Review and Prospects of Higgs Physics from CMS

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July 4th On-Line Workshop

Celebration of the discovery of the Higgs boson Anniversary from Africa

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  A day to remember
- A Higgs particle in Run-1:
  First contact with an entirely new particle
- A Higgs particle in Run-2:
  Completing the Higgs pattern
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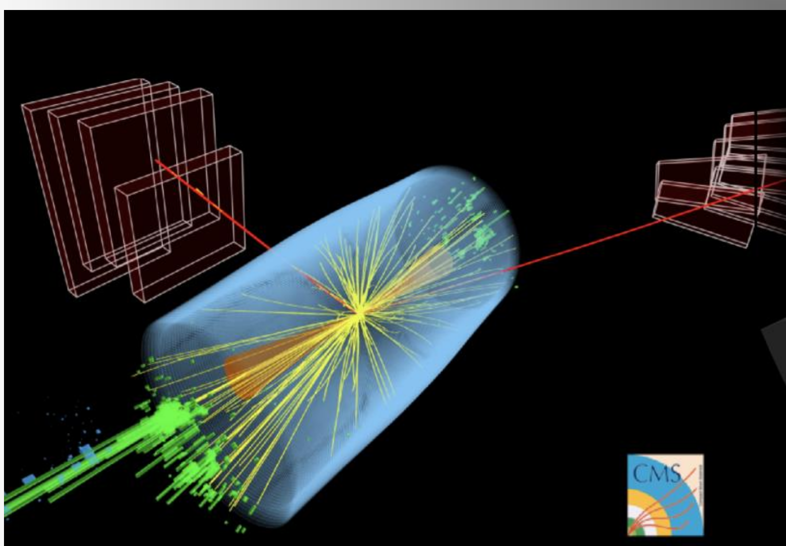
  Quo Vadis Higgs?

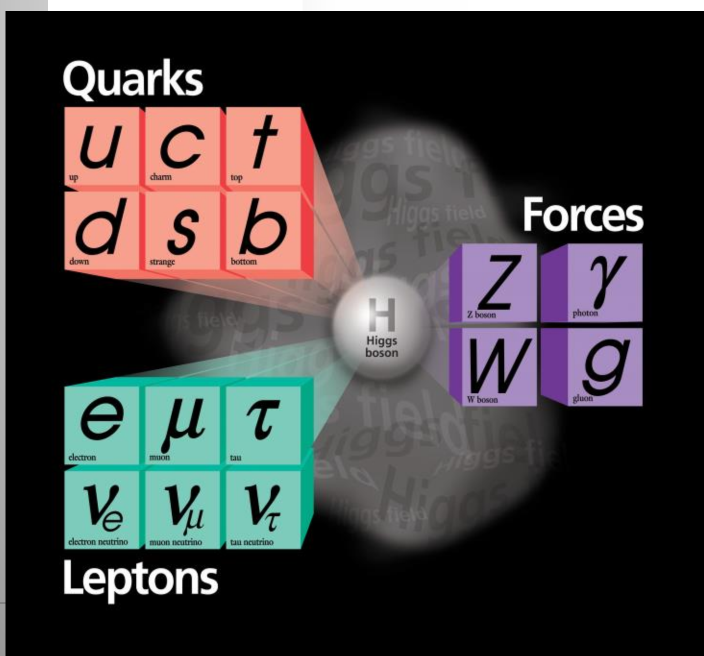


The "Standard Model"

Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics.
The new (final?) "Periodic Table" of fundamental elements:

Fermions   Bosons

Matter particles



Force particles

The most basic mechanism of the SM, that of granting mass to particles remained a mystery for a long time
A major step forward was made in July 2012 with the discovery of what could be the long-sought Higgs boson!!

Fermions: particles with spin ½
Bosons: particles with integer spin

The Hunt for the Higgs

Where do the masses of elementary particles come from?

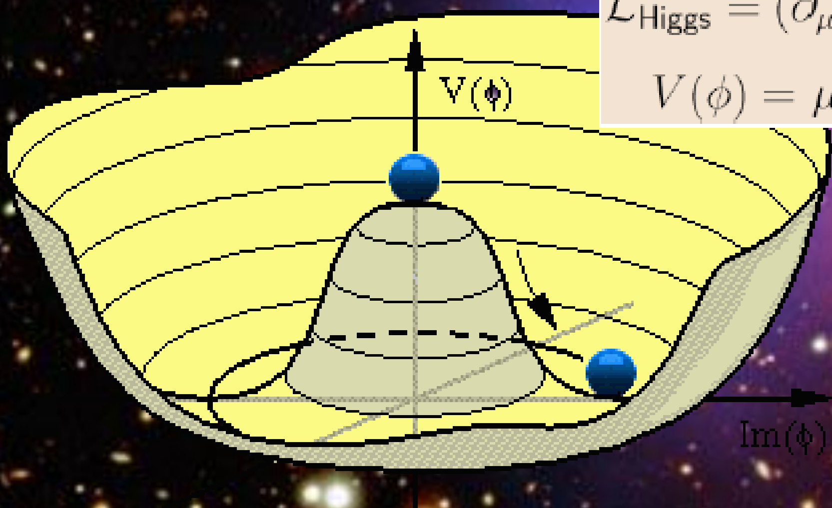
The key question (pre-2012): Does the Higgs particle exist? If so, where is the Higgs?

Massless particles move at the speed of light -> no atom formation!!

We do not know the mass of the Higgs Boson

$$\mathcal{L}_{\text{Higgs}} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

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

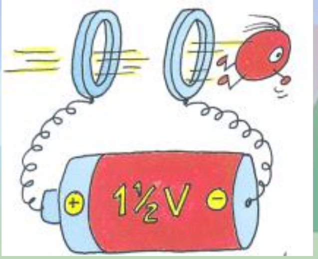


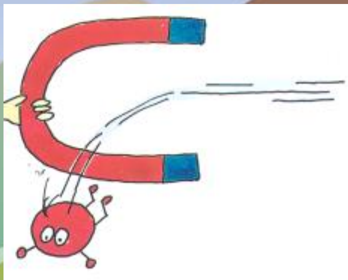
Scalar field with at least one scalar particle

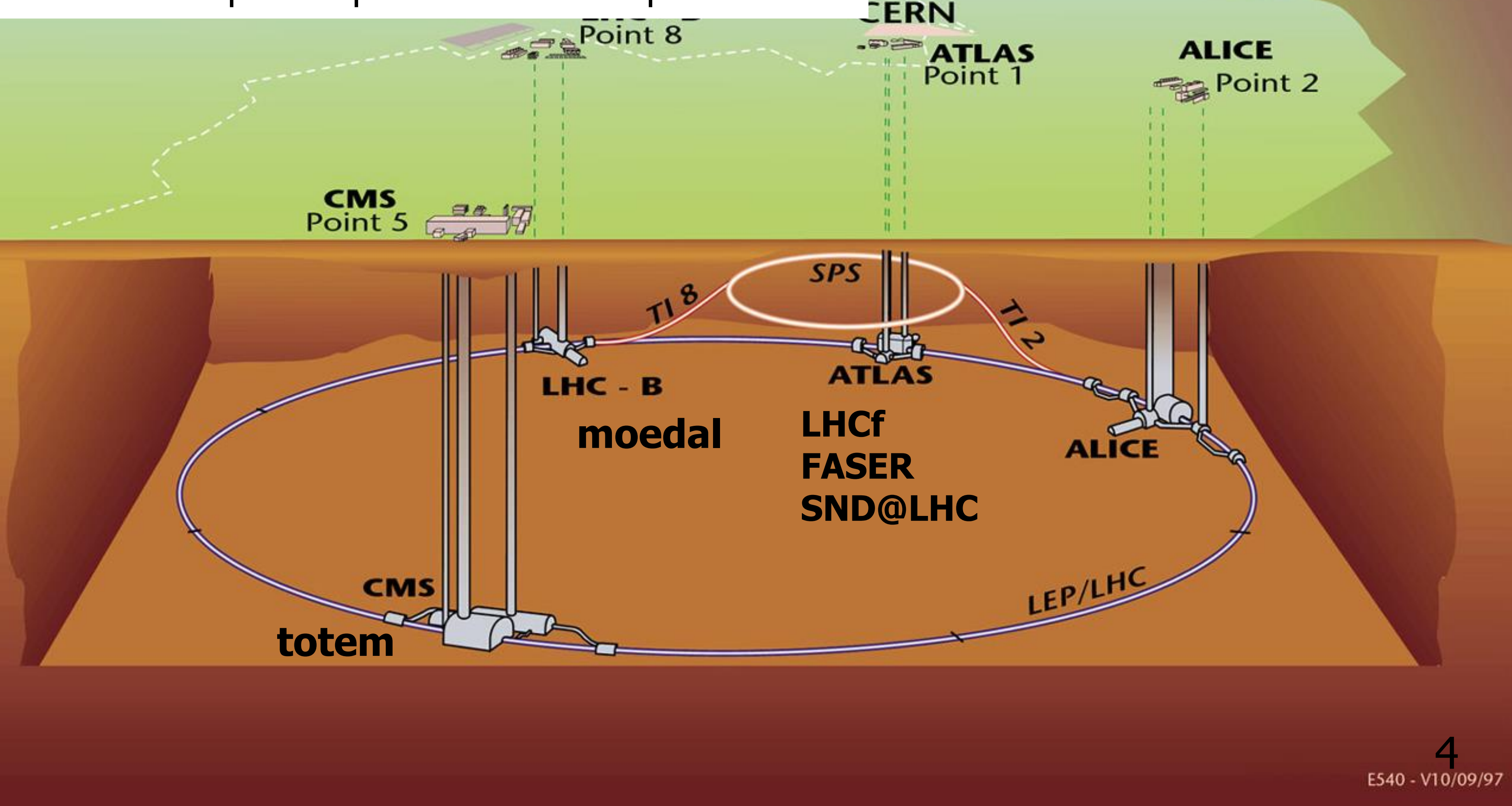
It could be anywhere from 114 to ~700 GeV

The LHC Machine and Experiments

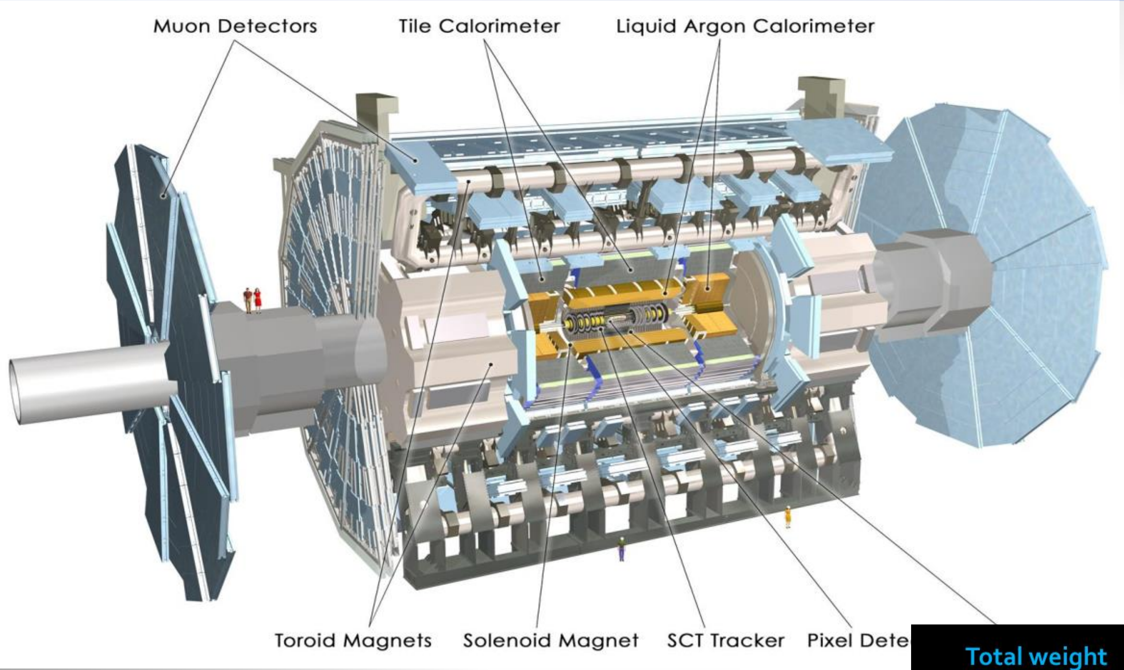
LHC is 100m underground
LHC is 27 km long
Magnet Temperature is 1.9 Kelvin = -271 Celsius
LHC has ~ 9000 magnets
LHC: 40 million proton-proton collisions per second



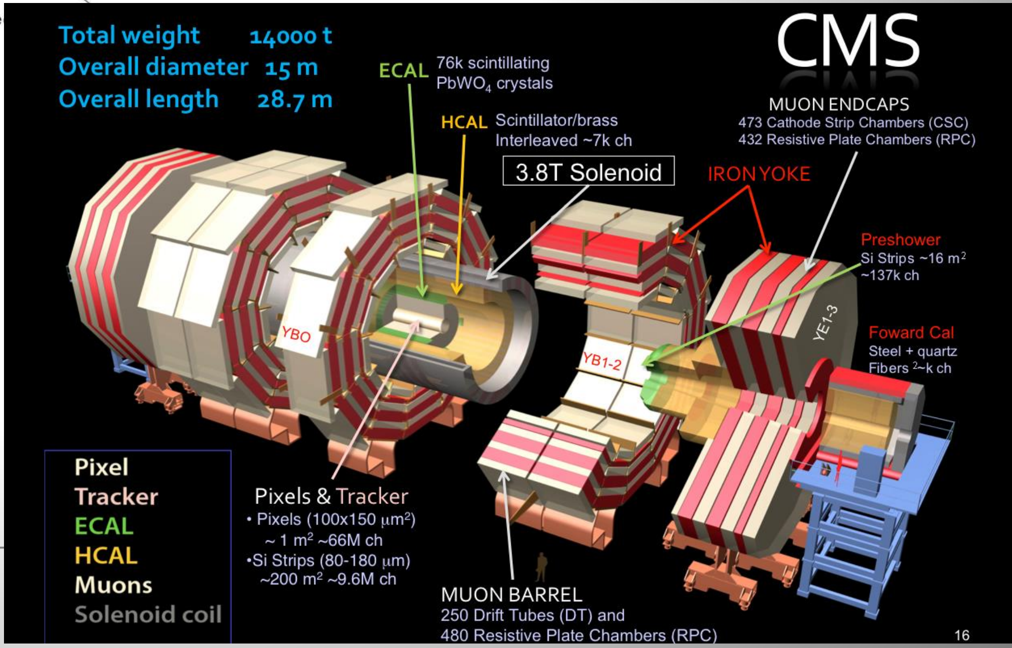




Higgs Hunters @ the LHC



The ATLAS experiment

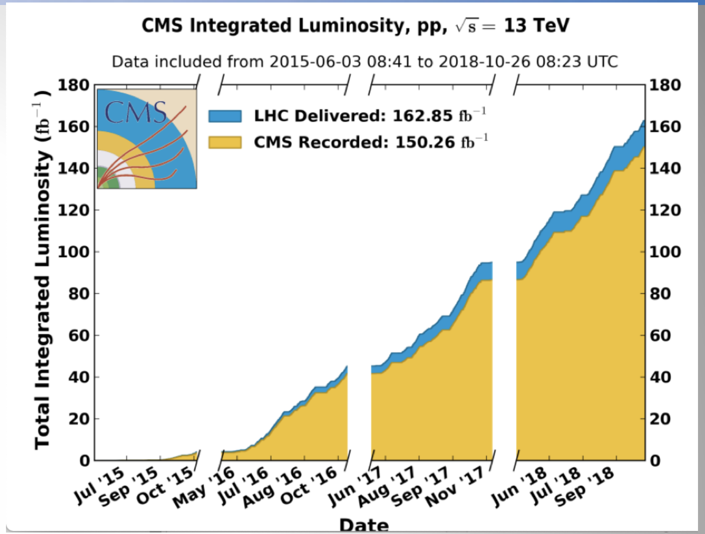


The CMS experiment

LHC Operations

pp Run-2 was finished on 24/10/18 6:00am

- 2010-2012: Run-1 at 7/8 TeV CM energy
  - Collected ~ 25 fb^{-1}
- 2015-2018: Run-2 at 13 TeV CM energy
  - Collected ~ 140 fb^{-1}



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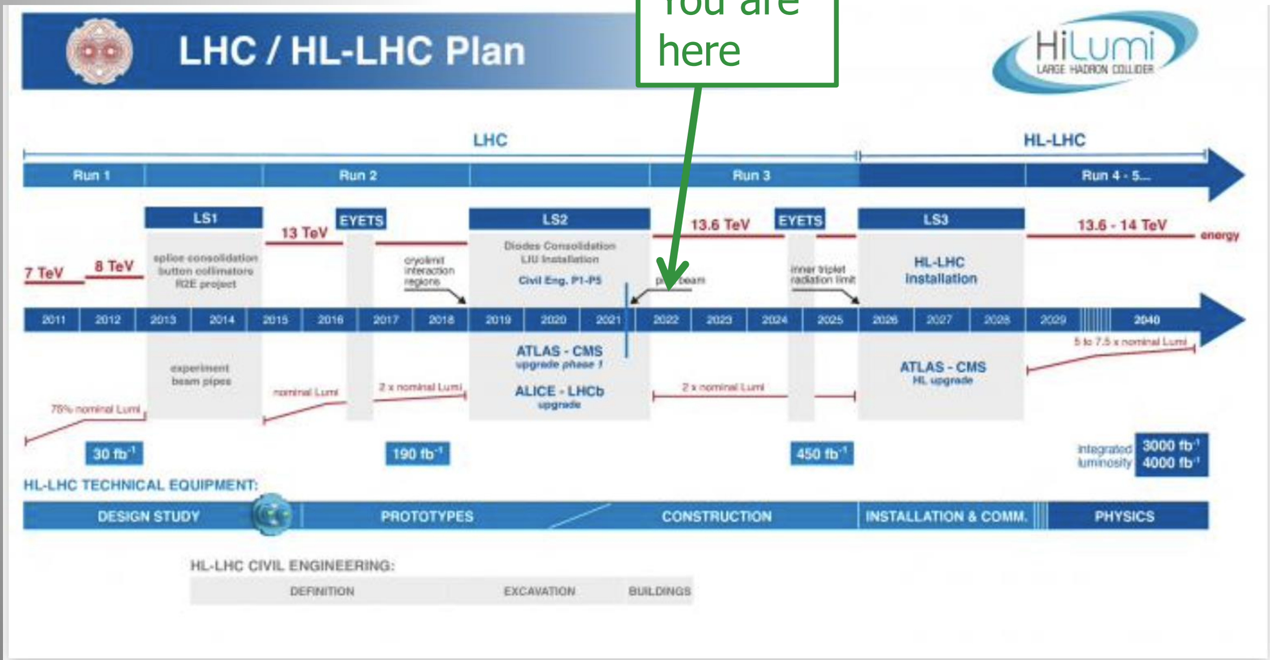


LHC is restarting after more than 3 years

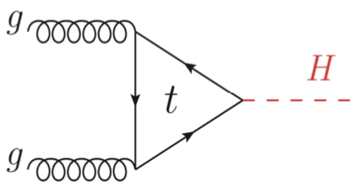
Expect >250 fb^{-1} by 2025 in Run-3 at 13.6 TeV CM energy.

Run-3 starts on 5/7 !!

Followed by HL-LHC: 3000 fb^{-1} per exp.

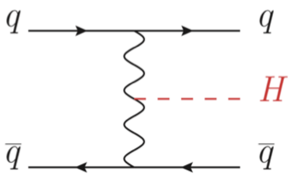
Higgs Production and Decay Processes

Production rates at Run 2 (13 TeV) for ~150 fb^{-1}



Gluon fusion process

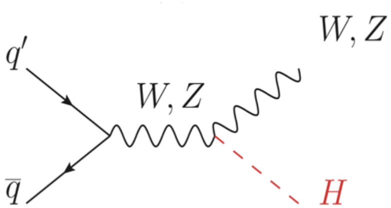
~8 M events produced



Vector Boson Fusion

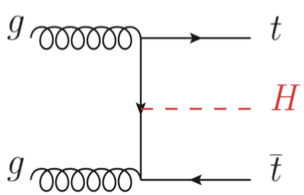
Two forward jets and a large rapidity gap

~600 k events produced



W and Z Associated Production

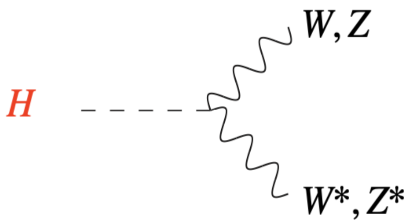
~400 k events produced



Top Assoc. Prod.

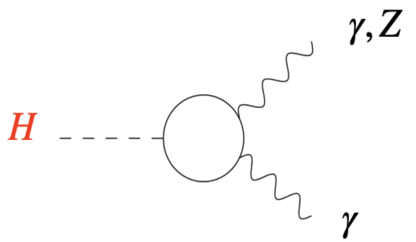
~80 k evts produced

Decay branching fractions



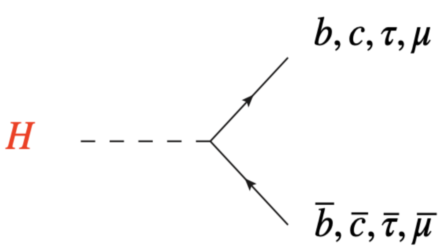
$\mathrm{Br}(H \rightarrow WW^*) = 22\,\%$

$\mathrm{Br}(H \rightarrow ZZ^*) = 3\,\%$



$\mathrm{Br}(H \rightarrow \gamma\gamma) = 0.2\,\%$

$\mathrm{Br}(H \rightarrow Z\gamma) = 0.2\,\%$



$\mathrm{Br}(H \rightarrow b\bar{b}) = 57\,\%$

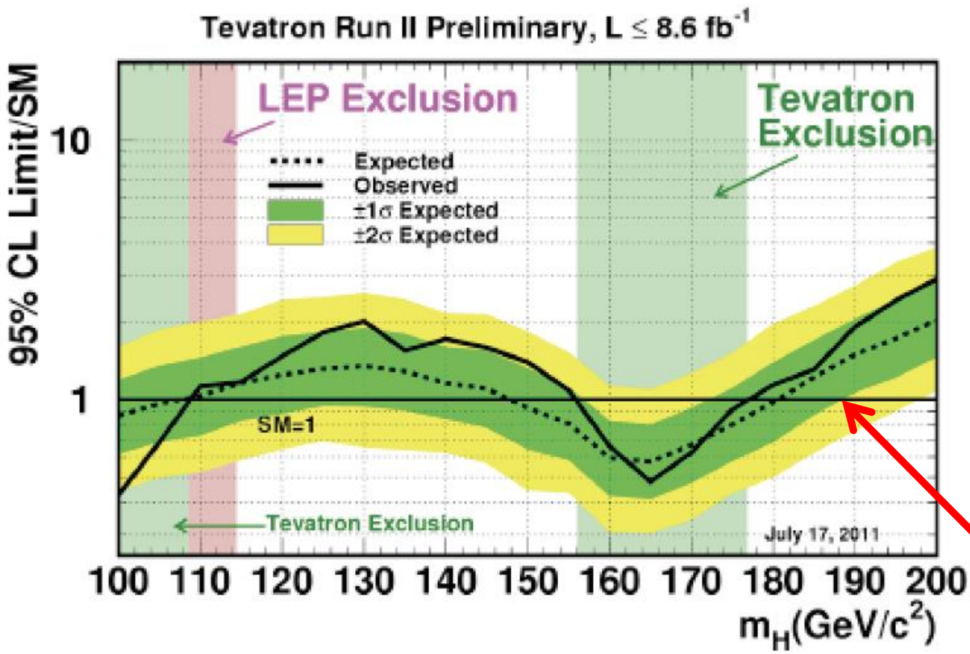
$\mathrm{Br}(H \rightarrow \tau^+\tau^-) = 6.3\,\%$

$\mathrm{Br}(H \rightarrow c\bar{c}) = 3\,\%$

$\mathrm{Br}(H \rightarrow \mu^+\mu^-) = 0.02\,\%$

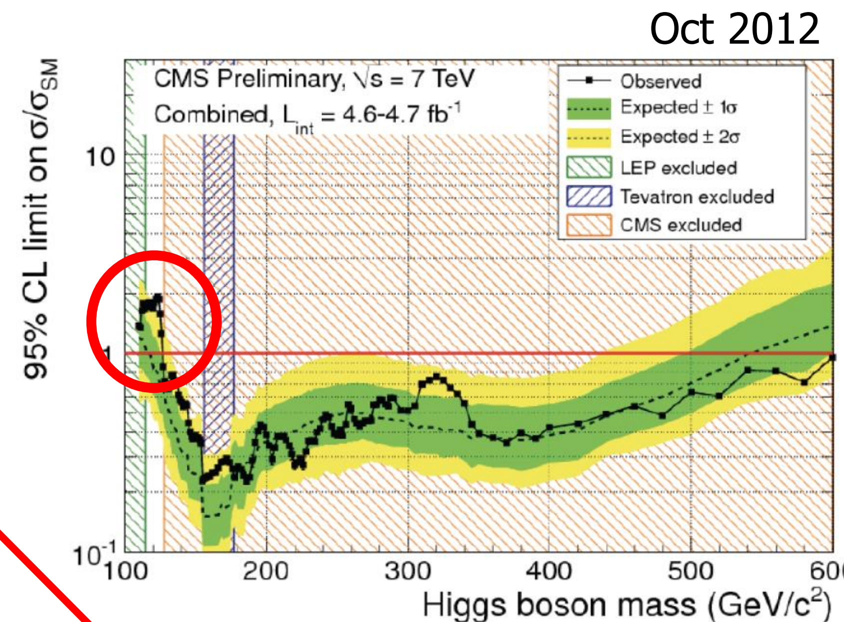
The Search for Higgs in 2011

Before the LHC



The LHC in 2011

Oct 2012



- Direct searches
  - LEP: $M_H > 114.4$ GeV
  - Tevatron: 156 GeV < M_H <176 GeV
- Indirect limits from electroweak searches
  - $M_H = 96^{+31}_{-24}$ GeV, M_H<169 GeV at 95% CL (standard fit)
  - $M_H = 120^{+12}_{-5}$ GeV ,M_H<143 GeV at 95% CL (including direct searches)
- SUSY prefers light Higgs boson (<~140 GeV)

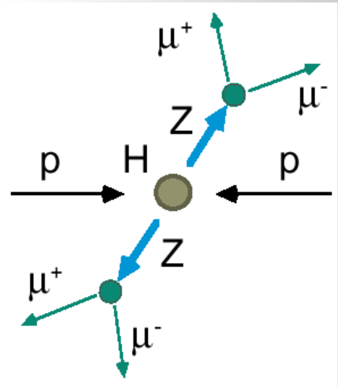
Closed all mass space for a SM Higgs except for the region 114.5-127 GeV This region "refuses to be excluded" with 2011 data and shows a slight excess. What will 2012 data say?

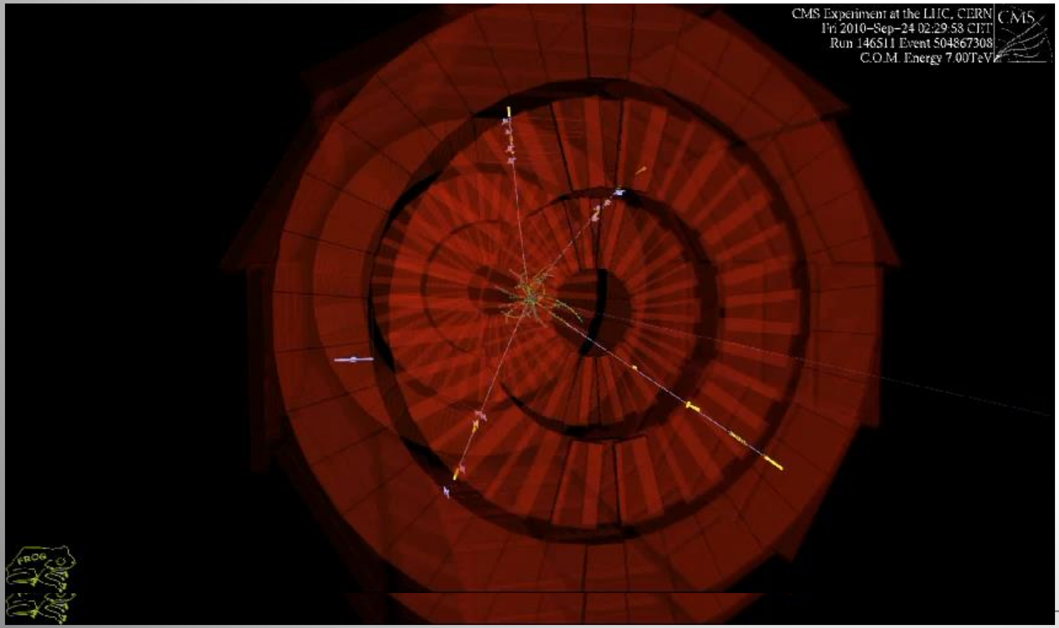
July 4th 2012

Example: H$\rightarrow$ ZZ$\rightarrow$ Four Leptons

A Higgs particle will decay immediately, eg in two heavy Z bosons
-> Select Z decays into electron or muon pairs

Eg we look for 4 muons
in the detector



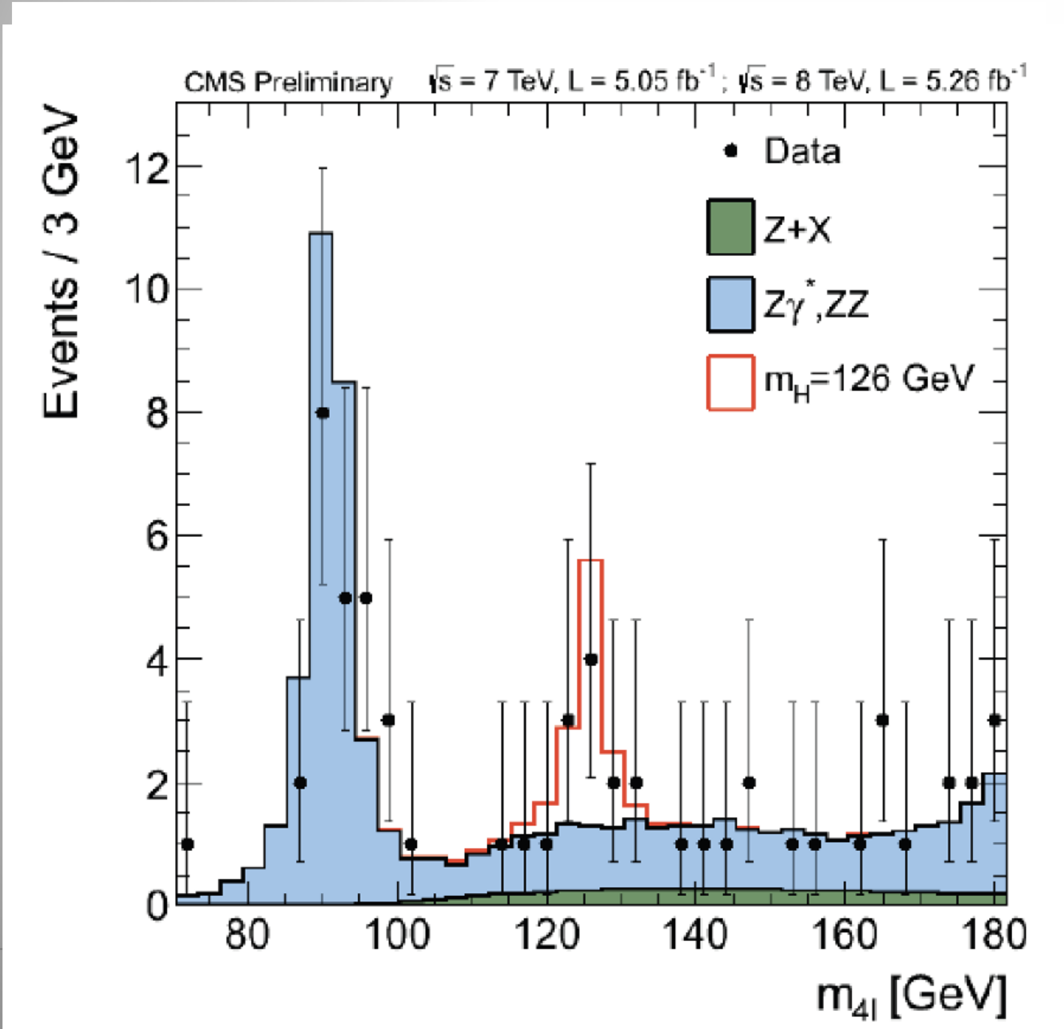


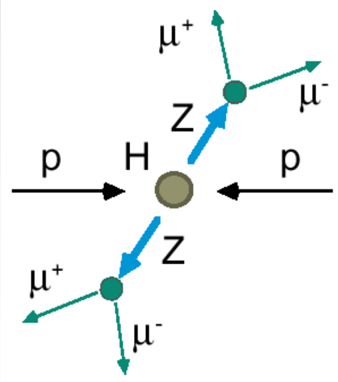
Real event from the original sample

But two Z bosons can also be produced in LHC collisions, without involving a Higgs!
We cannot say for sure on event by event (but we can reconstruct the total mass with the leptons)

Example: H→ ZZ→ Four Leptons

Data collected and analysed till 4th July 2012.
-> Invariant mass distribution of 4 charged leptons





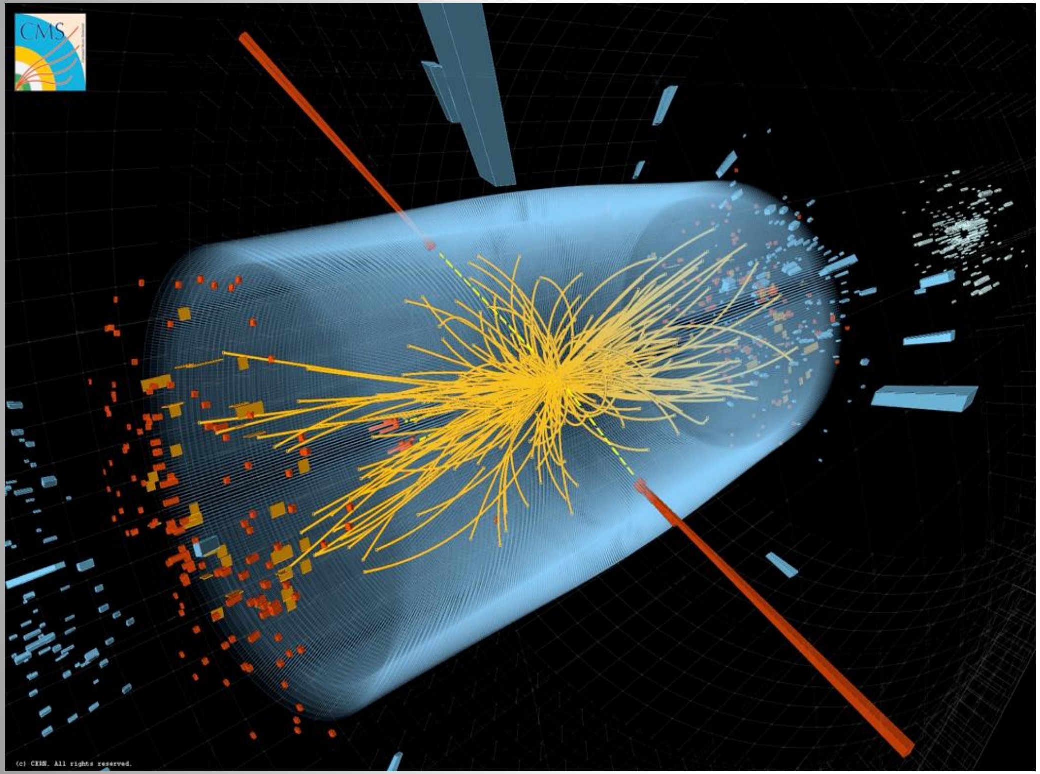
Any sign of a new particle here? We need a yardstick i.e. what do we expect from the SM on ZZ production?

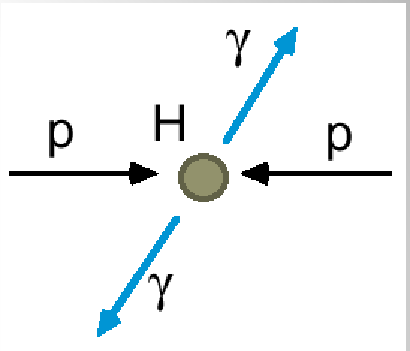
Add Monte Carlo prediction: some excess above SM at 125 GeV.
Consistent with a Higgs?

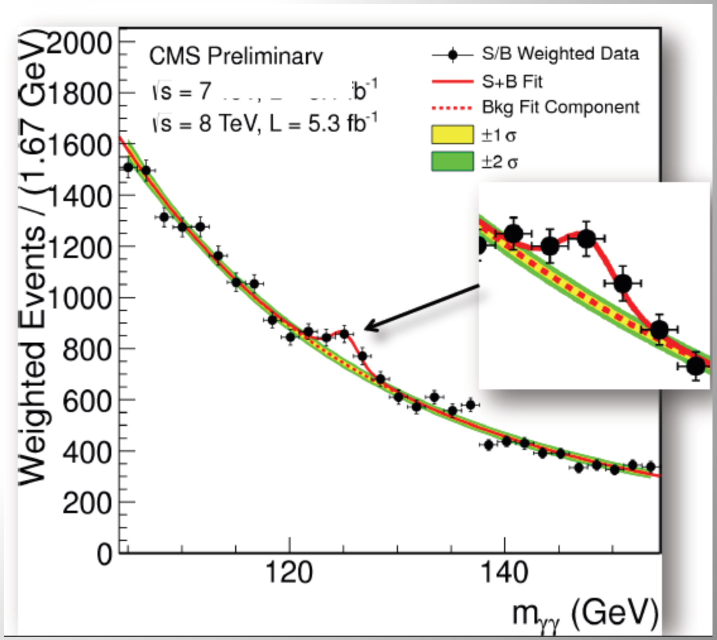
Add 126 GeV SM Higgs prediction: A nice match…

Example: H→ Two Photons

Different Higgs decay channel: decay to two photons





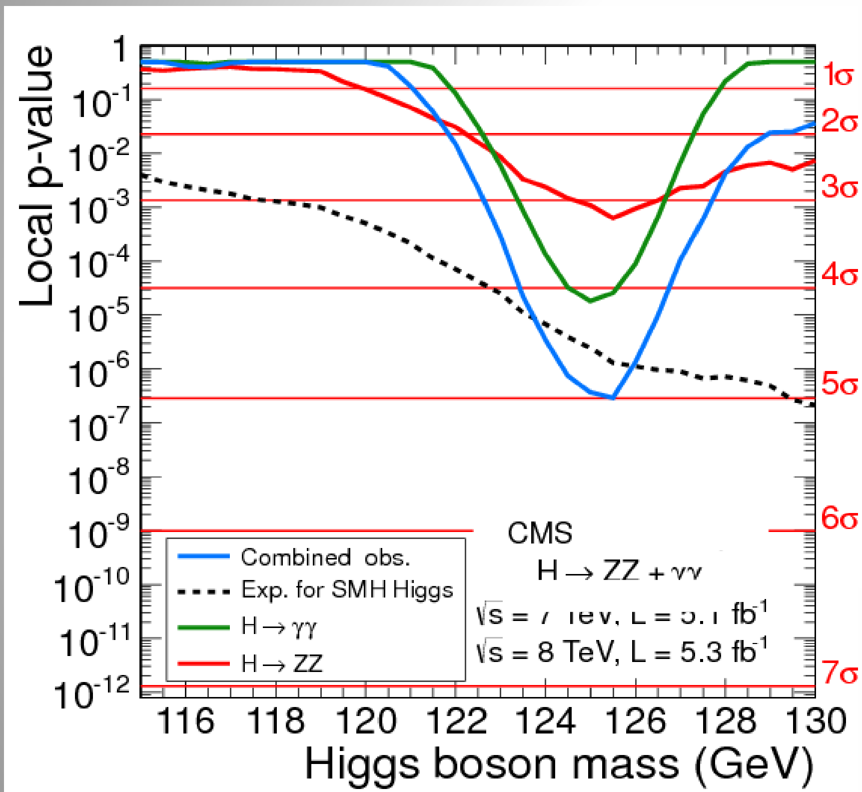


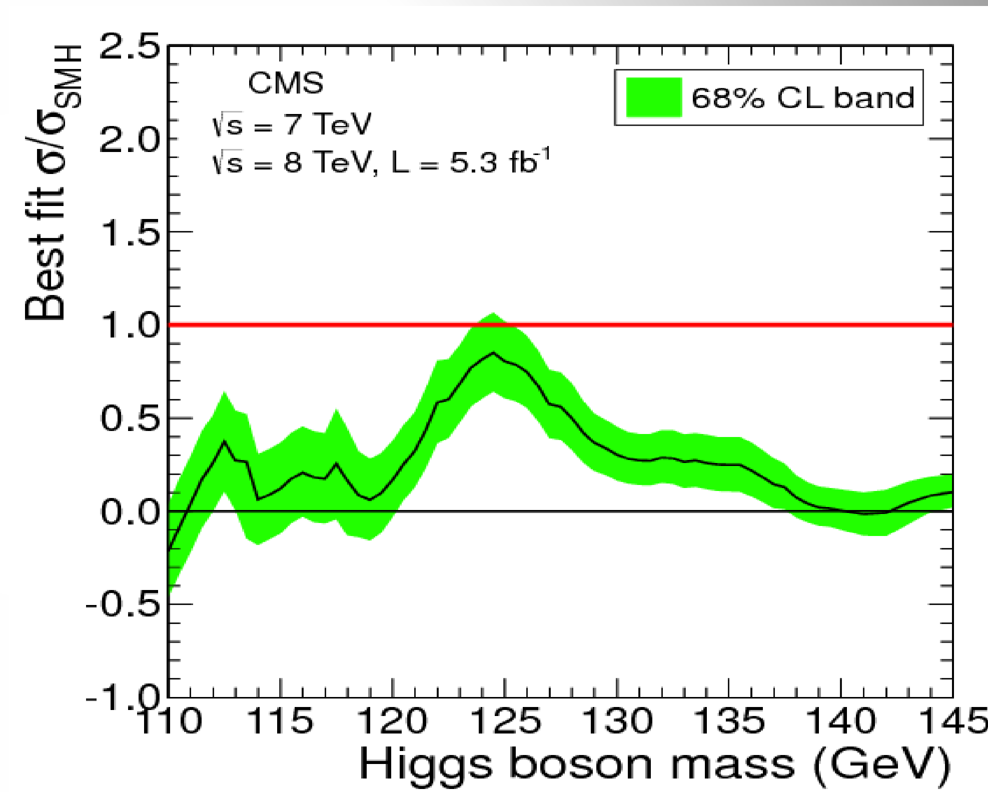
Observe an excess also at around 125 GeV

Results from Different Channels

July 4th 2012
Combined statistical strenght

July 4th 2012
Consistency with a SM Higgs





CMS observe a new boson with a significance of
5 sigma. ATLAS announces the same !
The particle is consistent with a Higgs-like boson

July 4th 2012

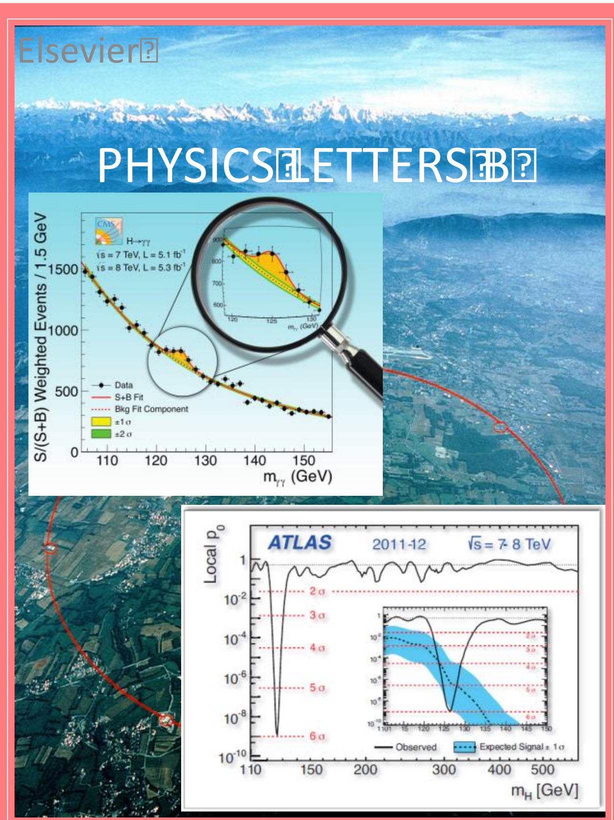
- Official announcement of the discovery of a Higgs-like particle with mass of 125-126 GeV by CMS and ATLAS.
- Historic seminar at CERN with simultaneous transmission and live link at the large particle physics conference of 2012 in Melbourne, Australia

CERN

Melbourne

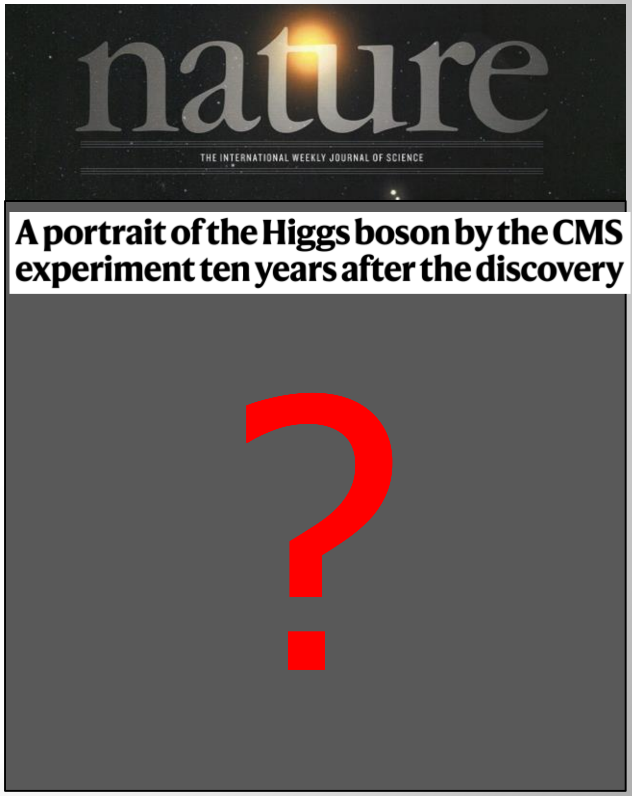
Now: 10 Years of Higgs Studies

2012: Special Physics Letters B edition with the ATLAS and CMS papers on the Higgs Discovery



More than 13,000 times cited so far…

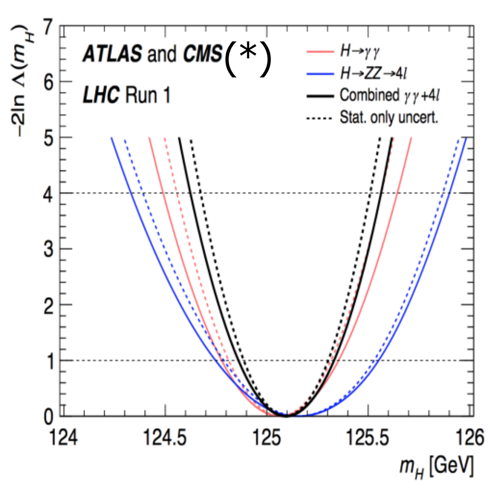
2022: Special Nature magazine edition with the ATLAS and CMS papers on 10 years of Higgs

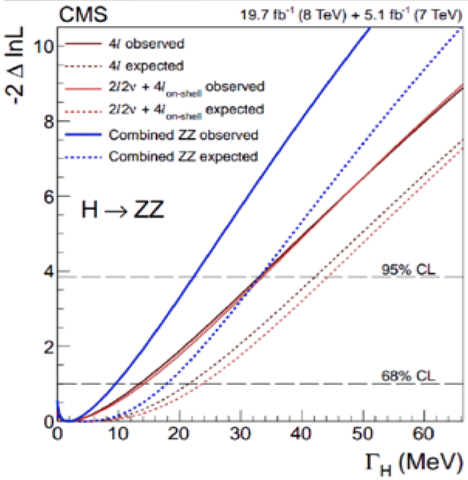


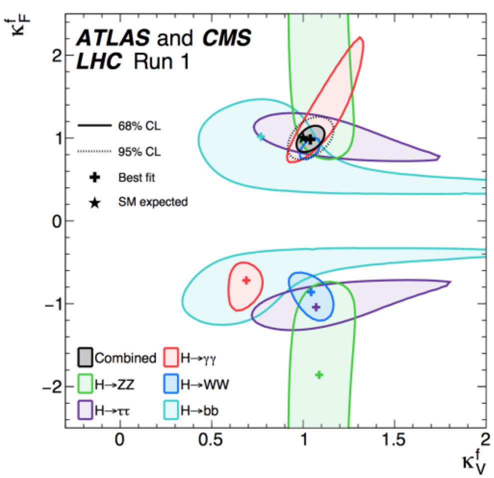
Released by Nature and to arXiv today: 2207.00043

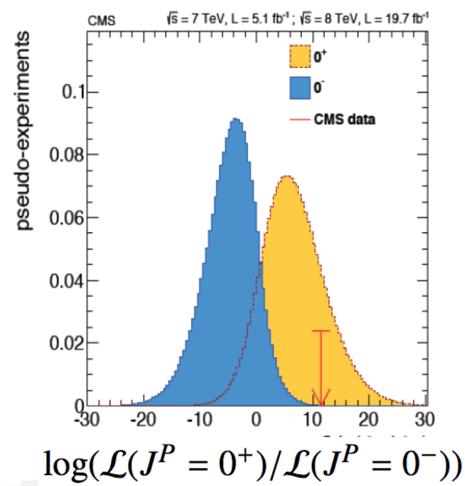
Brief Higgs Summary from Run-1

We knew already a lot on this Brand New Higgs Particle!!









Mass = CMS+ATLAS
125.09 ±0.21(stat)
±0.11(syst) GeV

Width
< 24 MeV
(95%CL)

Couplings are
within ~15-20%
of the SM values

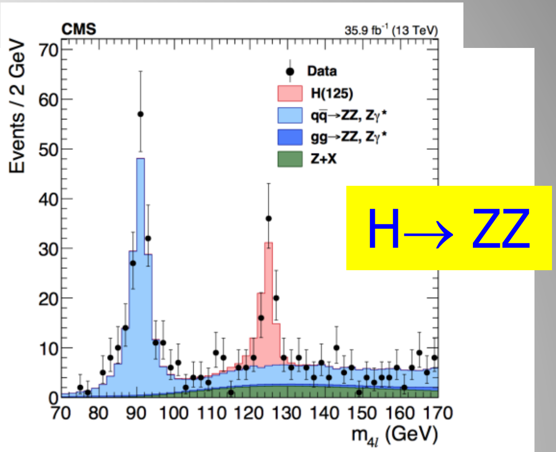
Spin =
$0^{+(+)}$ preferred
over 0^-,1,2

SM-like behaviour for most properties, but continue to look for anomalies, new/unexpected decay modes or couplings, multi-Higgs production…

(*) First ATLAS+CMS paper : > 5000 authors, a new record as noted by Nature!!

The Higgs Today

Higgs @ 13 TeV in Run-2

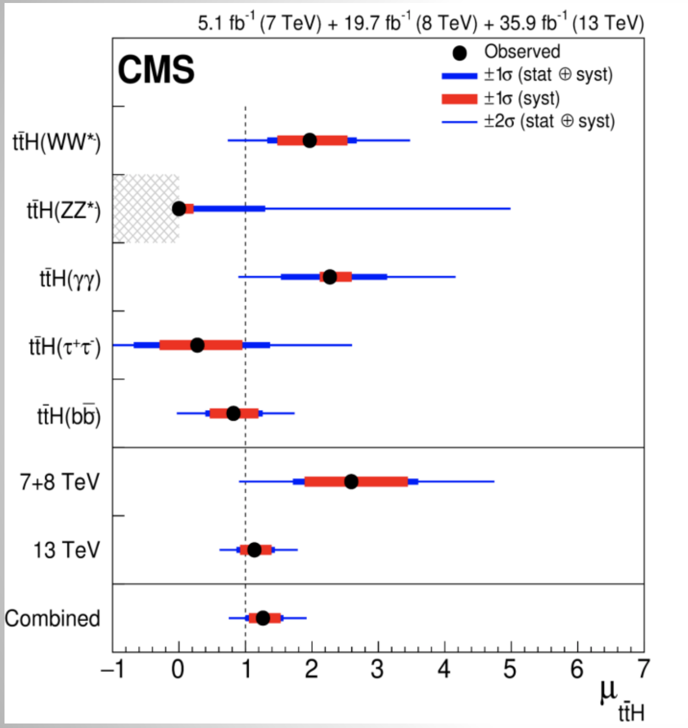


- Higgs particle is still there !! ☺
- More precision on Higgs properties
- New Combined Fits with all data
- Observation of H→ττ
- Direct observation of ttH production
- Observation of H→bb
- Evidence for H→$\mu\,\mu$ (second generation fermions)
- Detailed CP analysis eg in H→VV & H→ττ
- Differential distributions/STXS event classification…

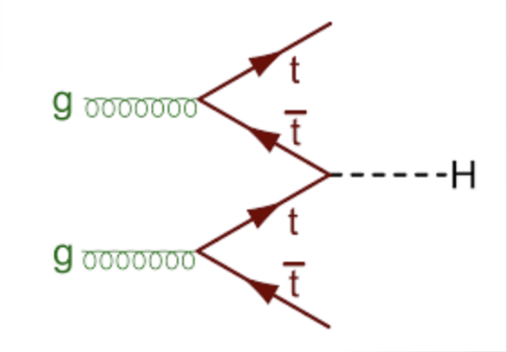
- The mild deviations seen in Run-1 seem to be gone ☹
- NEW: 10 year Anniversary Paper with Run-2 legacy

Higgs ttH Production

Observation of ttH production: Combination of all Higgs decay channels and combination with the 7/8 TeV data of Run-1



arXiv:1804.02610



7+8+13 TeV data

$$\boxed{\mu_{t\bar{t}H} = 1.26\,^{+0.31}_{-0.26}}$$

Significance = 5.9σ (exp 4.2σ)

arXiv:2011.03652

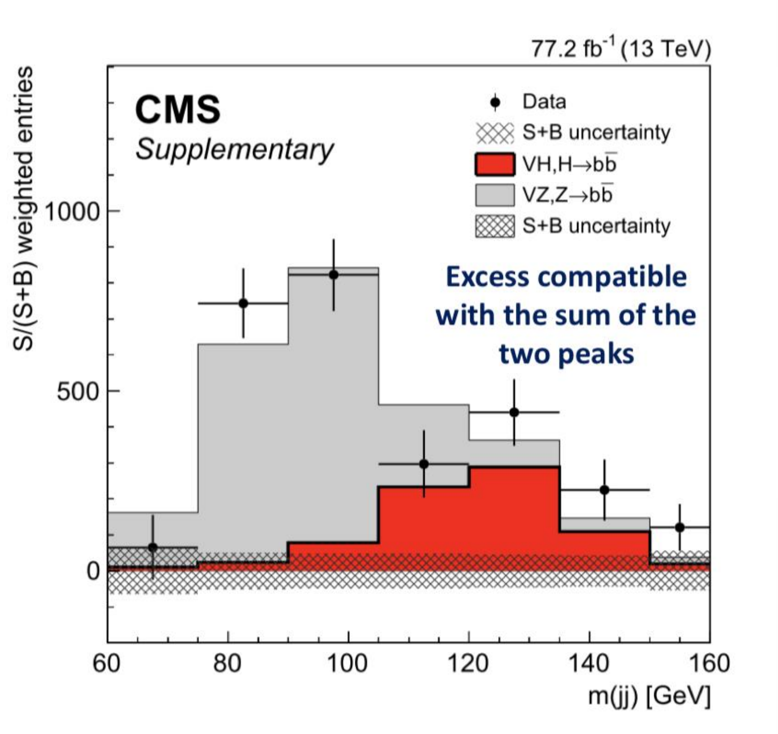
NEW: ttH and tH in final states with muons, electrons and hadronic taus using the full Run-2 data, giving the following μ values:

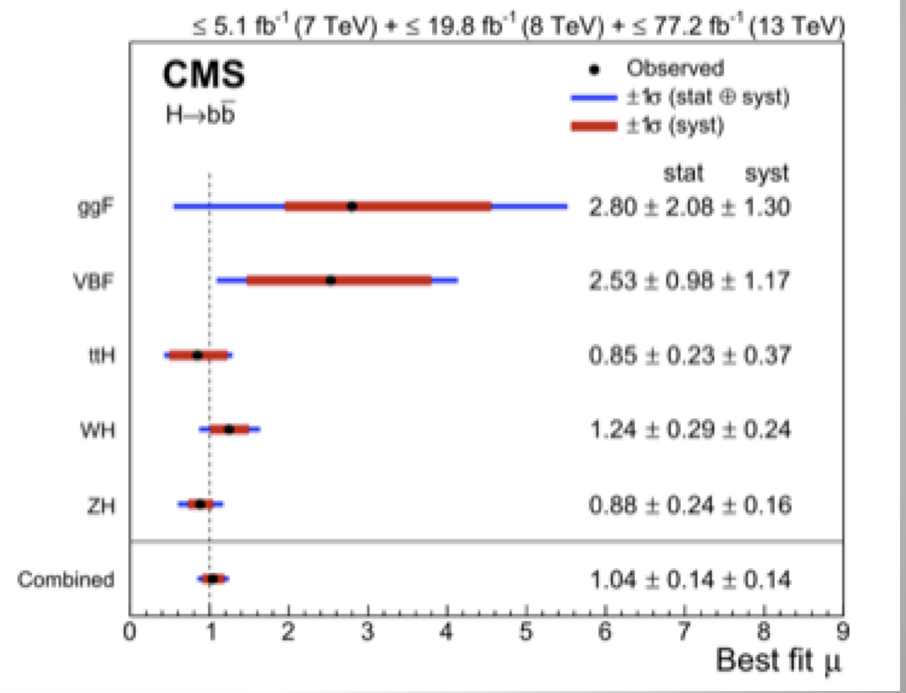
$\boxed{\text{ttH}: 0.92 \pm 0.19\,(\text{stat})^{+0.17}_{-0.13}\,(\text{syst})}$ and $\boxed{\text{tH}: 5.7 \pm 2.7\,(\text{stat}) \pm 3.0\,(\text{syst})}$

Higgs to bb Decay

H->bb decay: Combination of all Higgs decay channels and combination with the 7/8 TeV data of Run-1

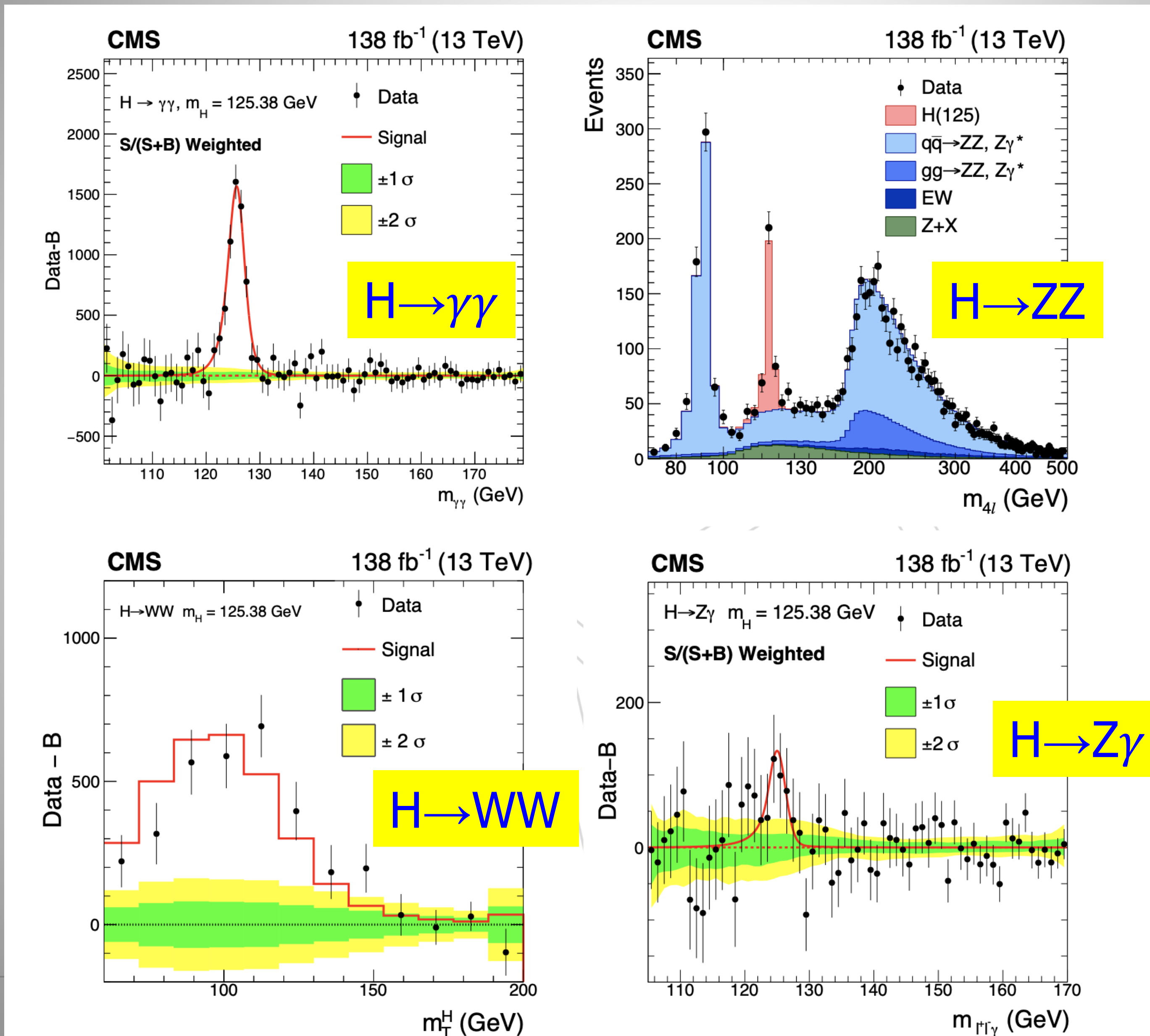
arXiv:1808.08242





H->bb observed (expected) with 5.6 (5.6)σ significance
Combined best fit $\mu = 1.04 \pm 0.20$

Higgs Decaying to Vector Bosons



2207.00043

These are the CMS Run-2 legacy results!

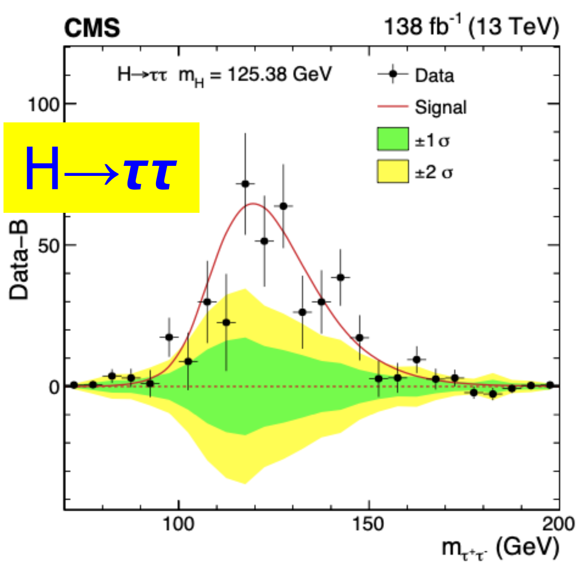
Full run-2 data sample

Higgs Decaying to Fermions

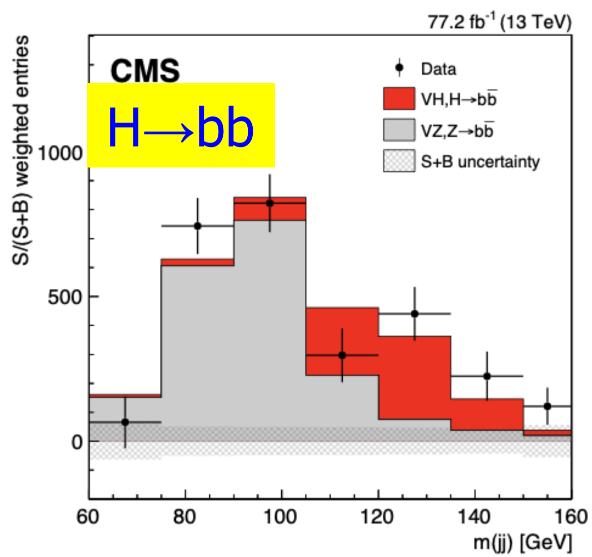
2207.00043

Background-subtracted results for H→$\tau\tau$, H→bb and H→$\mu\mu$ channels

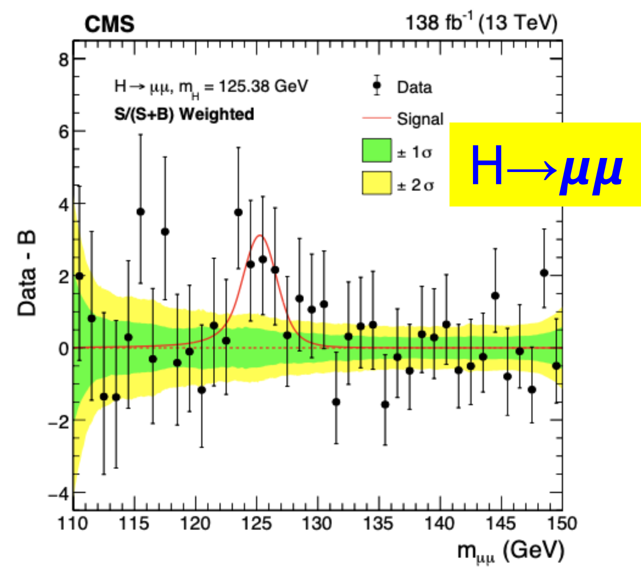
H→$\tau\tau$



H→bb



H→$\mu\mu$



CMS Run-2 legacy results!

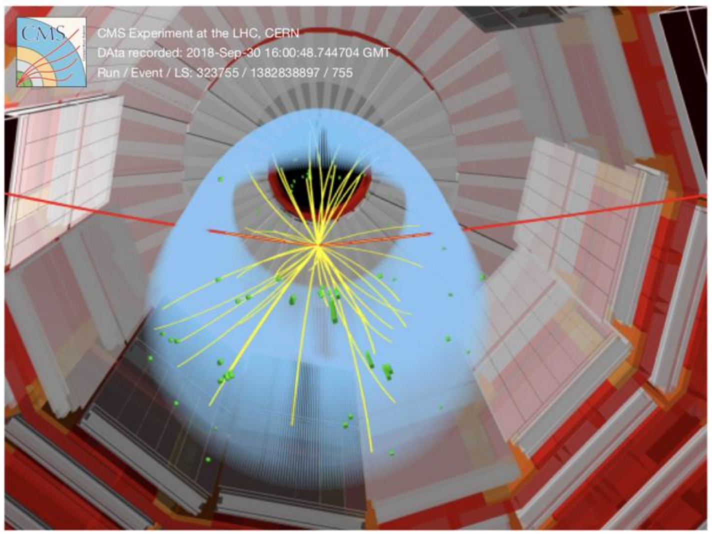
Higgs decaying to Di-Muons

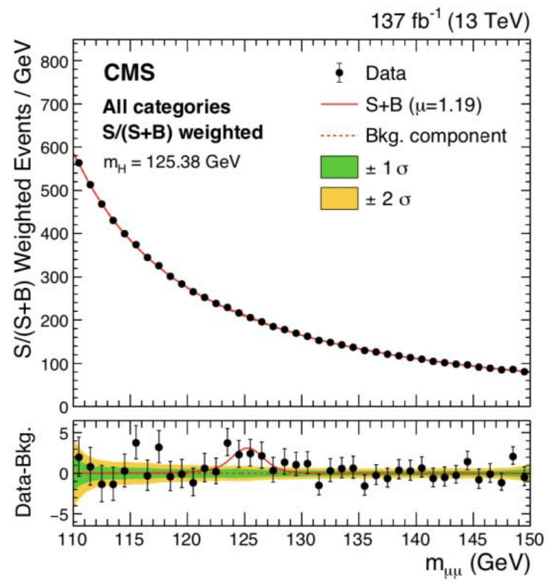
Evidence for H->$\mu\mu$ with full run-2 data sample (3 sigma)
-> Clean signature but small Branching Ratio: 0.02% only

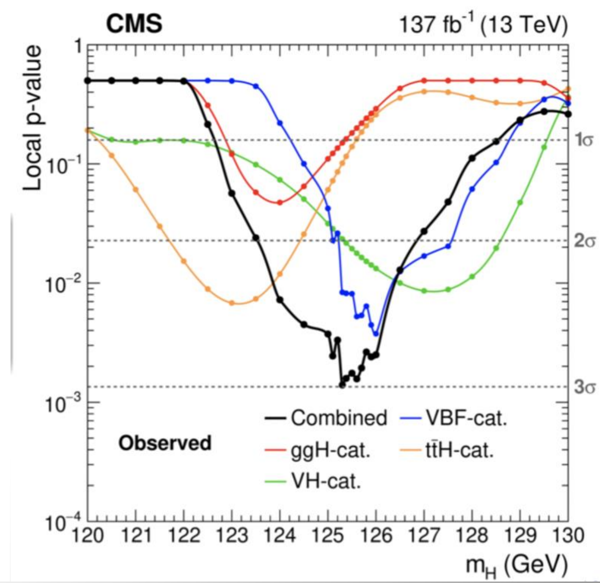
SM coupling strenght $\boldsymbol{\mu}$

$$\boxed{1.19^{+0.40}_{-0.39}\,(\text{stat})^{+0.15}_{-0.14}\,(\text{syst}).}$$

2009.04363







First evidence of Higgs coupling to second generation!

Signal Strenght Parameters

Higgs Production Modes

Higgs Decay Channels

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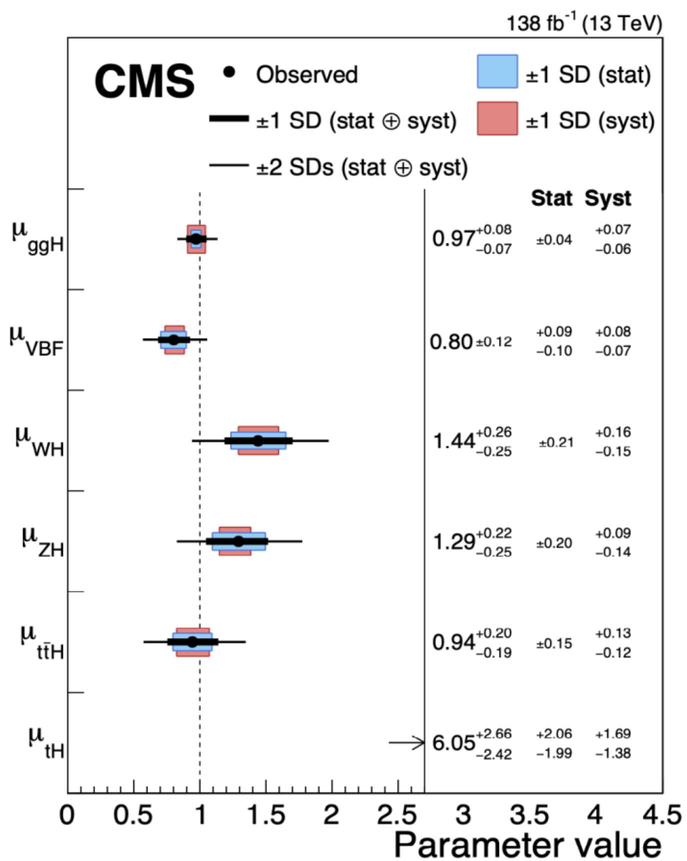
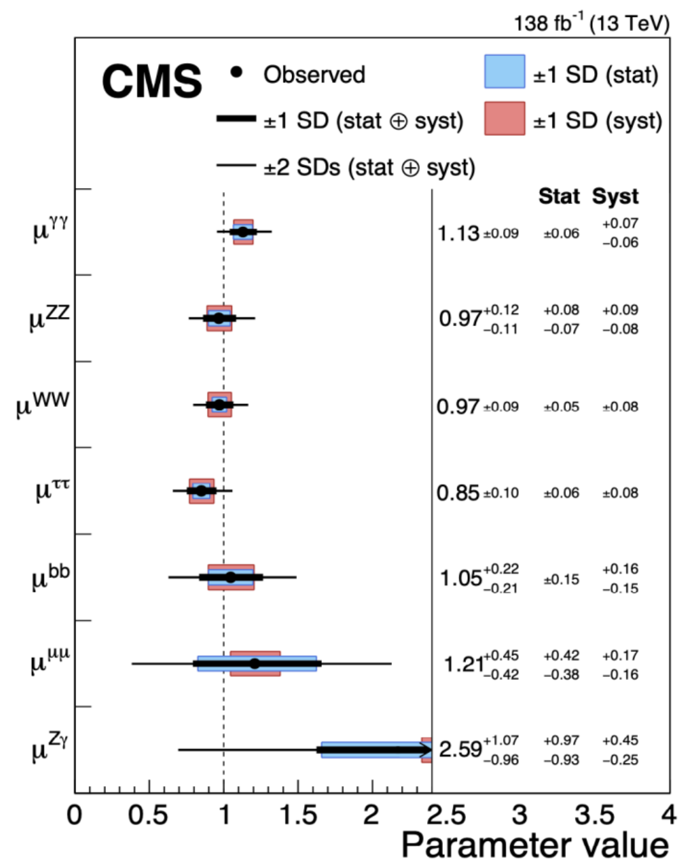




Compare observed yield with SM expectation

$$\mu_i = \sigma_i / (\sigma_i)_{SM}$$

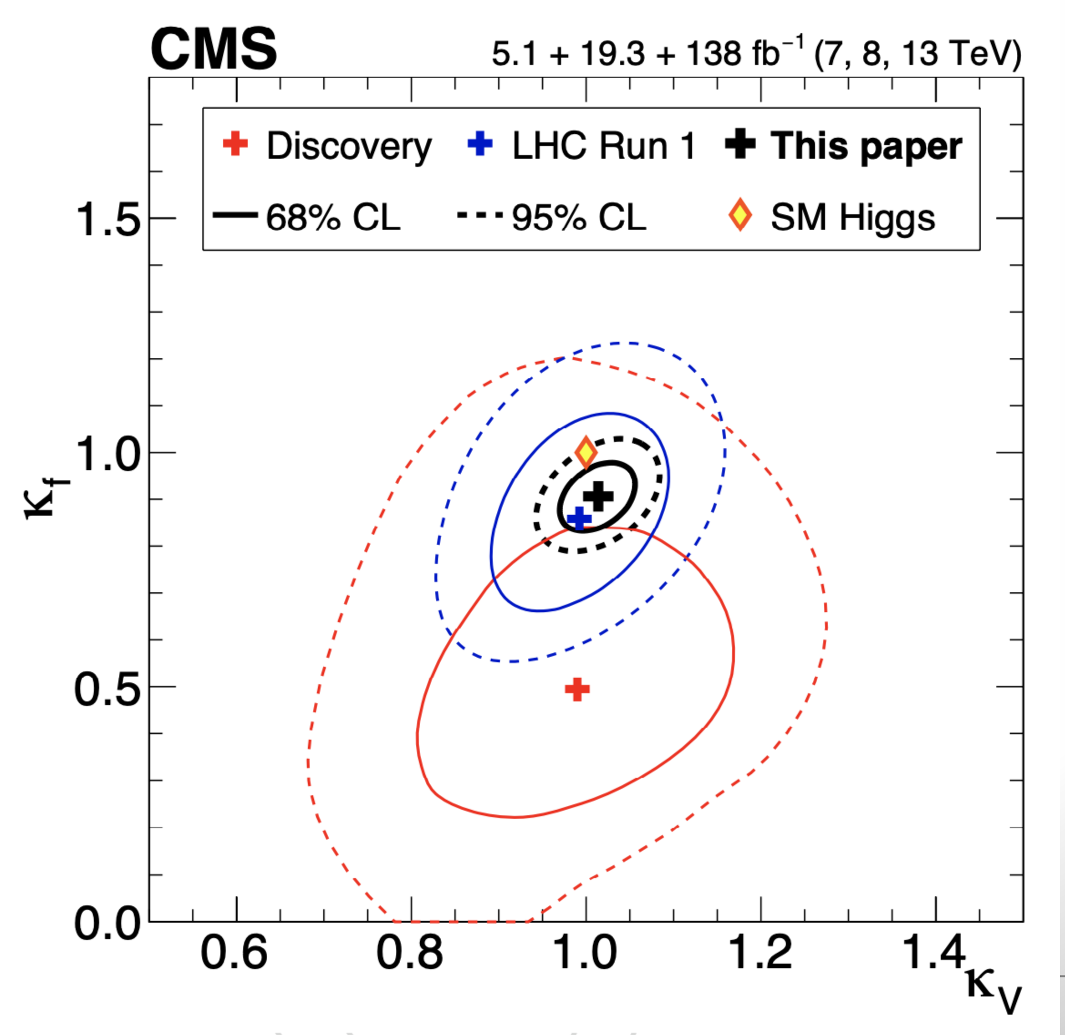
$$\mu^f = \mathcal{B}^f / (\mathcal{B}^f)_{SM}$$

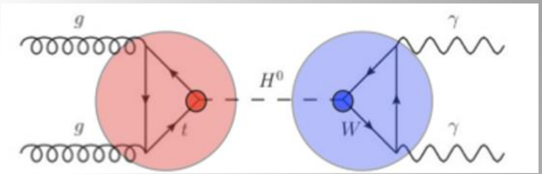
Global Higgs Signal Strenght: $\mu = 1.002 \pm 0.057$

The value $\boldsymbol{\mu}$ =1 is the expected value for the Standard Model

Coupling Modifiers

Constraints on the Higgs coupling modifiers to fermions and heavy gauge bosons, and the evolution with time from discovery till today





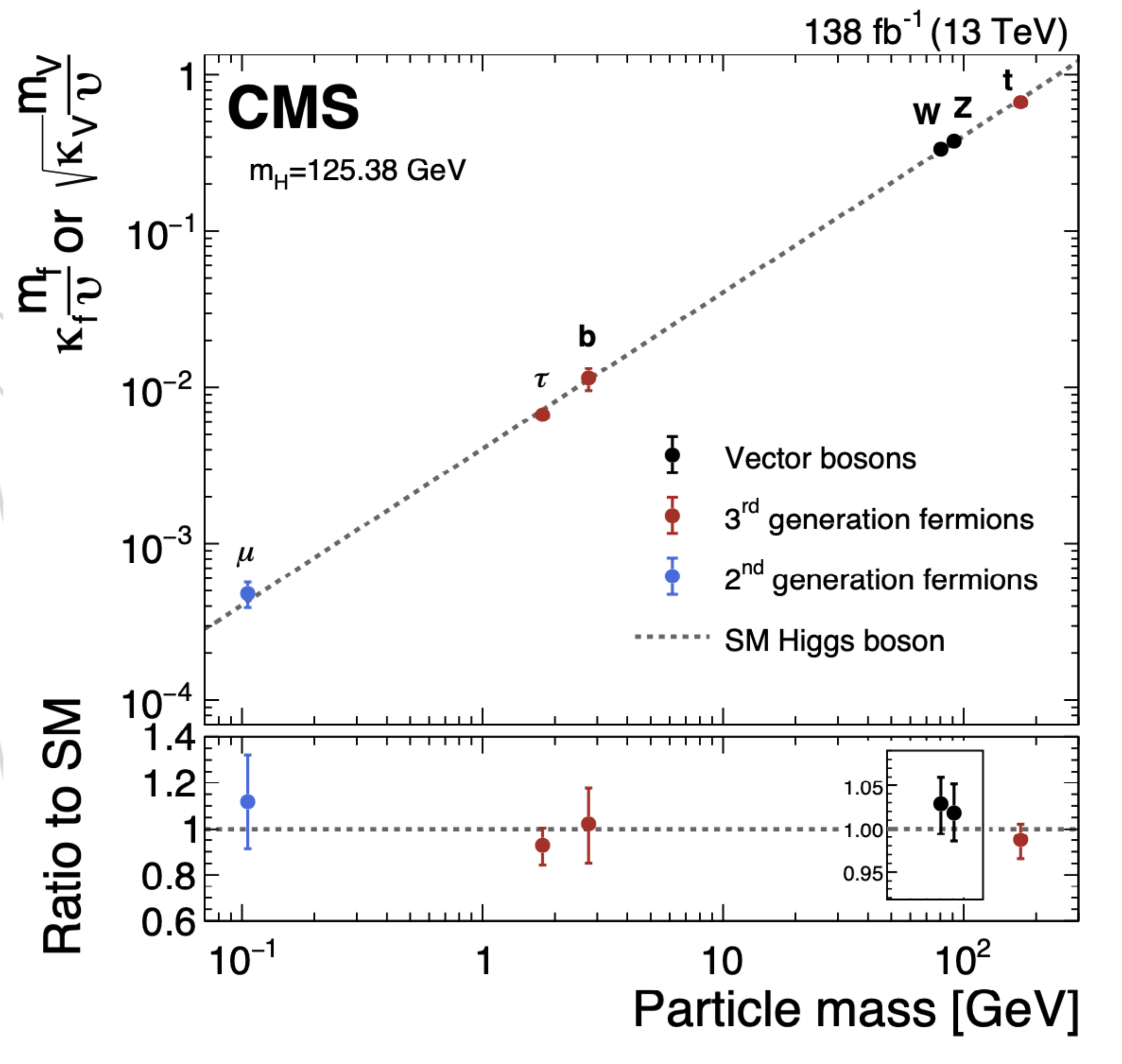
Coupling Modifiers:
In the κ-framework for cross sections and branching ratios

In the SM: κ=1

For a single contribution

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

Higgs Coupling to Fermions and Bosons



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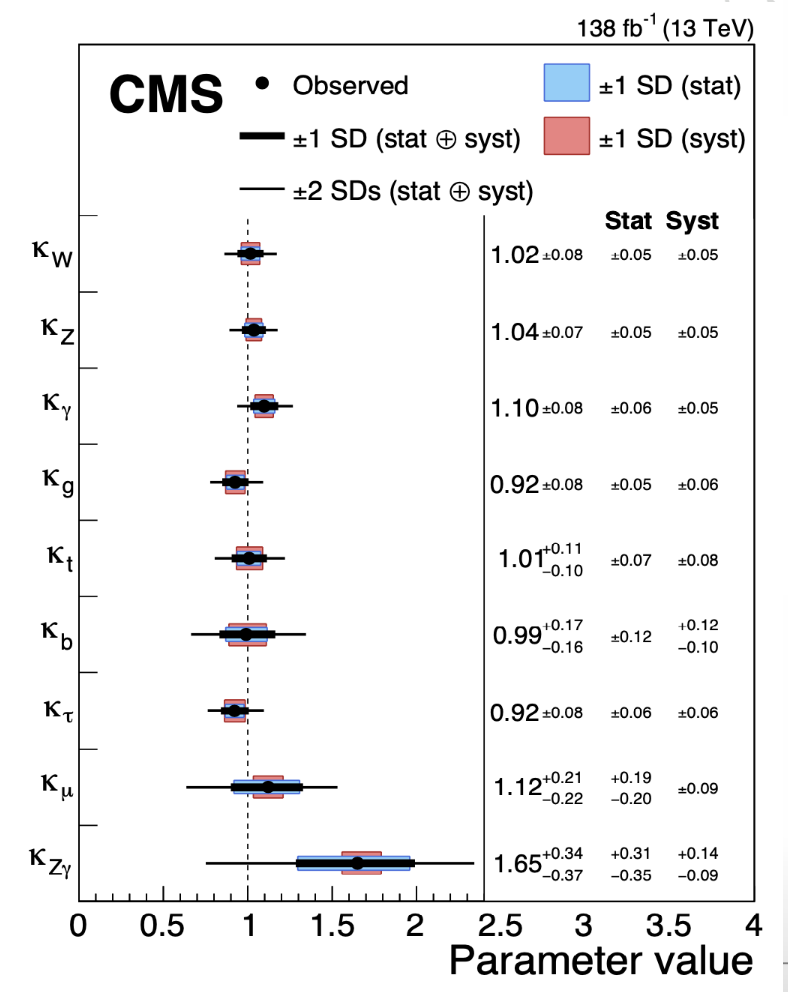
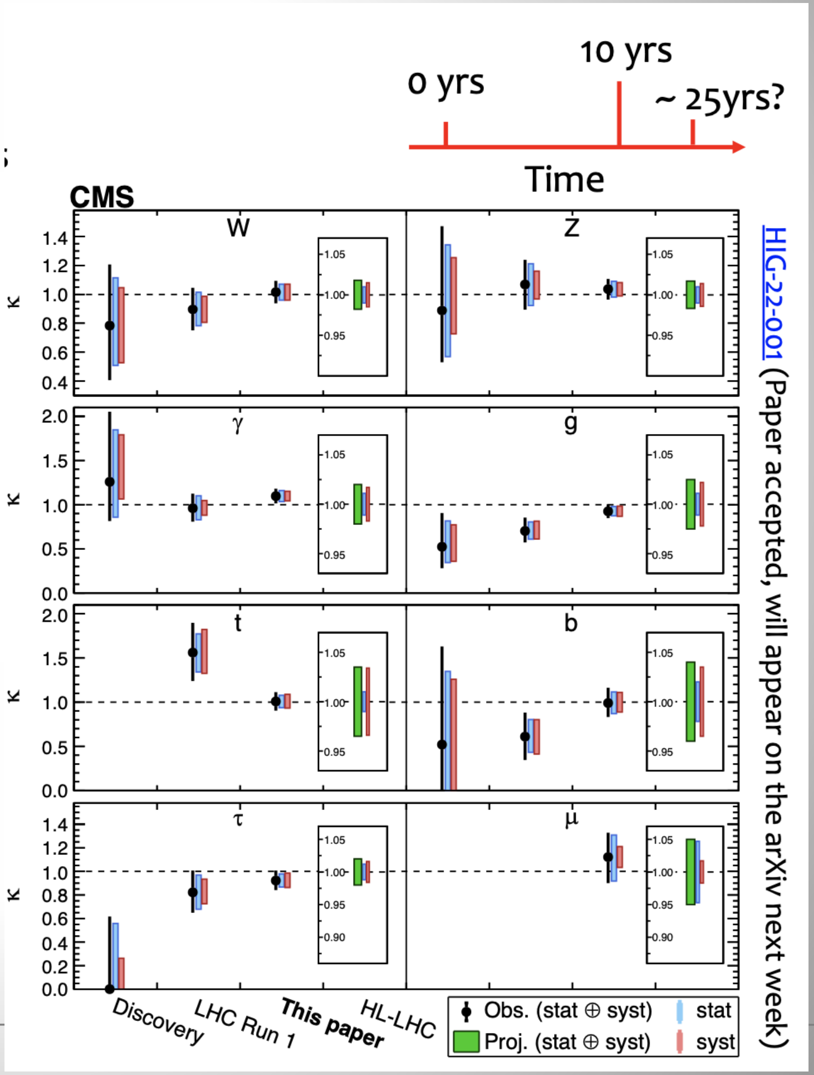
Scaled coupling modifiers for bosons and fermions

υ is the vacuum expectation (246 GeV)

Results from the fit of all channels

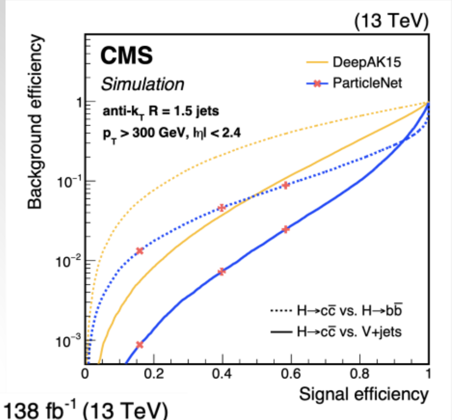
Different coupling modifiers and evolution with time from discovery till today

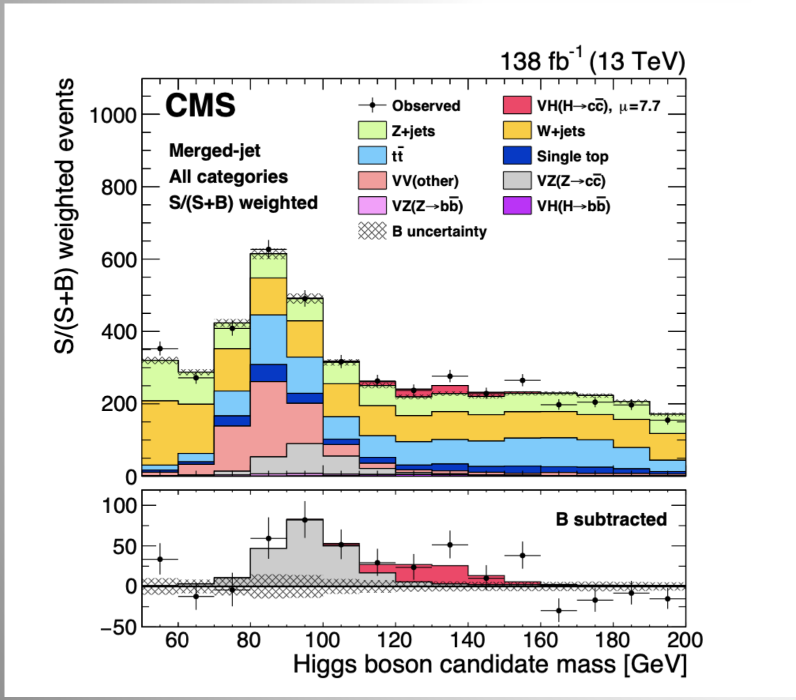


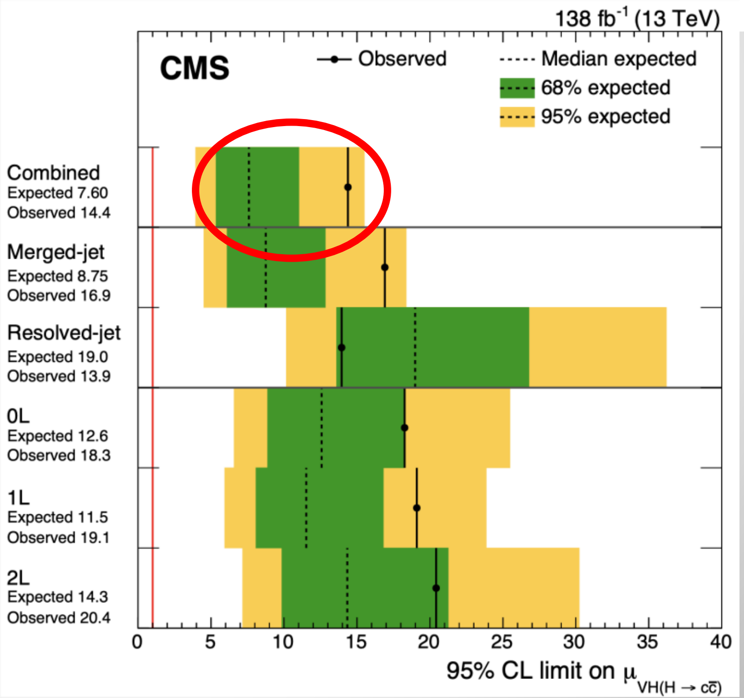


Higgs to Charm?

Search for H→ cc in HV assoc. production mode. Find c-jets using the PARTICLENET graph neural network, with jet tagging via particle clouds.
-> Observation of Z→ cc with 5.7σ significance

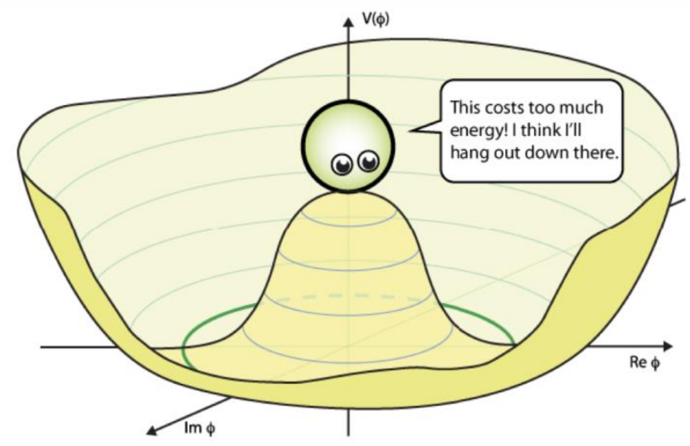






Observed (95%): **μ** upper limit <14 SM prediction, Yukawa coupling $1.1 < |\kappa_c| < 5.5$

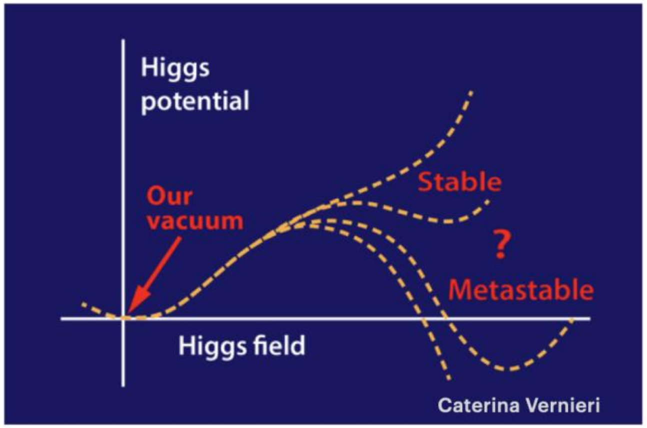
Higgs Self Coupling



$$\mathcal{L} = |D_\mu \Phi|^2 - \mu^2\Phi^2 - \lambda\Phi^4$$

For $\mu^2 < 0$, minimum $v = \sqrt{-\frac{\mu^2}{2\lambda}}$

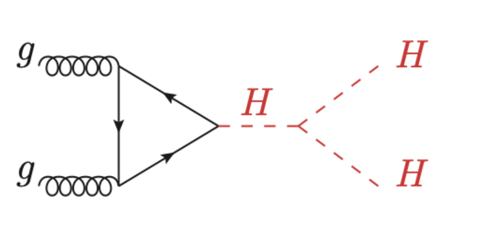
- Does the Higgs couple to itself?
- Access the shape of the Higgs potential…

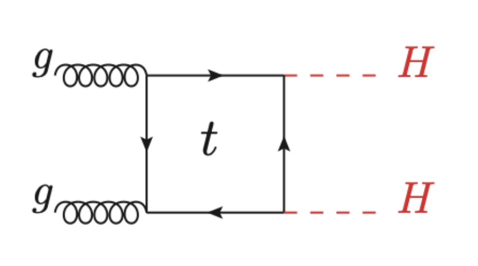


Main tool at the LHC to measure the Higgs self-coupling is via Higgs Pair production

- Small cross sections
- Negative interference with background
- Many decay channels to study

->A challenging measurement @ LHC!



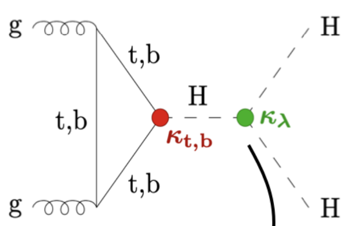


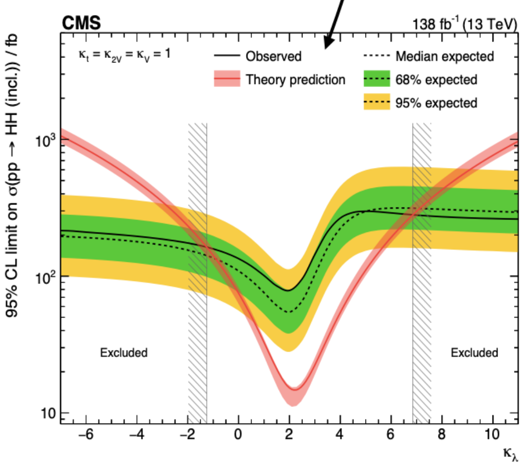
Higgs Pair Production

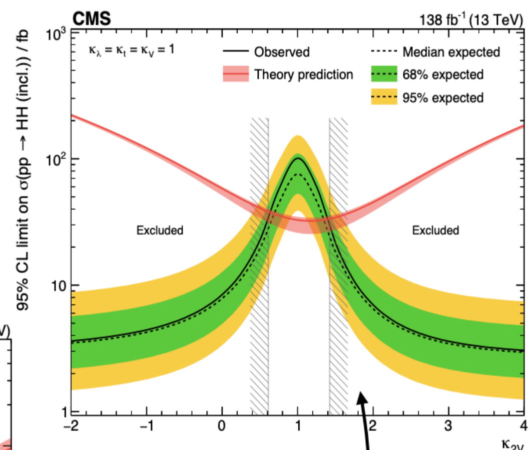
State of the art studies, including bbZZ, bb$\gamma\gamma$, bb$\tau\tau$, bbbb and multi-leptons

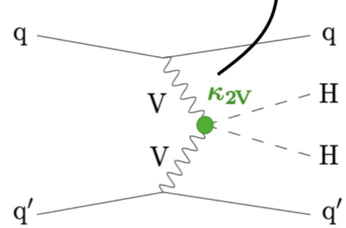
2207.00043

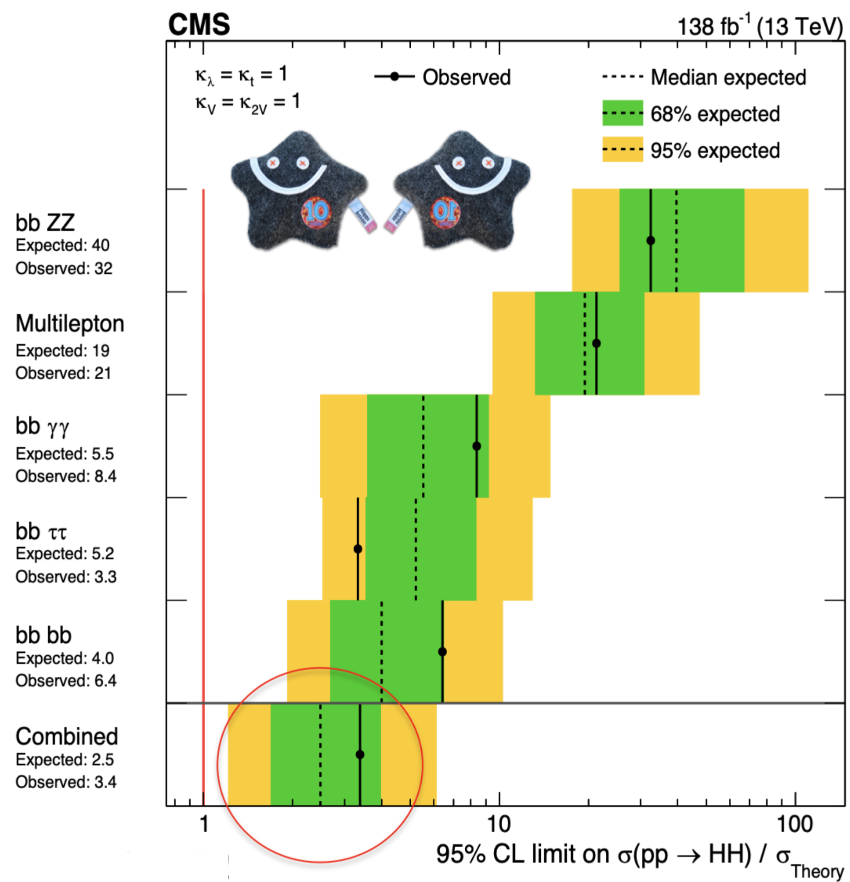
95% upper limits for κ_λ and κ_{2V}











N. Wardle

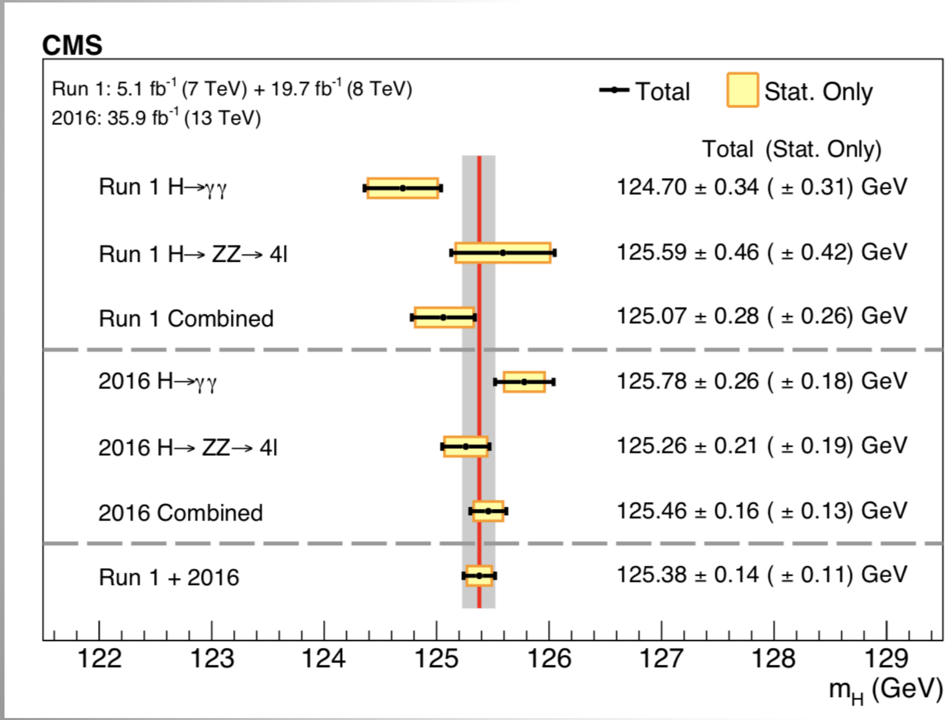
Result is a few times SM value already! Very promising for Run-3/HL-LHC

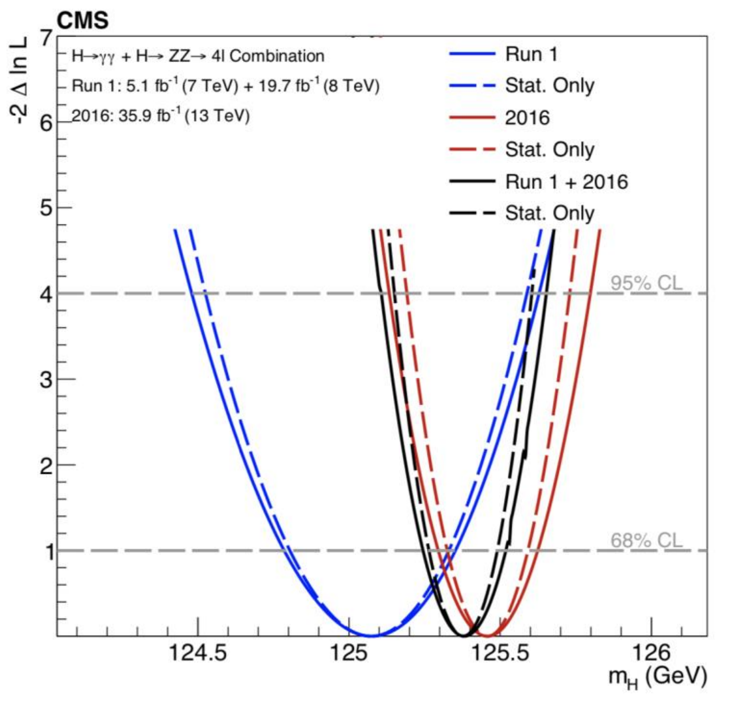
Higgs Properties: Higgs Mass

Higgs Mass from $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ\rightarrow$4leptons with run-1 and 2016 data

- Excellent detector performance and lepton/photon energy scale calibration
- Results still dominated by statistical uncertainties

2002.06398





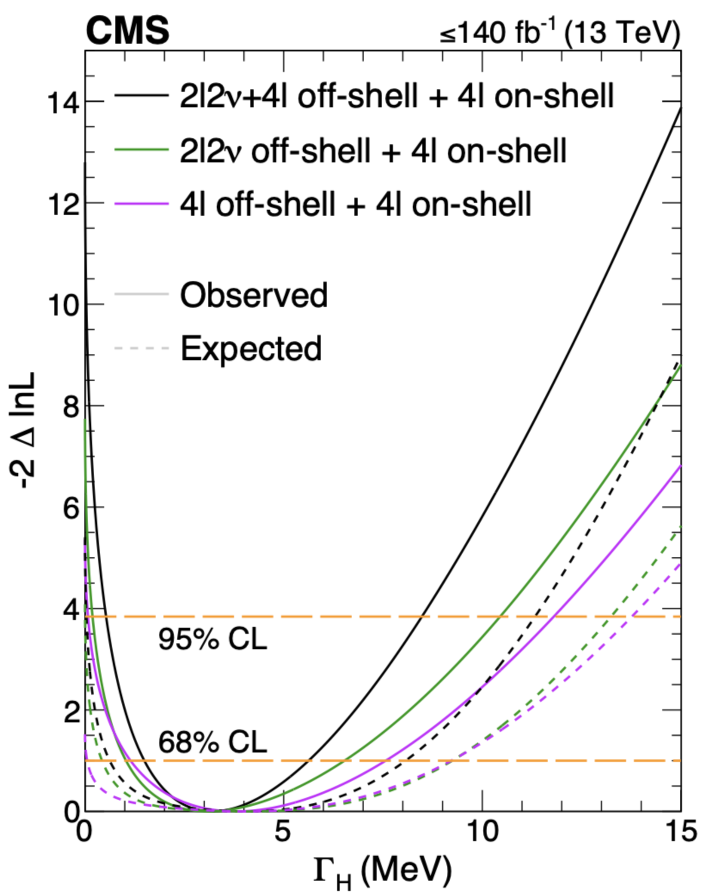
$$m_{\mathrm{H}} = 125.38 \pm 0.14\,\mathrm{GeV}$$

M_H is known to a precision of almost 1 per mille

Higgs Properties: Higgs Width

arXiv:1901.00174
arXiv:2202.06923

Direct resonance width measurement not possible.
Technique used: on-shell to off-shell cross section in H→ZZ



SM Higgs(125)
width = 4.1 MeV

$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}}$$

$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM} \qquad (\kappa_t^2 \kappa_V^2)_{on\ shell} = (\kappa_t^2 \kappa_V^2)_{off\ shell}$$

		68% | 95% CL	68% | 95% CL
Γ_H	$2\ell 2\nu + 4\ell$	$3.2^{+2.4}_{-1.7}$ | $^{+5.3}_{-2.7}$	$^{+4.0}_{-3.48}$ | $^{+7.2}_{-4.065}$
Γ_H	$2\ell 2\nu$	$3.1^{+3.4}_{-2.1}$ | $^{+7.3}_{-2.91}$	$^{+5.1}_{-3.67}$ | $^{+9.1}_{-4.099}$
Γ_H	4ℓ	$3.8^{+3.8}_{-2.7}$ | $^{+8.0}_{-3.727}$	$^{+5.1}_{-4.047}$ | < 13.8

➡ Result: $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

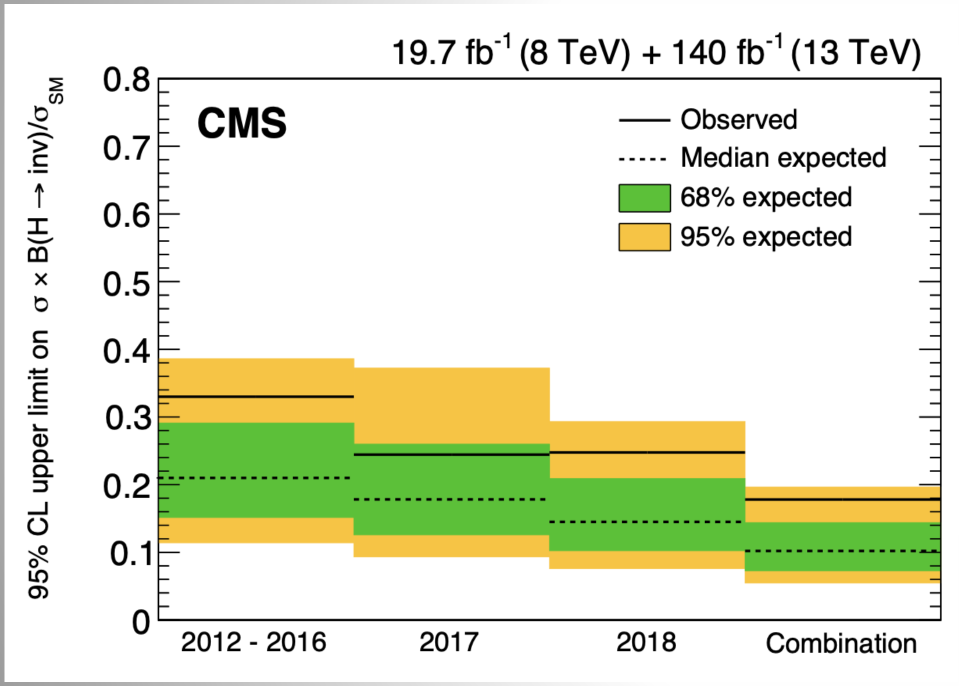
in addition

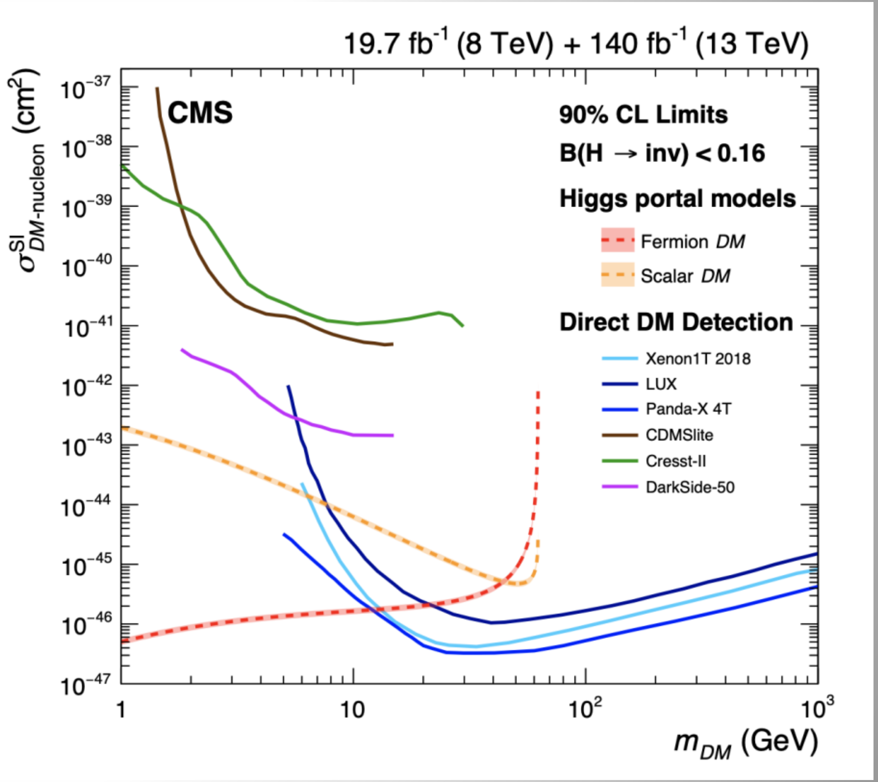
Evidence for Off-Shell production at 3.6σ

Invisible Decays of the Higgs Boson

Direct search for H decaying into invisibles, using VBF channels
- Major challenge is control of backgrounds
- Present limit BR(inv.) < 0.18 @ 95% CL (0.10 expexted)

2201.11585





HL-LHC projection $\left(\mu_{\mathrm{VBF},VH} \cdot \mathrm{BR_{inv}}\right)^{\text{HL-LHC}} \leq 2.5\%$

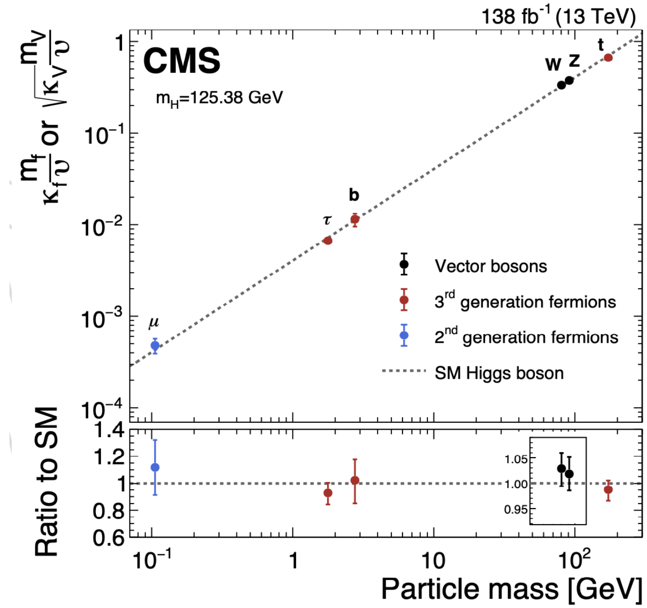
Dark Matter interpretation in terms of WIMP-Nucleon cross section limits

Brief Summary

- Channels covered with Run-2 data

Channel categories	Br	ggF ~8 M vets produced	VBF ~600 k vets produced	VH ~400 k vets produced	ttH ~80 k evts produced
Cross Section 13 TeV (8 TeV)		48.6 (21.4) pb*	3.8 (1.6) pb	2.3 (1.1) pb	0.5 (0.1) pb
γγ	0.2 %	✓	✓	✓	✓
ZZ	3%	✓	✓	✓	✓
WW	22%	✓	✓	✓	✓
ττ	6.3 %	✓	✓	✓	✓
bb	55%	✓	✓	✓	✓

Observed modes



More rare processes remain to be observed…

- Coupling uncertainties in range 5-12%
- Mass of the Higgs $m_{\mathrm{H}} = 125.38 \pm 0.14\,\mathrm{GeV}.$
- Width of the Higgs $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV
- Run-2 data is only 5% of the total data sample with HL-LHC!

The Future: Studying the Higgs

The Higgs gets 10 today

We know already a lot on Higgs but:

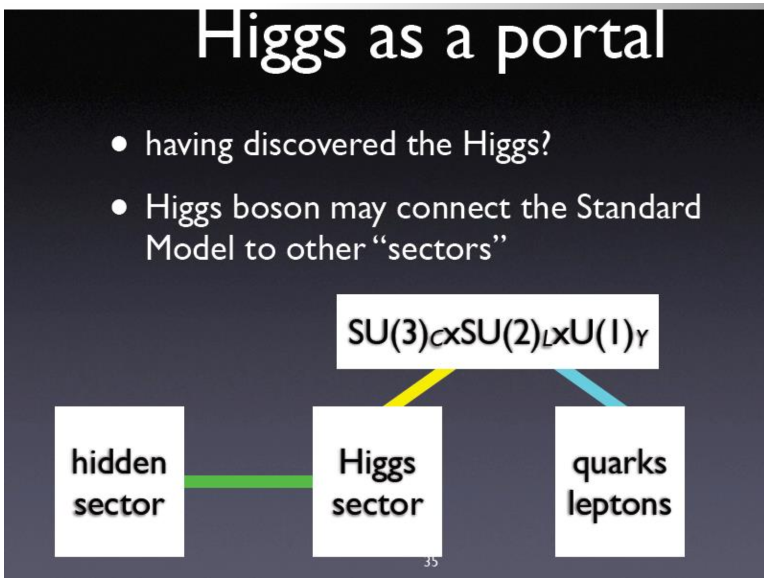
Many questions are still unanswered:

- What explains a Higgs mass ~ 125 GeV?
- What explains the particle mass pattern?
- What is the connection with Dark Matter?
- Is the boson fundamental or composite?
- Will BSM physics show up in the Higgs ?
- Are there more Higgs bosons?
- etc…

- A program for detailed studies is in place
- More LHC Data 2022-2025 with Run-3
- HL-LHC Data 2029-2040+ with 3000fb^{-1}
- Other/new machines in the future??
- ⑤

Will the Higgs shows us some surprises?

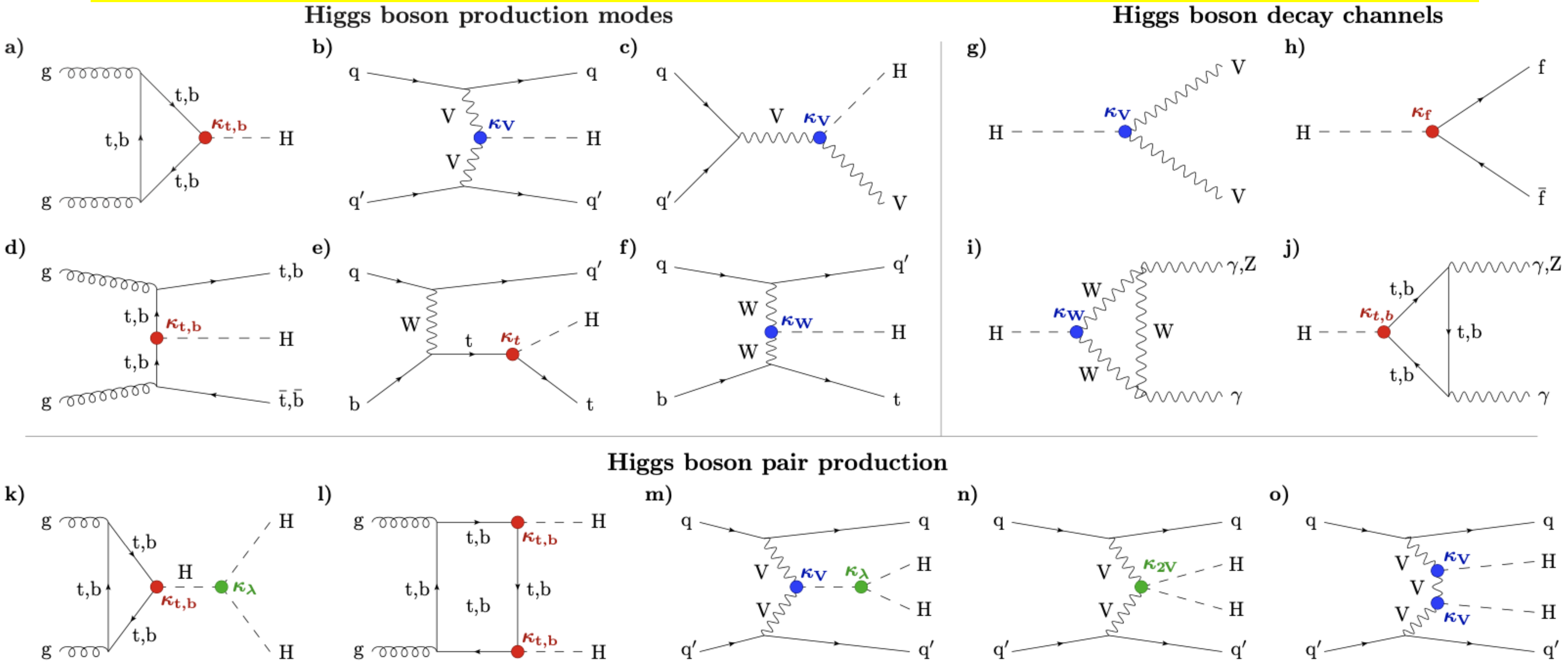
The Future will tell



Backup

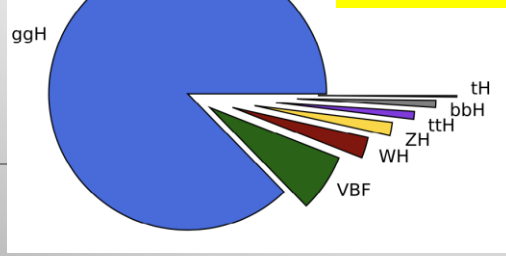
Higgs Production and Decay Processes

Processes studied for single and pair Higgs production

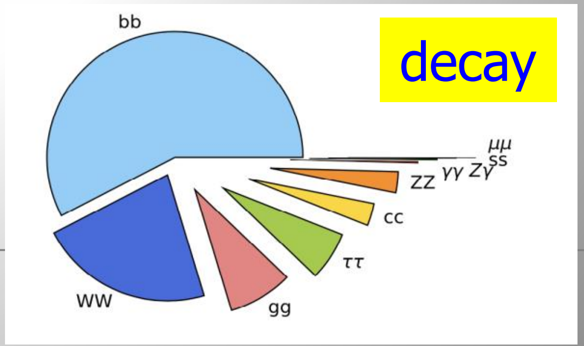


For pp at 13 TeV and a Higgs with mass 125.38 GeV

production

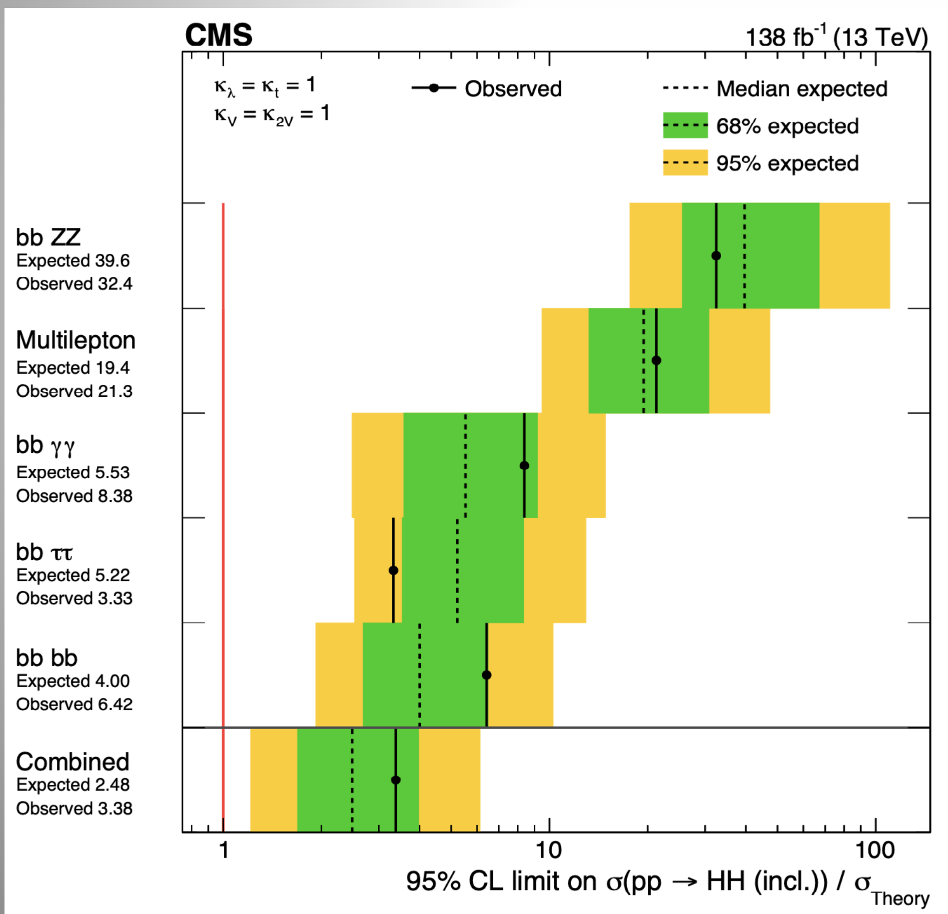


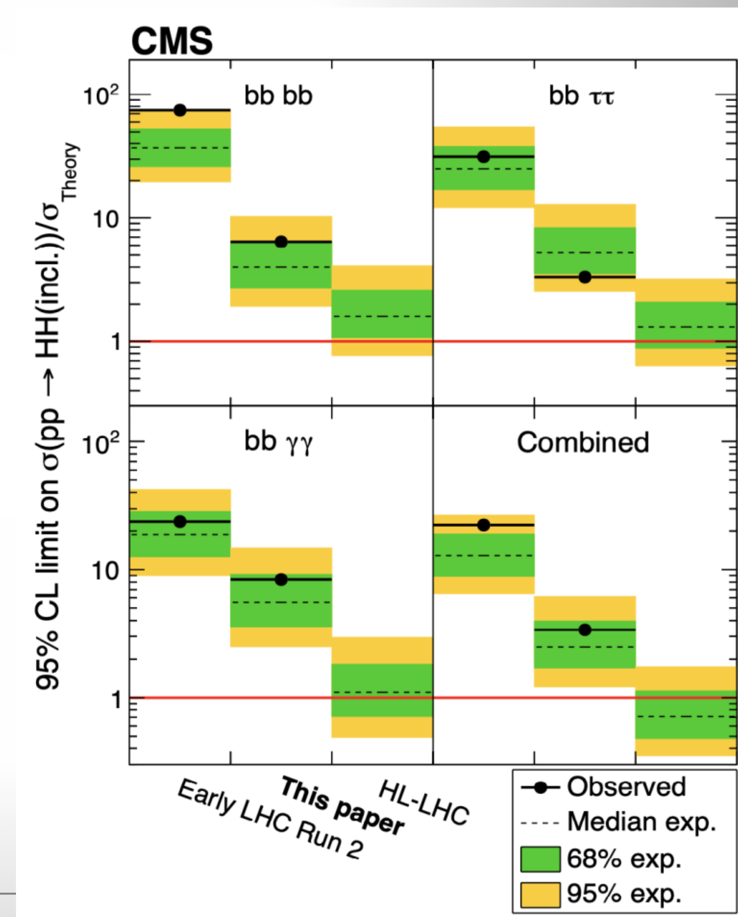
decay



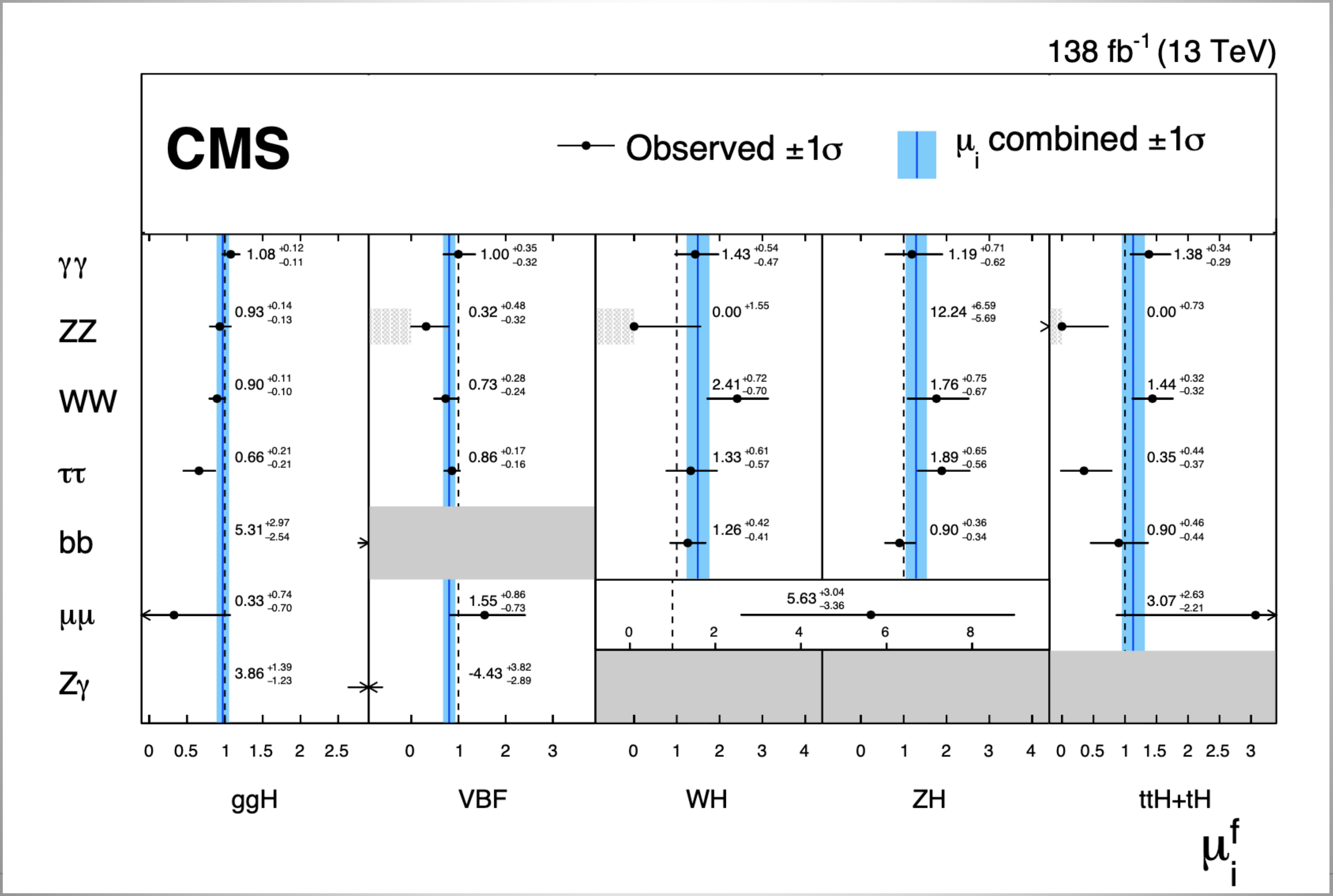
Higgs Pair production

Limits on the di-Higgs cross section ratios to SM expectation for different final states and the expected sensitivity evolution up to the HL-LHC data set of 3000 fb $^{-1}$

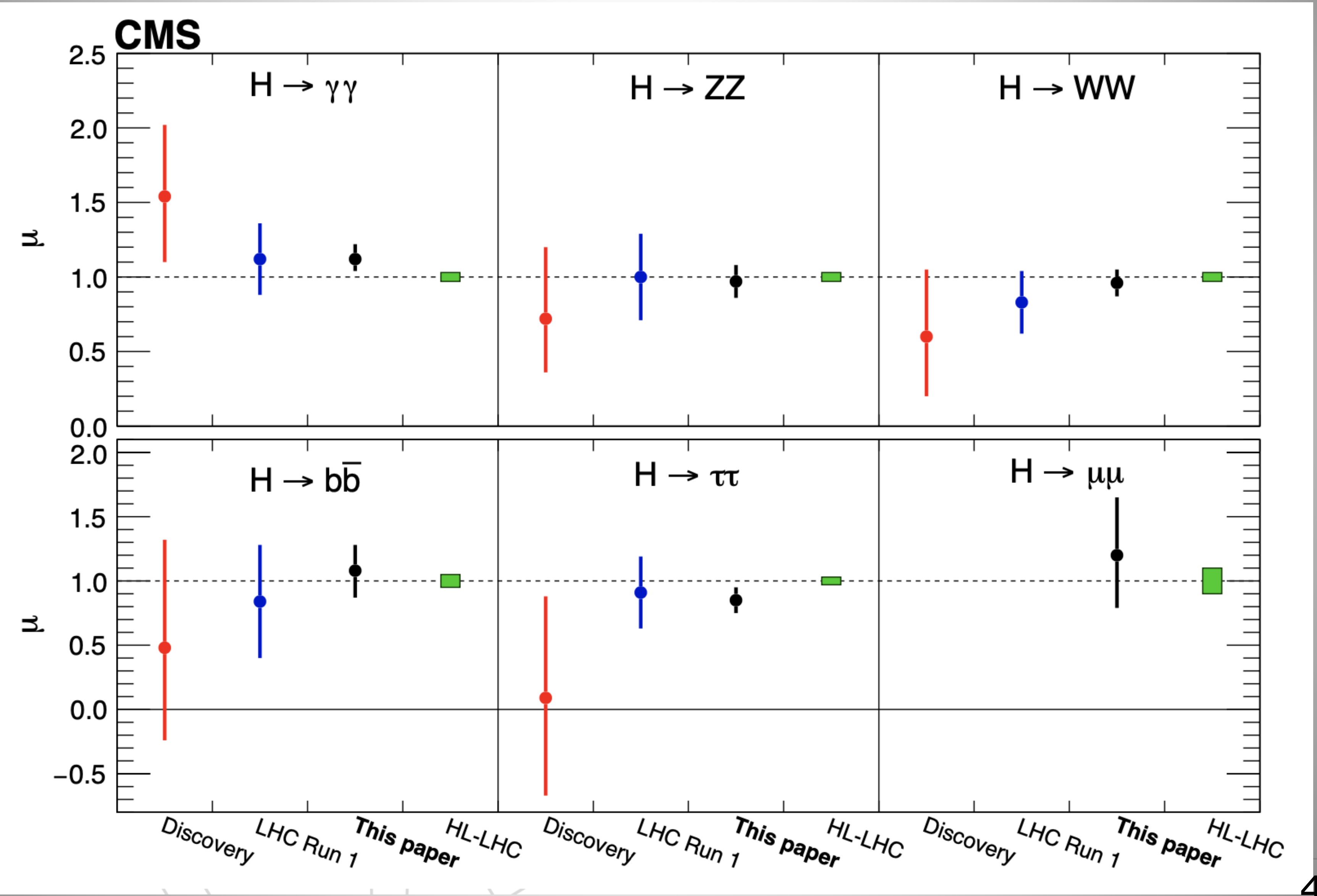


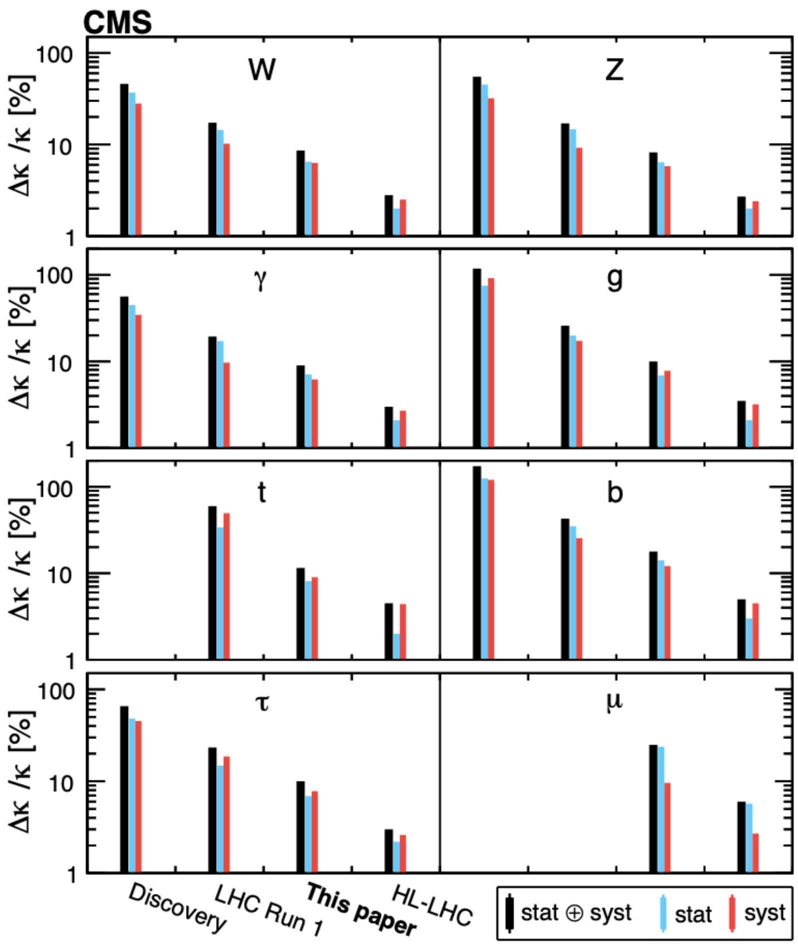


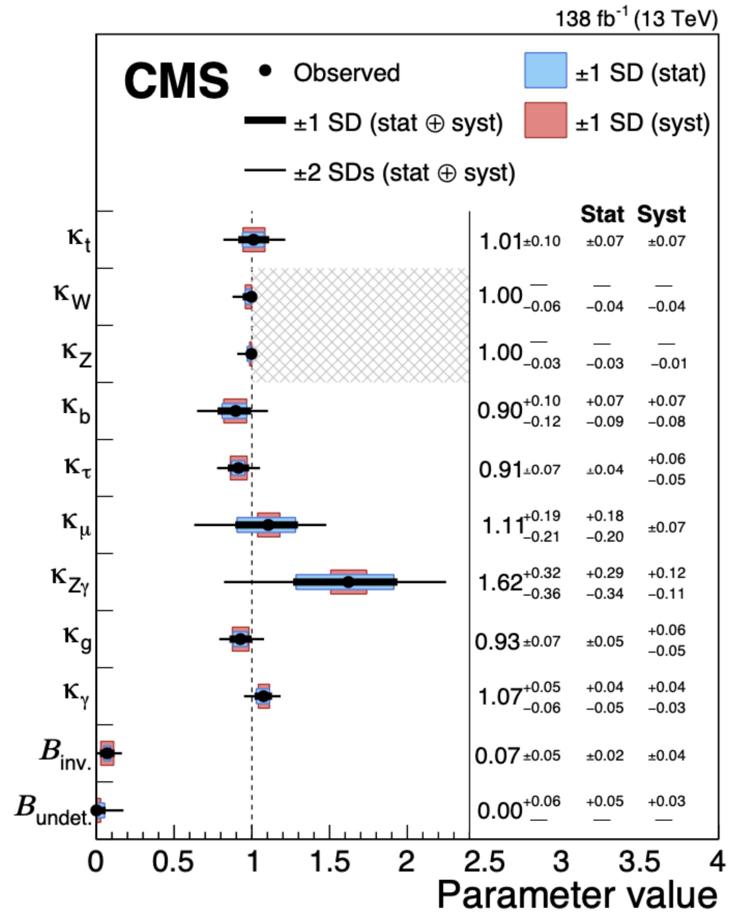
Signal strenght parameters



Signal Strenght Parameter Evolution




CMS
W
Z
γ
g
t
b
τ
μ
Δκ /κ [%]
100
10
1
Discovery
LHC Run 1
This paper
HL-LHC
stat ⊕ syst
stat
syst


138 fb-1 (13 TeV)
CMS
Observed
±1 SD (stat ⊕ syst)
±2 SDs (stat ⊕ syst)
±1 SD (stat)
±1 SD (syst)
Stat Syst
κt 1.01±0.10 ±0.07 ±0.07
κW 1.00 −0.06 −0.04 −0.04
κZ 1.00 −0.03 −0.03 −0.01
κb 0.90 +0.10 −0.12 +0.07 −0.09 +0.07 −0.08
κτ 0.91±0.07 ±0.04 +0.06 −0.05
κμ 1.11 +0.19 −0.21 +0.18 −0.20 ±0.07
κZγ 1.62 +0.32 −0.36 +0.29 −0.34 +0.12 −0.11
κg 0.93±0.07 ±0.05 +0.06 −0.05
κγ 1.07 +0.05 −0.06 +0.04 −0.05 +0.04 −0.03
Binv. 0.07±0.05 ±0.02 ±0.04
Bundet. 0.00 +0.06 +0.05 +0.03
0 0.5 1 1.5 2 2.5 3 3.5 4
Parameter value

Constraints from Higgs pair production