Status and prospects of Higgs boson physics

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After the Higgs boson discovery

After the discovery of the new particle in 2012, the ATLAS and CMS Collaborations started a vaste program of measurements of its properties to understand if the new particle is really the Standard Model Higgs boson

What are the main properties of the Higgs boson that we need to measure?

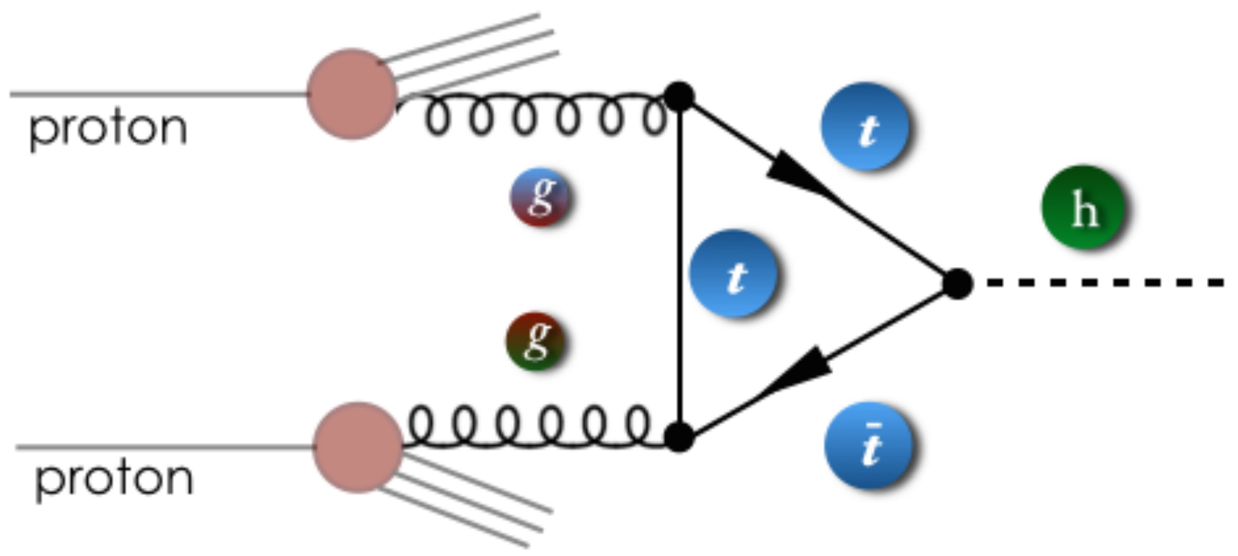
- Mass: value not fixed in the Standard Model, free parameter of the model
- Cross sections and branching rations for different production and decay modes: well-determined in the Standard Model once the Higgs boson mass is known
- Strength of couplings with other particles: fixed in the Standard Model, depending on the mass of the particles ($\propto m_f$ for fermions and $\propto m_V^2$ for vector bosons)
- Self-coupling: present in the Standard Model, with strength of self-coupling dependent on Higgs boson mass ($\propto m_H^2$)

Main goal of the LHC Run 2:

Measure all this properties with good precision and compare them to the Standard Model predictions to confirm or not if the observed particle is compatible with the Standard Model Higgs Boson

→ Any observed deviations from the Standard Model predictions could be a hint of the presence of new physics beyond the Standard Model!

Higgs boson production modes at the LHC

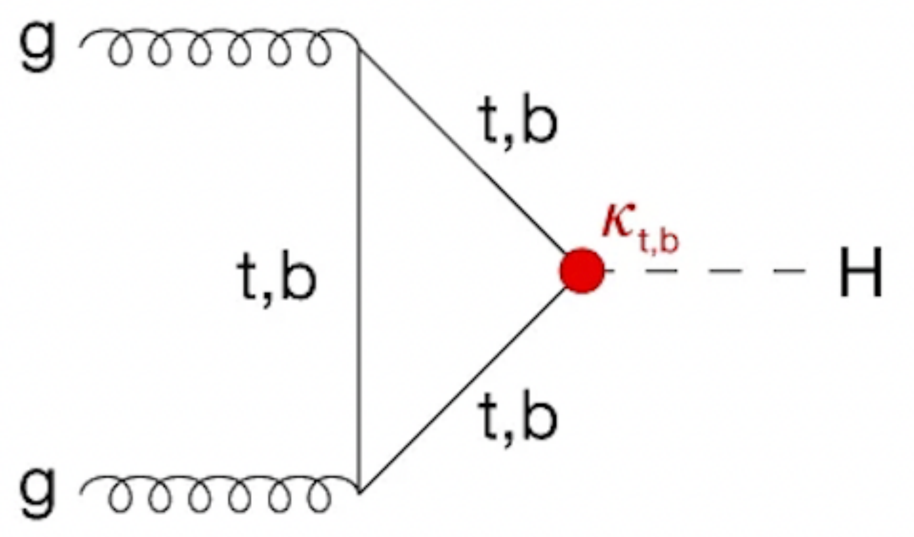


LHC is a pp collider

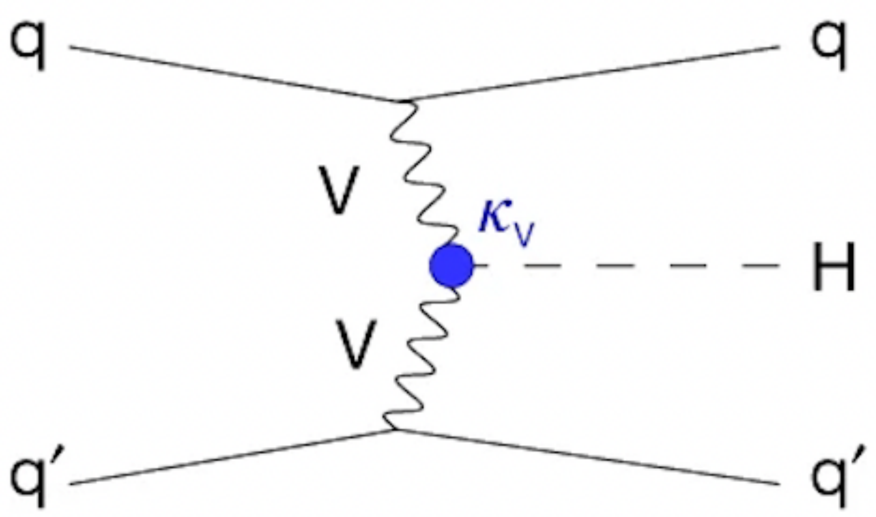
→ collider of gluons and quarks, processes with g/q in the initial state

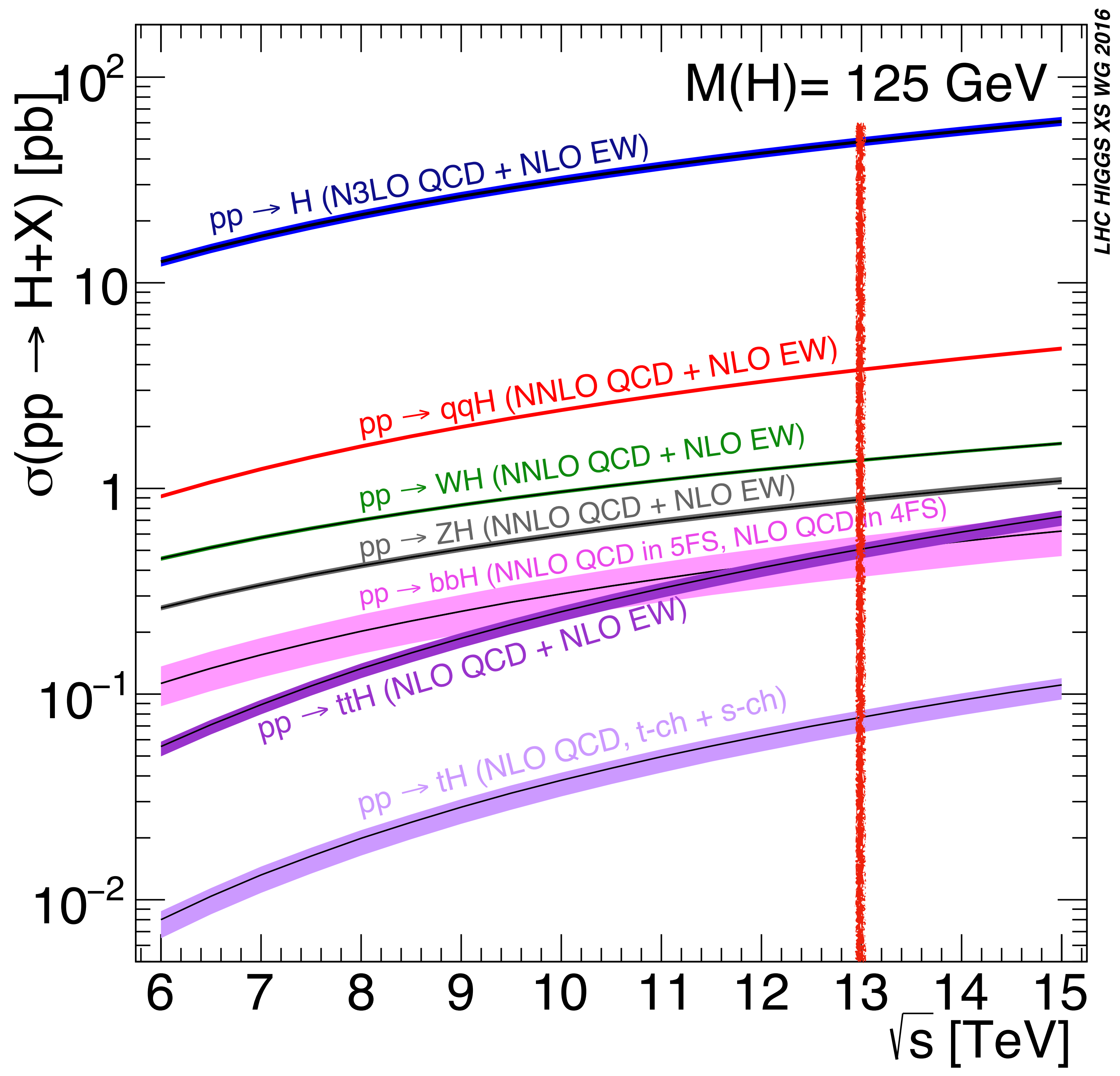
At the LHC 4 main Higgs boson production modes at $m_H = 125$ GeV

gluon-gluon fusion (ggF) $\sigma = 48$ pb

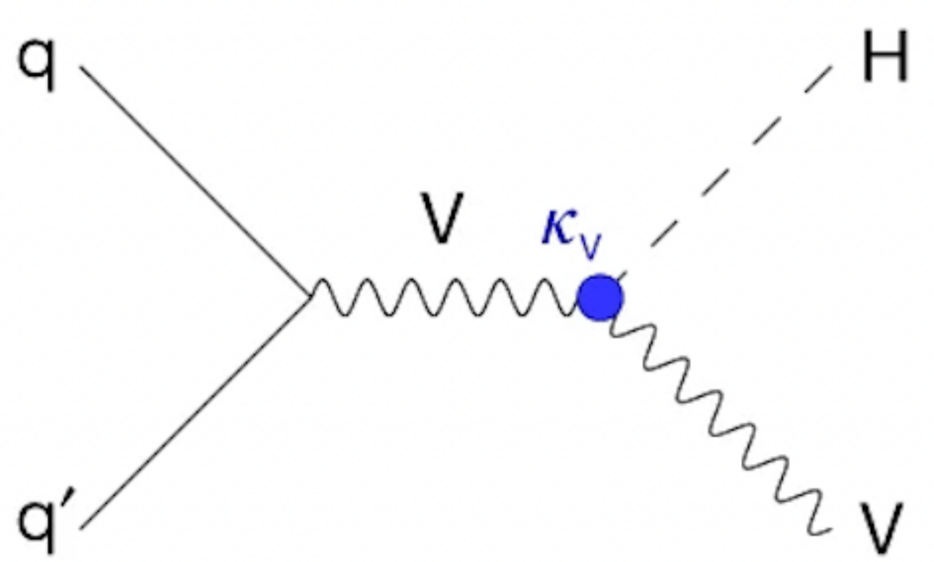


vector-boson fusion (VBF) $\sigma = 3.8$ pb

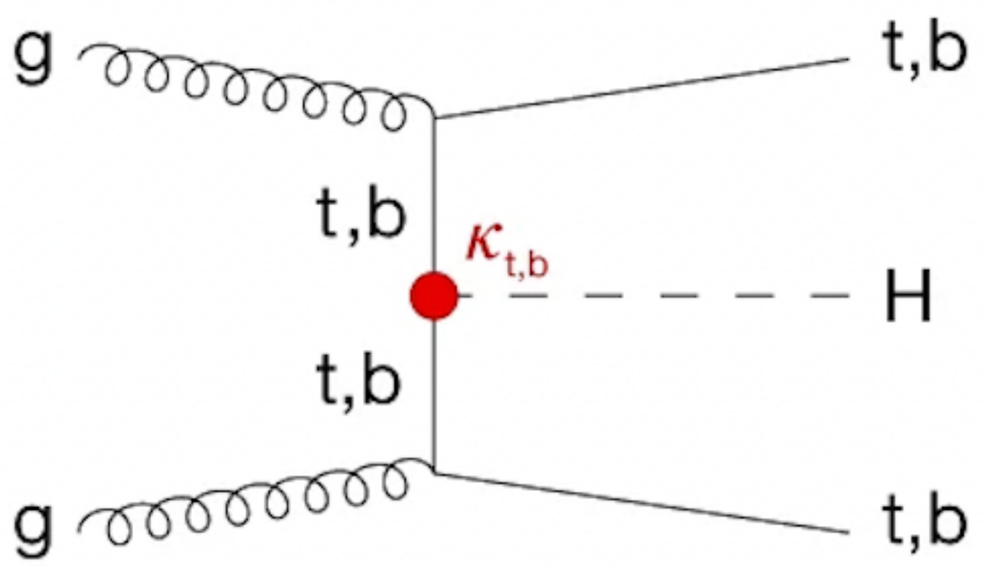




Associated production with vector bosons (VH) $\sigma = 2.3$ pb

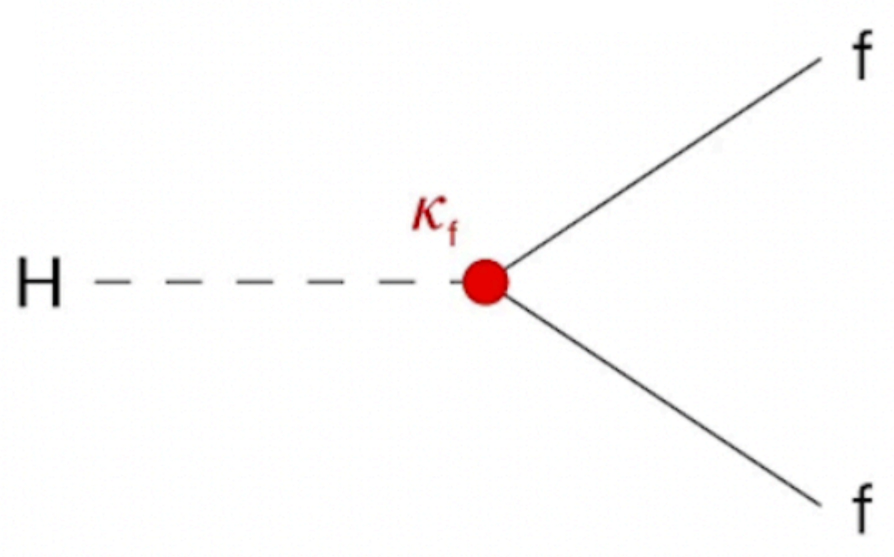


Associated production with top-quarks (ttH) $\sigma = 0.51$ pb or b-quarks (bbH) $\sigma = 0.49$ pb

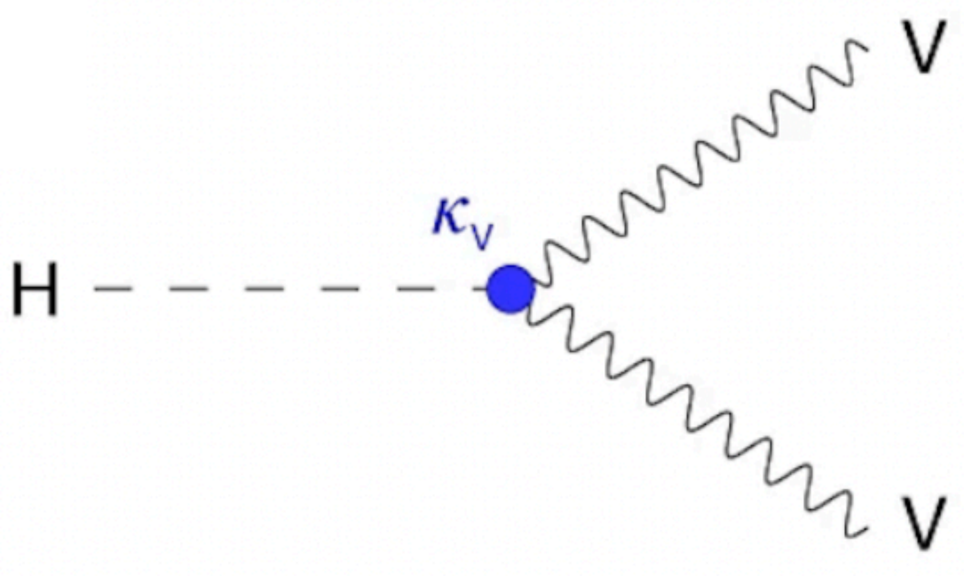


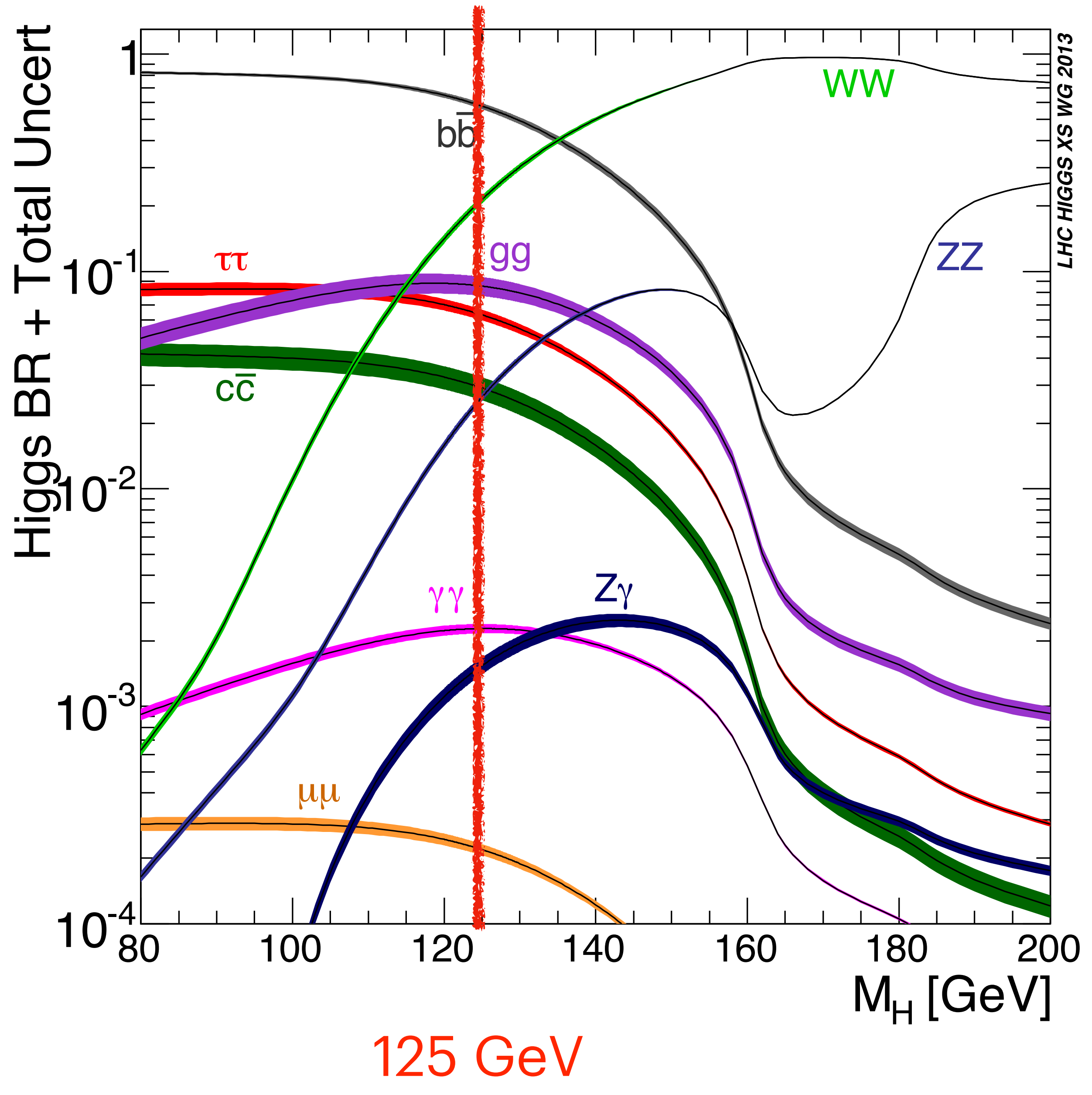
Higgs boson decay modes

Decays to fermions

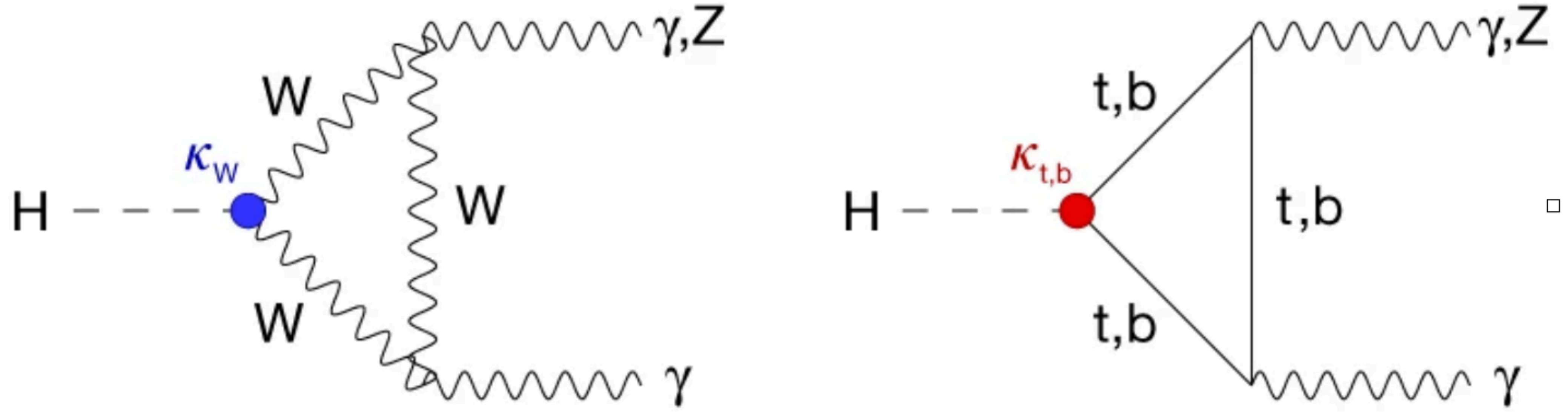


Decays to vector bosons

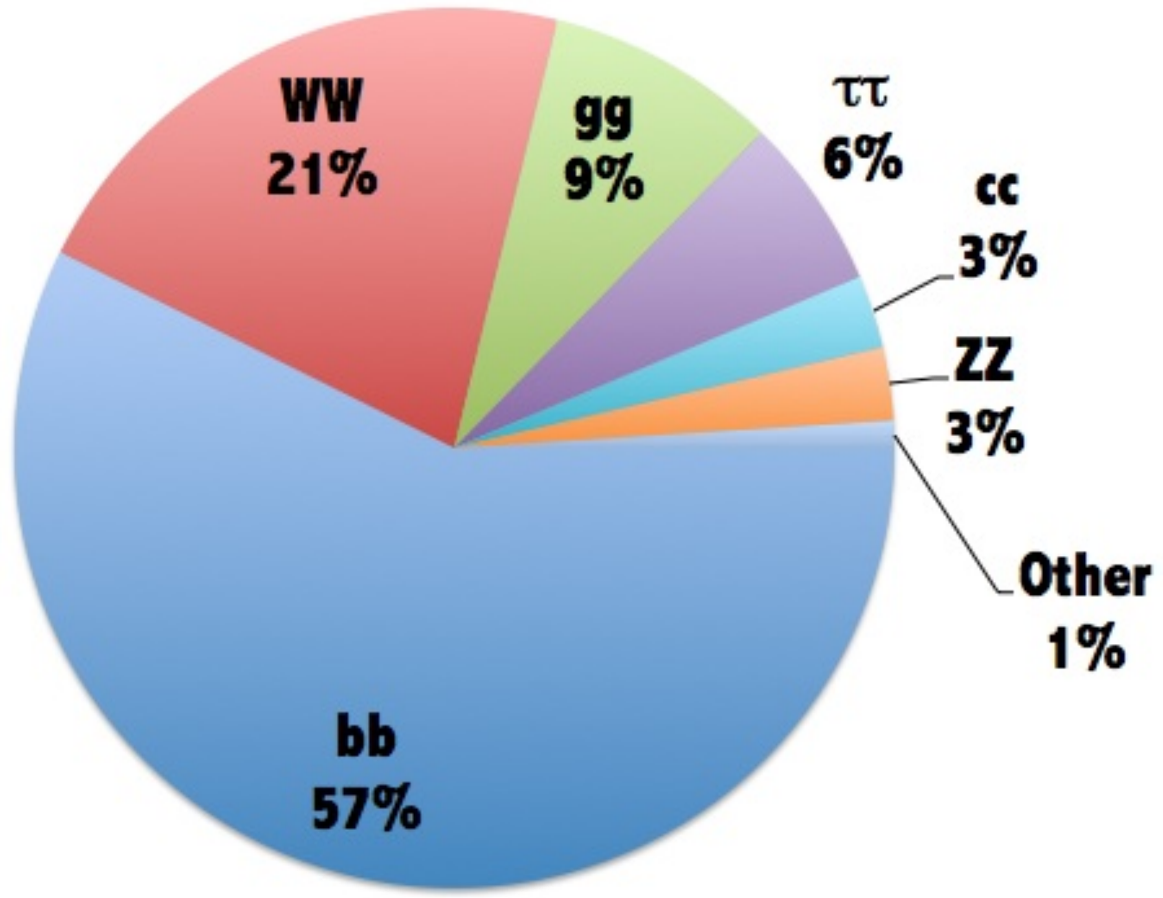




Decays to γγ/Zγ
(BRγγ=0.23%, BRZγ=0.15%)



Higgs decays at m_H=125GeV



What have we done in the past 10 years, after the Higgs boson discovery in 2012 until now?

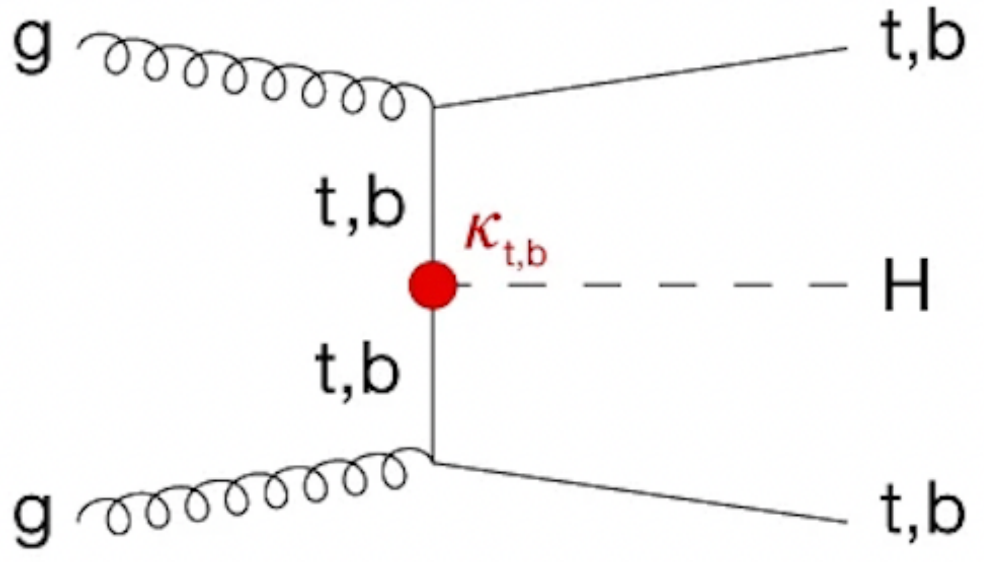
Not all results shown!
Just a "small" selection of interesting LHC Run 2 results obtained with very important contributions from ATLAS and CMS Roma1 groups

Observation and measurements of Higgs boson production and decay modes predicted by the Standard Model and not observed in Run 1

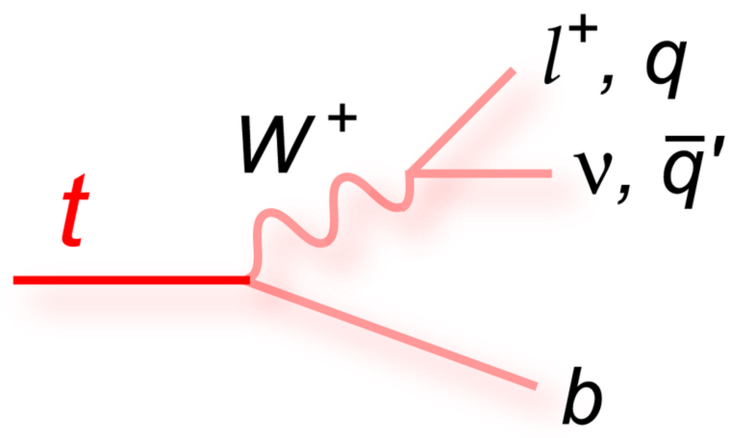
Observation of ttH production

Very challenging process to reconstruct as many different objects in the final state
from the decays of the top-quarks and of the Higgs boson

ttH production

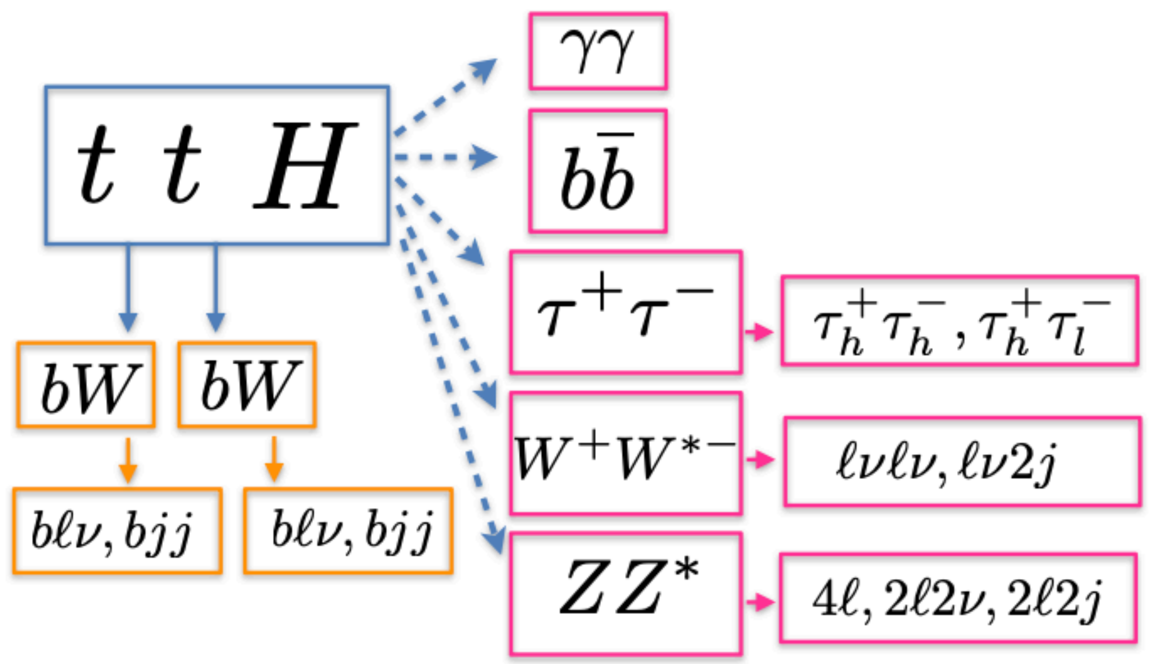


Top-quark decay



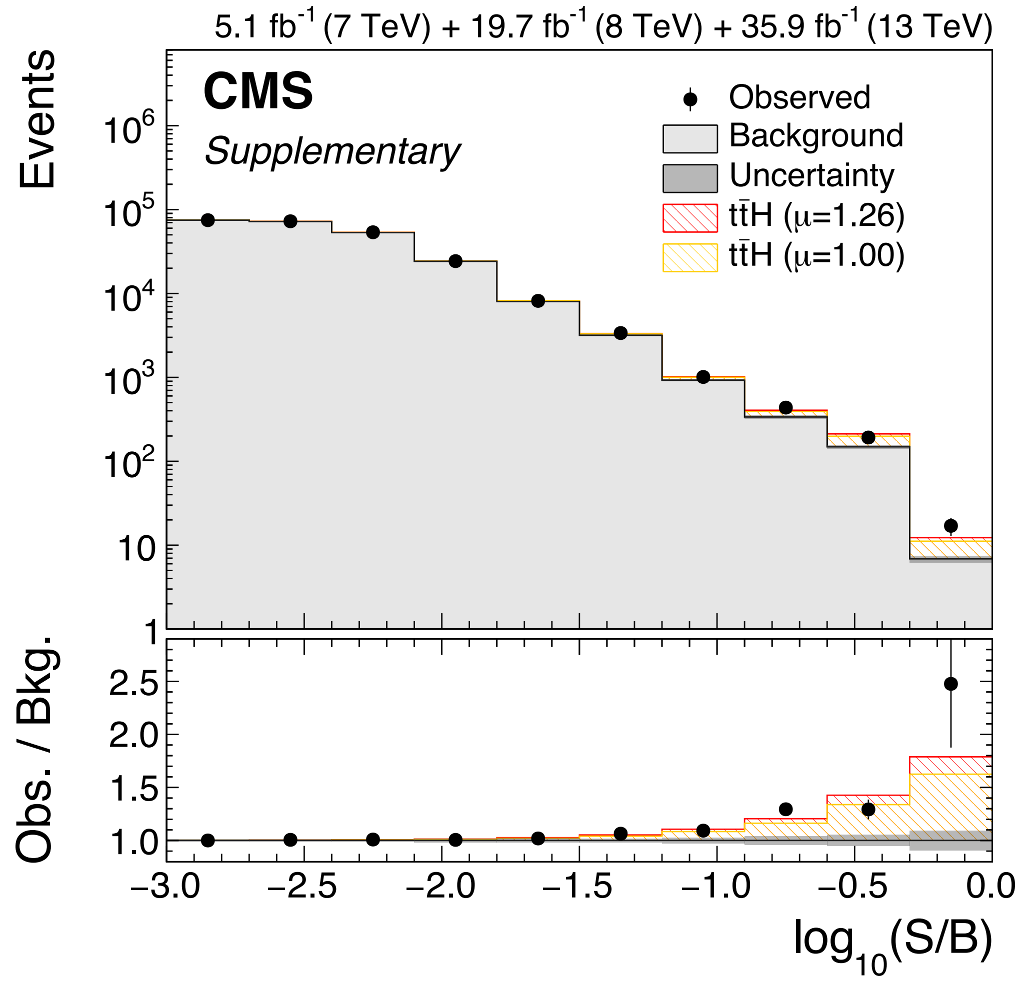
Observation of ttH production obtained
by ATLAS and CMS, with $> 5\sigma$ significance,
combining very complex analyses in many different final states!

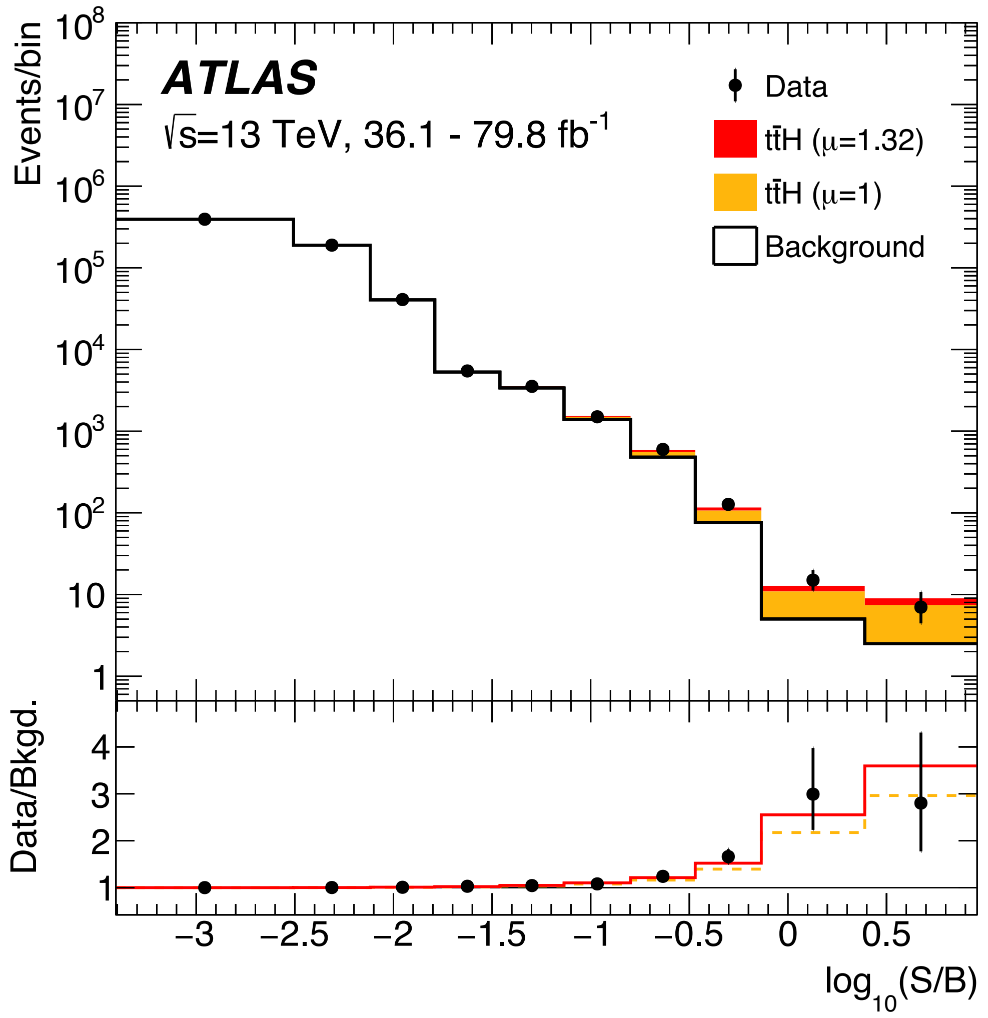
→ Confirmed the coupling of the Higgs boson to the top quark
(First direct observation of coupling to fermions,
observed only indirectly in Run 1 through ggF production)

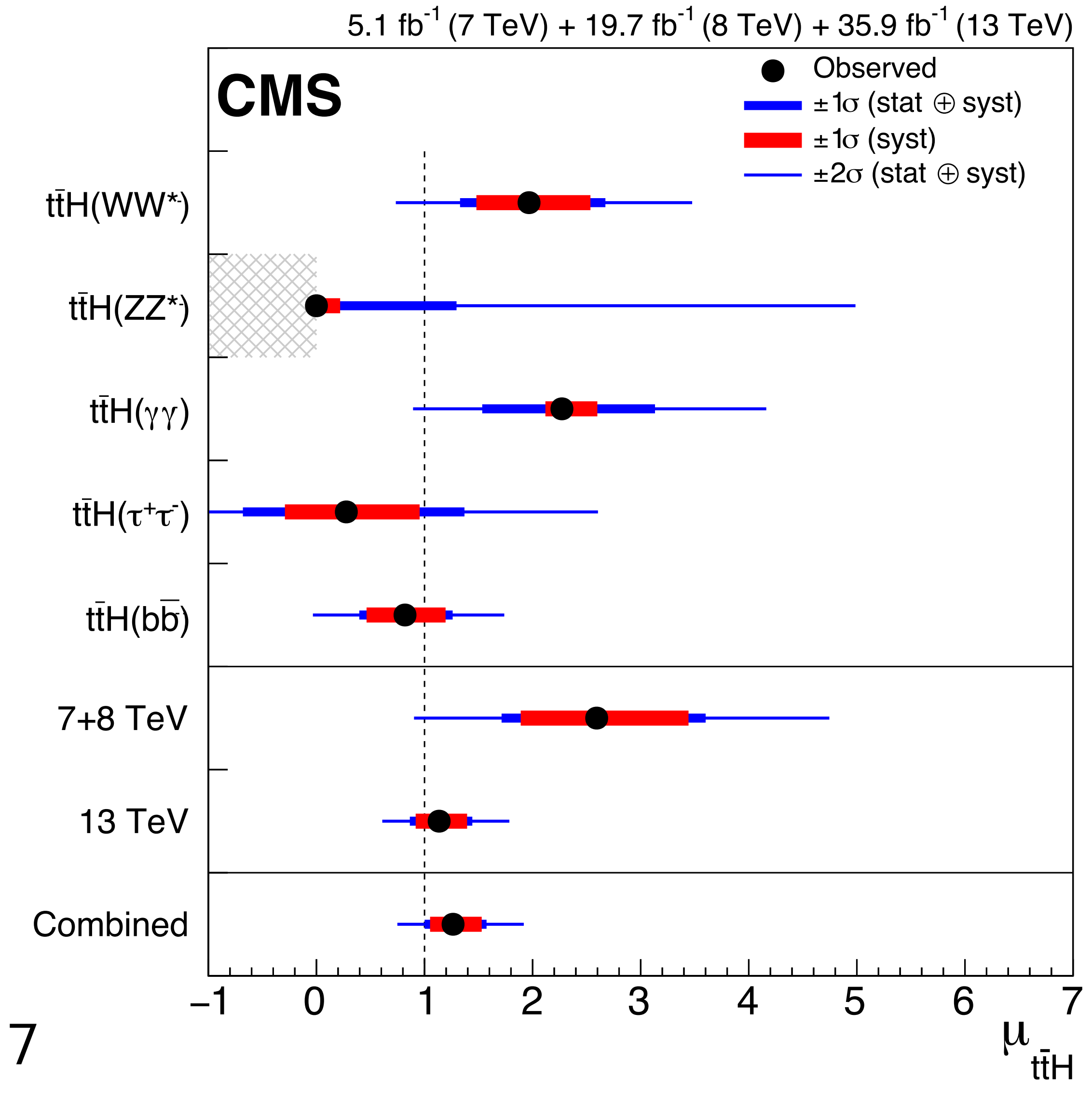


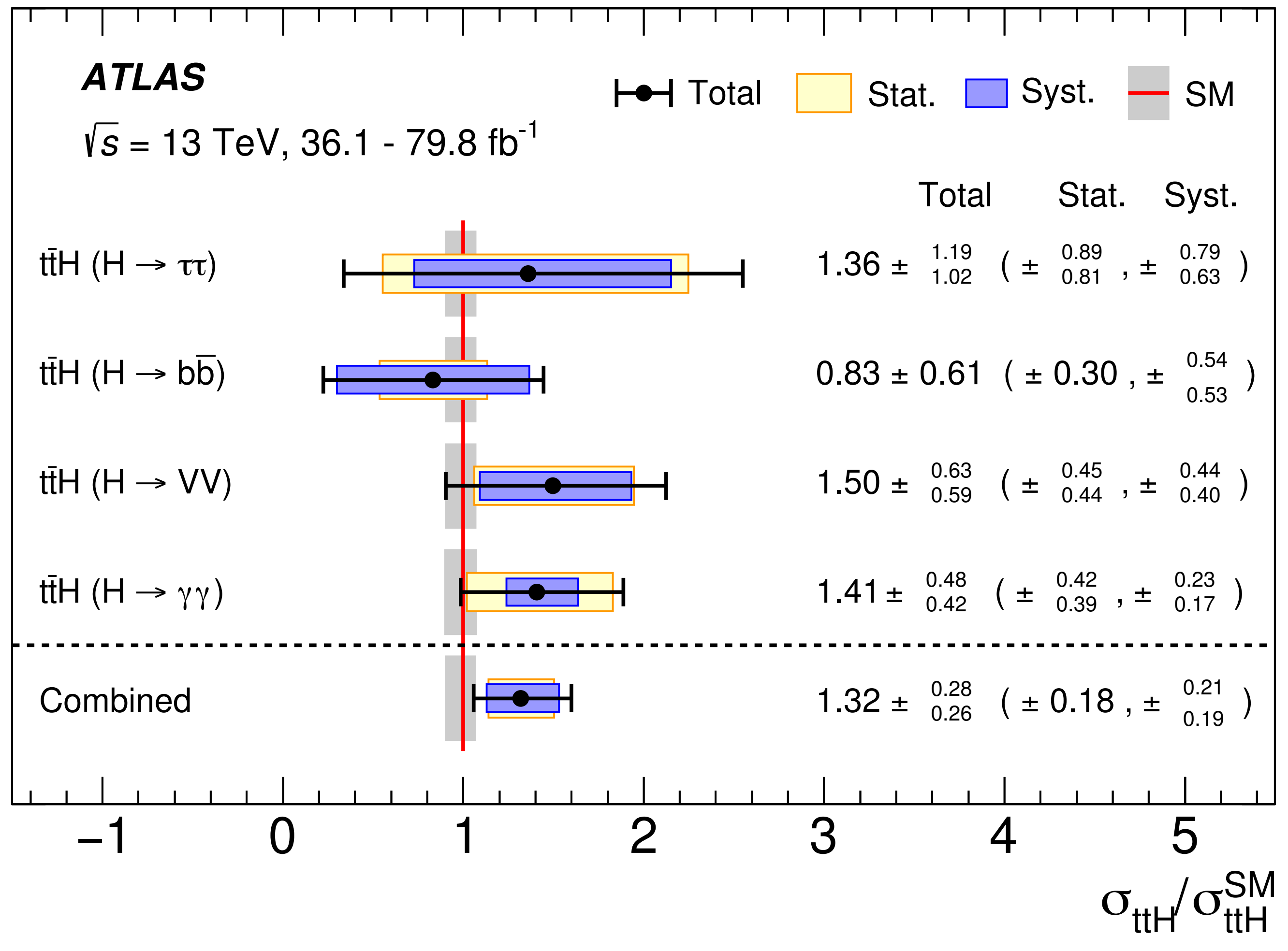
Signal strength measurements, $\mu_{ttH} = \sigma_{ttH}^{meas} / \sigma_{ttH}^{SM}$

Data/prediction comparison in bins with different S/B



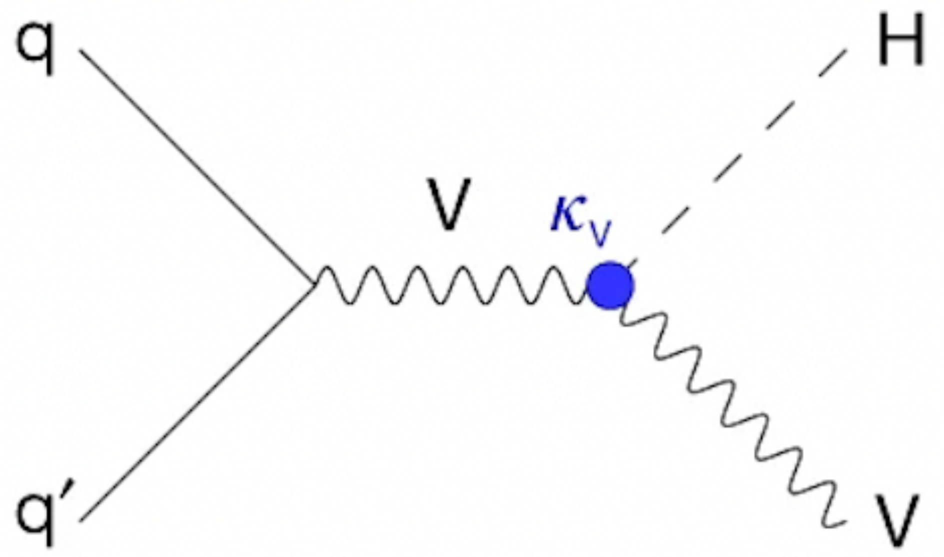




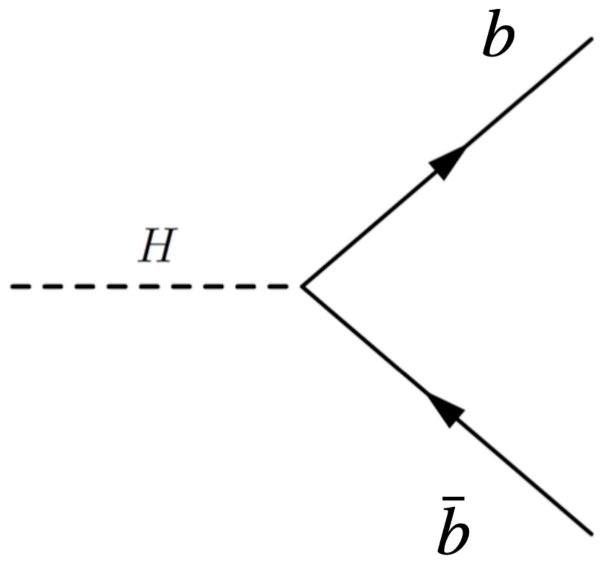


Observation of VH production and $H \to bb$ decay

VH (WH/ZH) production



H→bb decay

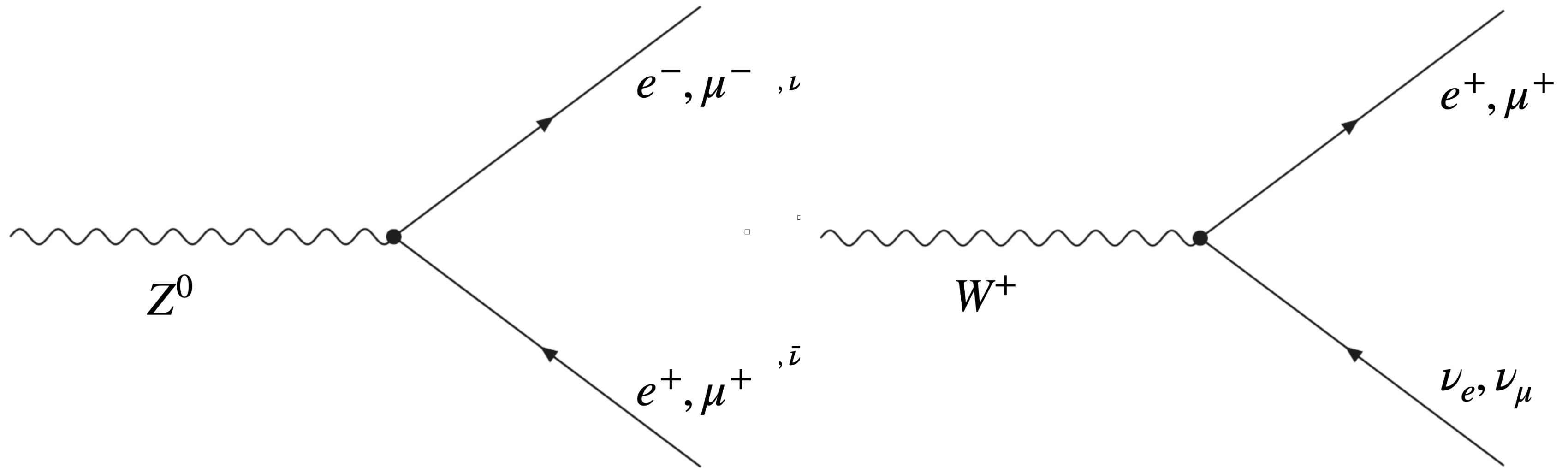


VH production process used as a tool for studying the decay of the Higgs boson to bb:

bb decay has a very large branching ratio (57%) but challenging to identify due to large multi-jet backgrounds

→ use VH (WH/ZH) process for easier signal event selections exploiting the presence of 1/2 leptons and MET from the W/Z decays

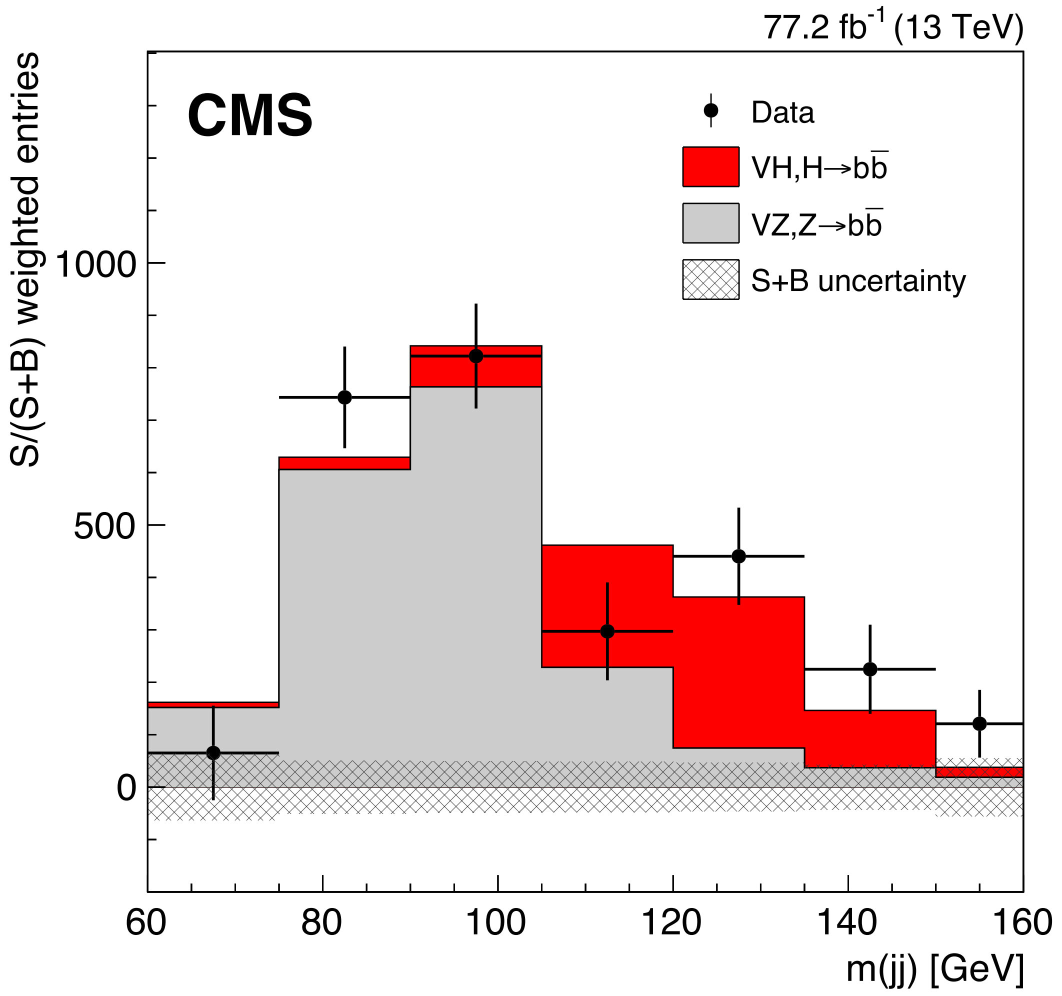
Z and W bosons decays

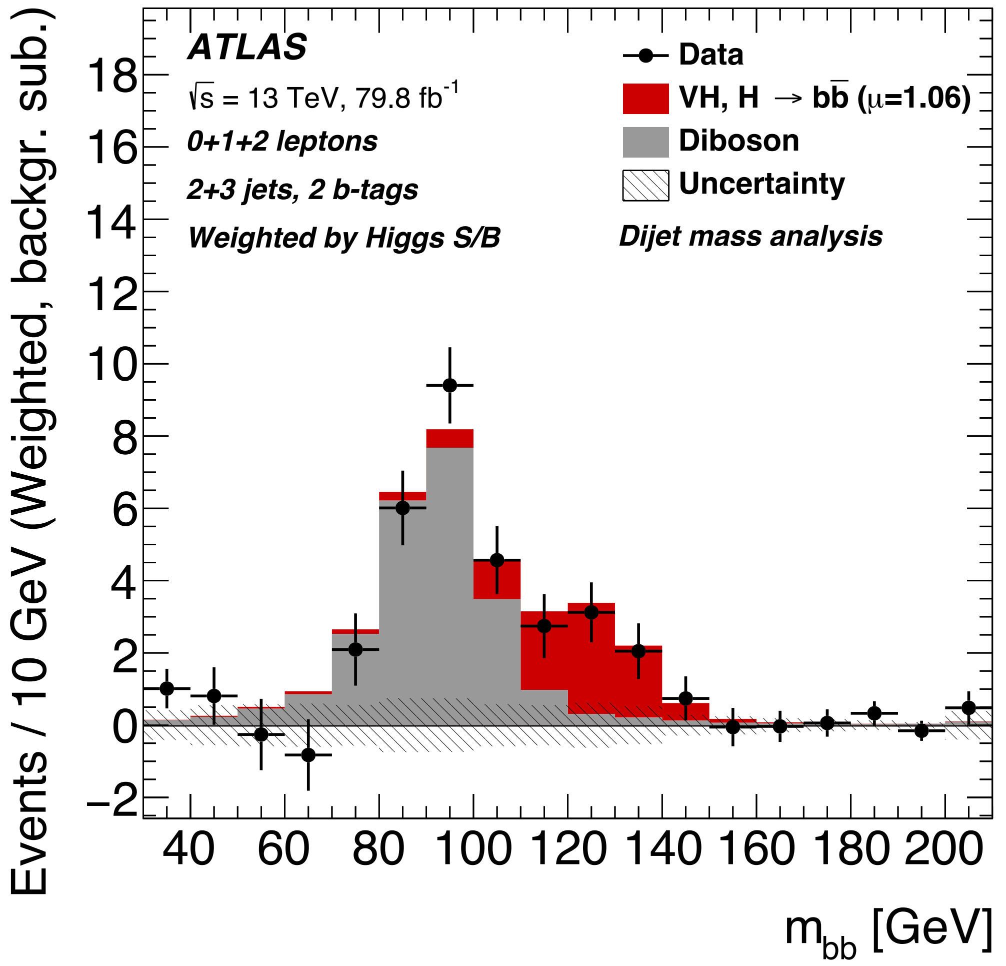


Observation of VH→bb by ATLAS and CMS with $> 5\sigma$ significance!

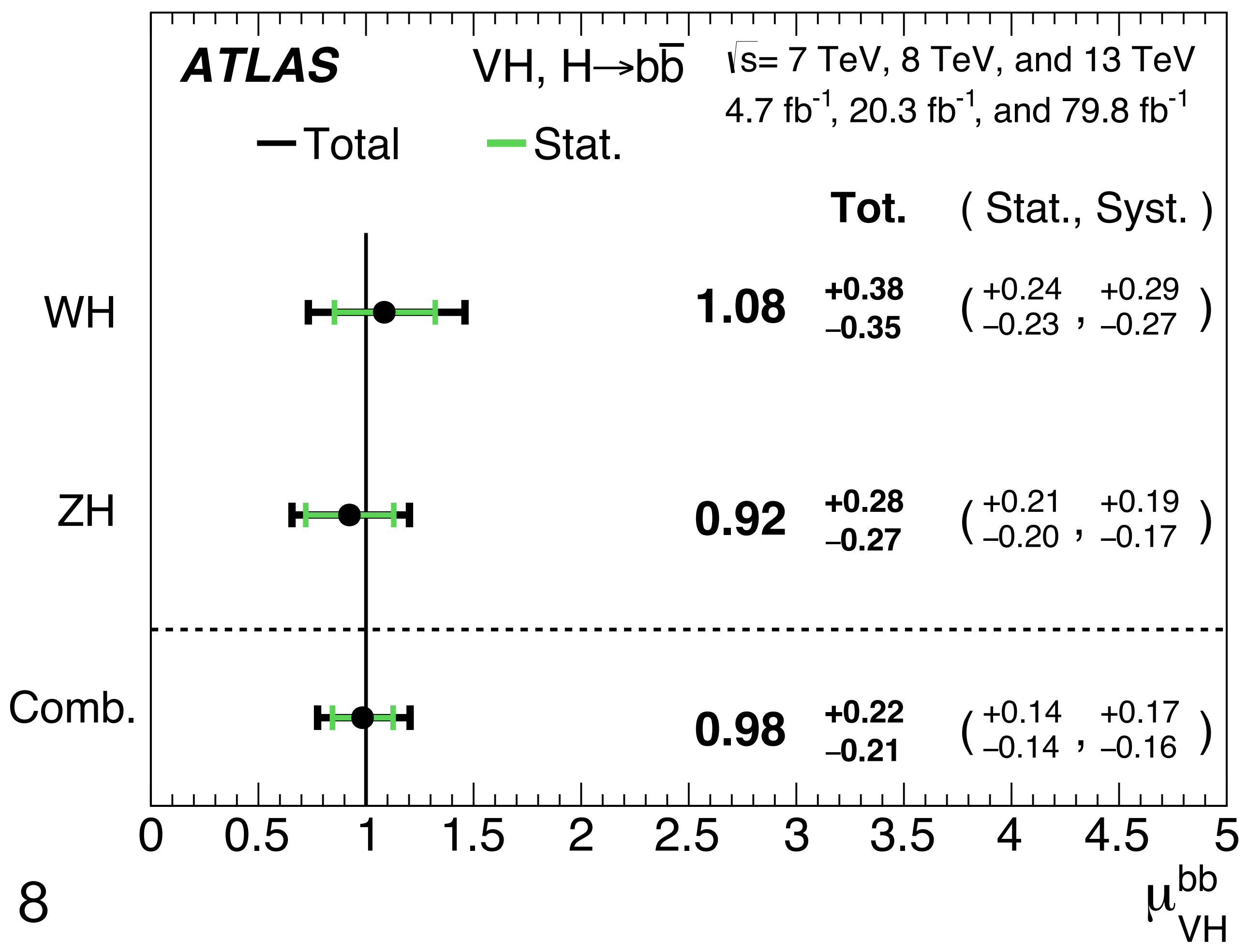
→ Observation of the coupling of the Higgs boson to the bottom quark

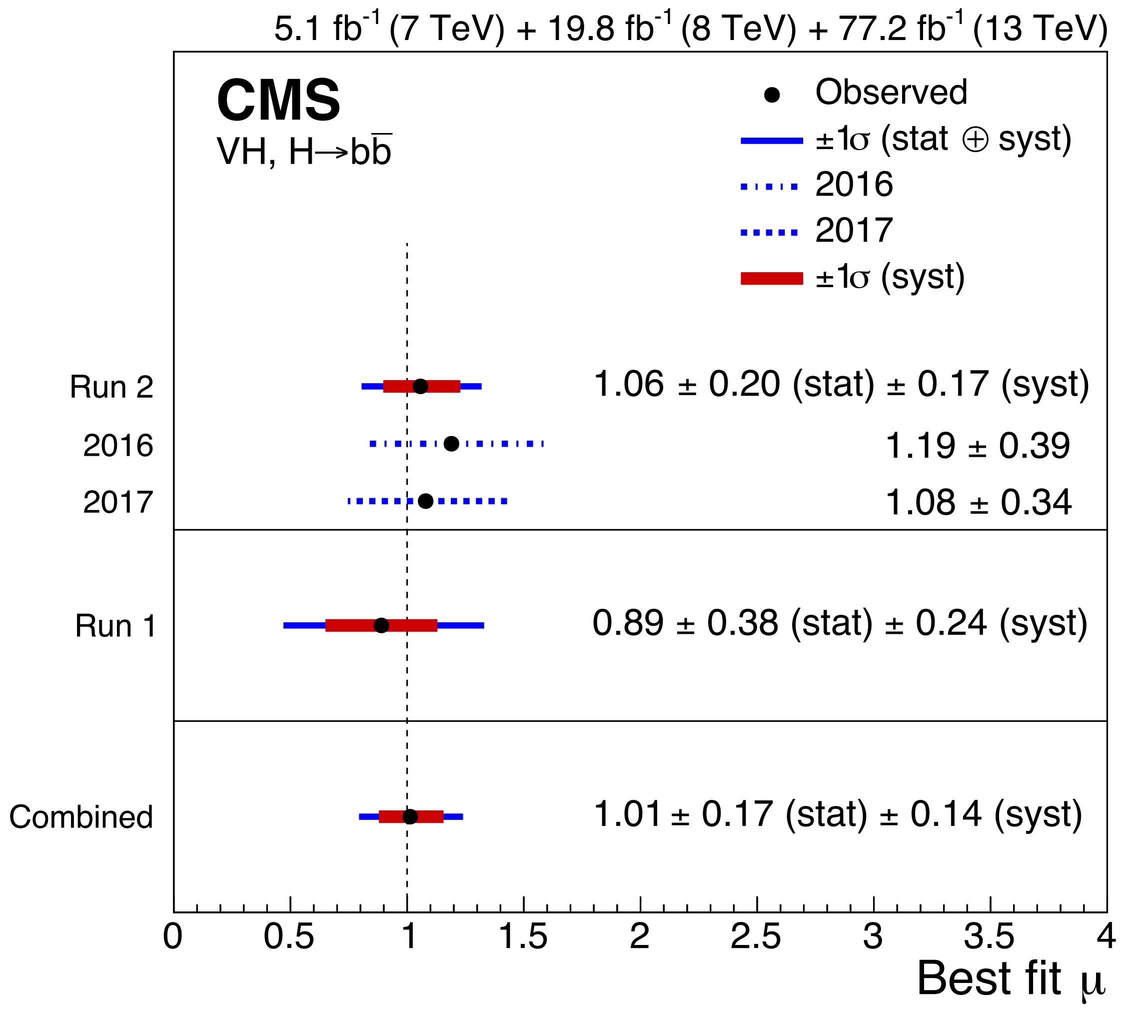
Data/prediction comparison in bins of m_{bb} (reconstructed m_H)





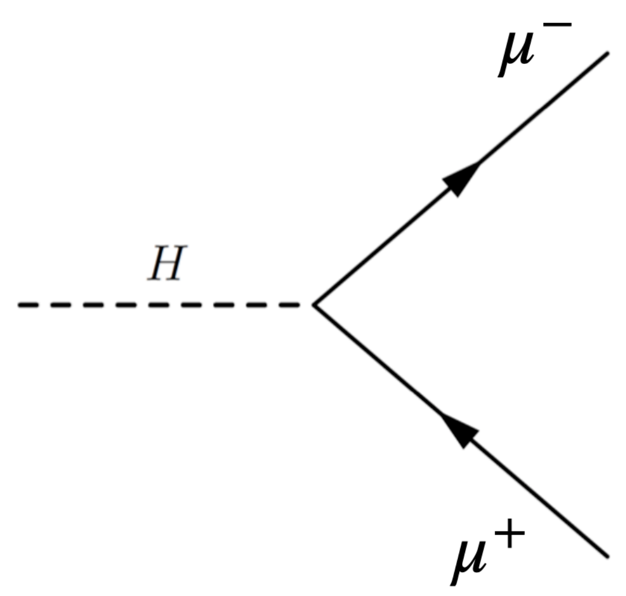
Signal strength measurements, $\mu_{VHbb} = \sigma^{meas}_{VHbb} / \sigma^{SM}_{VHbb}$



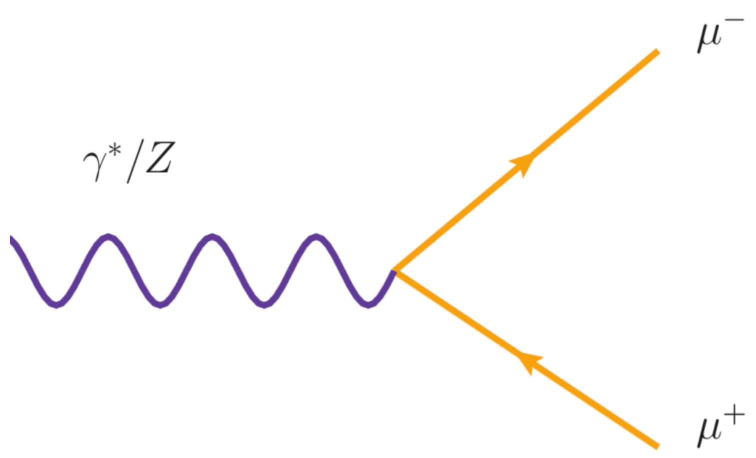


Evidence of the decay $H \to \mu\mu$

H→μμ decay signal



Drell-Yan μμ background



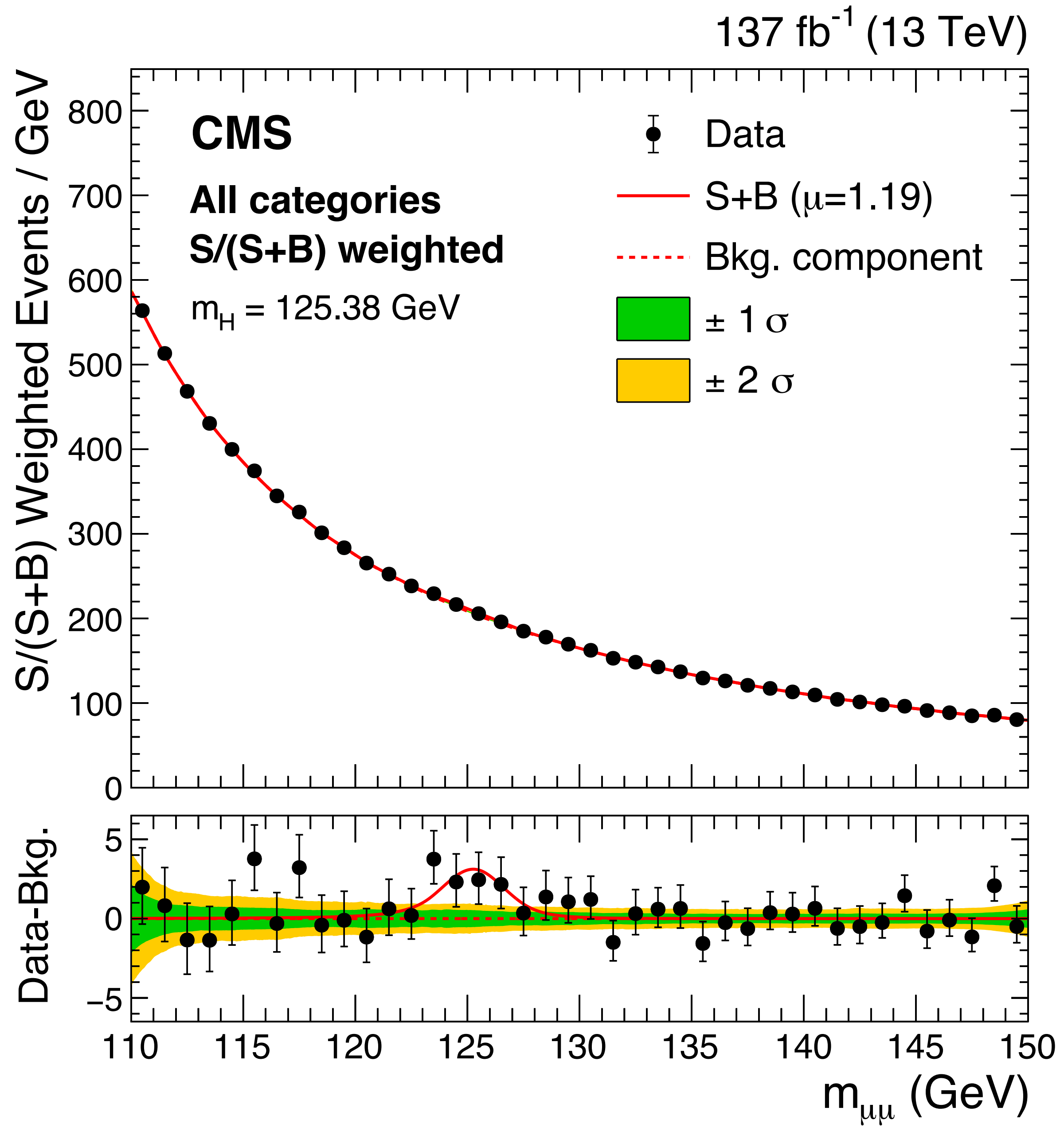
$H \to \mu\mu$ is a very rare decay of the Higgs boson (BR=0.02%)

Additional experimental challenge given by the very large Drell-Yan μμ background

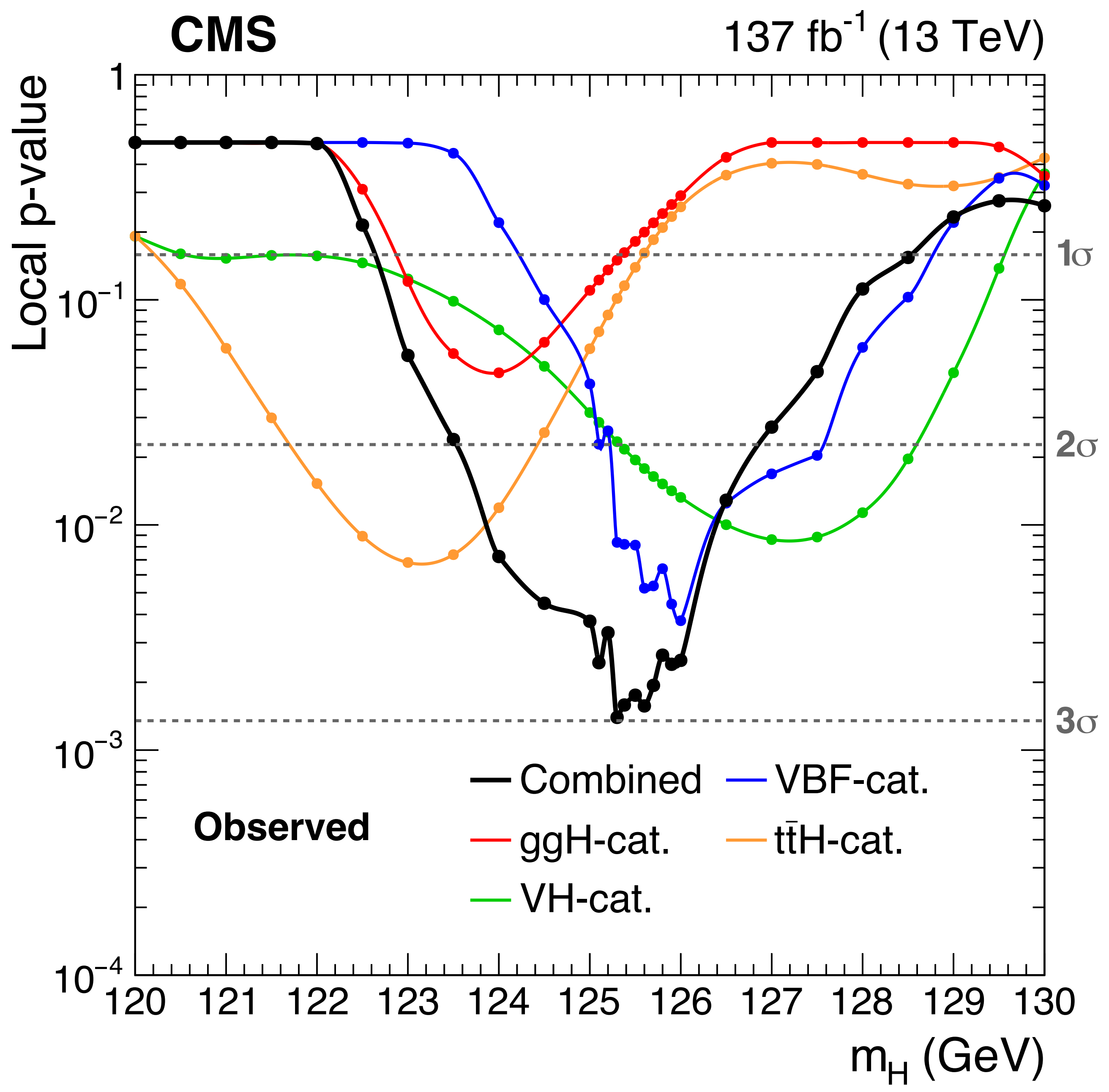
Strategy for the search for this rare decay:
combination of all main production modes (ggF, VBF, VH, ttH)

Evidence of H→μμ by CMS with 3σ significance (ATLAS 2σ significance)!

→ First direct measurement of the coupling of the Higgs boson to second-generation fermions



Data/prediction comparison in bins of $m_{\mu\mu}$ (reconstructed m_H)



H→μμ decay signal significance from different production modes and their combination

Precision measurements of Higgs boson properties

Higgs boson mass precision measurement

Crucial measurement as the mass is a free parameter of the Standard Model

→ it is the input needed to predict Higgs production cross sections and decay rates

Higgs mass measured in decay channels with good resolution: $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$

End-of-Run 1 measurement with precision of 0.2%,
latest measurements of the mass with Run 2 data:

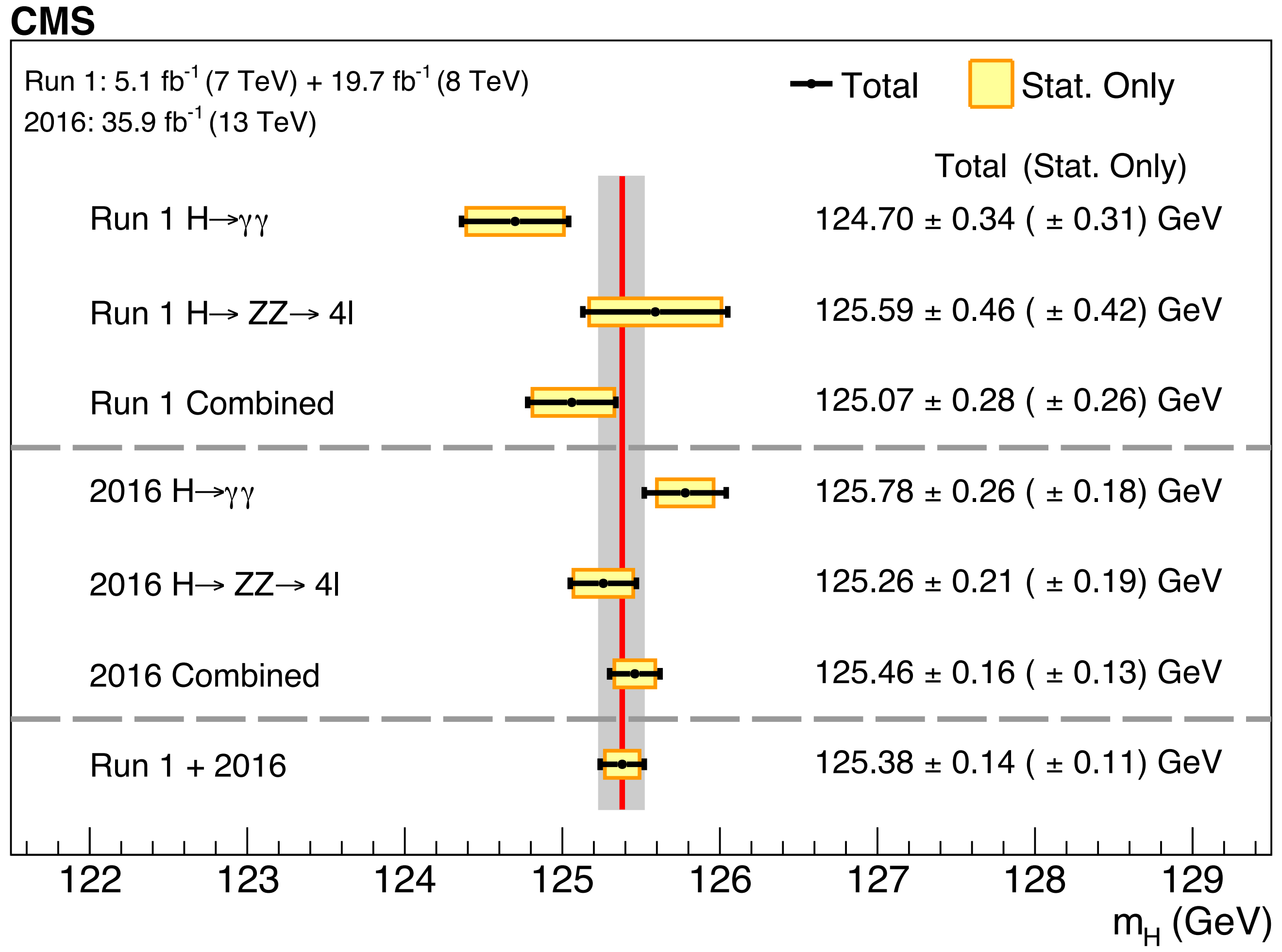
CMS:

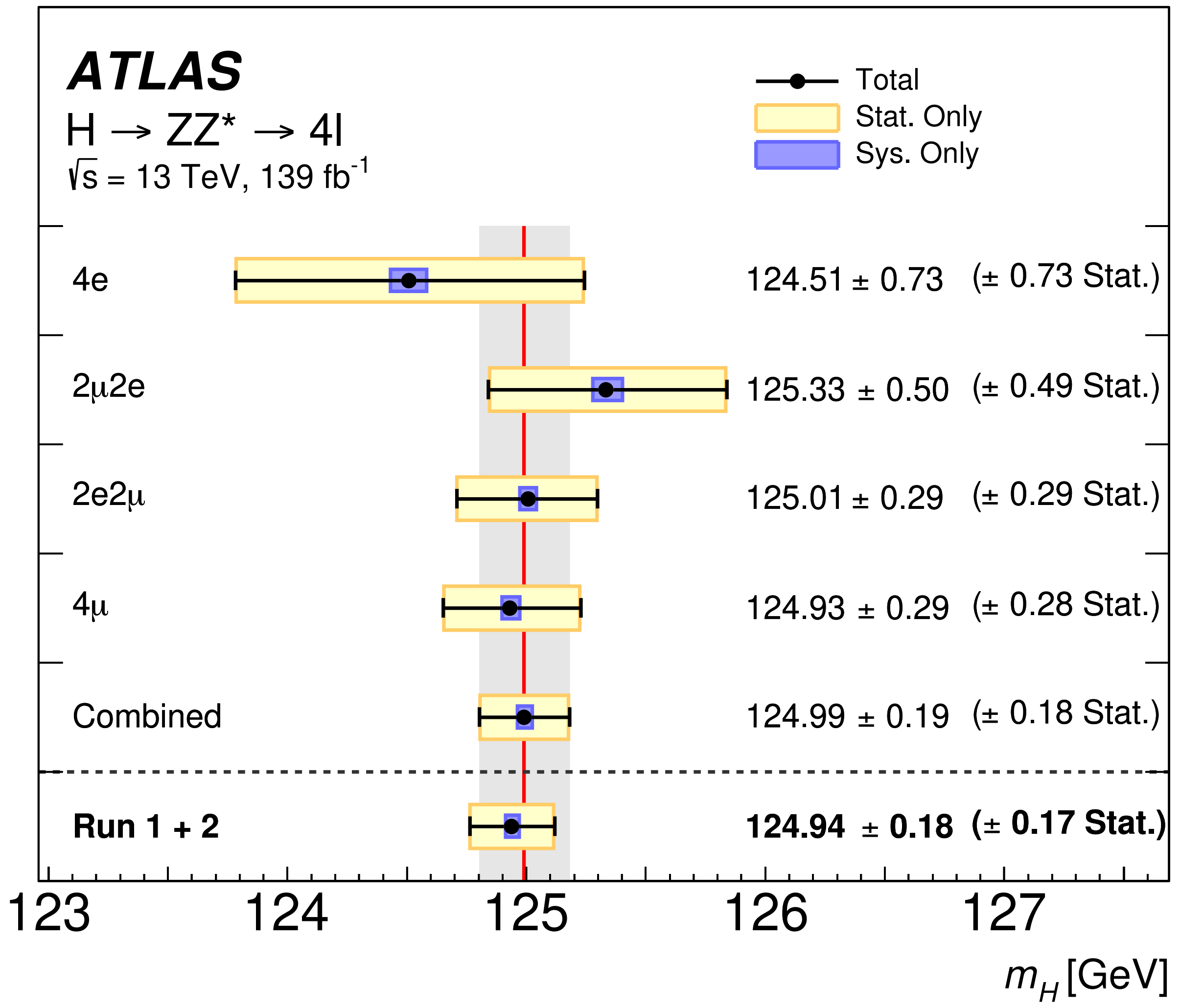
uncertainty of 0.11%, Run 1 + 2016 of Run 2 in $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$ channels,
measurements with full Run 2 data still ongoing

ATLAS:

uncertainty of 0.14% Run 1 + Run 2 in $H \to ZZ^* \to 4l$,
measurement in the $H \to \gamma\gamma$ channel with full Run 2 data still ongoing

→ Not yet the final Run 2 results, but already much improved results and additional improvements expected with the inclusion of the missing measurements and with ATLAS+CMS combination
(total uncertainty is dominated by statistical uncertainties and can improve a lot by including more data)

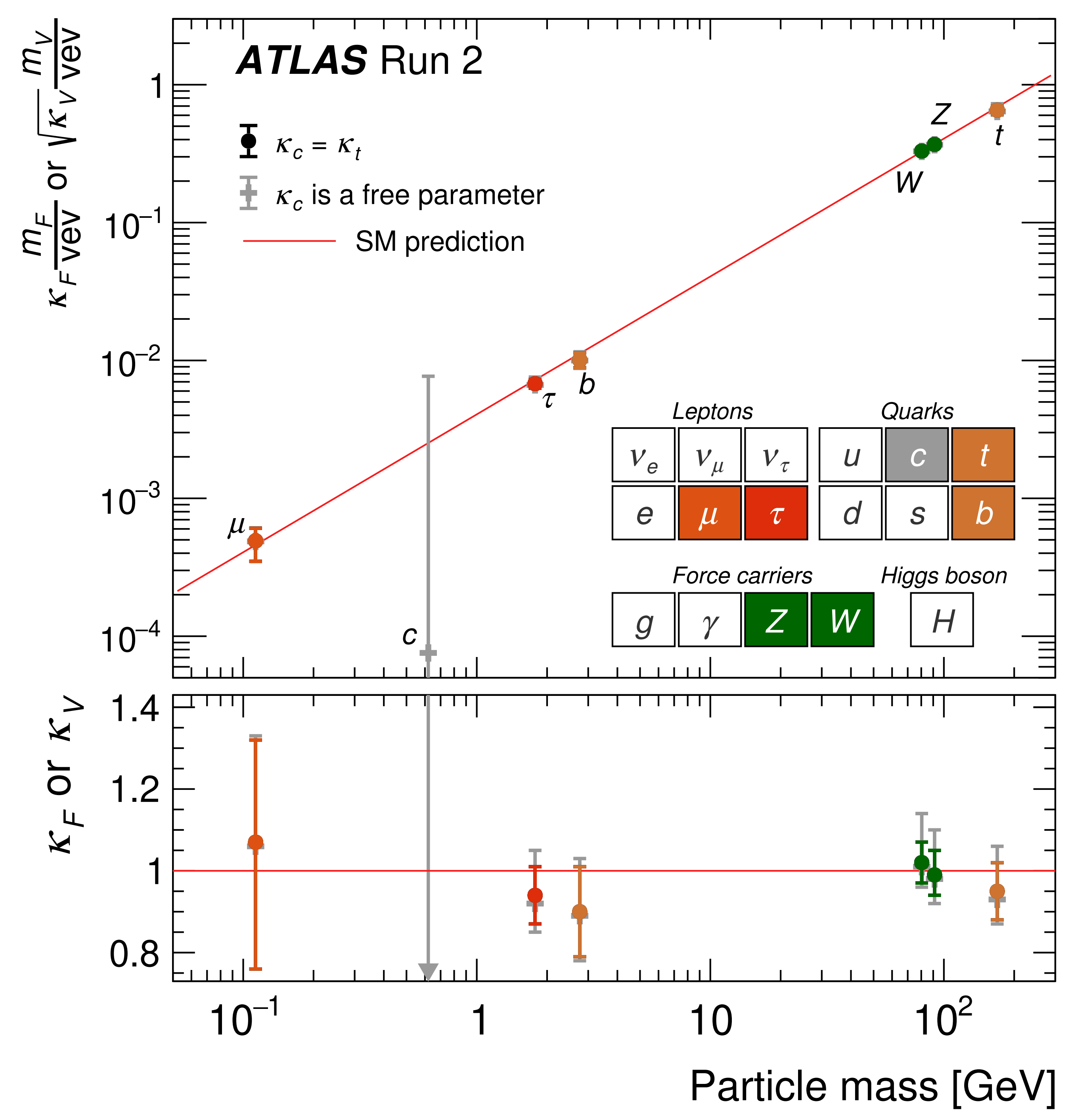


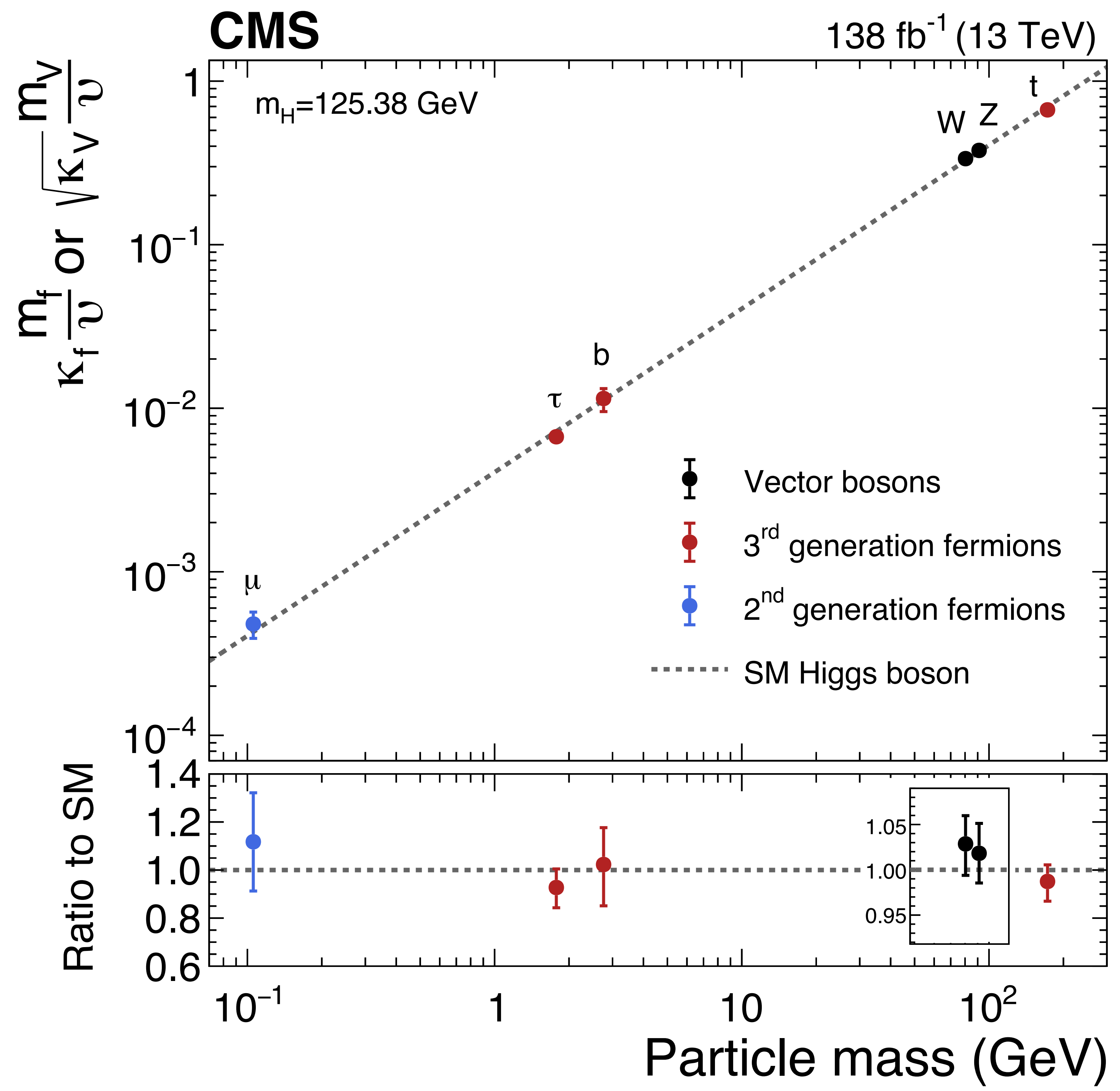


Higgs boson coupling measurements

After 10 years, 4 main production modes (ggF, VBF, VH, ttH) and 5 decay channels observed (bb, WW, ττ, ZZ, γγ)

From the direct measurements of production and decay rates in the different channels,
it is possible to extract measurements of the Higgs boson couplings





All measurements of couplings as a function of particle masses
in agreement with Standard Model predictions within uncertainties

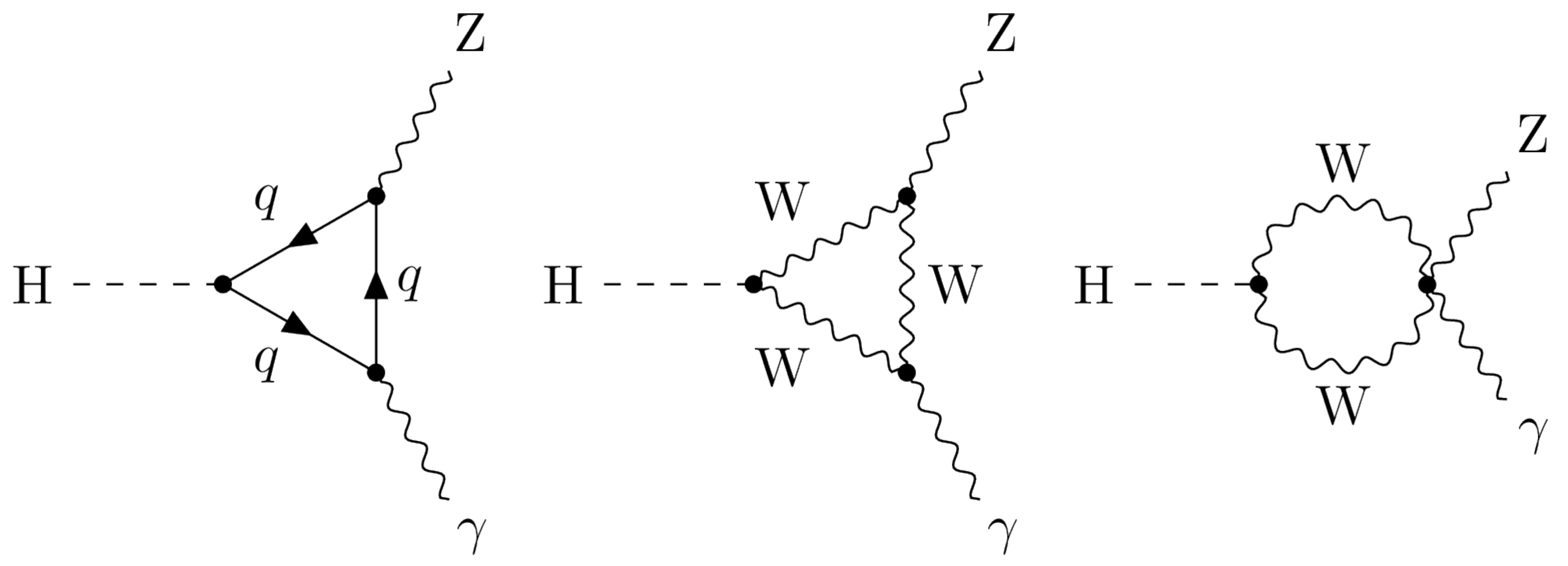
(plots show "reduced" couplings as a function of mass, defined to have same dependence on the mass for fermions and vector bosons)

- Higgs boson couplings to vector bosons measured with a precision of ~5%
- Higgs boson couplings to 3rd generation fermions measured with a precision of ~10%
- First measurements of Higgs boson couplings to 2nd generation fermions (~20% precision on coupling to muons)

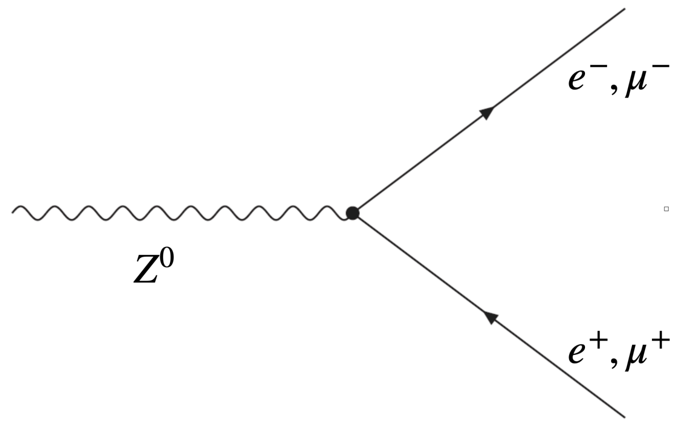
Some examples of searches for not yet observed Standard Model Higgs boson processes

Search for the decay $H \to Z\gamma$

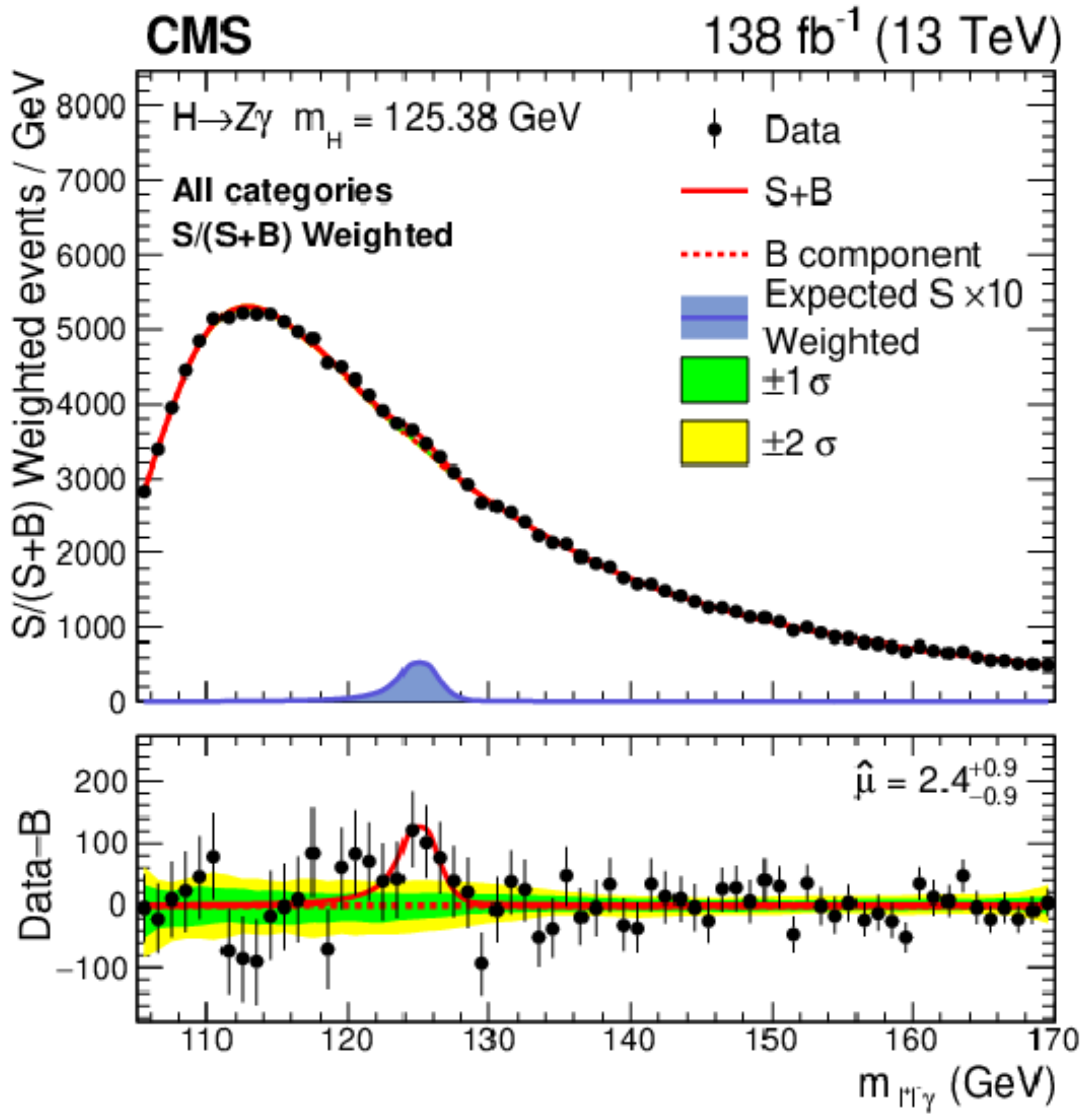
H→Zγ decay signal



Z → ee/μμ decay



Data/prediction comparison in bins of $m_{ll\gamma}$ (reconstructed m_H)



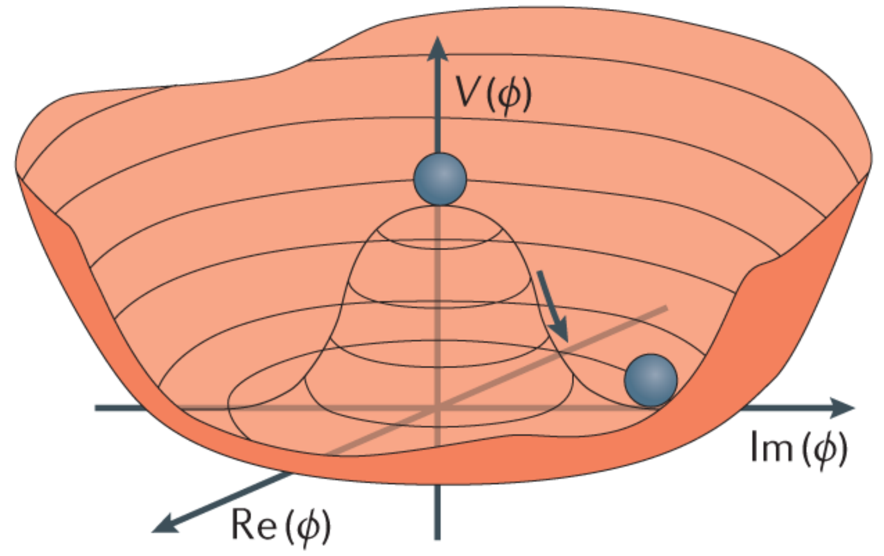
$H \to Z\gamma$ is a rare decay of the Higgs boson
occurring through quantum loops (BR=0.15%)
→ Might be sensitive to new Higgs boson coupling structure
and/or new particles in the loops

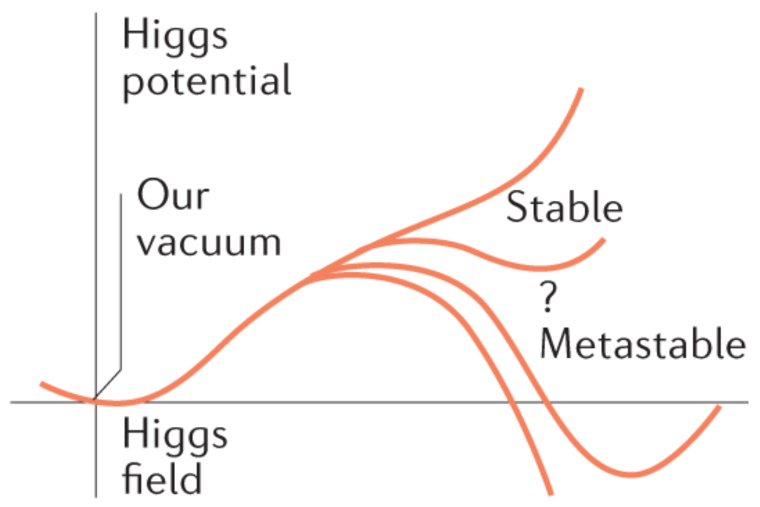
Search for this rare decay performed exploiting all main
Higgs boson production modes (ggF, VBF, VH, ttH)
and in the decay channels with Z → ee/μμ

CMS 2.7σ observed significance (1.2σ expected for SM signal),
ATLAS 2.2σ observed significance (1.2σ expected for SM signal)

→ Not yet evidence as significance is below 3σ,
but interesting results from both experiments
(Close to evidence and small excess compared to expectations!)

Search for HH production

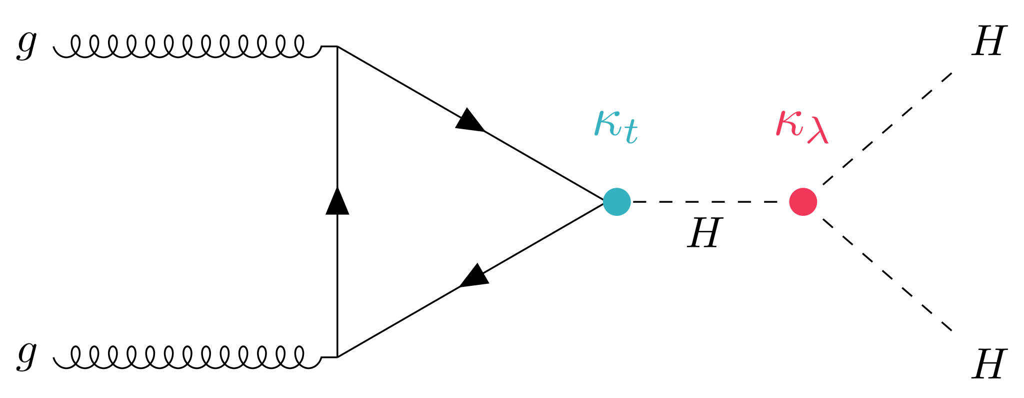




The Standard Model predicts that the Higgs boson also couples to itself

→ the strength of the Higgs boson self-coupling is directly connected to the shape of the Higgs potential, determining the stability of the universe

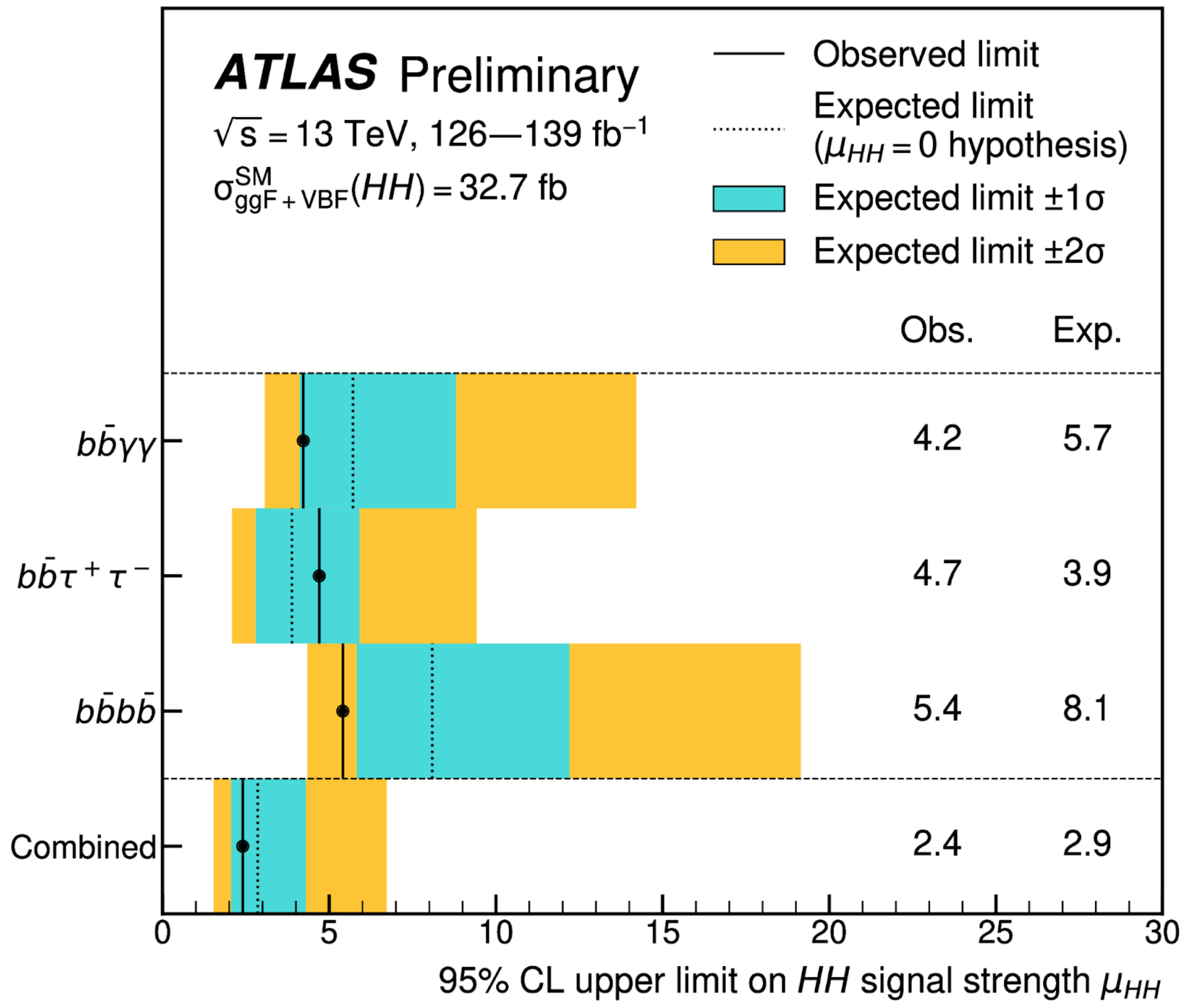
ggF HH production

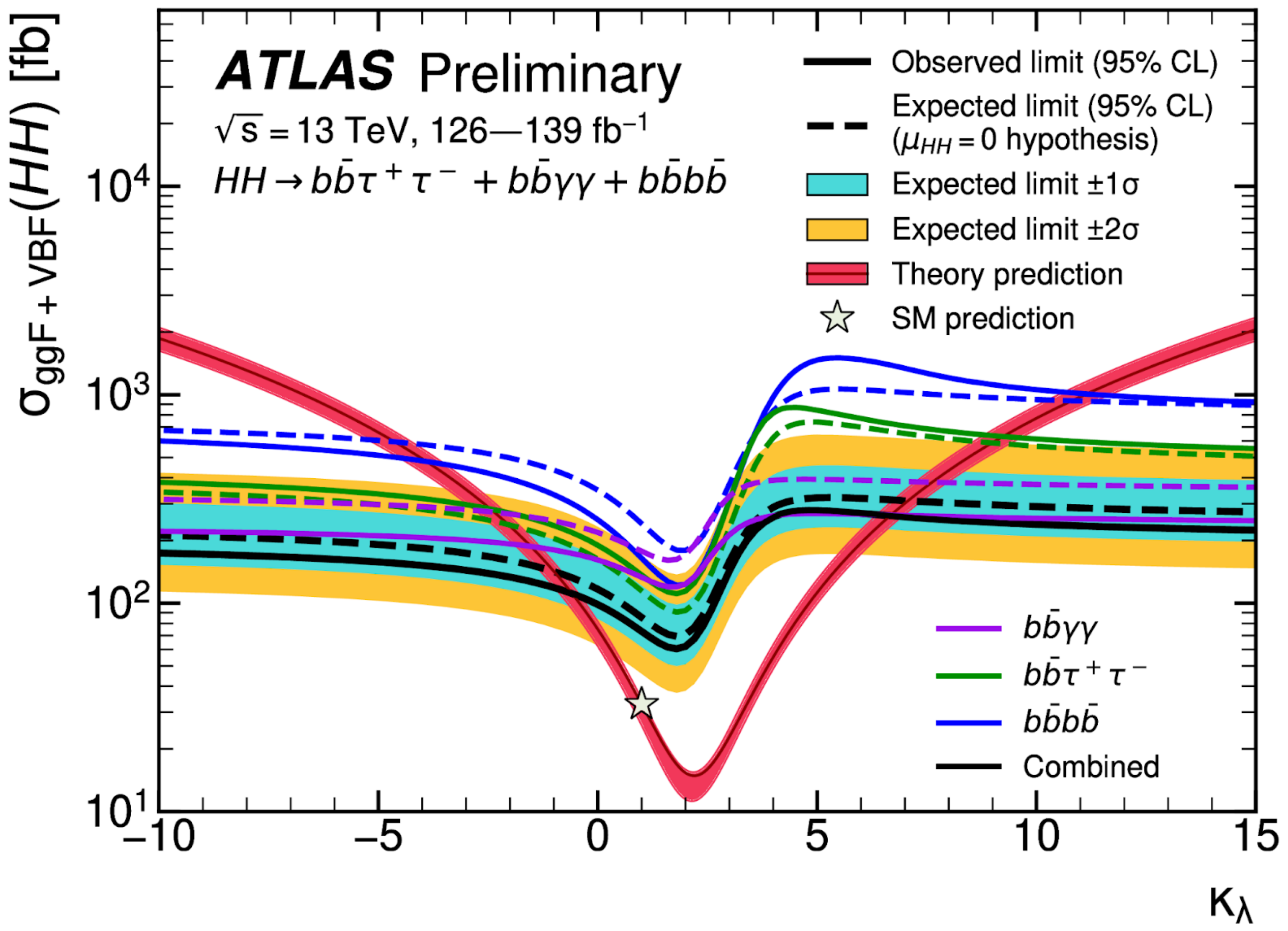


HH production allows to directly measure the Higgs boson self-coupling, and test the shape of the potential, but production cross section is very small!

(>1000 times smaller than single-Higgs production!)

→ HH searches performed combining different different decay channels





Signal not observed yet:

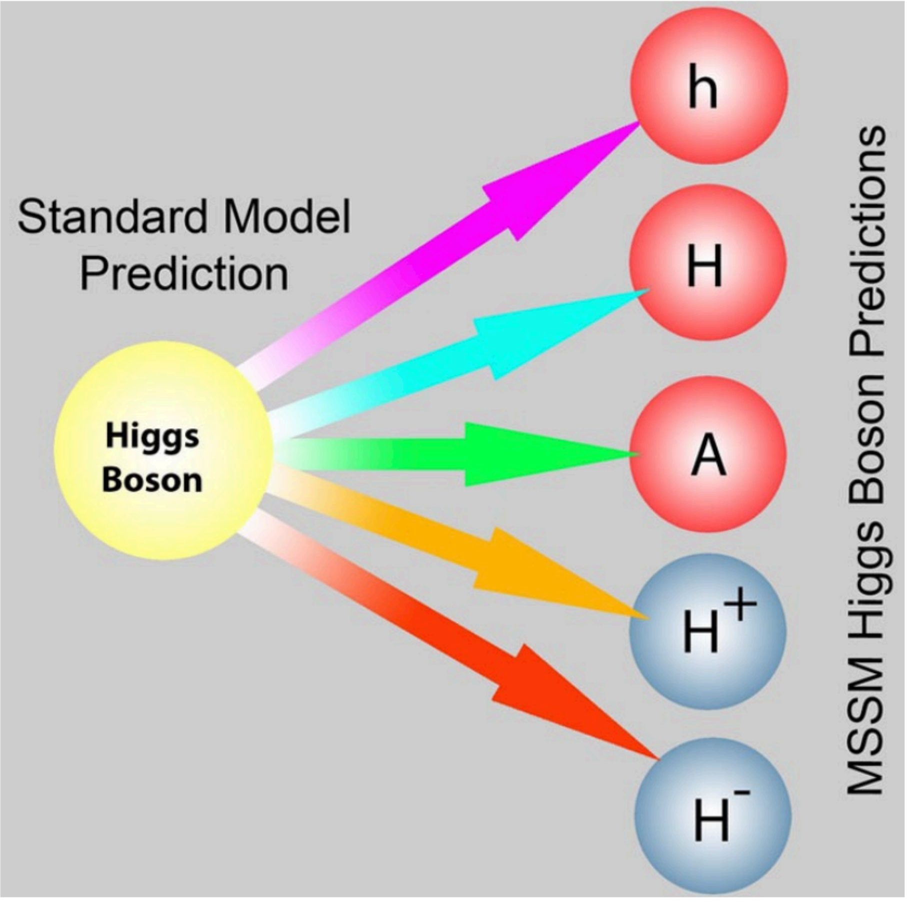
Upper limit on HH signal set at ~3 x SM at 95% CL and results used to set direct limits on Higgs self-coupling, most stringent constraints from ATLAS,

$-0.6 < |\kappa_\lambda| < 6.6$ at 95% CL

($\kappa_\lambda = \lambda_3^{meas}/\lambda_3^{SM} = 1$ in SM)

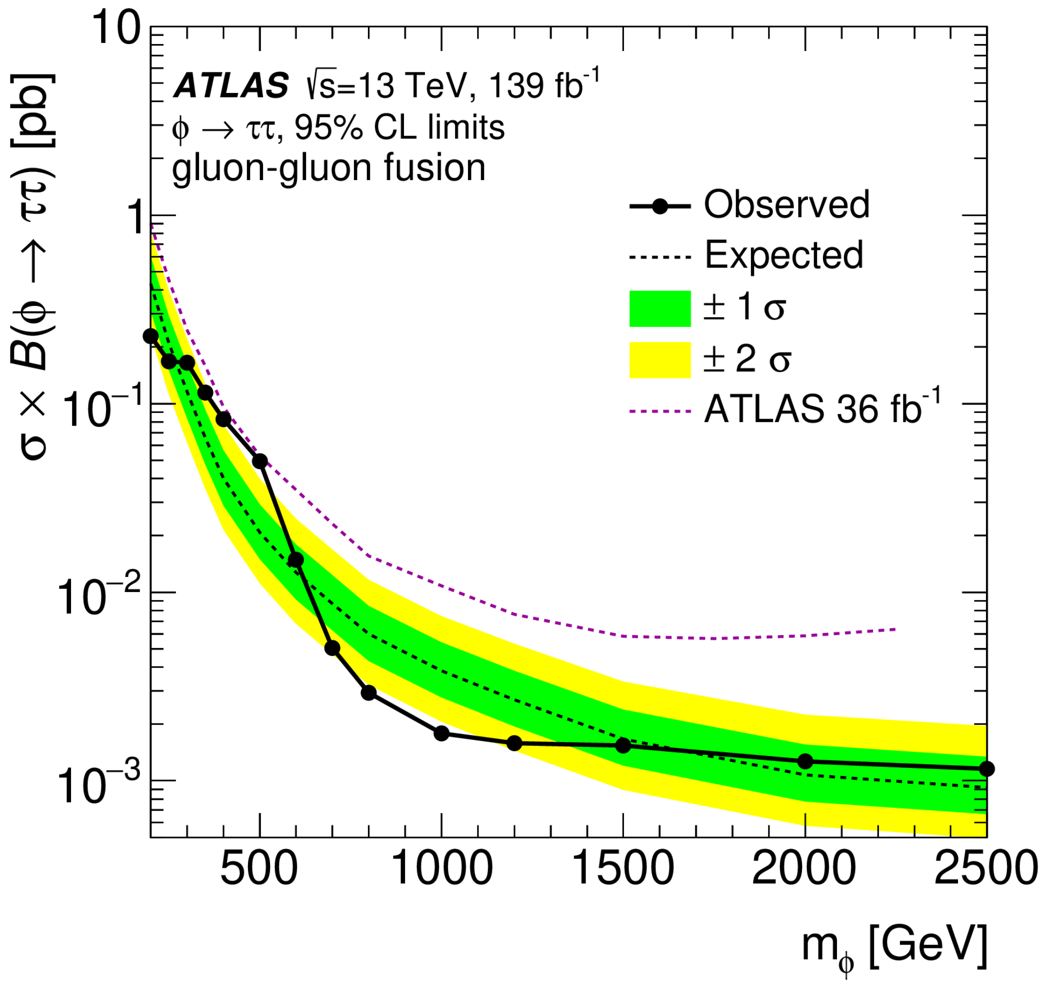
Some examples of direct searches for beyond-the-Standard-Model Higgs boson physics

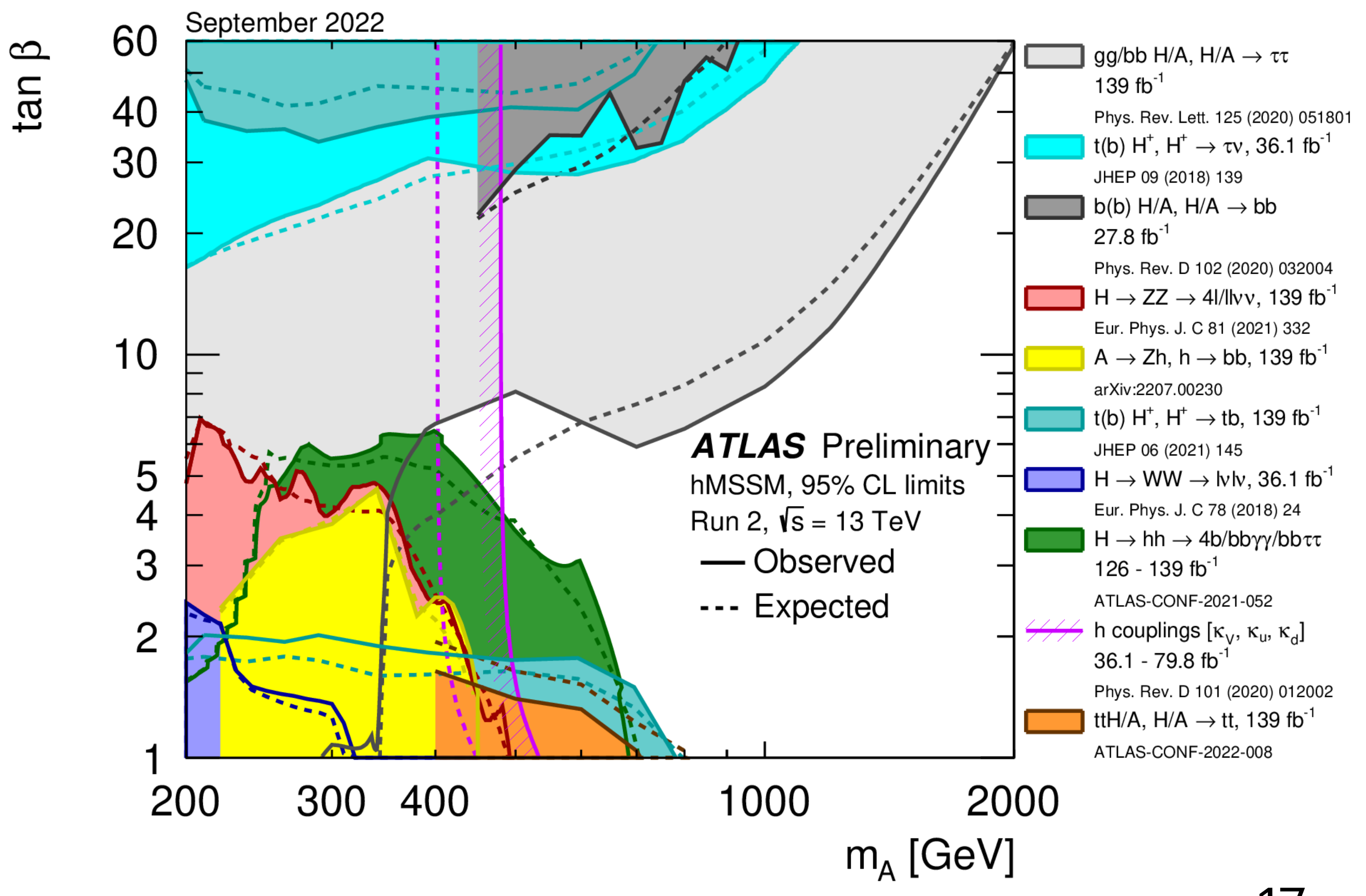
Searches for additional new Higgs bosons



Many extensions of the Standard Model predict more Higgs bosons
(minimal extension predicts 5 Higgs bosons)
→ Many searches performed by ATLAS and CMS for additional Higgs bosons in different mass ranges and decay channels

No new particle found so far
→ Upper limits set on the production cross section of the new particle as a function of its mass

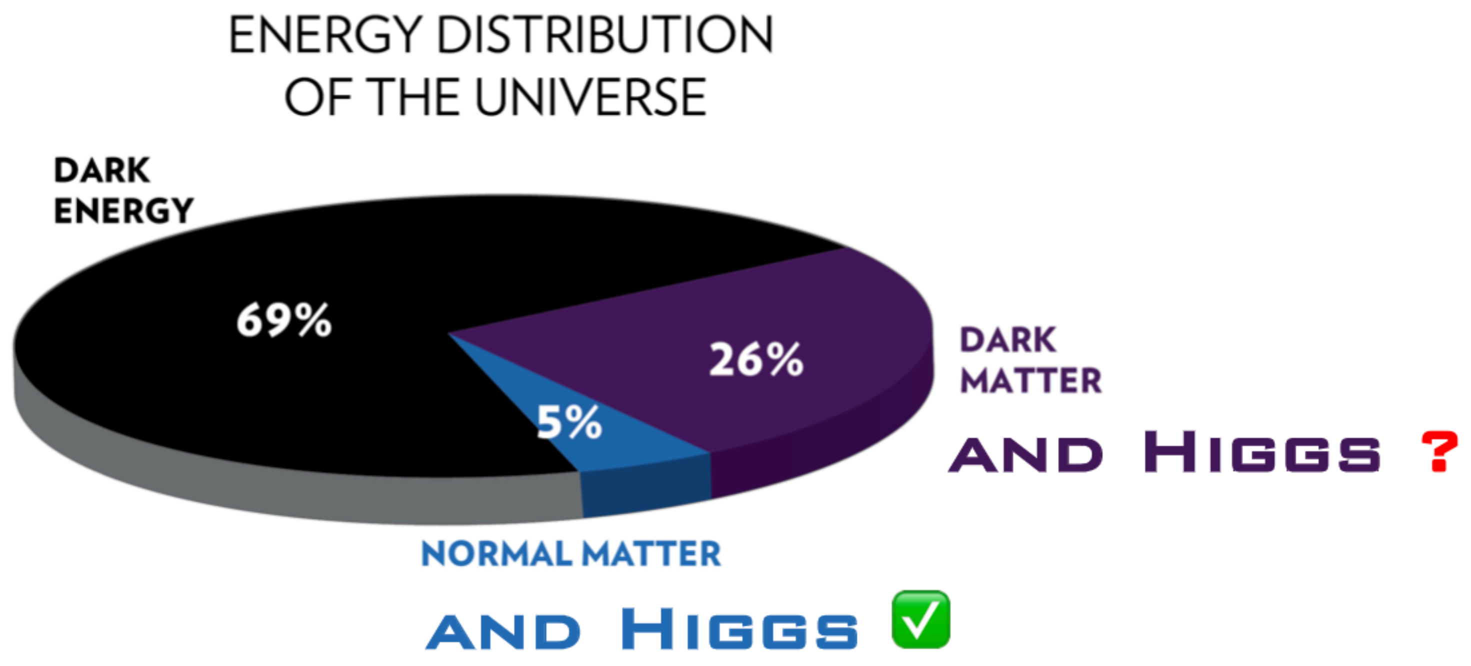




→ From the upper limits on the cross sections, exclusion limits can be set on several models predicting additional Higgs bosons, as a function of the new Higgs boson mass and of the parameters of the model

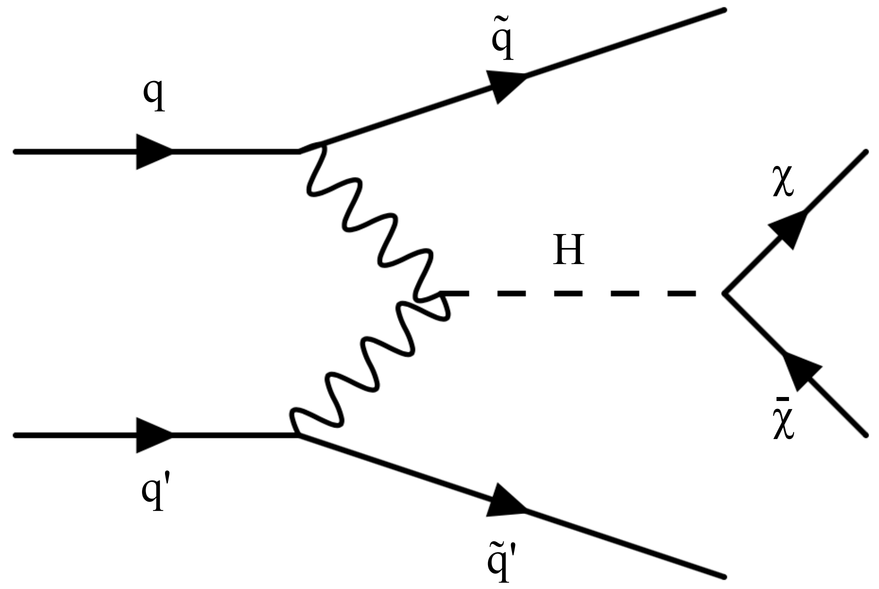
→ Large mass and parameters ranges tested and excluded, but still also large range yet to be explored!

Searches for Higgs boson decay to dark-matter



In some beyond-the-Standard model theories,
dark matter particles could also have mass from the Higgs mechanism

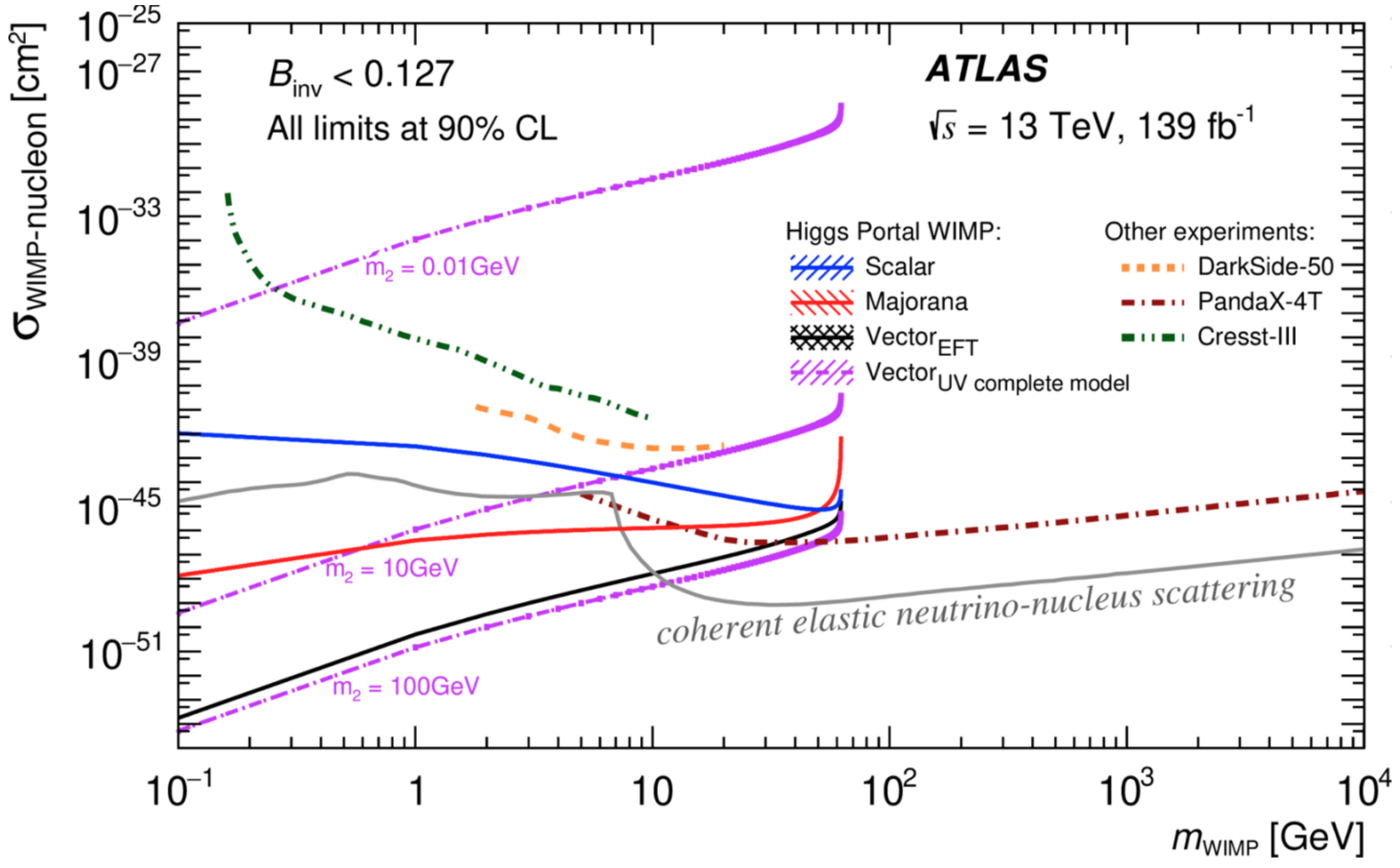
→ If the Higgs Boson couples to dark matter particles, it could decay into dark matter particles if they have a sufficiently low mass



Searches by ATLAS and CMS for Higgs boson decaying to invisible particles (VBF production mode most sensitive given the large cross section and the topology with additional jets that helps rejecting large backgrounds)

No signal of Higgs boson decaying to invisible observed so far

→ Upper limits set on the branching ratio for this decay channel at ~15%



→ From the limits on the Higgs decay branching ratio, exclusion limits can be set on the cross section of the dark-matter-nucleon interaction

→ Limits from ATLAS and CMS are highly competitive with other experiments of direct searches for dark-matter, especially for low-mass dark matter particles (below 10 GeV)

What are we doing now and what do we plan to do in the next years?

LHC Run 3

- Run 2 ended in 2018

  → Still analysing the Run 2 data!

- Run 3 started in July this year and will continue until 2025!

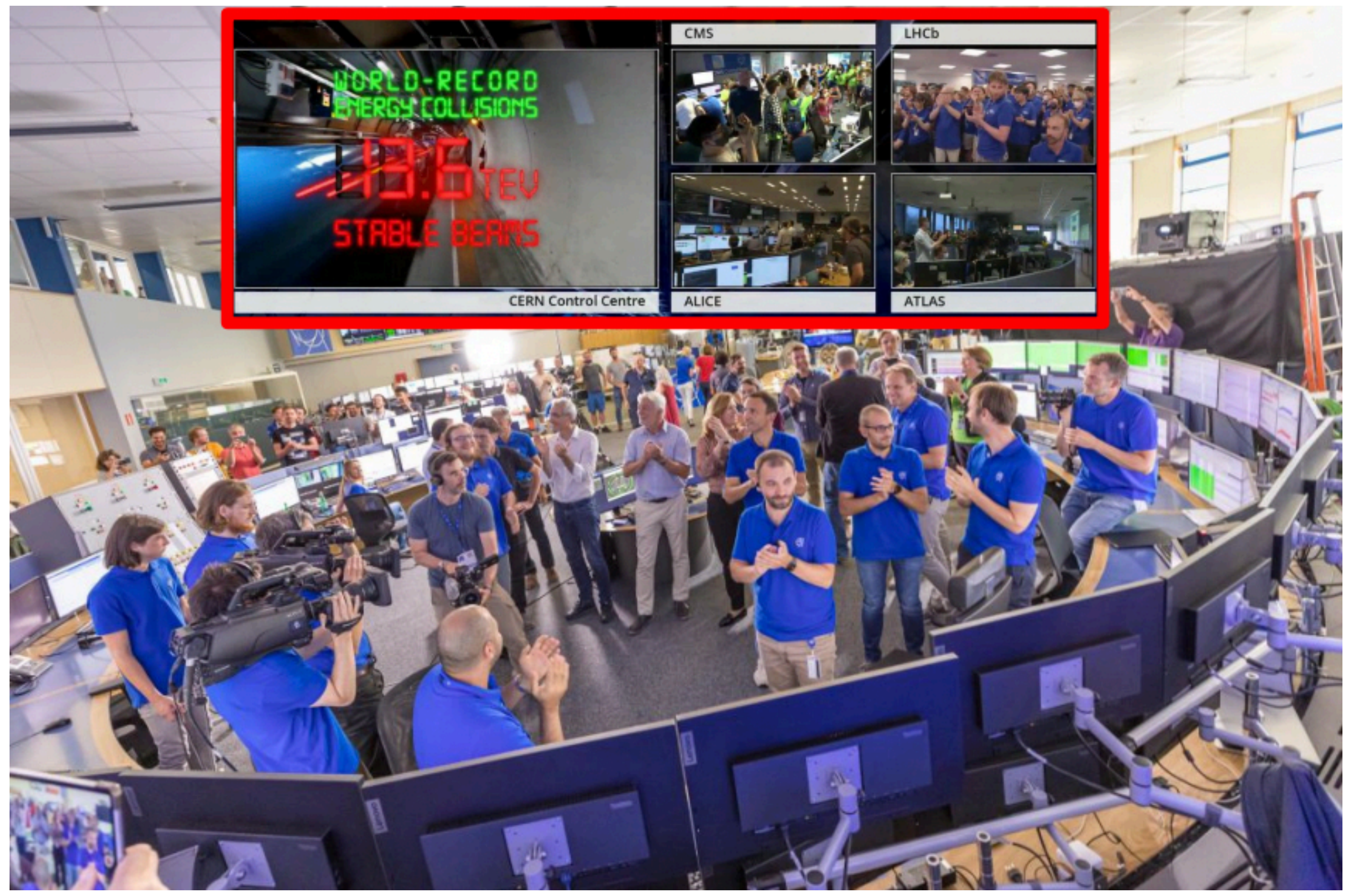
  → increased energy from 13 TeV to 13.6 TeV and increased instantaneous luminosity compared to Run 2 (and longer data-taking period)

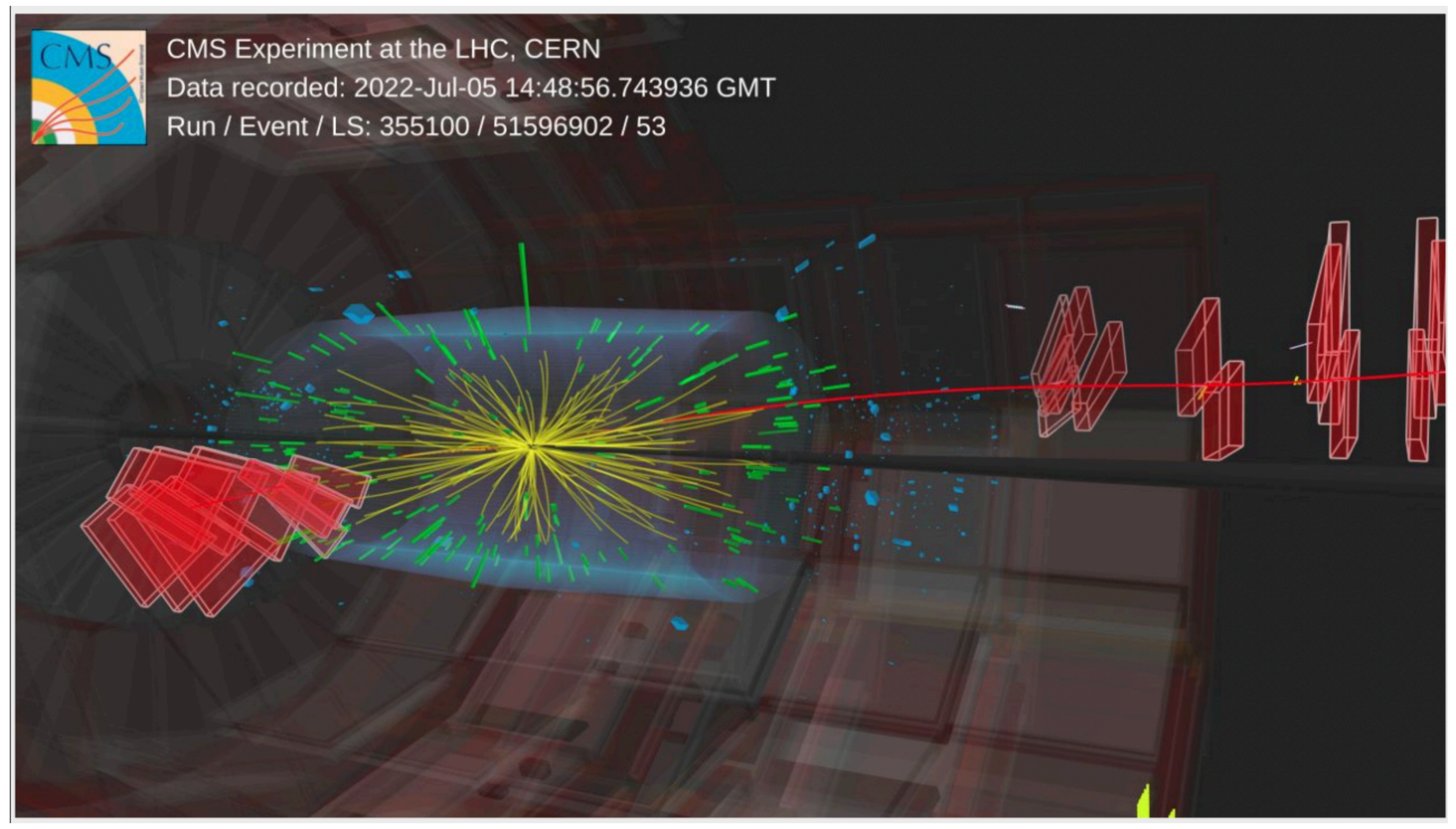
  → $450\ \mathrm{fb}^{-1}$ expected at the end of the Run 3 (factor of 3 more data!)

- Very busy and exciting period now with the ongoing data-taking

  → Very important now to ensure that the detector operates in safe conditions and the quality of the collected data is good for the physics analyses

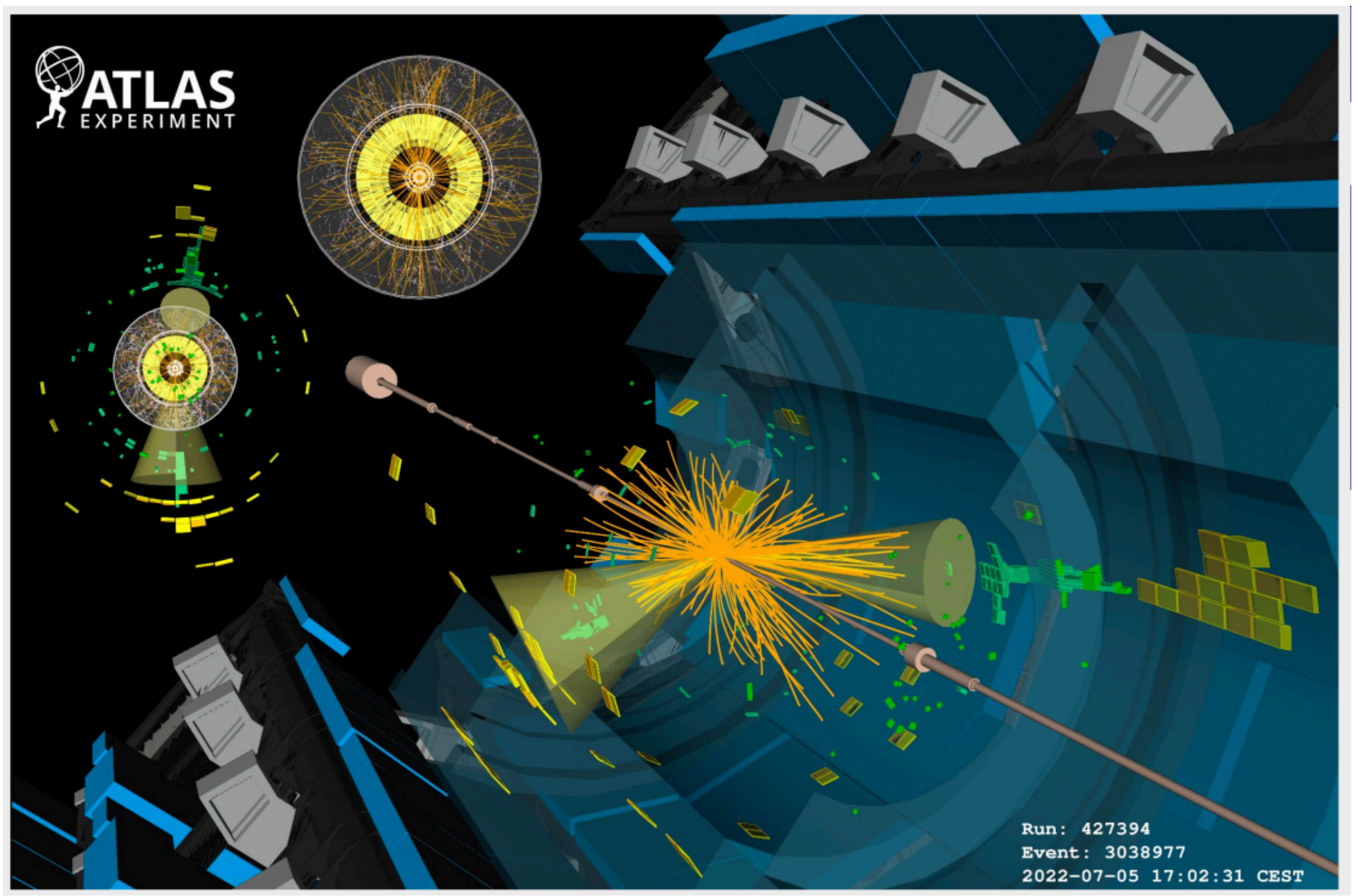
  → Data-taking will continue until 2025, and the analysis of the Run 3 data will probably go on at least until 2027-2028!





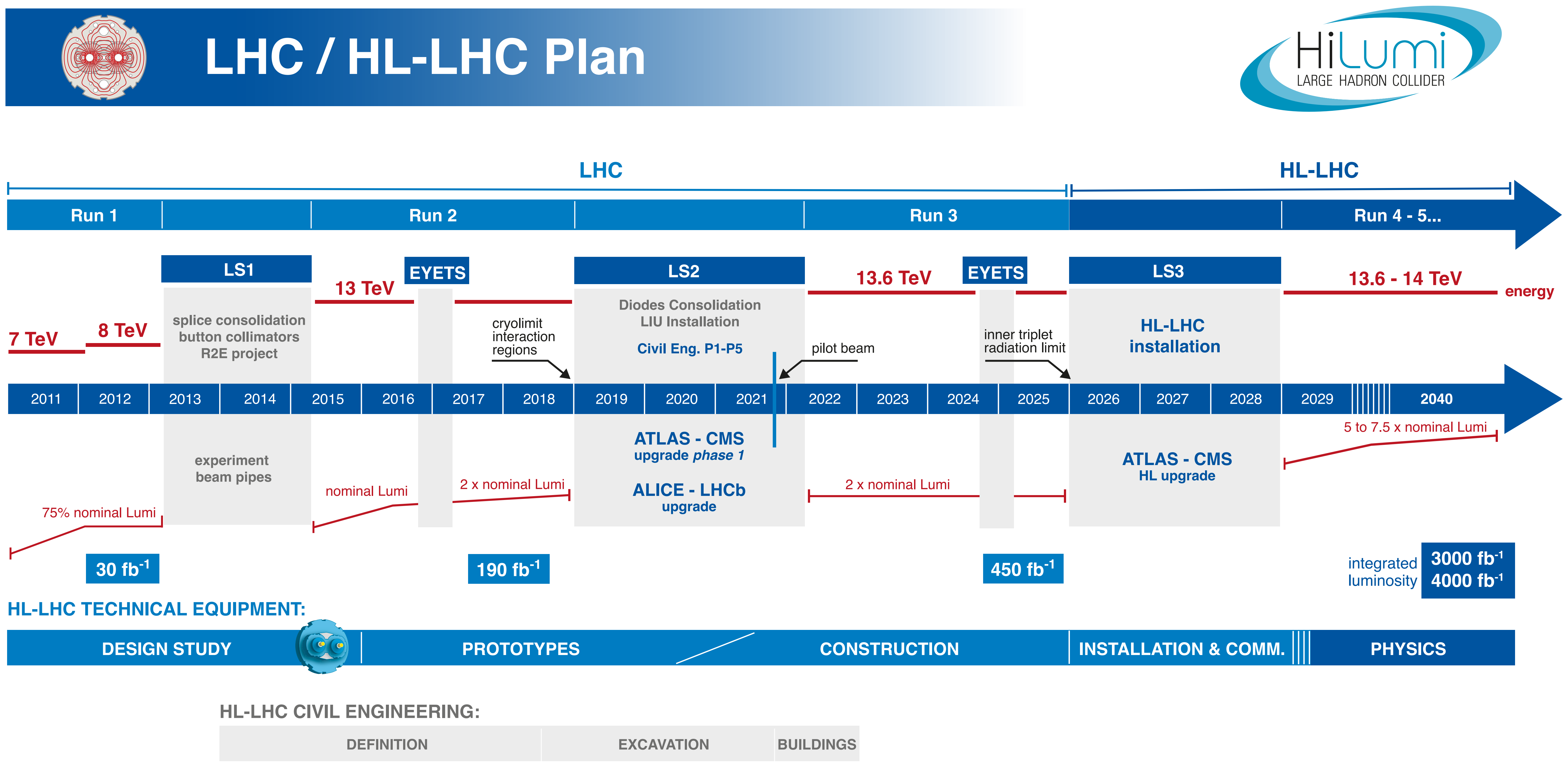
Some examples of interesting LHC Run 3 expectations:

- Observation of H → μμ decay
- Evidence (and possibly observation?) of H → Zγ decay
- Exclusion of $\kappa_\lambda = 0$ hypothesis (Higgs boson does not couple to itself)
- More precise measurements of all Higgs boson properties



What do we expect to be able to do in a more far future?

High-Luminosity LHC (HL-LHC)



After the LHC Run 3 that will end in 2025,
the High-Luminosity LHC Runs (Run 4 and Run 5) will start in 2029 and will continue until 2040:

- Increased centre-of-mass energy from 13.6 TeV to 14 TeV and increased instantaneous luminosity

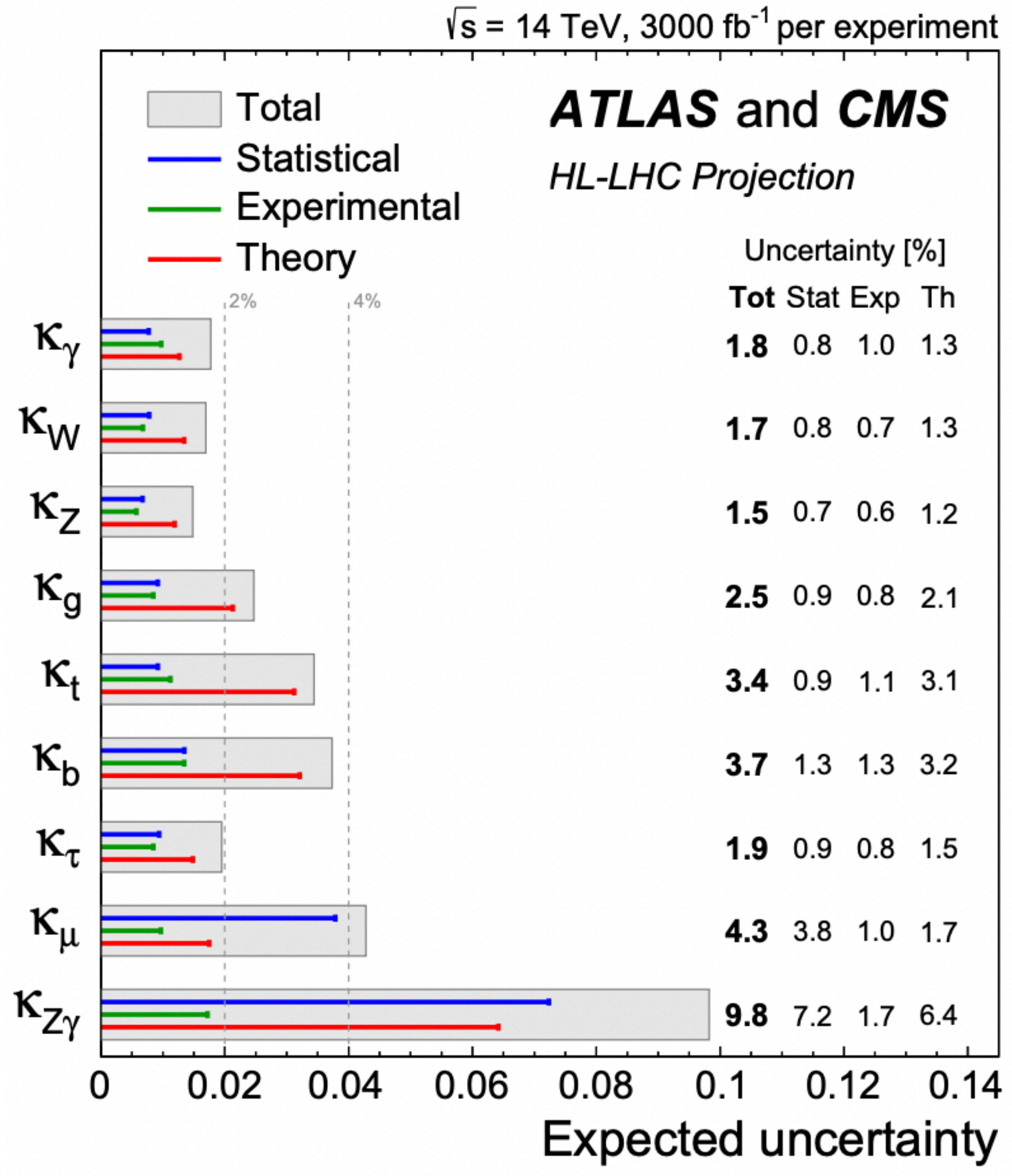
$\rightarrow 3000 - 4000\ \mathrm{fb}^{-1}$ expected at the end of the HL-LHC (factor of 20-30 more data!)

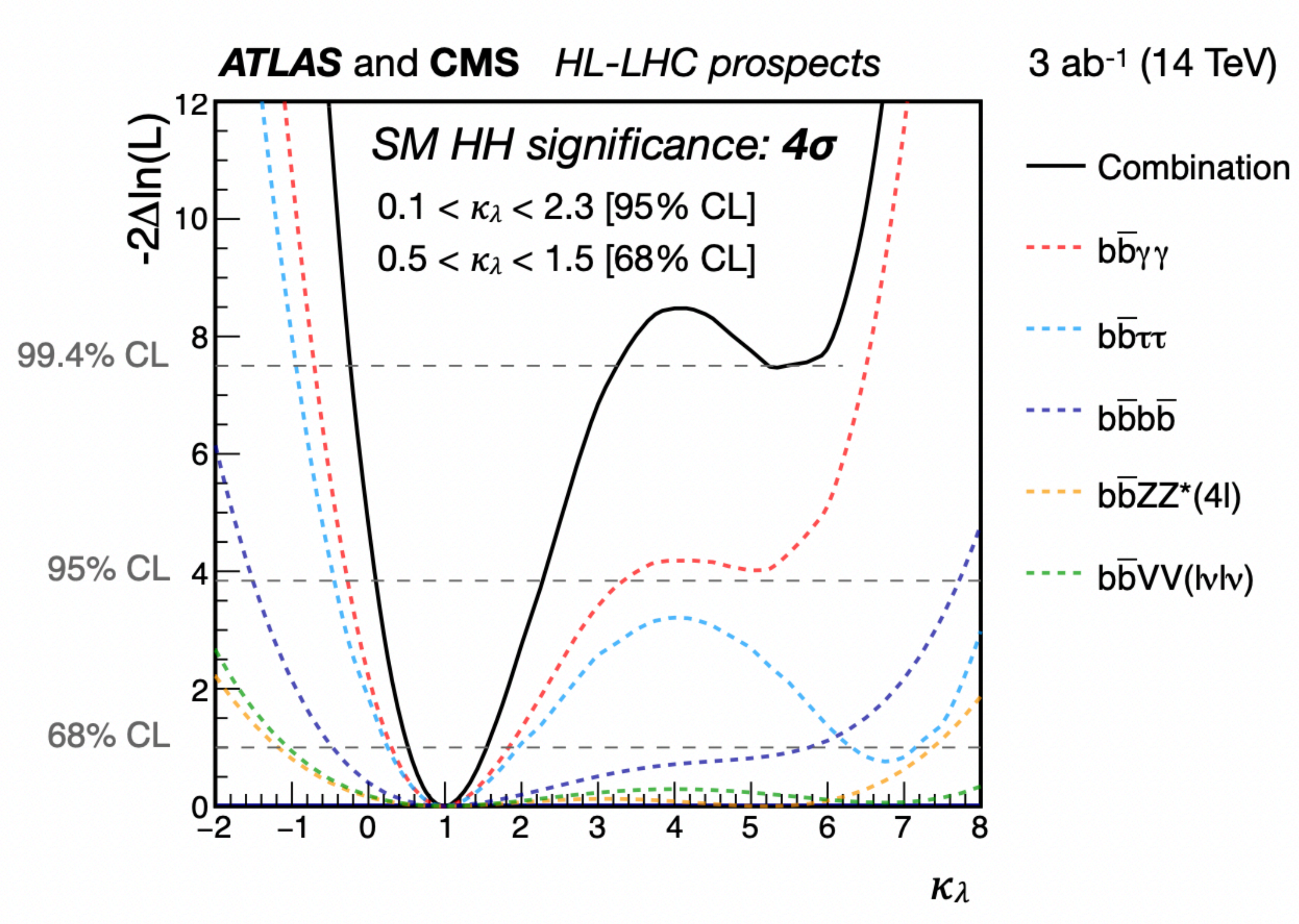
The HL-LHC will be a Higgs boson factory that will produce about 200M Higgs bosons!

$\rightarrow$ This very large dataset will be fundamental for precision measurements of the Higgs boson properties

High-Luminosity LHC (HL-LHC) expectations

Extrapolations from the current Run 2 results to predict what we expect with the HL-LHC dataset





- Precision measurements of Higgs boson couplings with uncertainties of few%-level

  → Very important milestone as many beyond-the-Standard-Model theories predict deviations of the couplings at few%-level
- Examples of still very challenging process to measure at the HL-LHC:
  - Higgs decay to invisible particles:

    expected upper limit on branching ratio at ~2%

    → SM BR=0.1%, out of reach at the HL-LHC, new analysis techniques could improve this!
  - HH production and Higgs boson self-coupling:

    expected 4σ significance for the SM HH signal and uncertainty on κ_λ ~50%

    → Extrapolation not far from observation, could reach 5σ with new analysis techniques!

Collecting more data is not always enough!
Hard work and creativity of people are key ingredients
to improve these expectations!
(Run 2 results are much better than anticipated at the end of Run 1,
surely the HL-LHC results will be much better than we think now!)

Conclusions and outlook

The Higgs boson discovery in 2012 was not the end of the story,
but the start of a new era of exploration at the LHC

So far Higgs boson measurements are compatible with the Standard Model,
but there are still many open questions!

Improving precision of the Higgs boson measurements with data from LHC
remains one of the key goals of experimental particle physics

We have still a lot of data to collect and analyse in the years to come!

Plenty of room for contributions of new young students that can
really make a difference with their work and creativity!

Thank you for your attention!

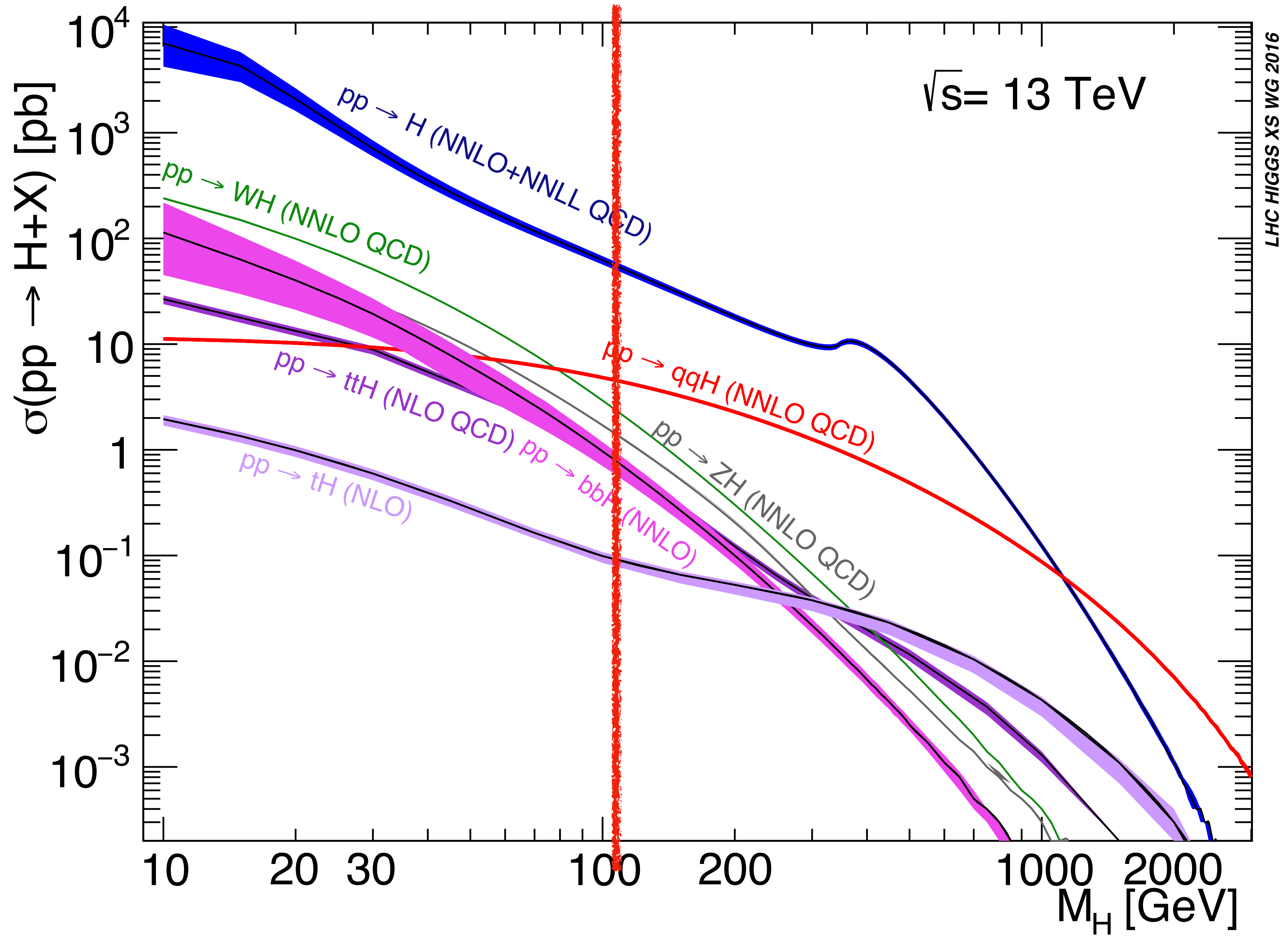
Questions? :)

Back-up slides

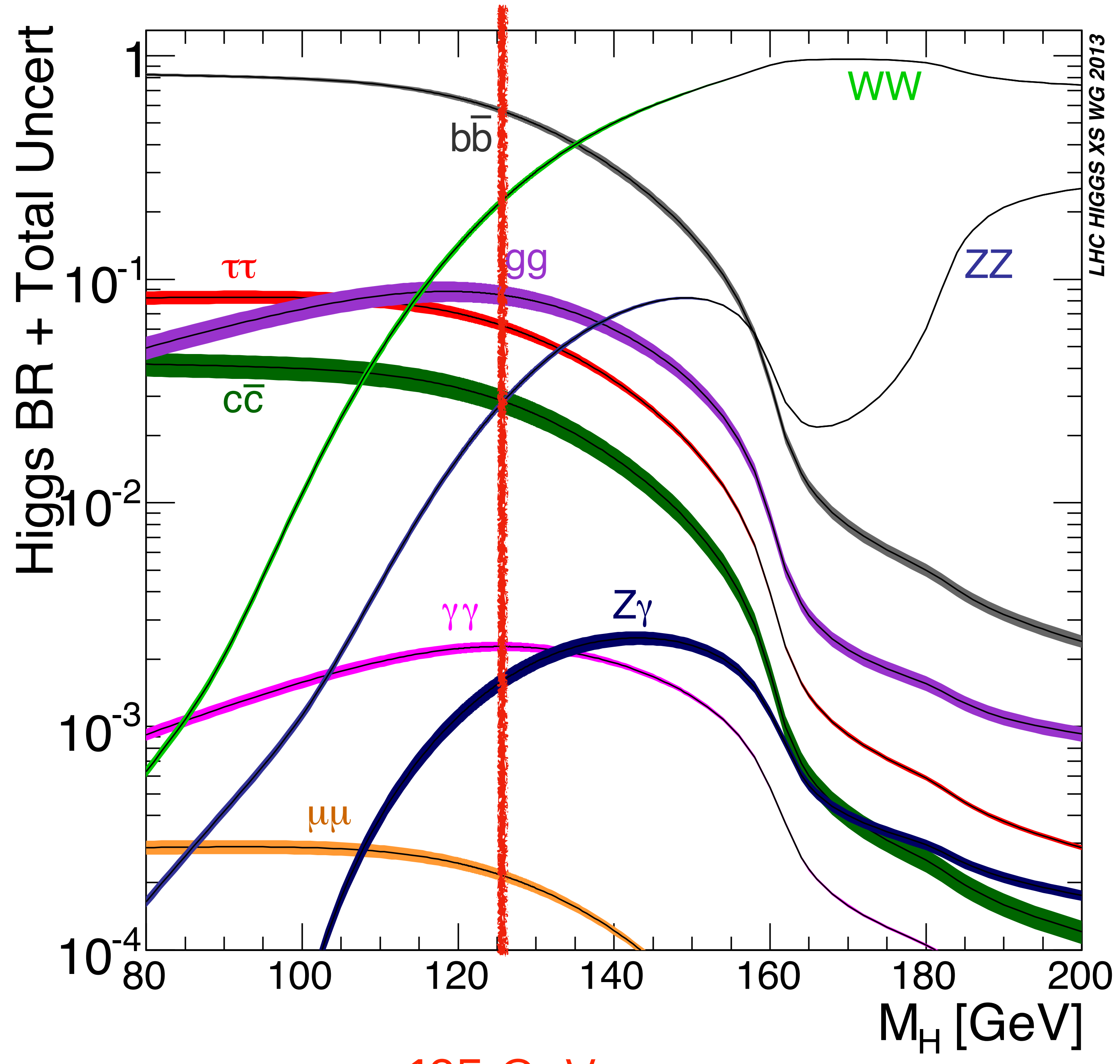
Higgs boson production modes and decay modes

Once the mass of the Higgs boson is known,
all the possible production and decay modes are known in the Standard Model,
with well-determined values of cross sections and branching ratios

→ The experimental measurements can be compared
to the Standard Model predictions to test the validity of the model



125 GeV



125 GeV

Strong dependence of production cross sections and decay branching ratios on the mass

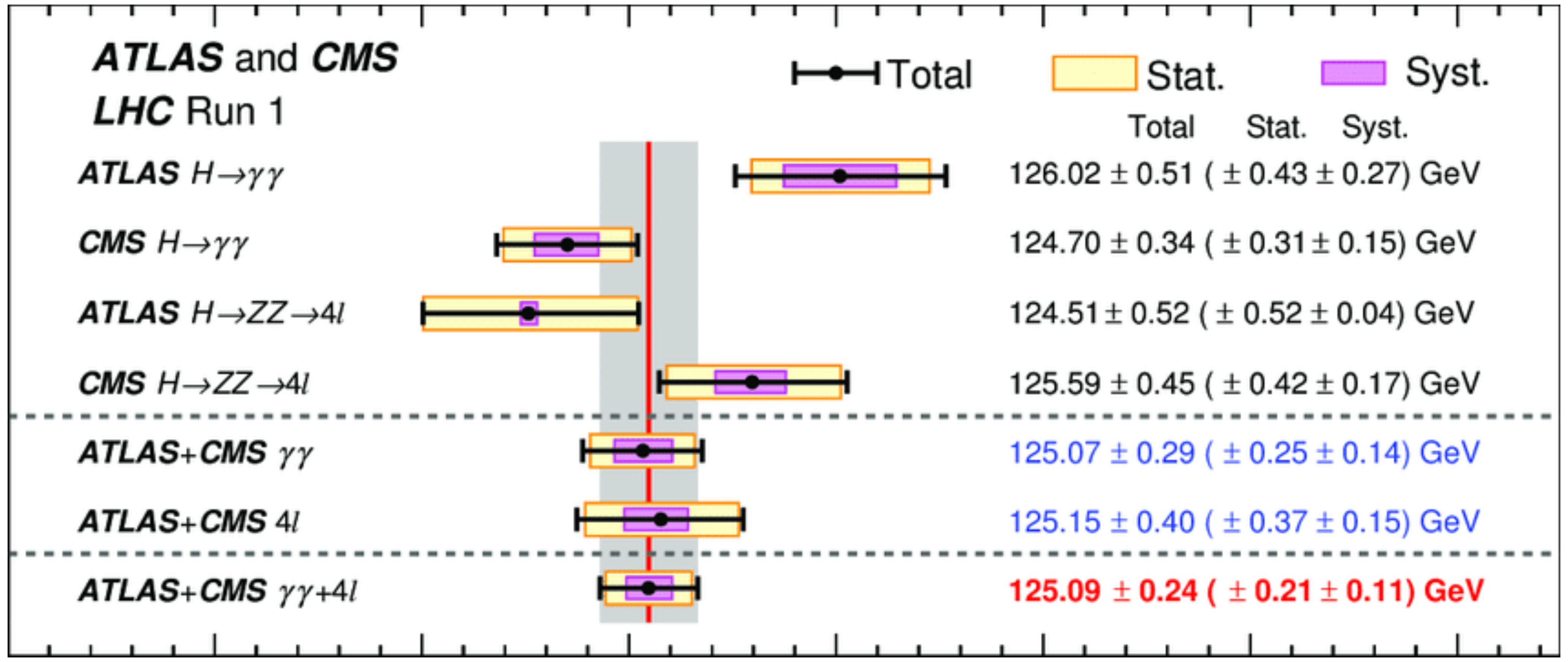
→ Very important to have precise measurement of the mass to have precise evaluation of their expected theoretical values

Legacy Run 1
Higgs boson measurements

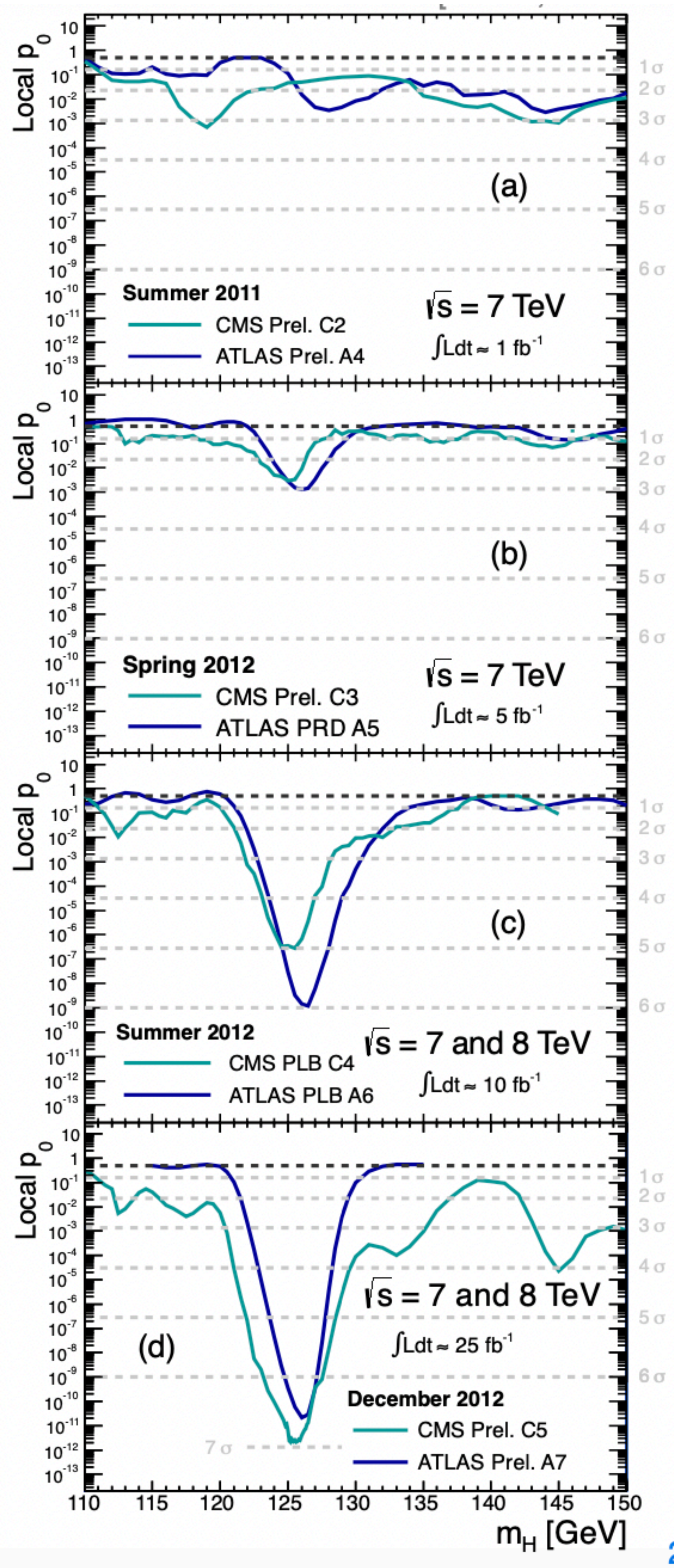
Legacy Run 1 Higgs boson measurements

Higgs boson discovered in July 2012 with $10\ \mathrm{fb}^{-1}$ of data, after the end of Run 1 full dataset of $25\ \mathrm{fb}^{-1}$ analysed:

- Observation of the new particle established with higher significance (7σ)
- Mass measured with uncertainty of 0.2% combining ATLAS and CMS γγ and ZZ(4l) channels
- Observation of gluon fusion production
- Observation of decays H → ZZ(4l), H → γγ, and H → WW



- Vector boson fusion production observed with ATLAS+CMS combination
- Decay H → ττ observed with ATLAS+CMS combination
- Higgs boson couplings measured with a precision of 10-20%



Main goal of the LHC Run 2:

observe more production and decay modes of the Higgs boson and measure Higgs boson signal strength and couplings with good precision to compare them to the Standard Model predictions to confirm or not if the observed particle is compatible with the SM Higgs Boson

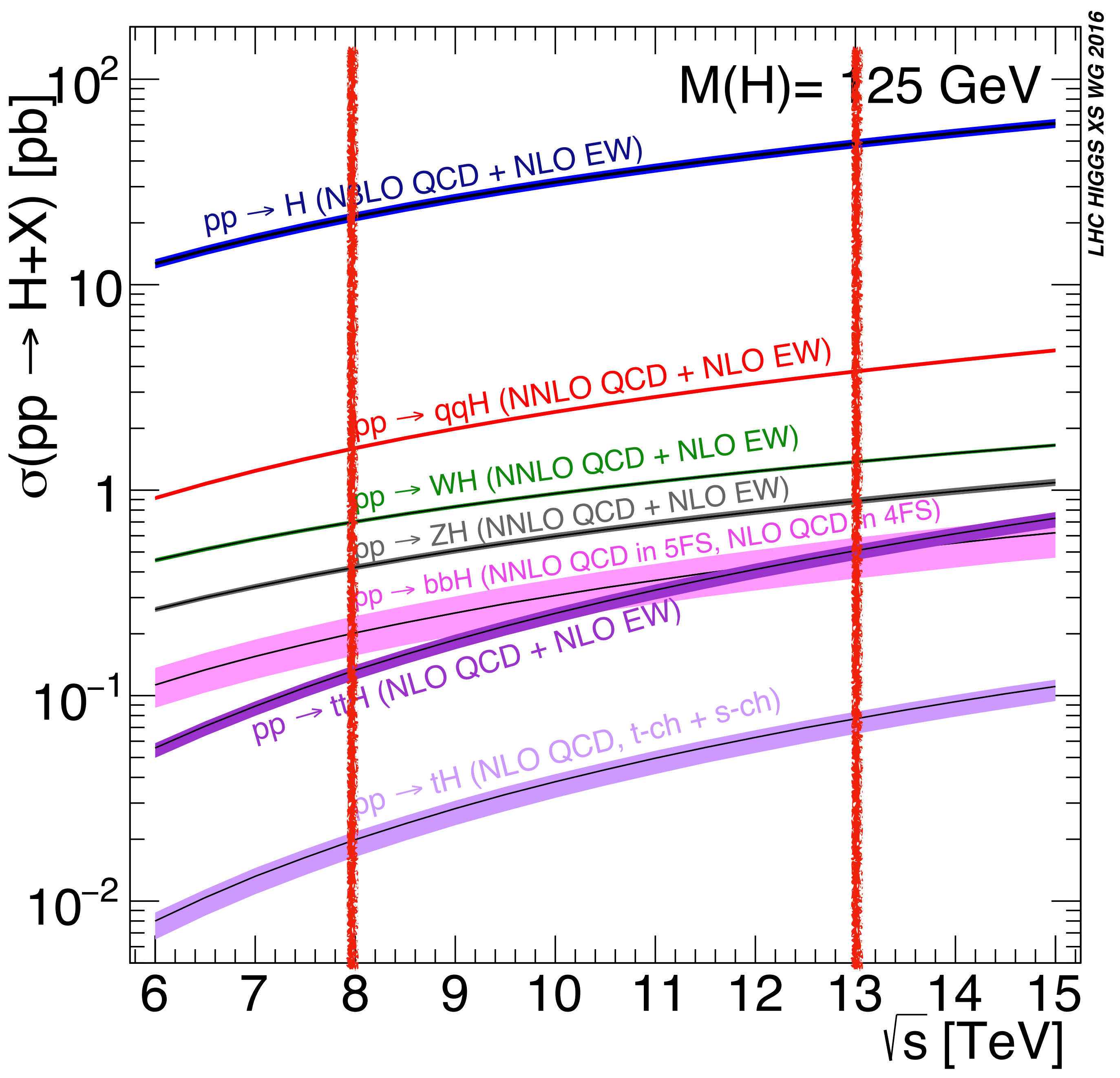
→ Any deviations from the predictions of the model could be a hint of the presence of new physics beyond the Standard Model!

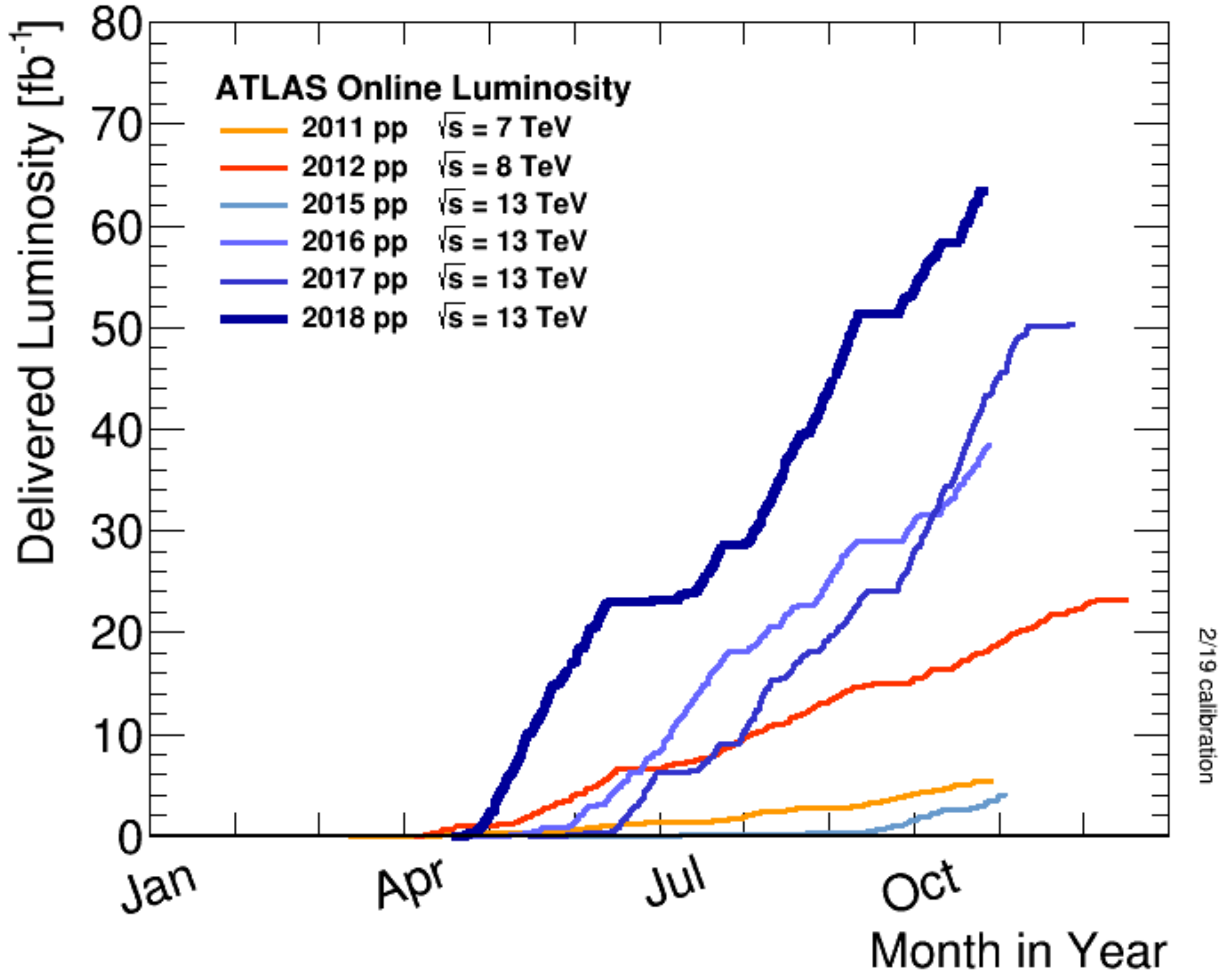
LHC Run 2

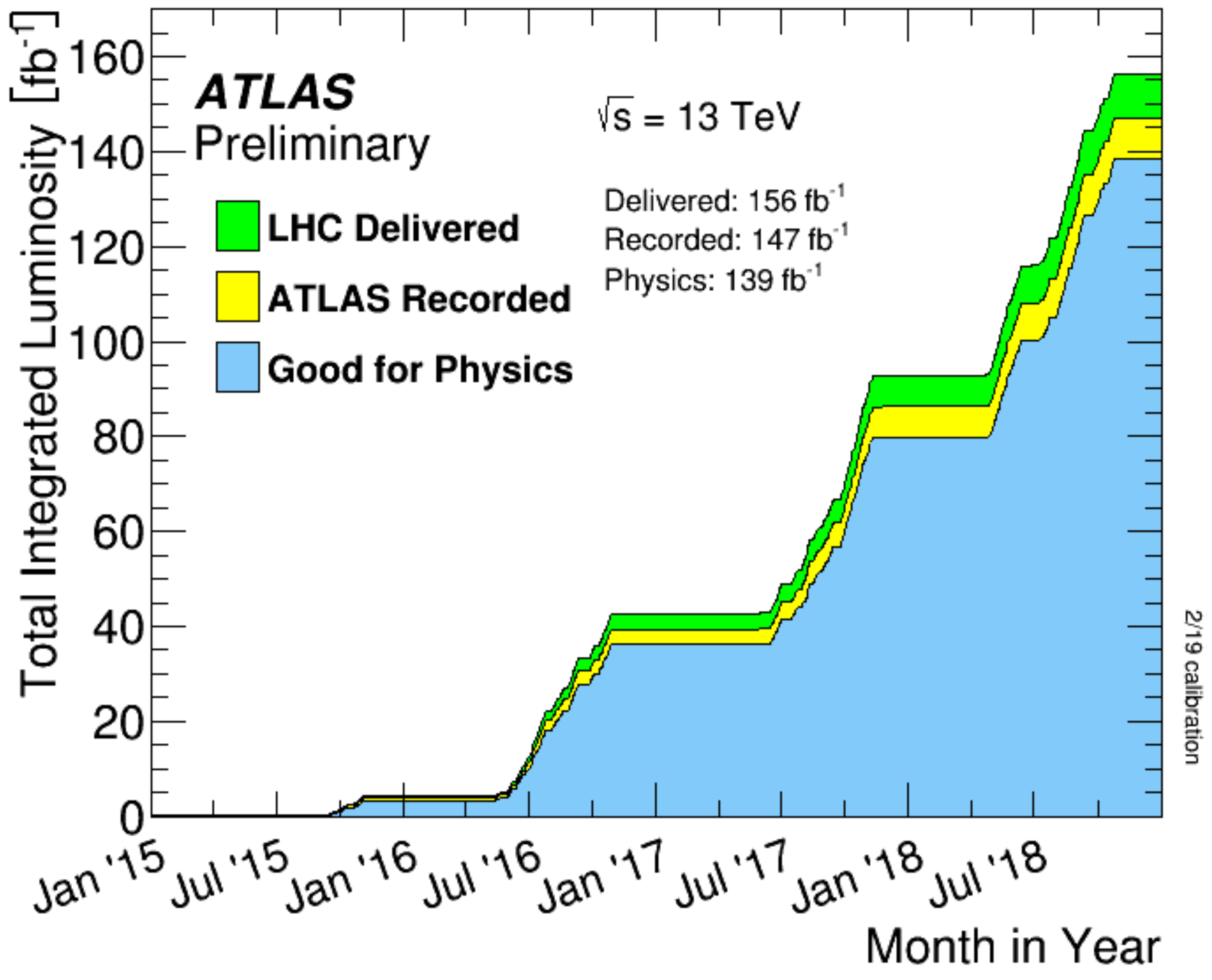
- After the LHC Run 1 that ended in 2012, the LHC Run 2 started in 2015 and continued until 2018
- Increased centre-of-mass energy from 8 TeV to 13 TeV

  → Important increase in the Higgs boson production cross section from ~25 pb at 8 TeV to ~55 pb at 13 TeV
- Increased instantaneous luminosity (and longer data-taking period)

  → Increased total integrated luminosity, from $20\ \mathrm{fb}^{-1}$ of Run 1 to $140\ \mathrm{fb}^{-1}$ of Run 2







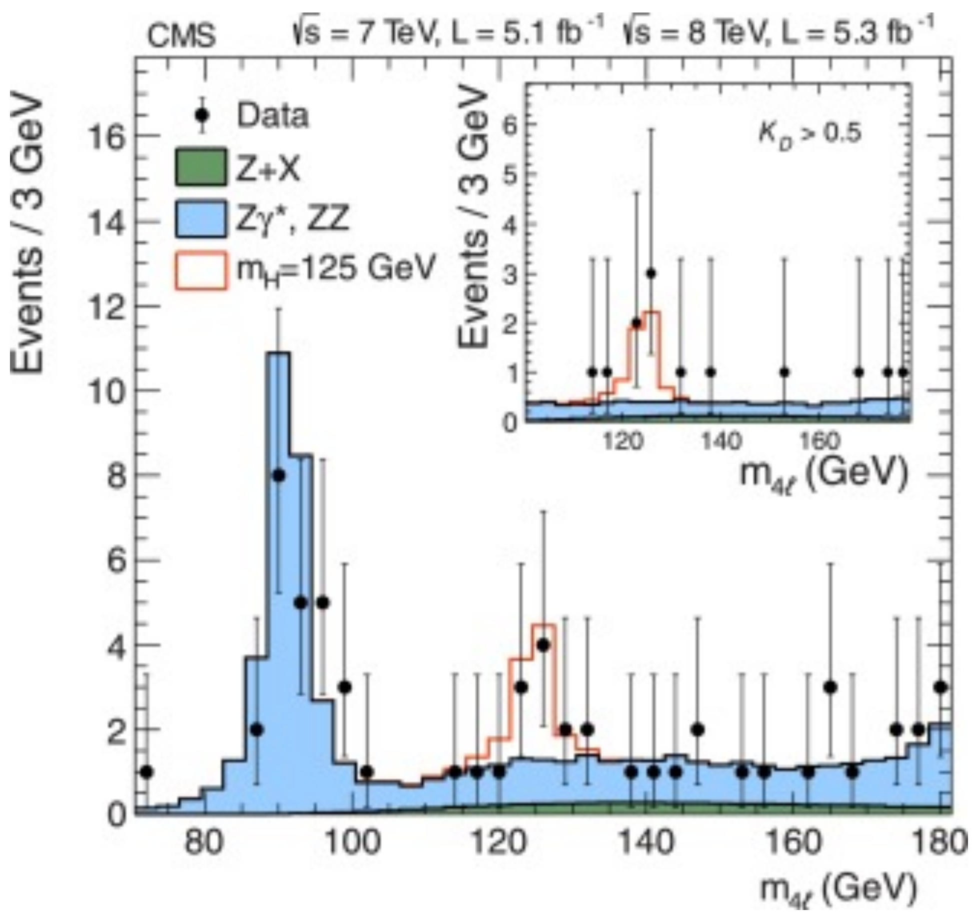
→ About 8M Higgs bosons produced during the LHC Run 2!
Very important dataset to study the properties of the new particle!

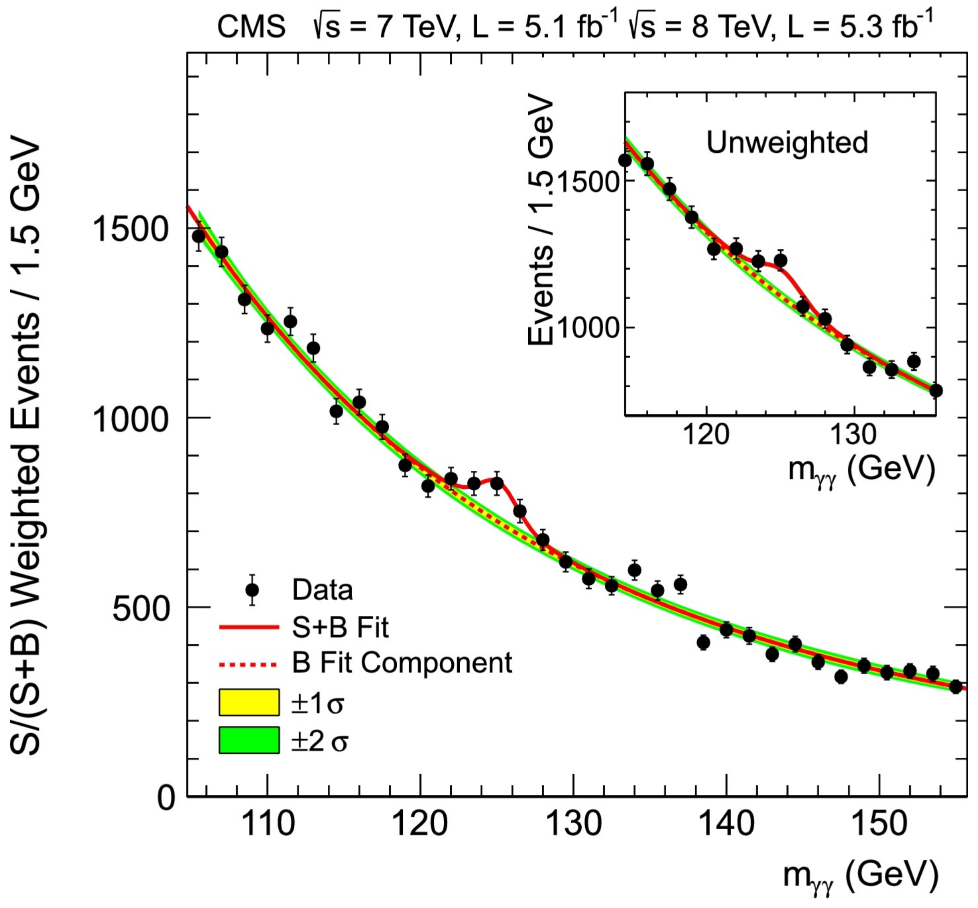
Evolution of the discovery channels: $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$

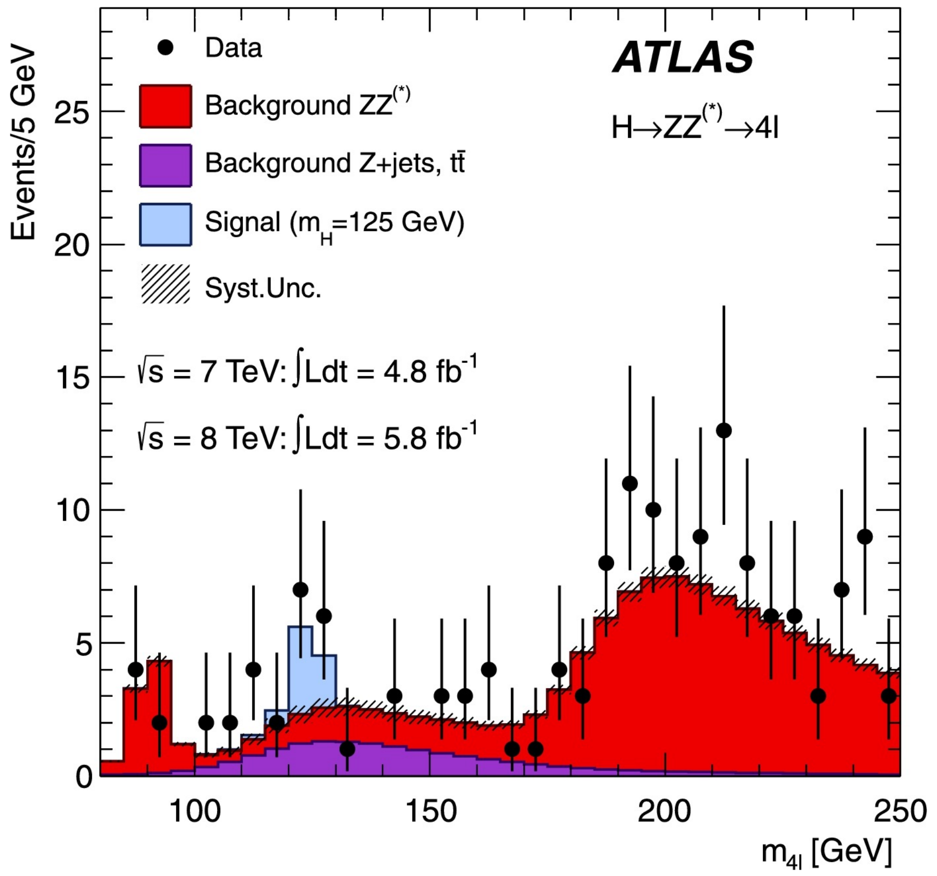
Evolution of the discovery channels

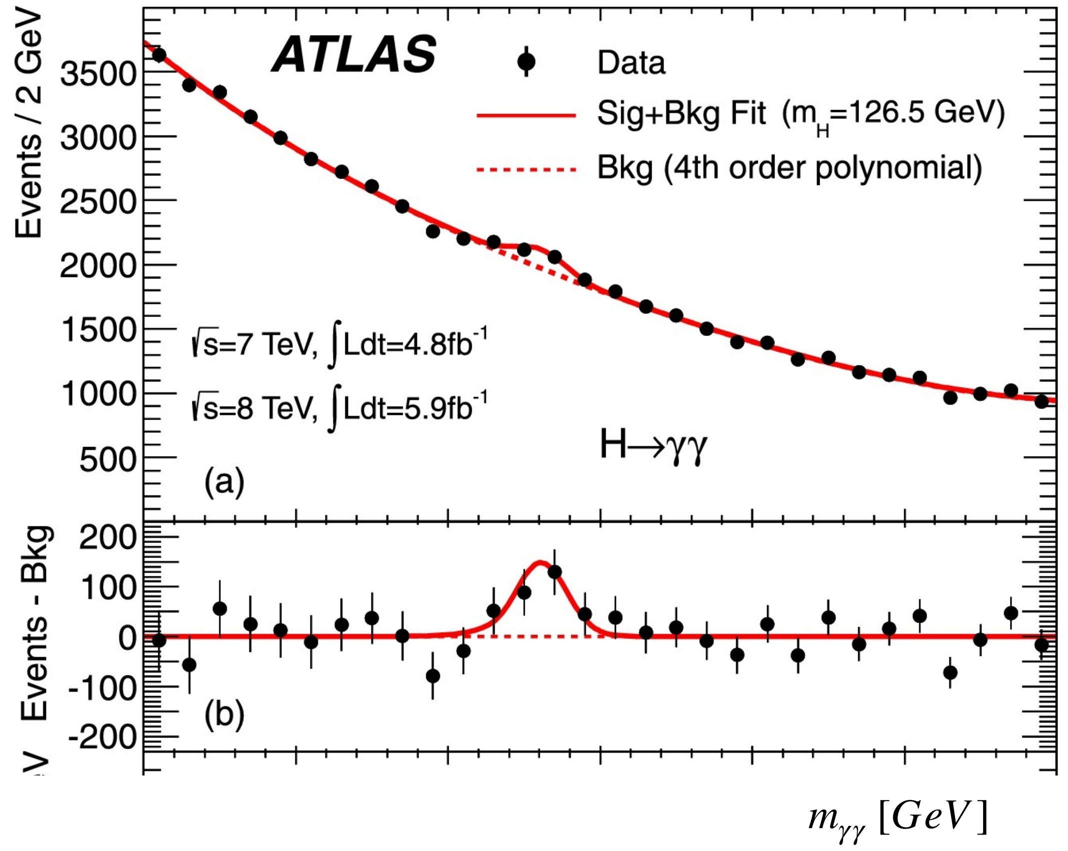
During Run 2 consolidated the analyses of the discovery channels

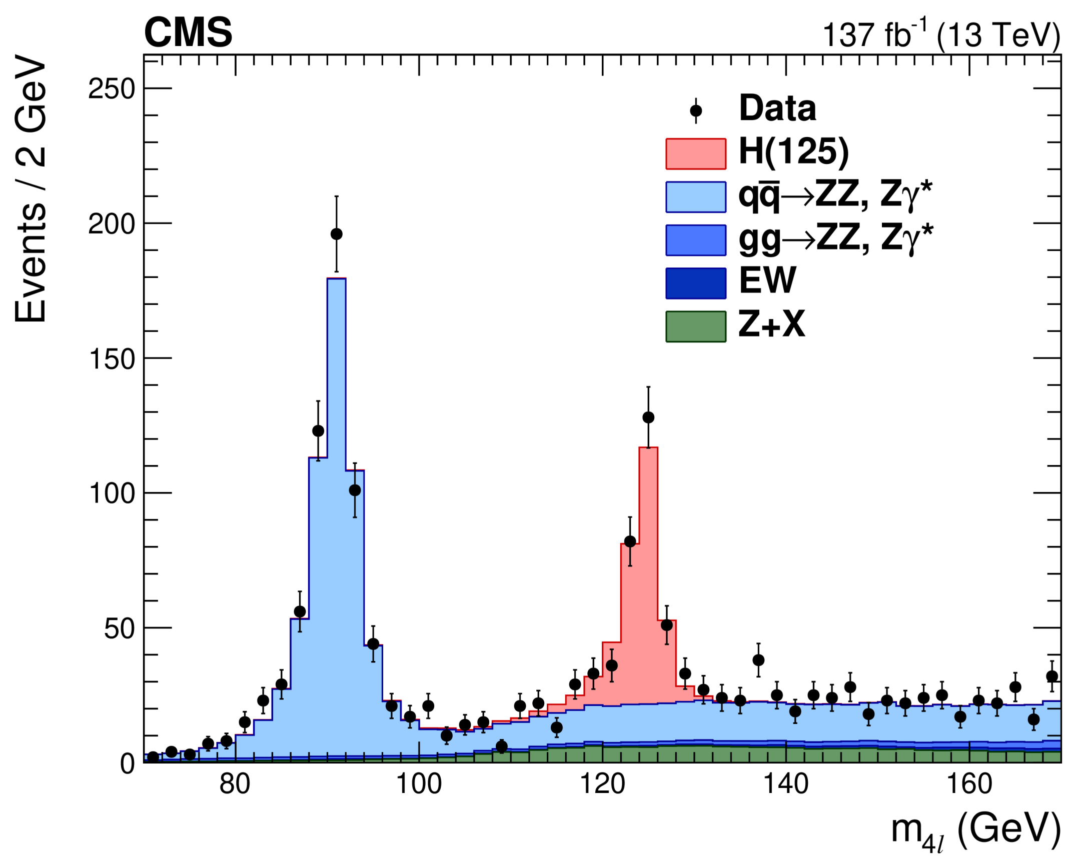
Much increased statistics in these channels with very good resolution that play a key role in the precision measurements of the Higgs boson properties (mass, width, spin, couplings)

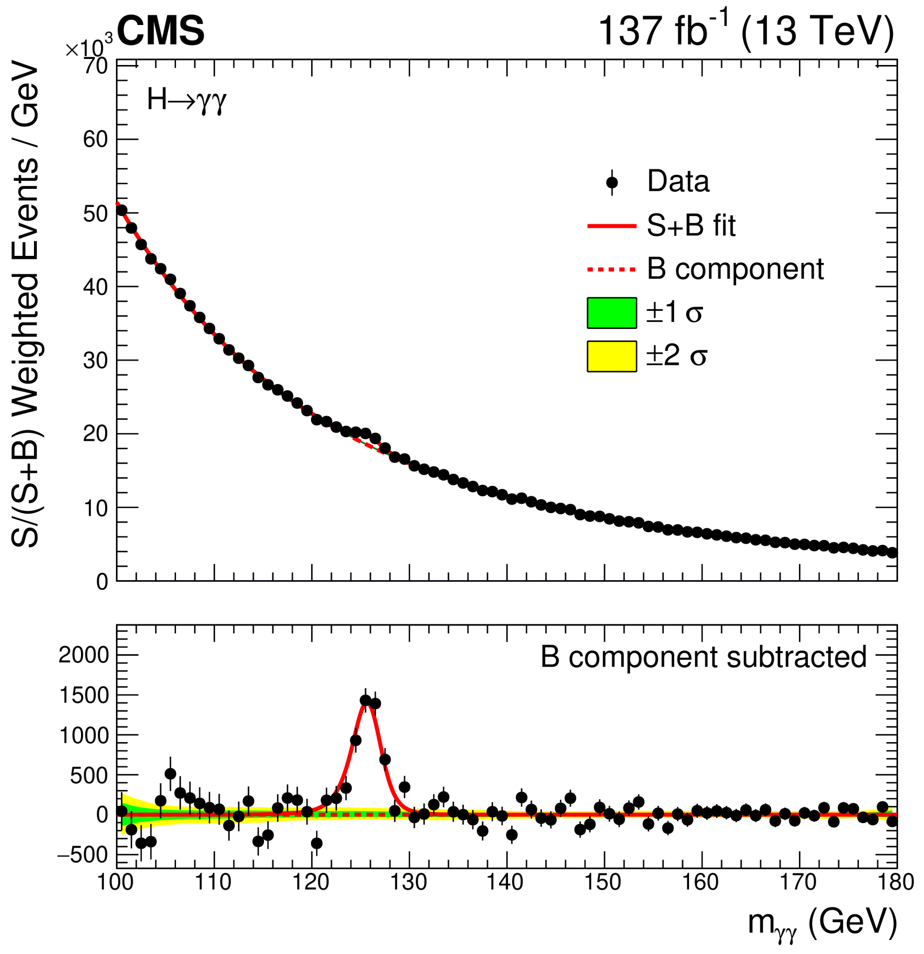


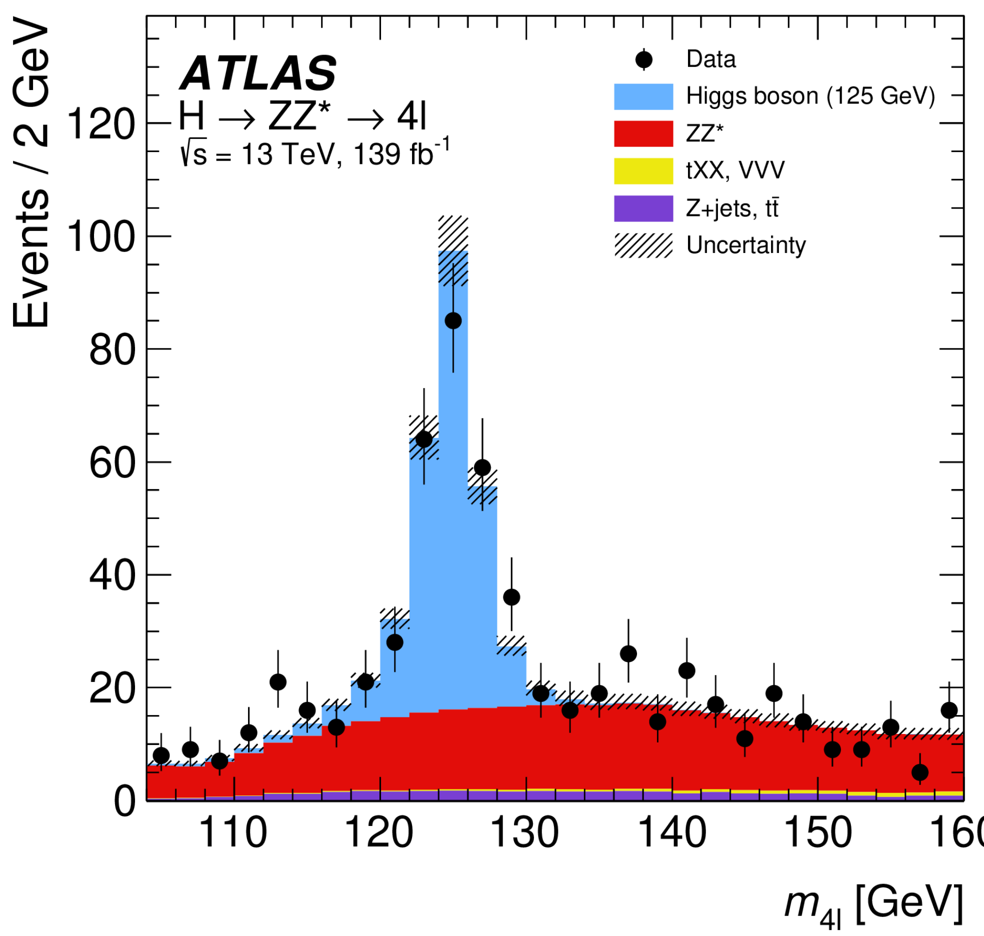


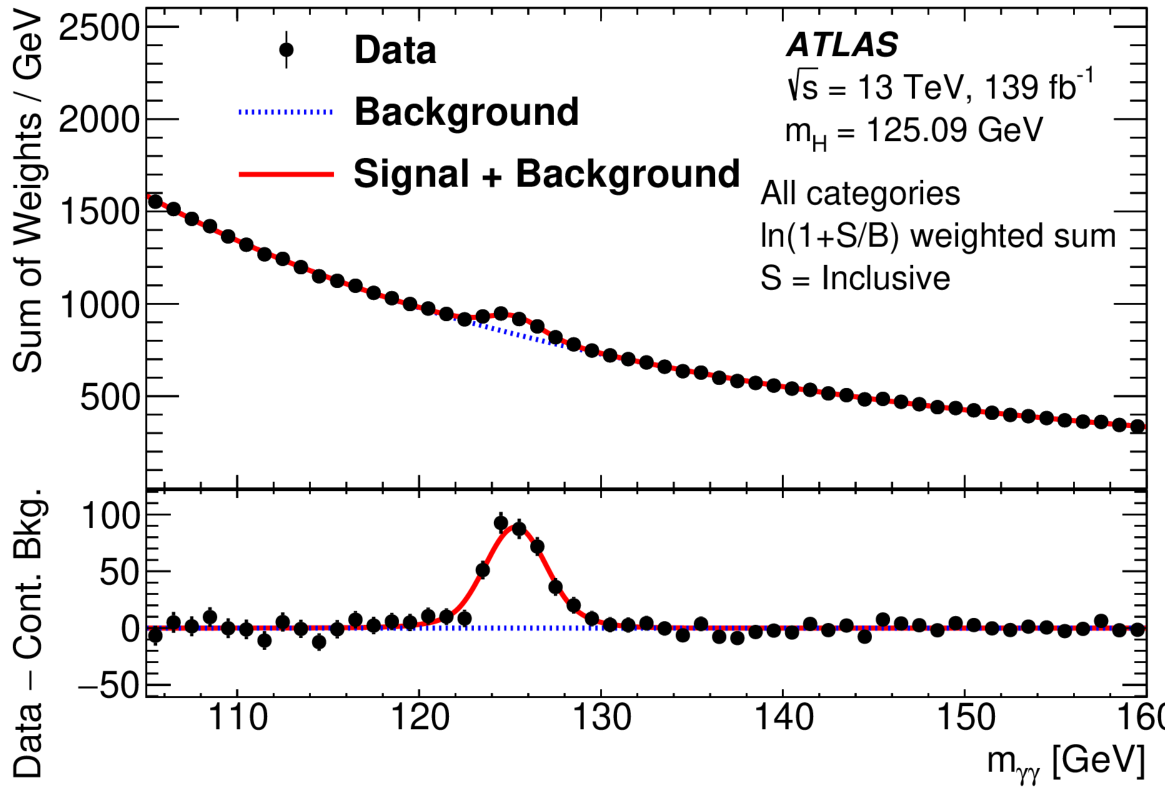




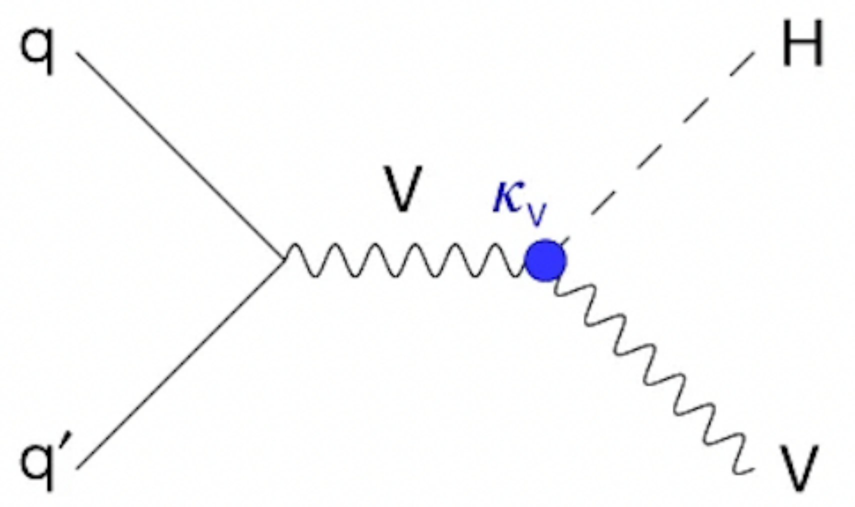








Search for the decay $H \to cc$

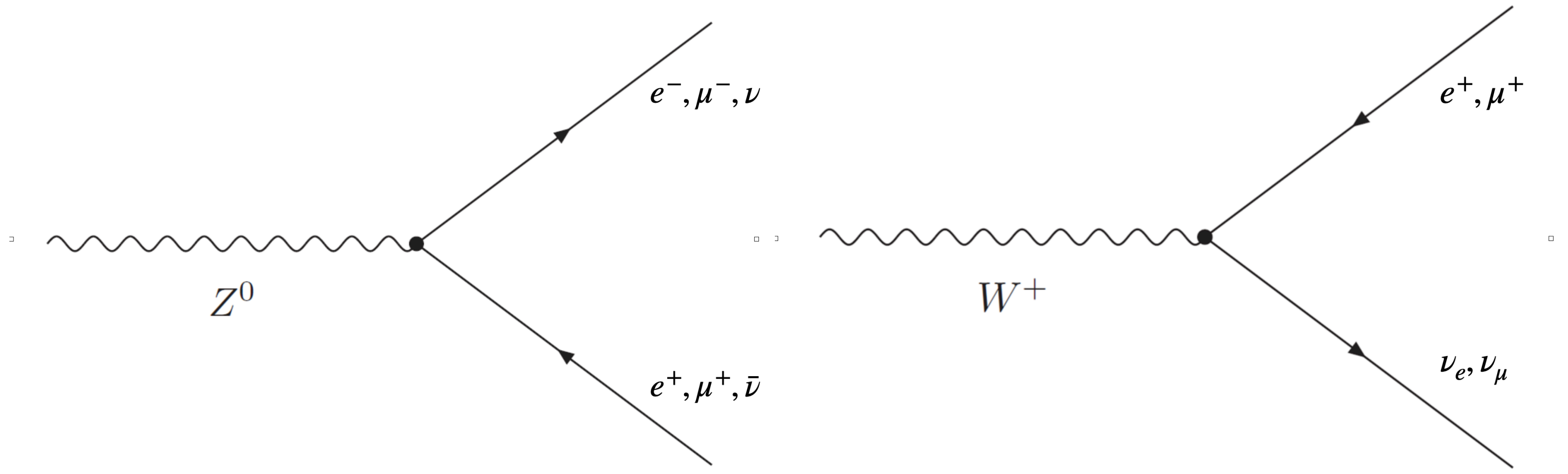


cc decay has a branching ratio of 2.8%, larger than the rare decays like Zγ or μμ,
but challenging to identify due to large multi-jet and resonant H→bb backgrounds
(charm quarks are much harder to identify than muons or photons)

→ use VH (WH/ZH) process for easier signal event selections (as done for the H→bb case)

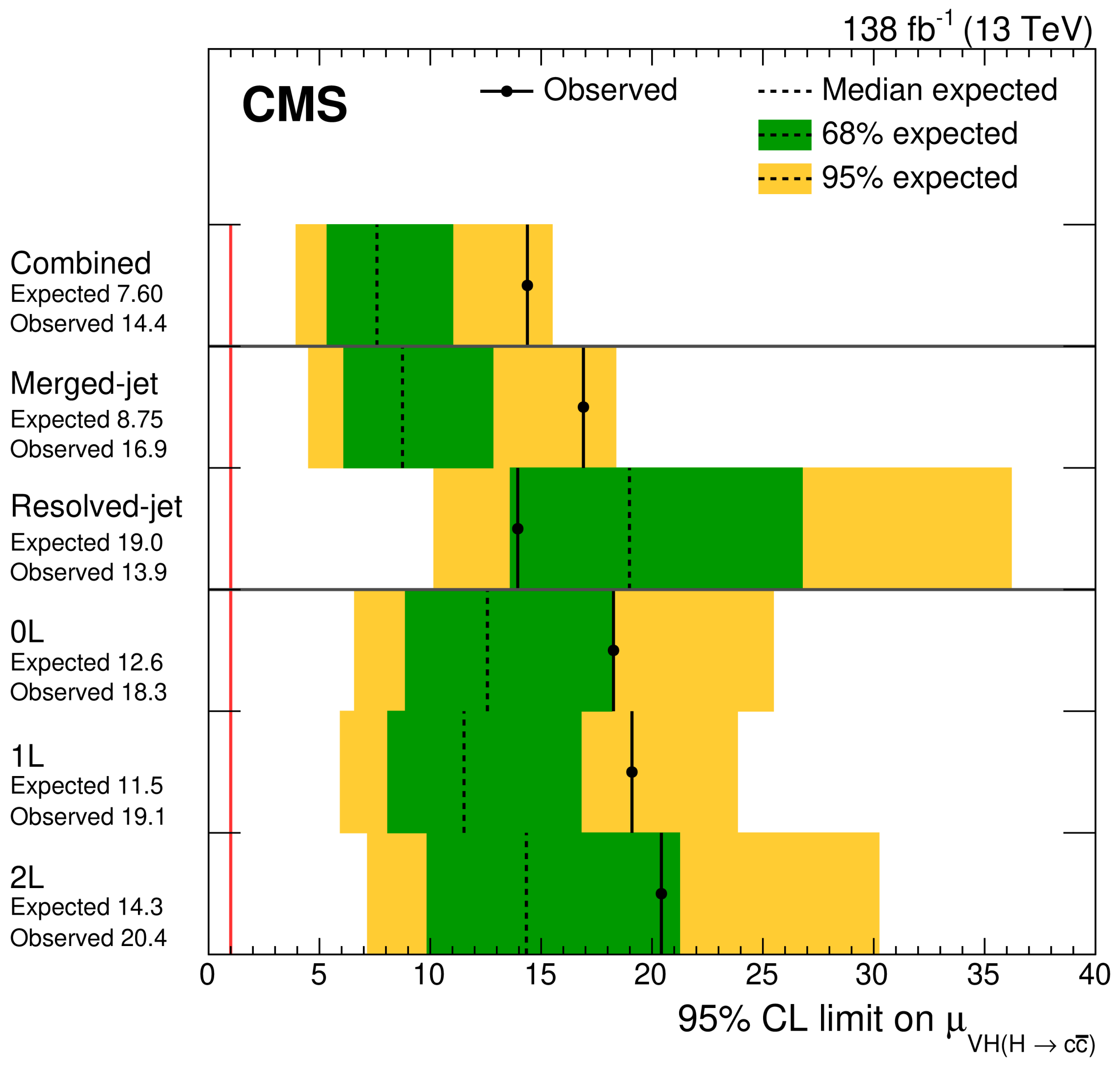
→ use of advanced machine learning techniques
to distinguish c-jets from b-jets and light-jets

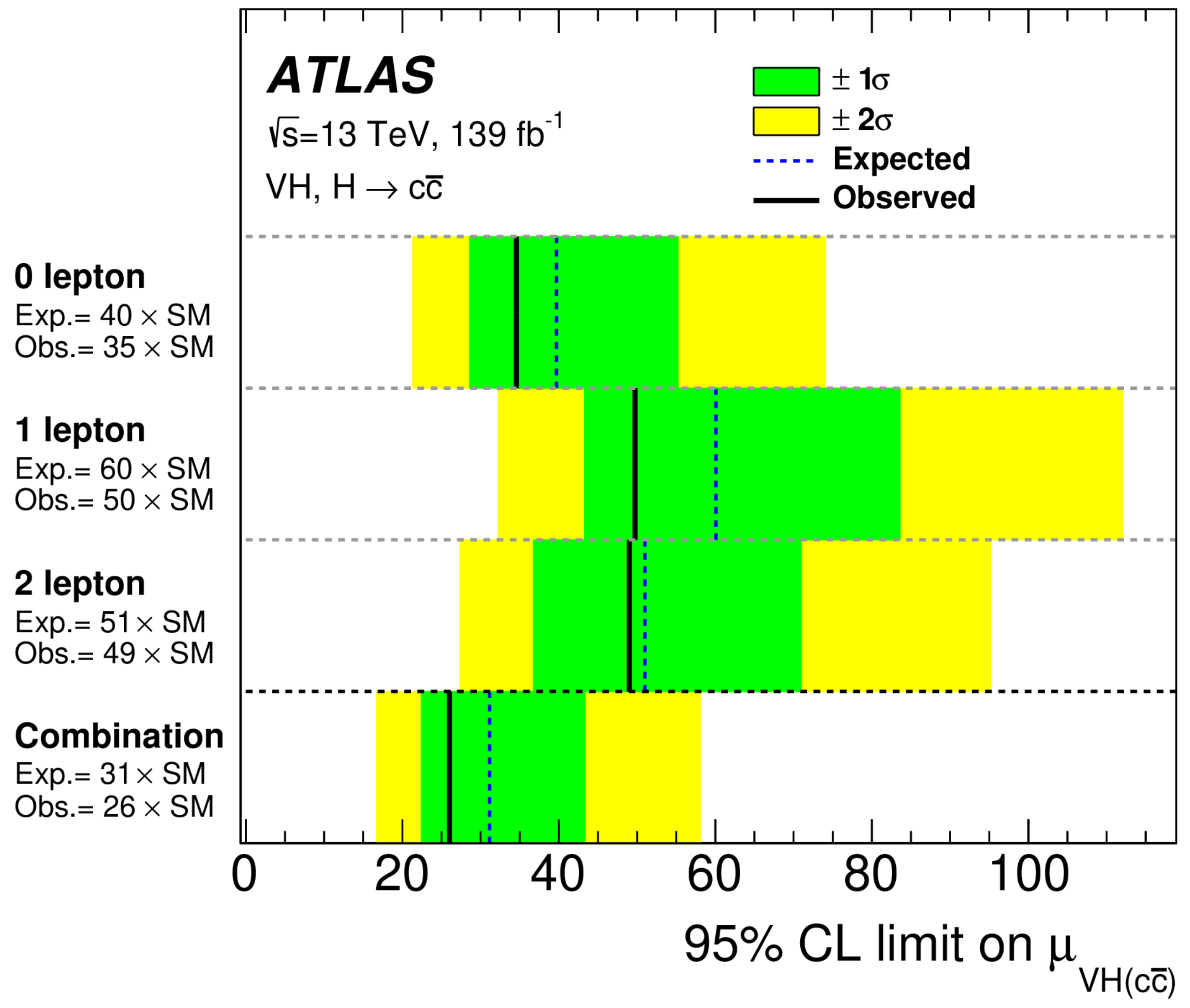
Z and W bosons decays



Signal not observed yet and sensitivity of ATLAS and CMS searches
still very far from being able to observe this decay
(upper limits on VHcc signal set at ~15 x SM at 95% CL)

95% CL upper limits on μ_{VHcc}





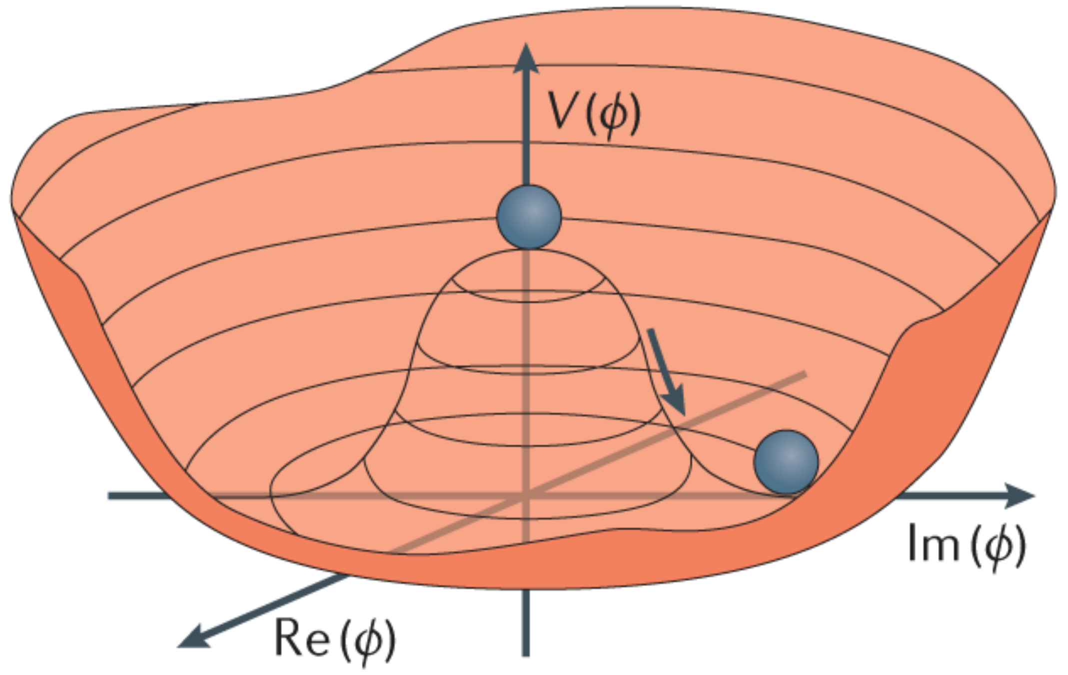
Results can be used to set direct limits on the Higgs
coupling to c-quarks: most stringent constraints from CMS,
$1.1 < |\kappa_c| < 5.5$ at 95% CL ($\kappa_c = y_c^{meas}/y_c^{SM} = 1$ in SM)

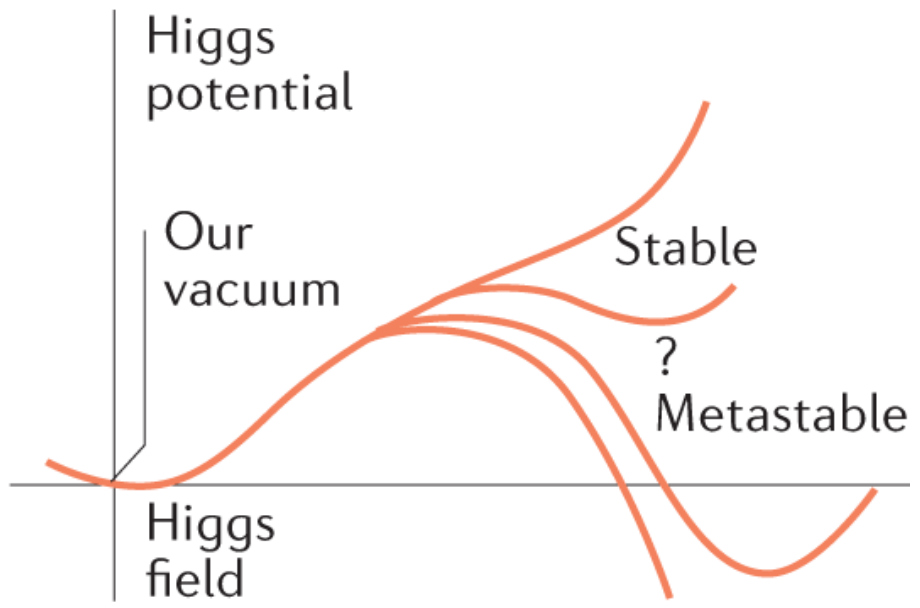
Search for HH production

The Standard Model predicts that the Higgs boson also couples to itself

→ the strength of the Higgs boson self-coupling is directly connected to the shape of the Higgs potential, determining the stability of the universe

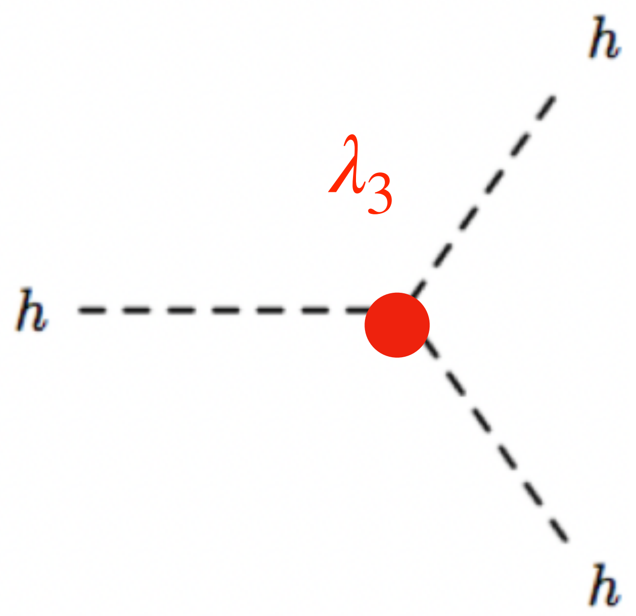
$$V(\Phi) = \mu^2\Phi^2 + \lambda\Phi^4$$





Expanding around the minimum, $\Phi = \nu + h$:

$$V(h) = \lambda\nu^2h^2 + \lambda\nu h^3 + \frac{1}{4}\lambda h^4 = \frac{1}{2}m_h^2h^2 + \lambda_3h^3 + \lambda_4h^4$$



triple Higgs coupling

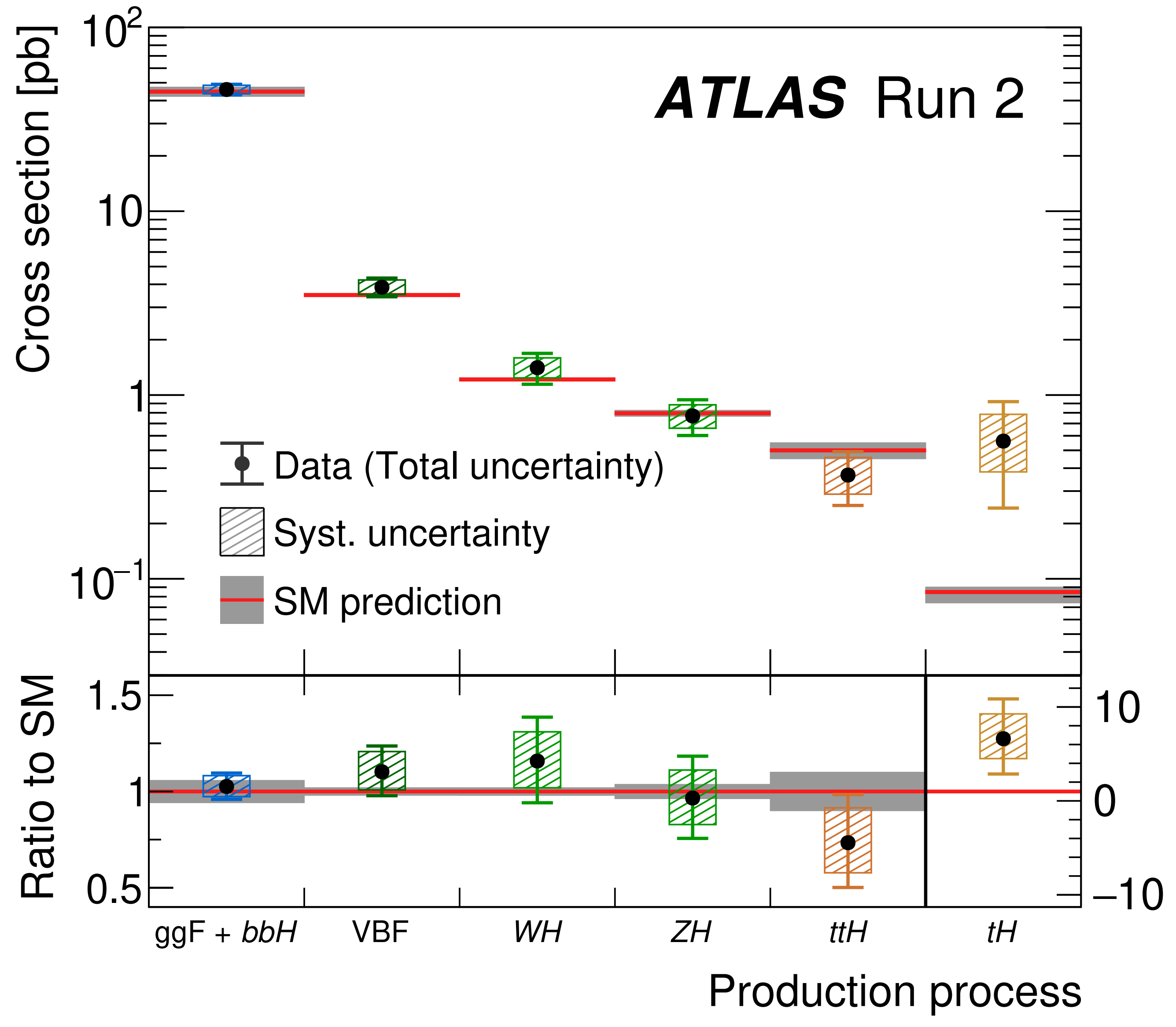
$$\lambda_3 = \lambda\nu = \frac{m_h^2}{2\nu}$$

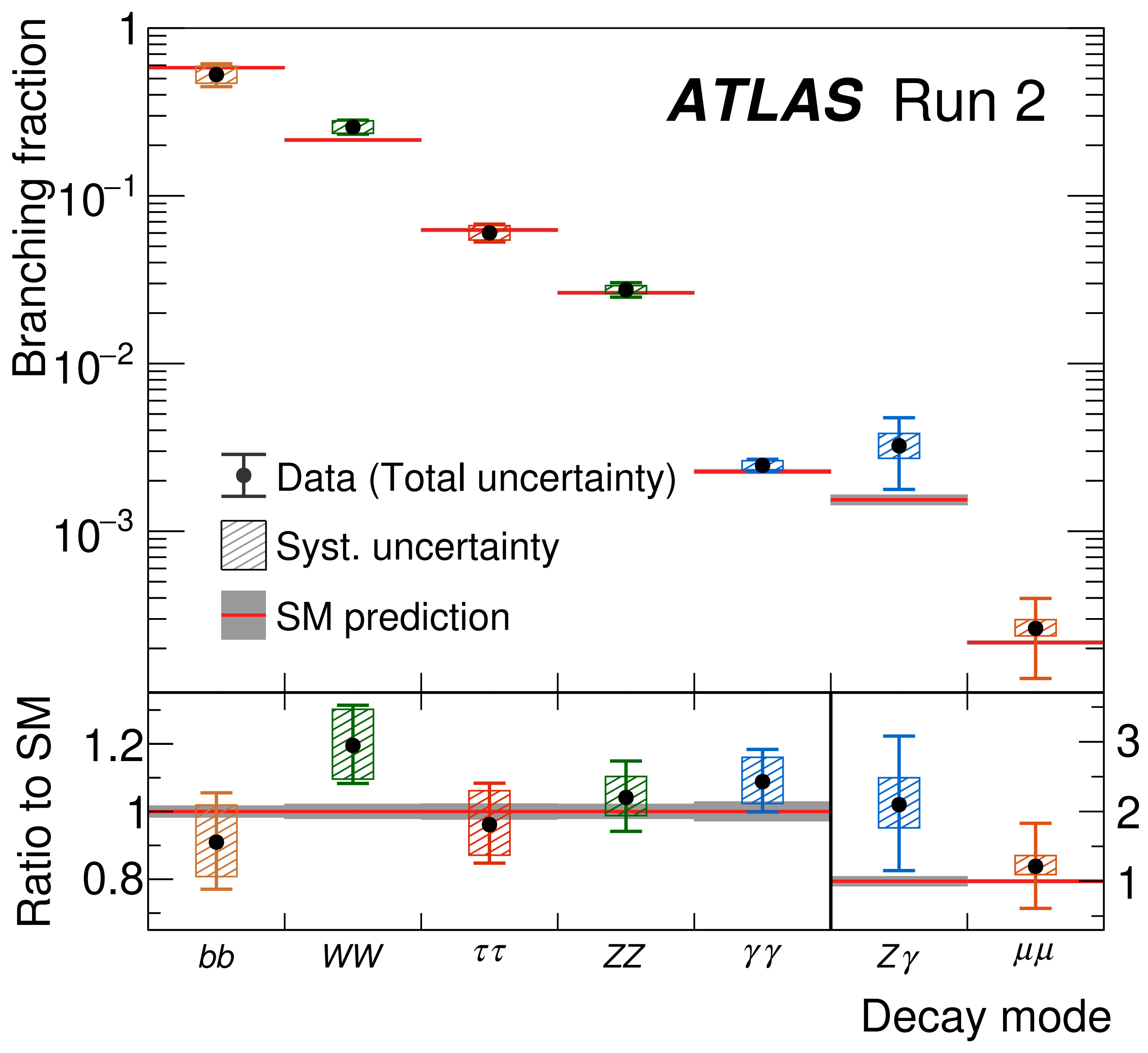
In the SM the Higgs self-coupling has well-defined value once the Higgs mass is known ($\propto m_H^2$)

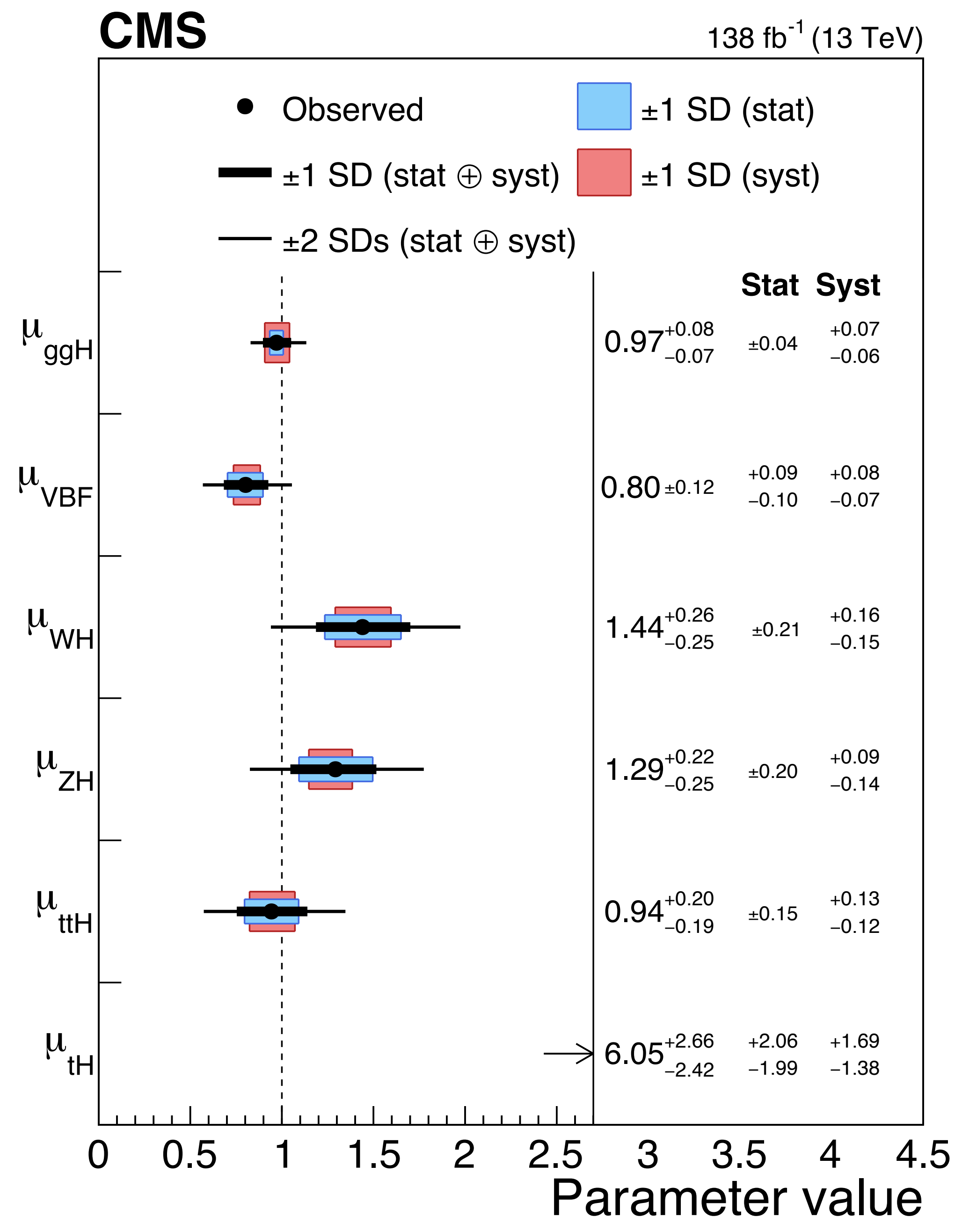
HH production allows to directly measure the Higgs boson self-coupling at the LHC and probe the shape of the Higgs potential

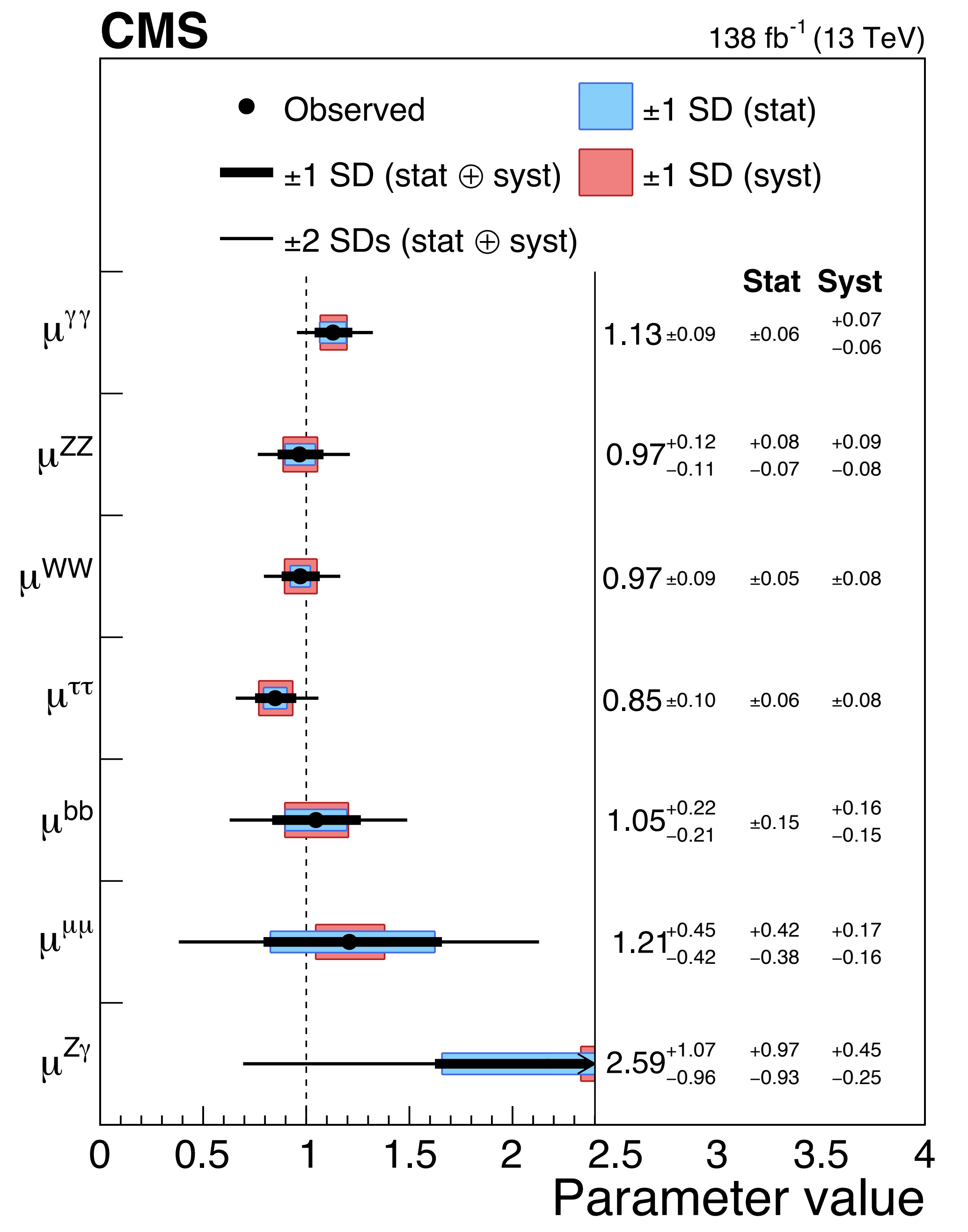
Higgs boson signal strength measurements

After 10 years, 4 main production modes (ggF, VBF, VH, ttH) and 5 decay channels observed (bb, WW, ττ, ZZ, γγ)









Signal strength, $\mu = \sigma^{meas}/\sigma^{SM}$ or $\mu = BR^{meas}/BR^{SM}$,

measured with 10-20% precision for the observed production and decay modes,

Global signal strength measured with 6% precision combining all measurements

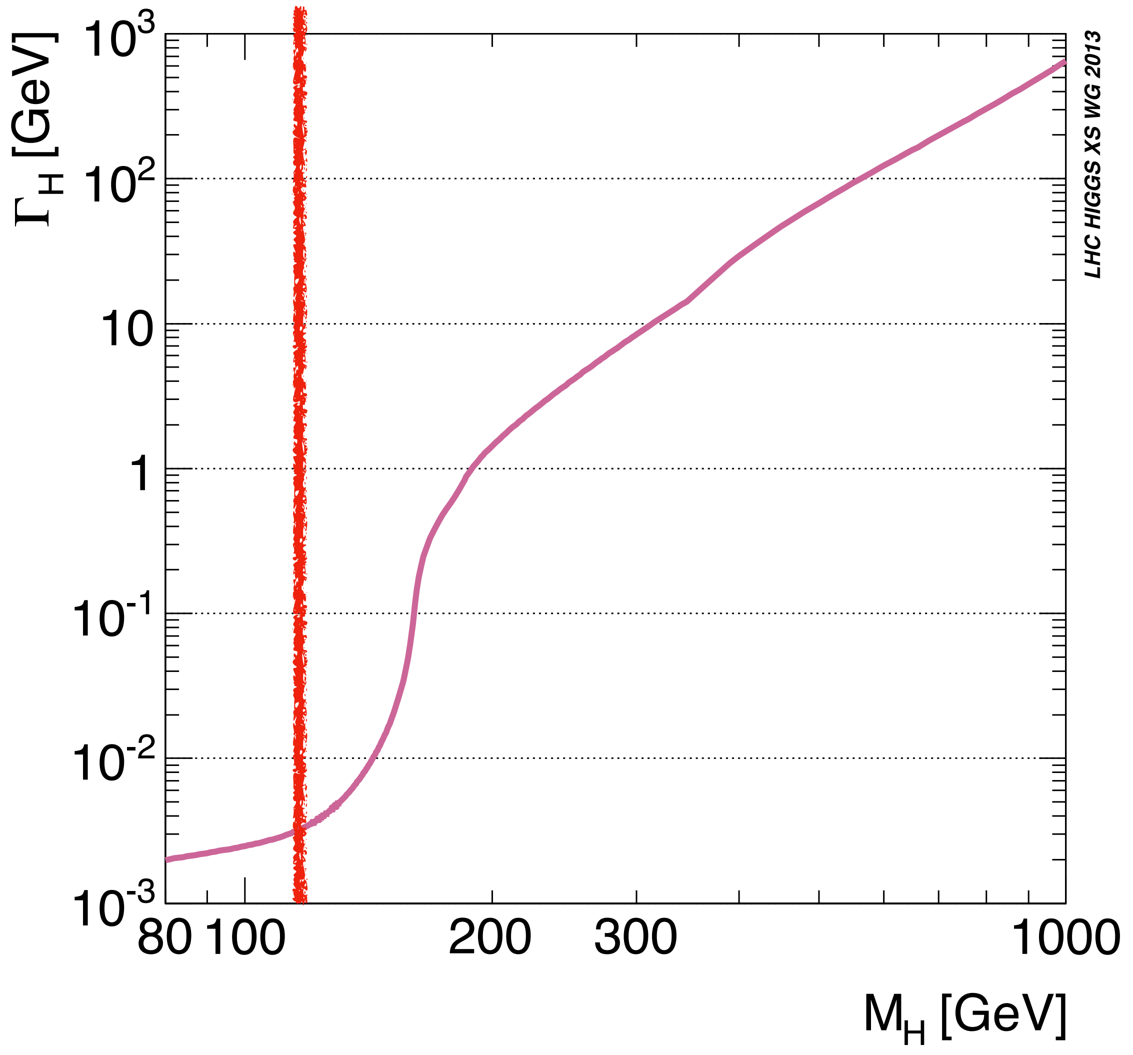
→ All measurements in agreement with Standard Model Higgs boson signal within experimental uncertainties

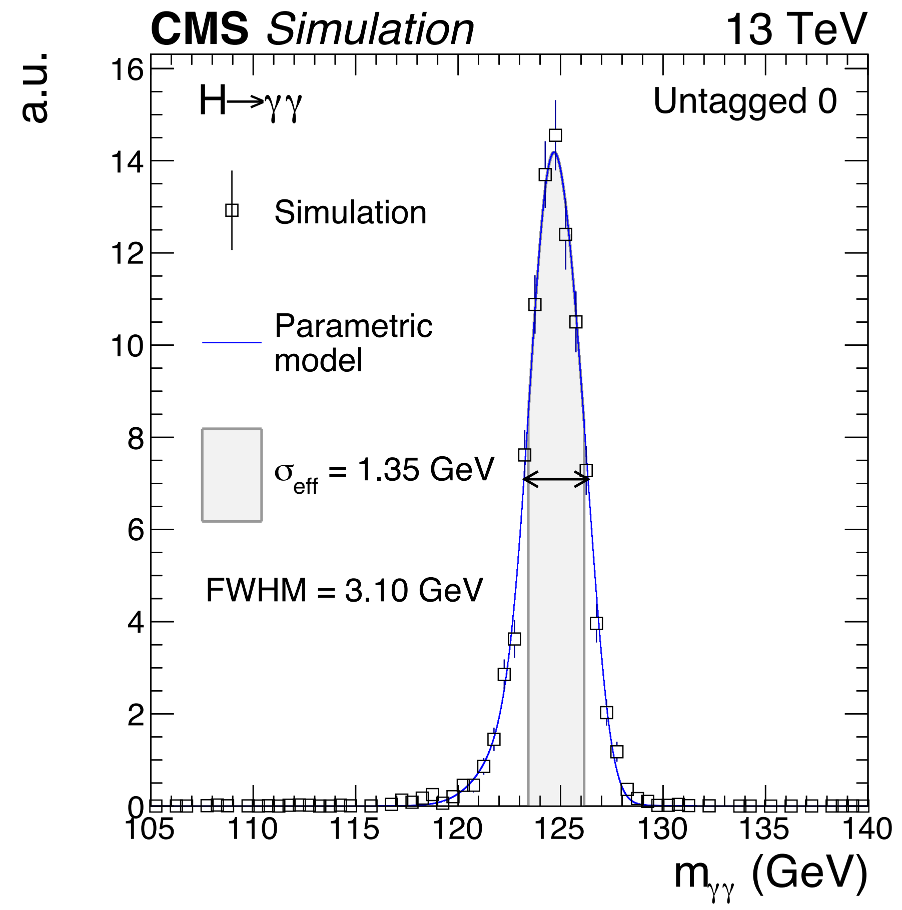
Higgs boson width

Higgs boson width is small, at 125 GeV: $\Gamma_H^{SM} = 4.1\ \mathrm{MeV}$

→ direct measurements (from resonance lineshape) very limited by the experimental resolution

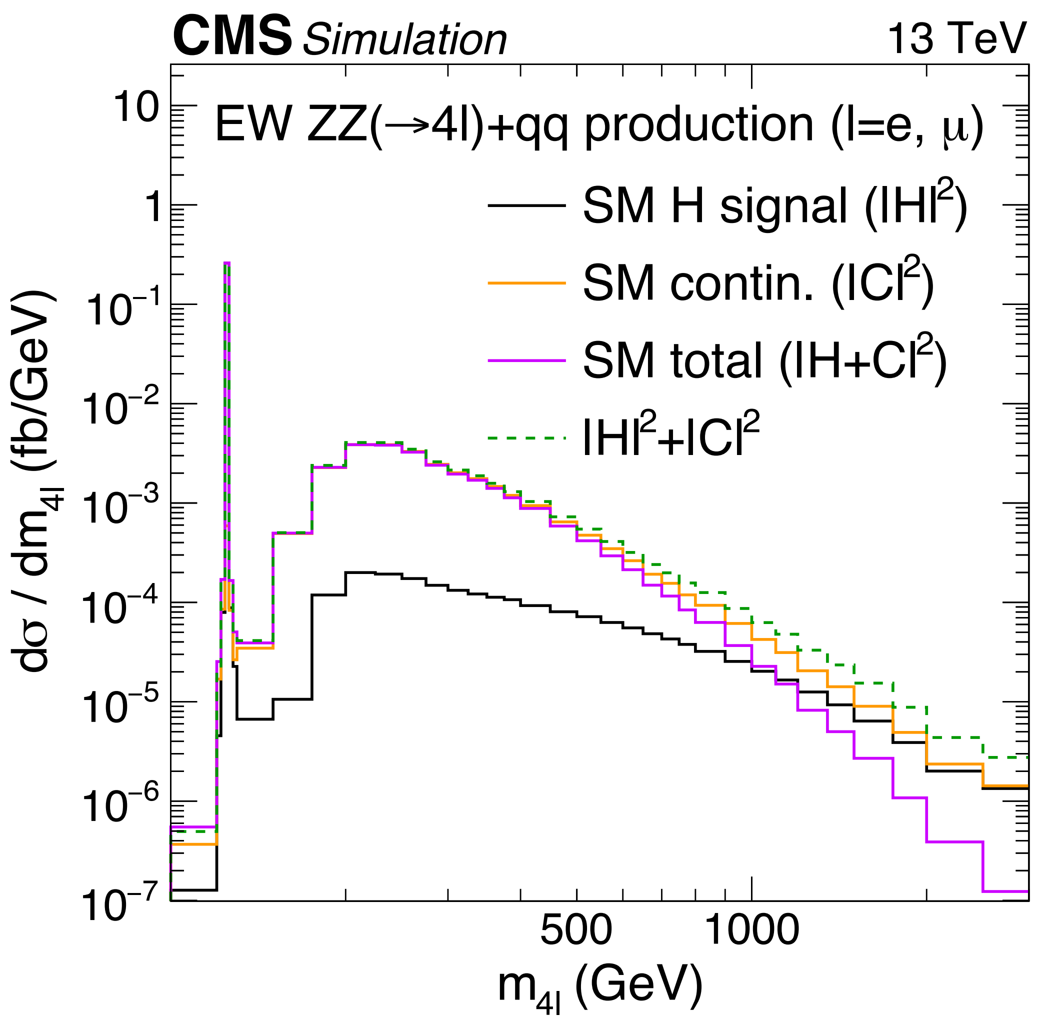
(order of 1 GeV in the channels with good resolution)



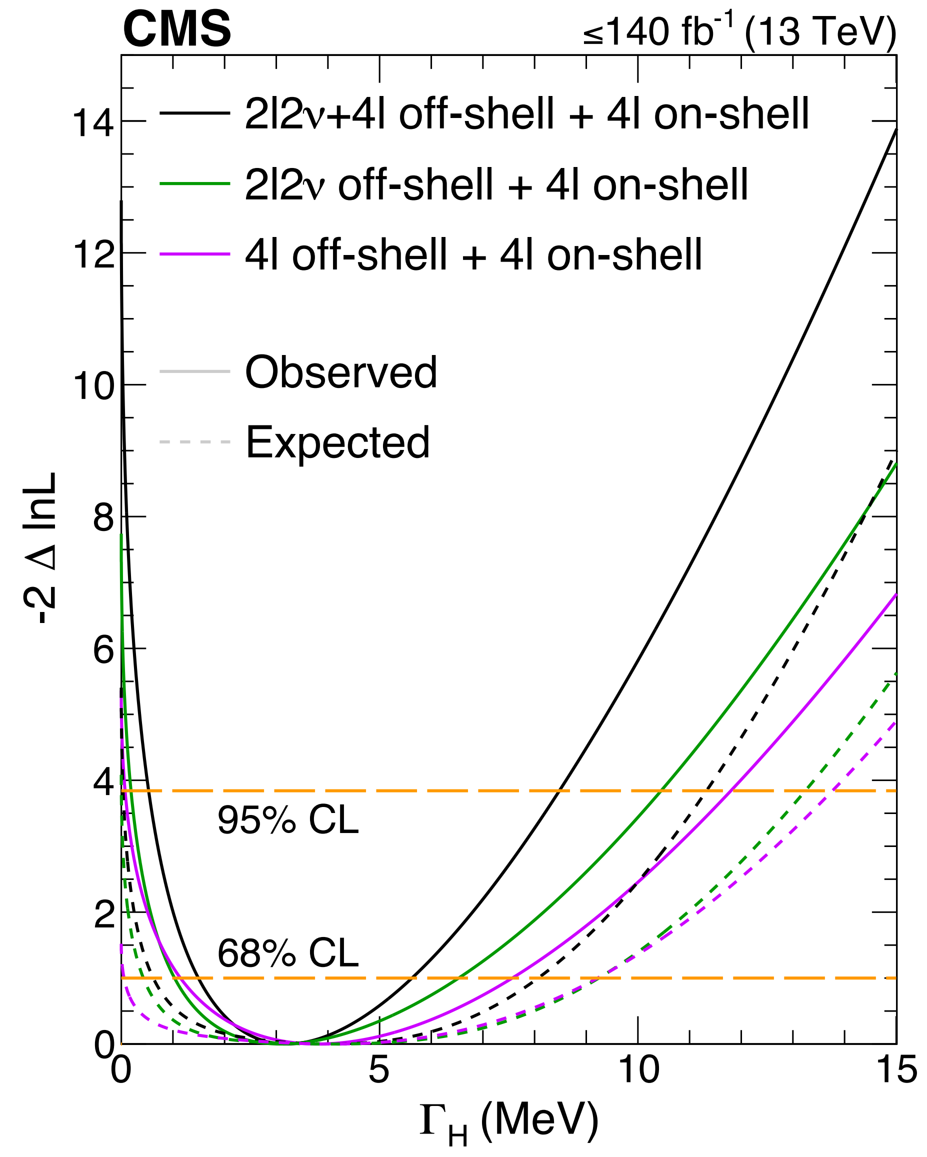


- Γ_H can be extracted through a combined measurement of on-shell and off-shell Higgs boson production:

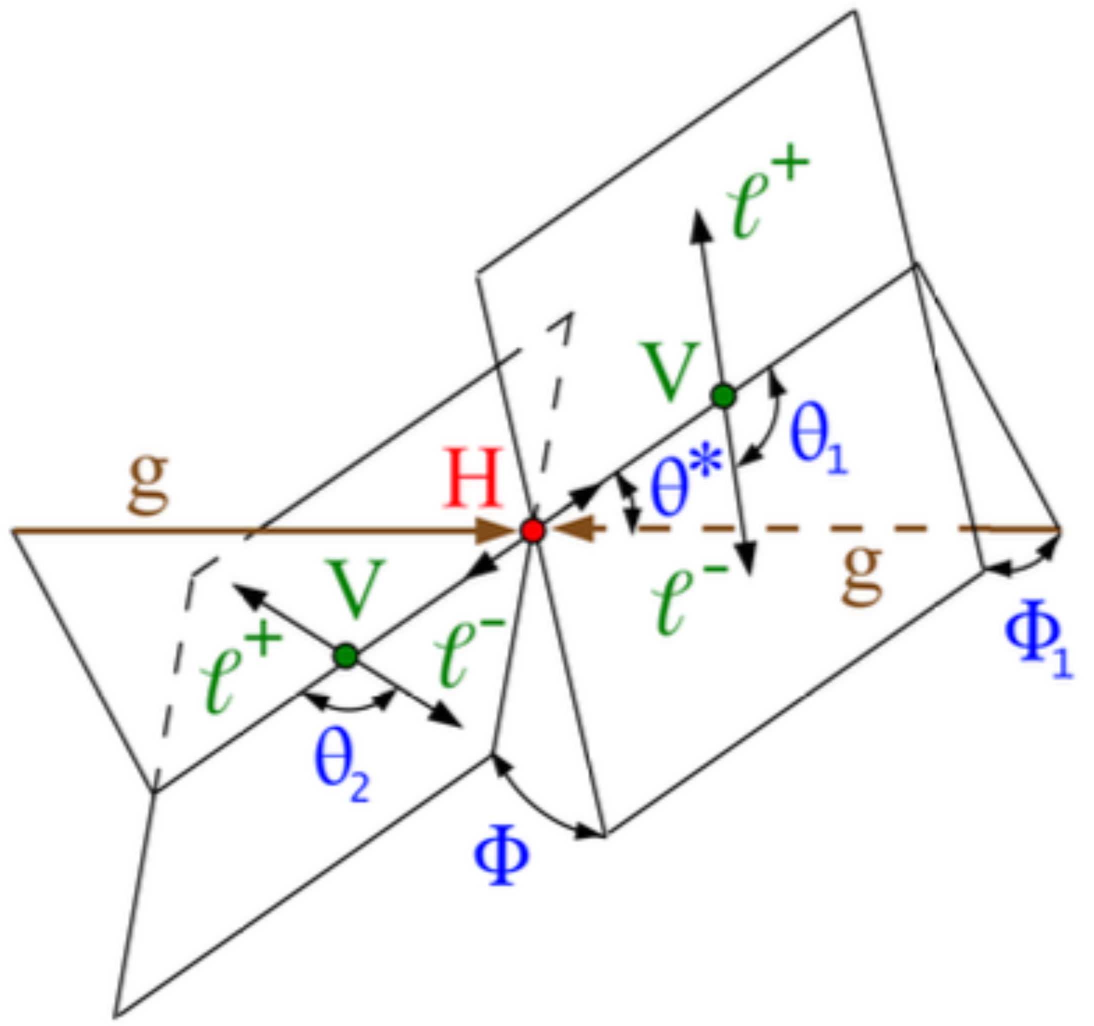
$$\frac{\mu_{off-shell}}{\mu_{on-shell}} = \frac{\Gamma_H}{\Gamma_H^{SM}} \quad \rightarrow \quad \Gamma_H = \frac{\mu_{off-shell}}{\mu_{on-shell}} \Gamma_H^{SM}$$

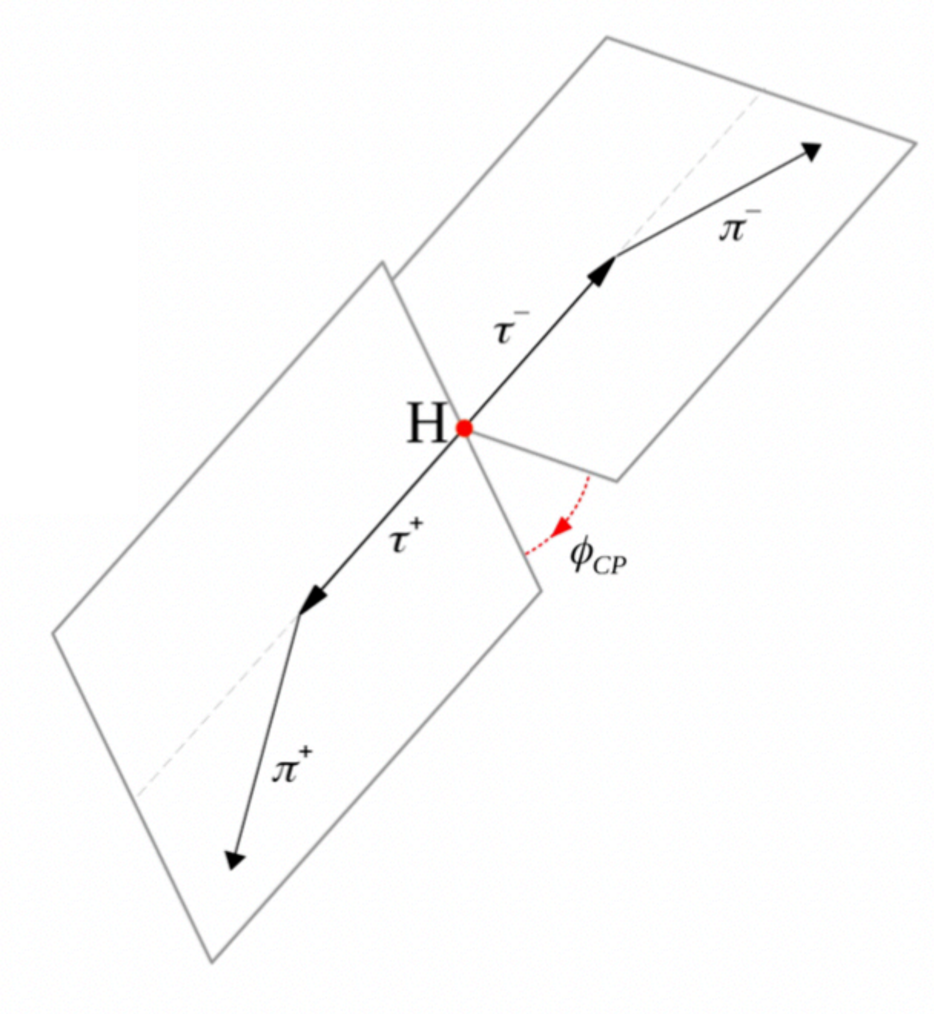


- Destructive interference between on-shell and off-shell production
- First evidence for off-shell Higgs boson production with 3.6σ by CMS combining 4l and 2l2v channels (Deficit vs expectation without off-shell, magenta vs black)
- Width measured as $\Gamma_H = 3.2^{+2.5}_{-1.7}\ \mathrm{MeV}$



Higgs boson spin and CP





SM Higgs has spin 0 and positive (even) parity ($J^{CP} = 0{+}{+}$)

Experimentally tested studying angular correlations between decay products in bosonic decays (WW,ZZ,γγ) or ττ decay

→ At the end of Run 1, we already knew Higgs had spin 0 (spin 1 and spin 2 hypotheses excluded)

Spin is a property of the particle, while CP is a property of the coupling (SM predicts 0++ for all)

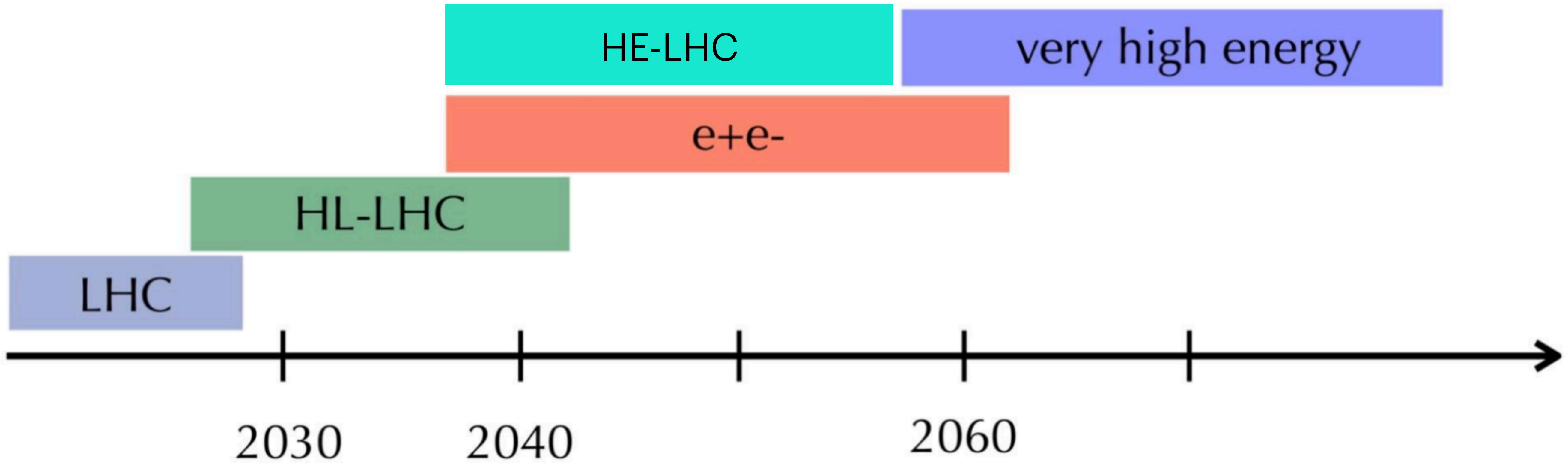
→ CP structure of the various couplings investigated in Run 2

in different processes of production and decay involving different couplings,

all results compatible with parity +

Possible future colliders (post HL-LHC)

Several post HL-LHC possible future colliders being studied and under discussion, that could start operating around 2050



2 main groups of colliders: hadron colliders for exploring high energies or lepton colliders for precision measurements

Some examples of possible future colliders at CERN:

- High-Energy LHC (HE-LHC): pp collider with a centre-of-mass energy of 27 TeV (re-using the 27 km LHC tunnel)
- Future Circular Collider (FCCee): ee circular collider with a centre-of-mass energy up to 350 GeV (100 km tunnel)
- Future Circular Collider (FCChh): pp circular collider with a centre-of-mass energy of 100 TeV (same 100 km tunnel of FCCee)

→ Plan not fixed yet, many interesting studies ongoing to understand what is the best option!

	HL-LHC	HE-LHC	FCC (ee+hh)
Uncertainty on Higgs couplings to vector bosons and fermions	Few %-level	%-level	0.1%-1%
Upper limit on Higgs BR to invisible	2%	1.5%	0.02%
Uncertainty on Higgs self-coupling	50%	15%	5%