%	~-(3-9)%	~-9%
Top Partner	~-2%	~-2%	~1%

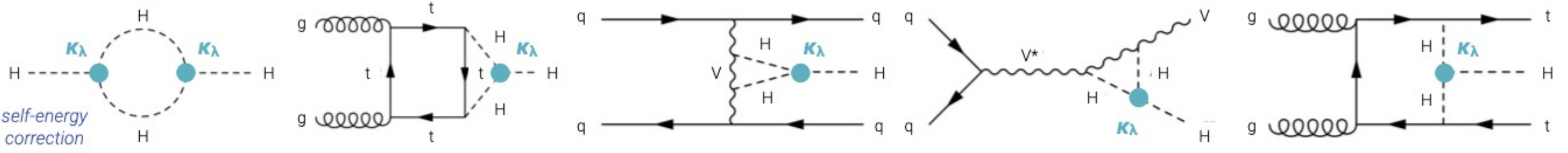
Patterns of deviations can pinpoint specific BSM physics

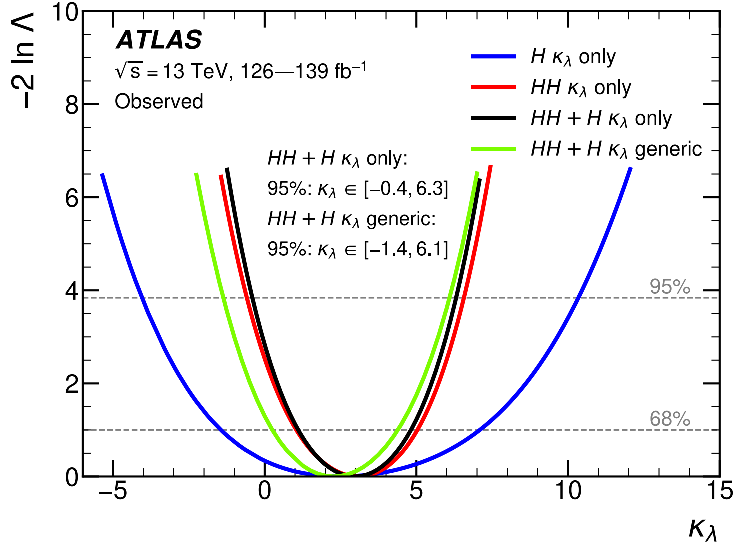
- Generically new physics effects on couplings $\sim \frac{v^2}{M^2} \sim \mathcal{O}(6\%)$ for M=1 TeV
- Only now are we approaching sensitivity where we expect deviations

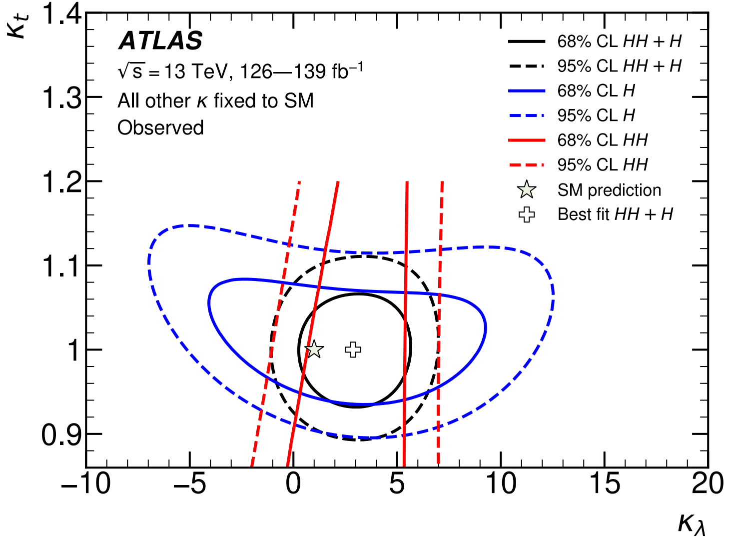
Sally Dawson

More tools at hand! Constraining κ_λ with single-Higgs

- Single Higgs boson productions and decays as well as kinematics sensitive to the self-coupling through EW corrections





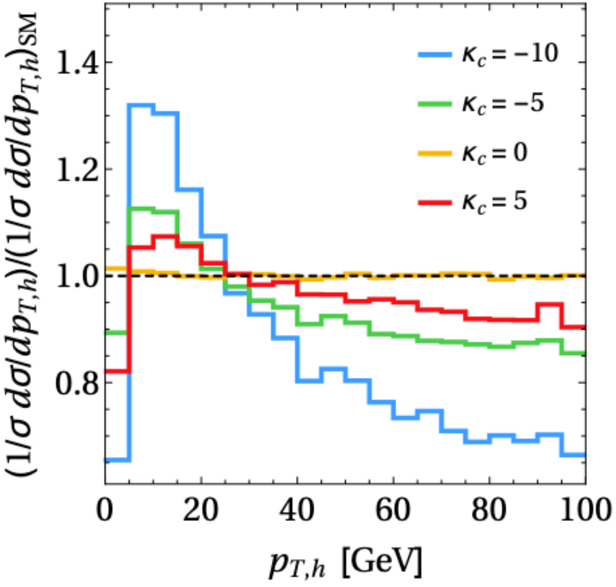


arXiv:2211.01216

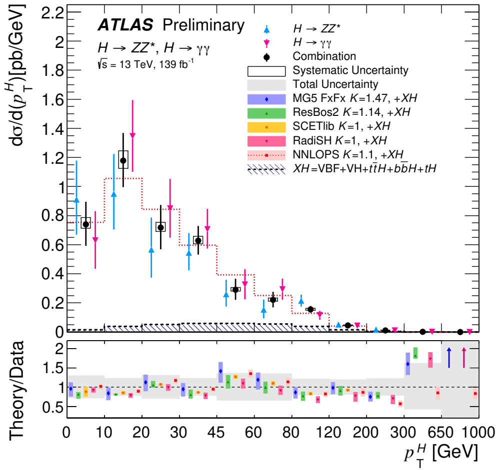
Direct H→cc search is not the only tool…

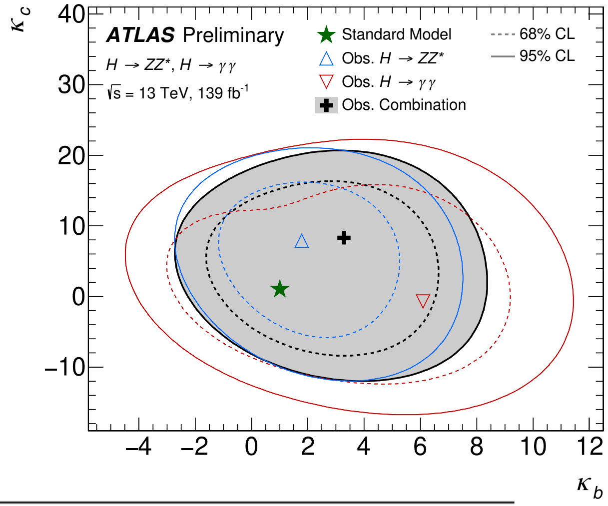
- Charm quark contributes to ggF loop, modification to Higgs-charm coupling can alter p_T^H
- Analogous effect on quark-initiated production of the Higgs boson
- Shape of differential p_TH cross-section can be interpreted in term of Higgs-charm coupling

arXiv:1606.09253



ATLAS-CONF-2022-002



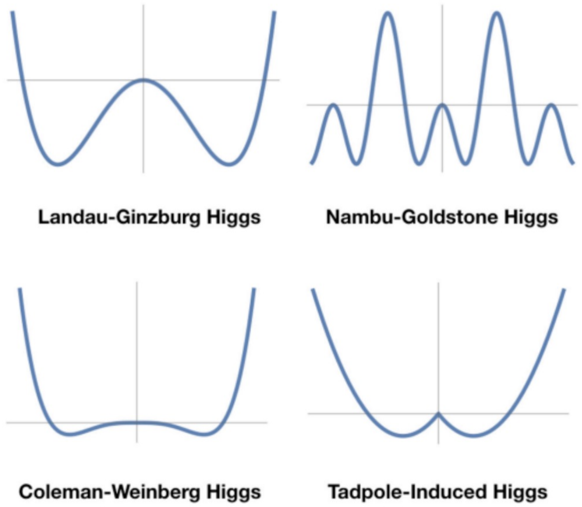


Channel	Parameter best-fit	Observed 95% confidence interval	Expected 95% confidence interval
Combined	$\kappa_b = 3.3^{+2.4}_{-4.1}$	$[-2.1,\ 7.4]$	$[-2.2,\ 7.4]$
	$\kappa_c = 8.3^{+5.5}_{-13.8}$	$[-10.1,\ 18.3]$	$[-10.3,\ 16.6]$

Is it the Standard Model Higgs potential?

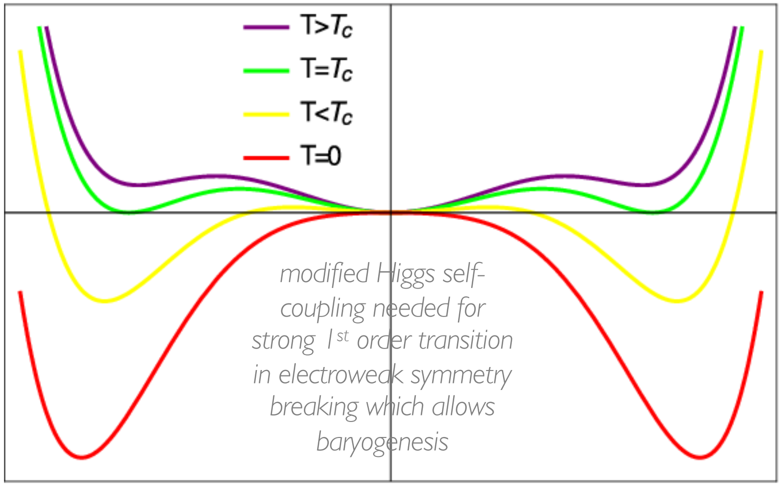
- How the Higgs potential is realized in Nature can provide important answers to many open points in our understanding of Nature…
  - ✓ e.g. BSM scenarios of Higgs sector, electroweak phase transition in the SM, baryogenesis…

Different models predicts different potential shape



Phys. Rev. D 101, 075023 (2020)

Evolution of Higgs potential could explain matter/antimatter asymmetry via electroweak baryogenesis



arXiv:1511.03969

Higgs at FC-ee

L = 5 ab^{-1}

ZH = 10^6

VBF = 2×10^4

L = 1.5 ab^{-1}

ZH = 2.5×10^5

VBF = 5×10^4