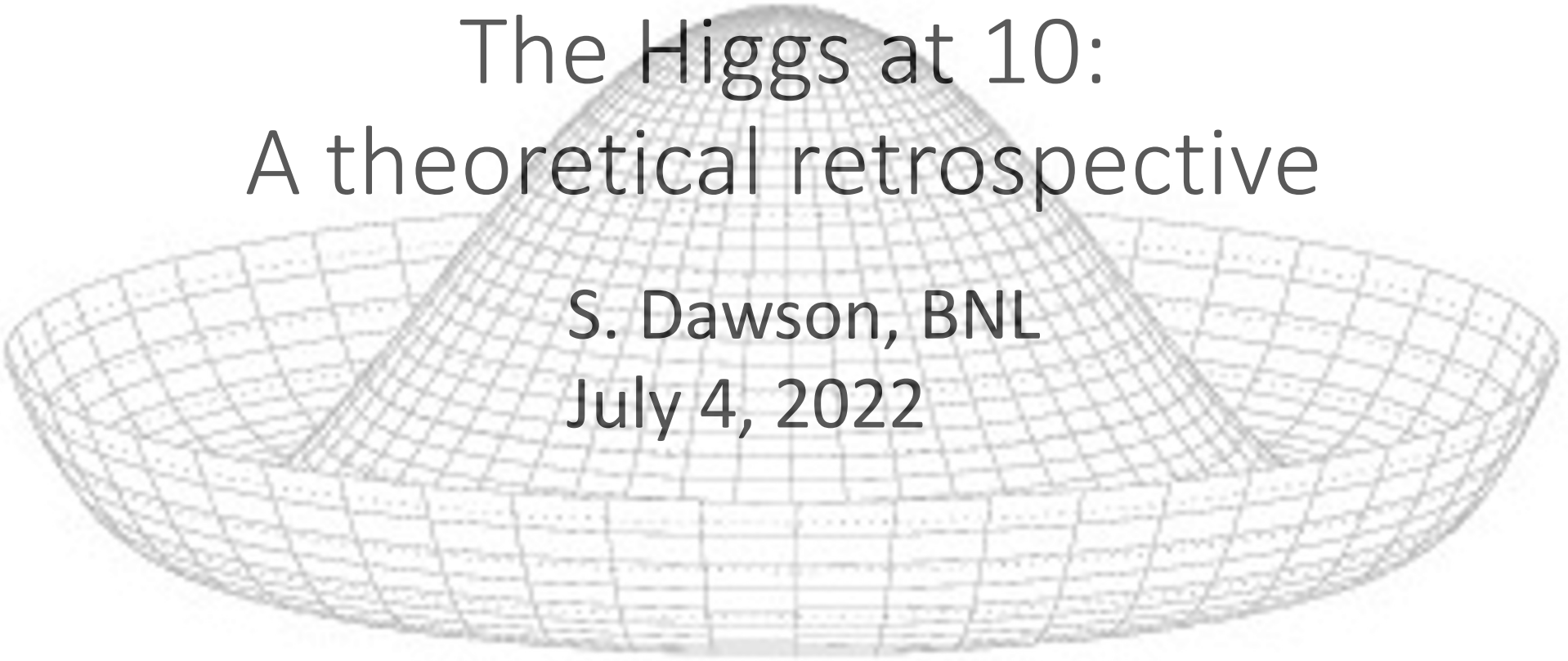


# The Higgs at 10: A theoretical retrospective

S. Dawson, BNL

July 4, 2022

# A Long Journey

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)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
*Tait Institute of Mathematical Physics, University of Edinburgh, Scotland*

Received 27 July 1964

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)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

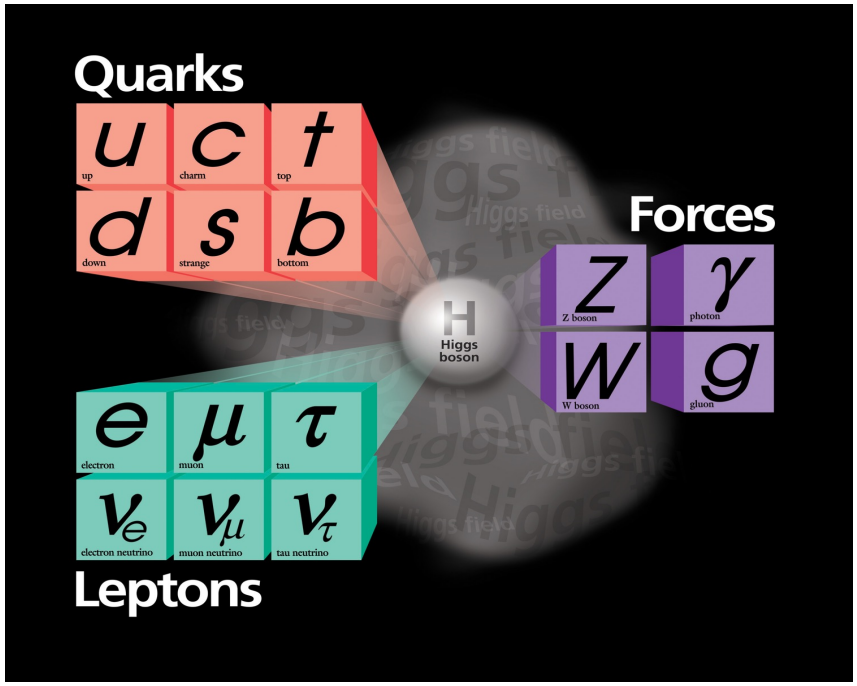
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

The idea of symmetry still guides search for new physics

# Why is the Higgs Boson so Important?

A well understood and well tested model

Model doesn't make sense without Higgs or something like it




*STANDARD MODEL*

The Higgs is a scalar particle whose interactions with other particles are predicted in terms of the Higgs mass

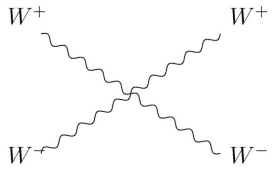
# First Study of the Higgs, 1976

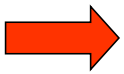
- The beginning of Higgs phenomenology

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

# Unitarity, 1977

- We did know something about the Higgs mass
- Either $M_H < 800$ GeV or perturbative unitarity violated around 3 TeV



Cross sections grow with energy without Higgs

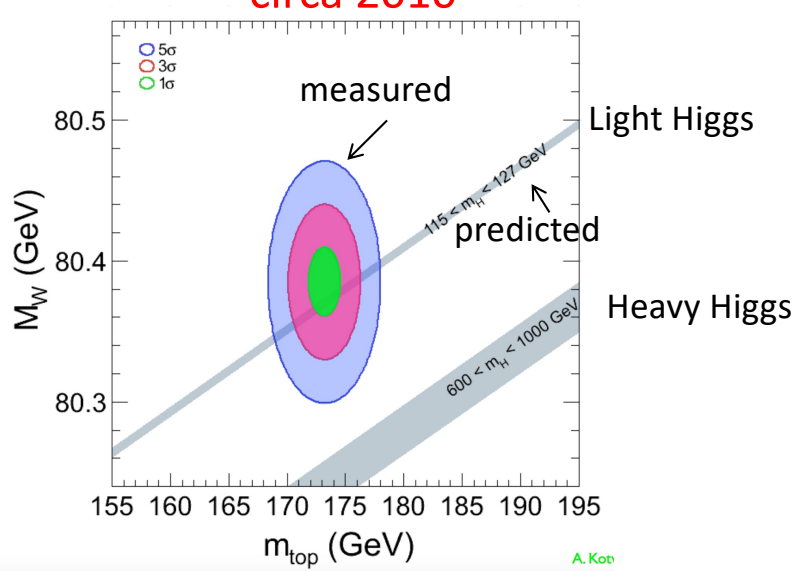
- Led to the powerful idea of a ”no-lose” theorem
- “The LHC had to find a Higgs or something else at an accessible scale”

Lee, Quigg, and Thacker

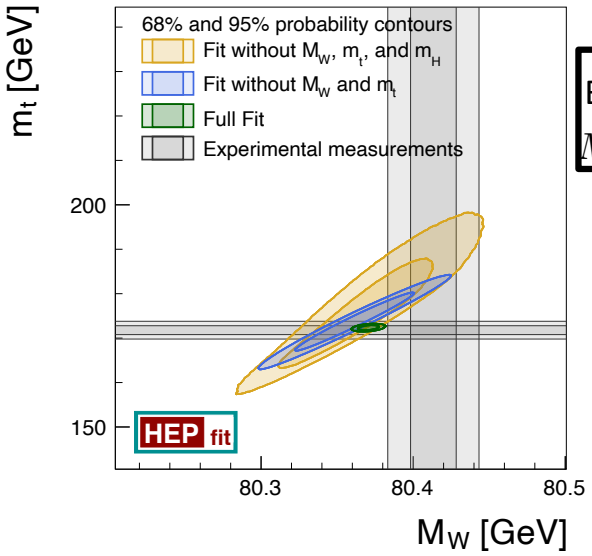
# The Power of Quantum Effects

- *Before* the Higgs discovery, we had evidence of its existence from quantum corrections ***if*** Standard Model is full theory

*circa 2010




2022

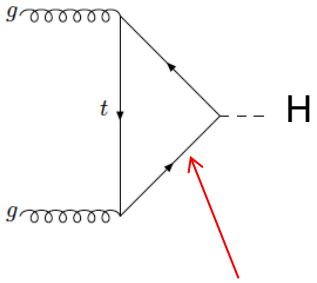



Blue is fit with measured $M_H = 125.21 \pm .12\ GeV$

Precision gives information on BSM physics

2204.04204

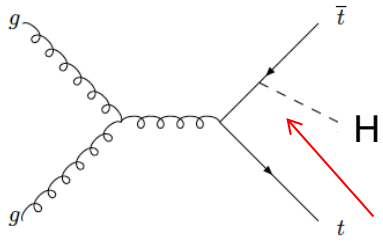
# Higgs Production at a Hadron Collider



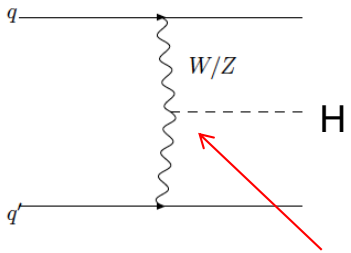

May include new physics in loop

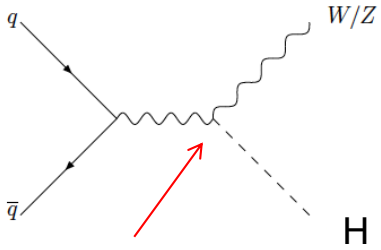
Most important processes:

$$gg \to H$$
$$q\bar{q} \to q\bar{q}H$$
$$q\bar{q} \to ZH, WH$$
$$gg \to t\bar{t}H$$




Direct measurement of ttH Yukawa



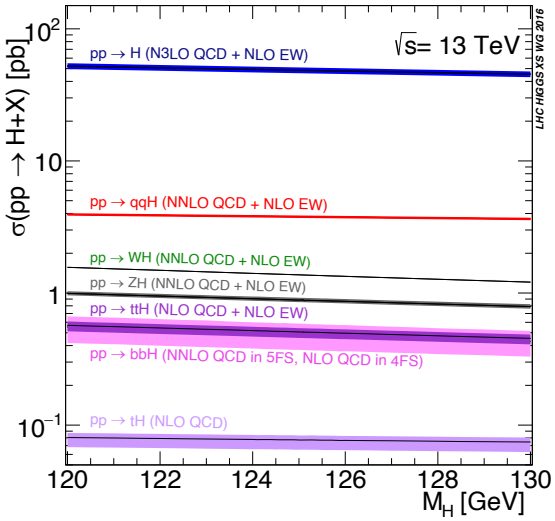



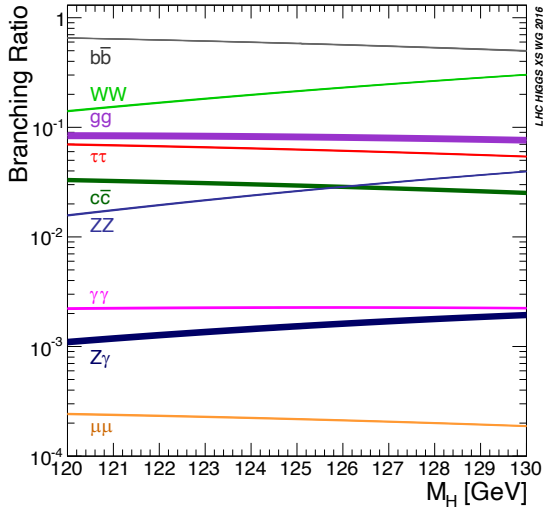

Vanishes if v=0: Fundamental test of EWSB mechanism

All these channels observed

Different signatures and backgrounds

# Beyond the Standard Model: Look for deviations from predictions




Many decay channels accessible for 125 GeV Higgs

Many of the most precise calculations done after the Higgs discovery

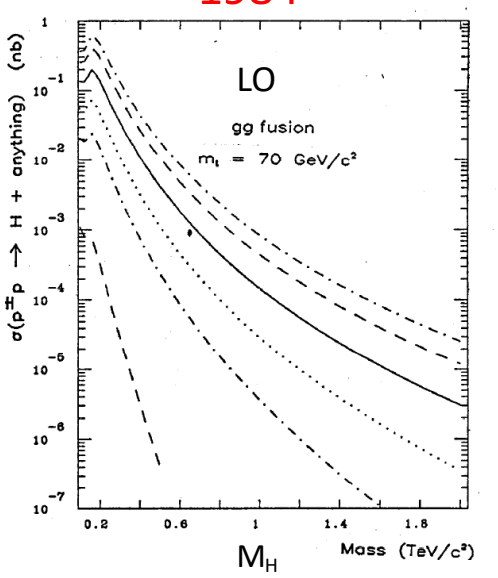
Note NNLO QCD + NLO EW is the new norm

Higgs Cross Section Working Group

# Precision physics at a Hadron Collider

- Can you do precision physics at a hadron collider? YES!

1984

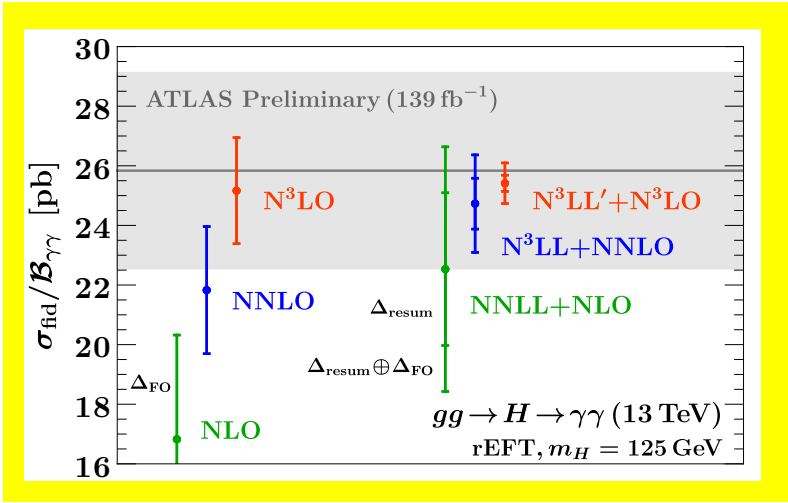



√S=2,10,20,40,70,100 TeV

EHLQ

Major lesson from last 10 years at LHC: Higgs physics is precision physics

2021

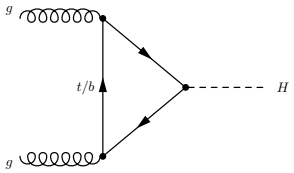



Fiducial cross section to N³LO + N³LL'
→ Uncertainty ~O(3%)

2102.08039

# Theory Critical for Interpreting Data

- Calculation of Higgs production from gluon fusion to N$^3$LO required:
  - New analytic and mathematical techniques
  - New computational techniques
  - Surprisingly large corrections to gluon fusion production




LO NLO NNLO N$^3$LO

100% increase

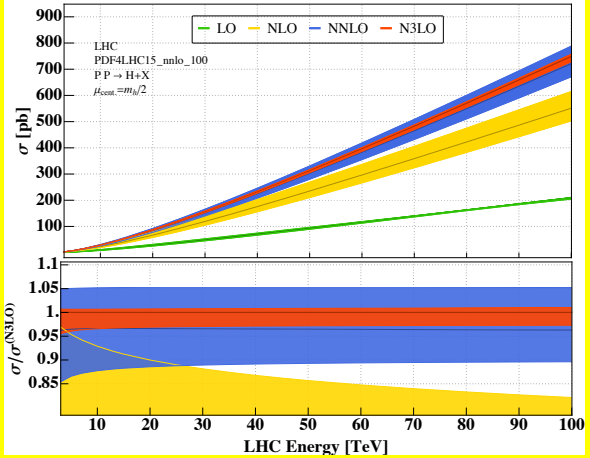
20% increase

2% increase

1977 → 1995 → 2002 → 2015

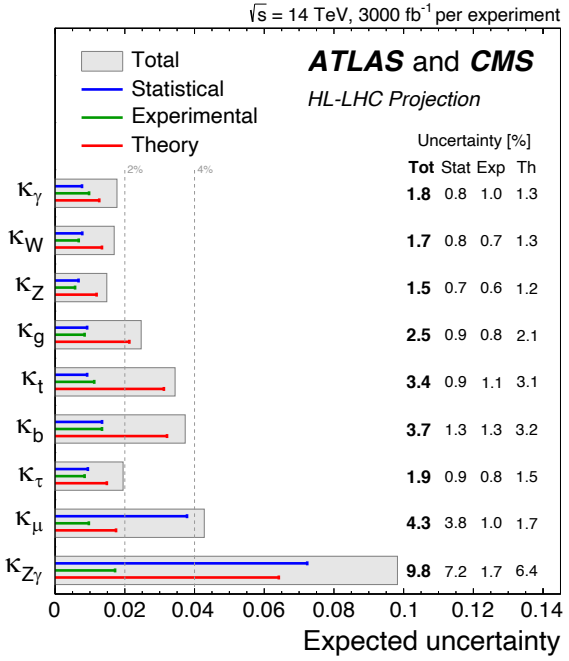
# It’s all about the uncertainties

Gluon fusion production of Higgs




Bands are uncertainties at different orders

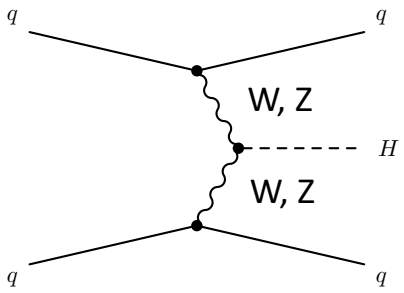
More work needed so that theory uncertainties do not limit understanding of Higgs measurements, despite immense theory progress

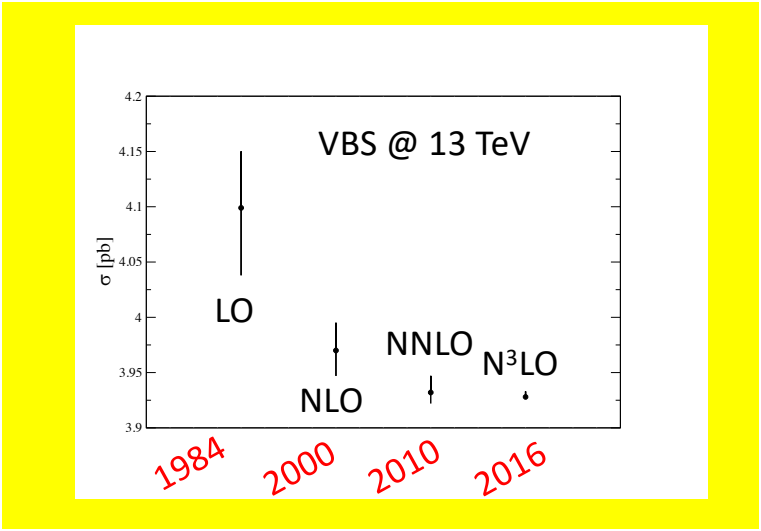



2203.13923

# Vector boson scattering

- The W can be thought of as a parton in the proton, 1984
- Distinctive signature of forward jets




Precise measurement of Hττ coupling, and anomalous gauge boson couplings

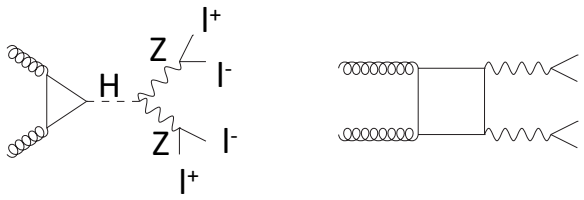
Impressive reduction of theory uncertainties

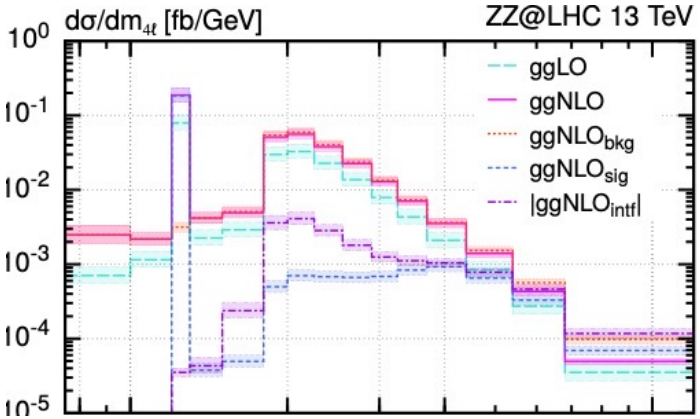
Differential distributions at NNLO known

1606.00840

# Measuring the Higgs width

- 2010: Theorists: “It can’t be done at the LHC”
- 2012-2013: Theorists: "Maybe it can be done at the LHC” through off-shell interference effects
- 2022: CMS measurement



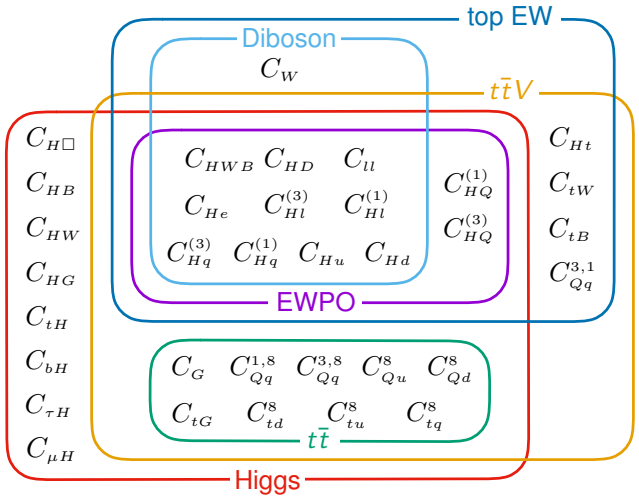




* Lots of theory assumptions

2102.08344

# After discovery

- 2012: Higgs deviations as scaling of SM predictions (κ framework)
  - Higgs measurements as independent results
- 2022: Higgs is part of the big picture
  - Higgs, top, diboson, precision electroweak measurements are all connected by theory
  - Global fits to different types of data will be needed to get the maximum information
  - Growing coordination between theorists and experimentalists



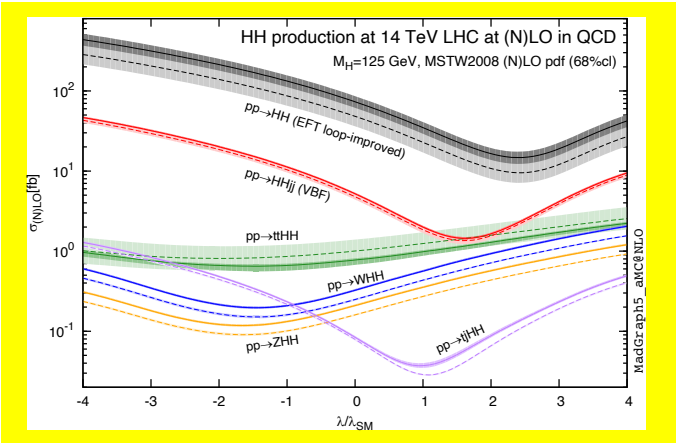

LHC EFT WG

# We haven't verified shape of the Higgs potential

Crucial for making sure SM picture is correct

$$V = \frac{M_H^2}{2} H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

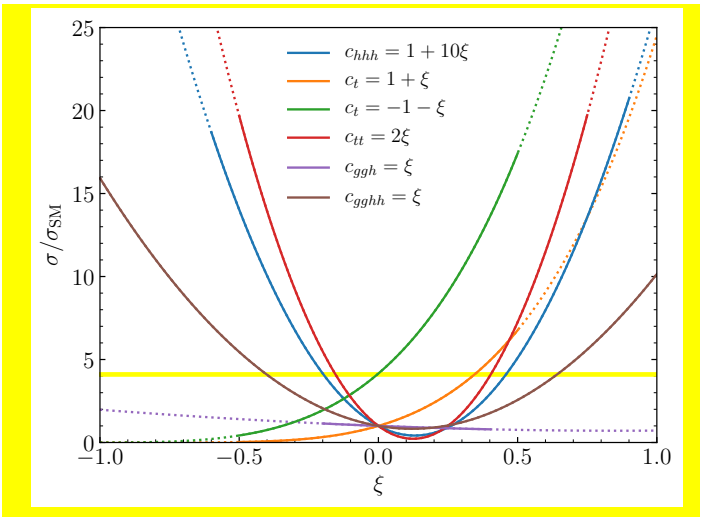
2012: Look for variations in Higgs trilinear coupling




NLO(approx), no $M_t$ effects

1401.7340

2022: Look for variations in Higgs trilinear coupling along with other possible coupling variations




NNLO (approx) +NLO with $M_t$ effects

2106.14050

# The Future

- LHC has gone from discovery to precision Higgs physics
- Interplay of theory and experiment will be even more important in the future
- In order to match experimental precision on Higgs measurements, a continuing program of theory calculations is essential
- Precision Higgs physics is telescope to high scale physics

Apologies! Many crucial theory advances in the last 10 years not mentioned here