Whatever happened to the Higgs?

10 Years Later

Christoph Paus, MIT

Wine & Cheese Seminar
at Fermilab
July 15, 2022

Outline

Introduction

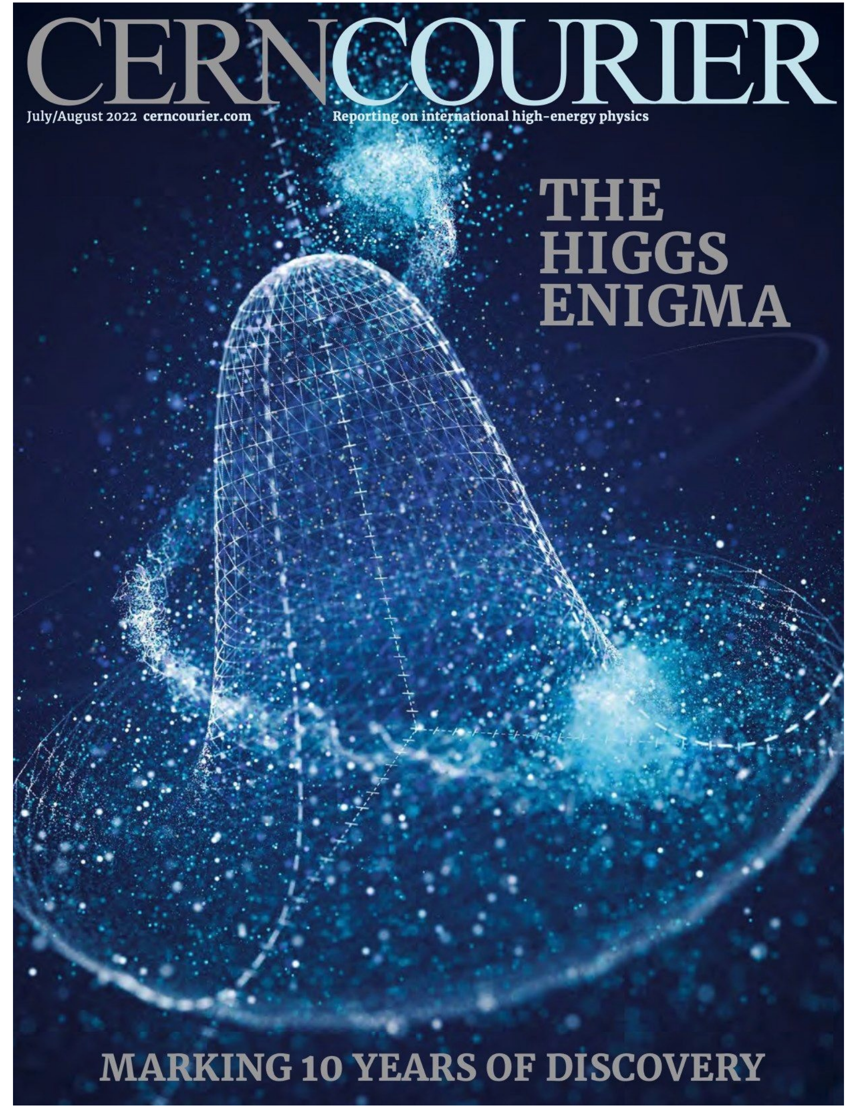
The discovery

- Anatomy of the discovery
- From a narrow resonance to the Higgs boson
- Some important lessons ...

What we know today about the Higgs?

- Signal strengths: in production and decay
- Coupling strengths
- The Mass
- Self coupling?

What does the future hold?



References

Higgs10 event at CERN

- Indico link
- Higgs10 publications in Nature by
  - ATLAS *"A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery"* *[Nature 607 (2022) 52]* and
  - CMS *"A portrait of the Higgs boson by the CMS experiment ten years after the discovery"* *[Nature 607 (2022) 60]*

All publications from ATLAS and CMS

- ATLAS publications on Higgs (150+ papers)
- CMS publications on Higgs (150+ papers)

Impossible to talk about all of what is going on in Higgs experiment I made a personal selection.

Theory in a nutshell

The Standard Model *of Particle Physics*

Building blocks: matter (fermions), forces (bosons)

$$\mathcal{L} = [i\overline{\psi}\gamma^\mu\partial_\mu\psi - m\overline{\psi}\psi] -$$ *Free fermion*

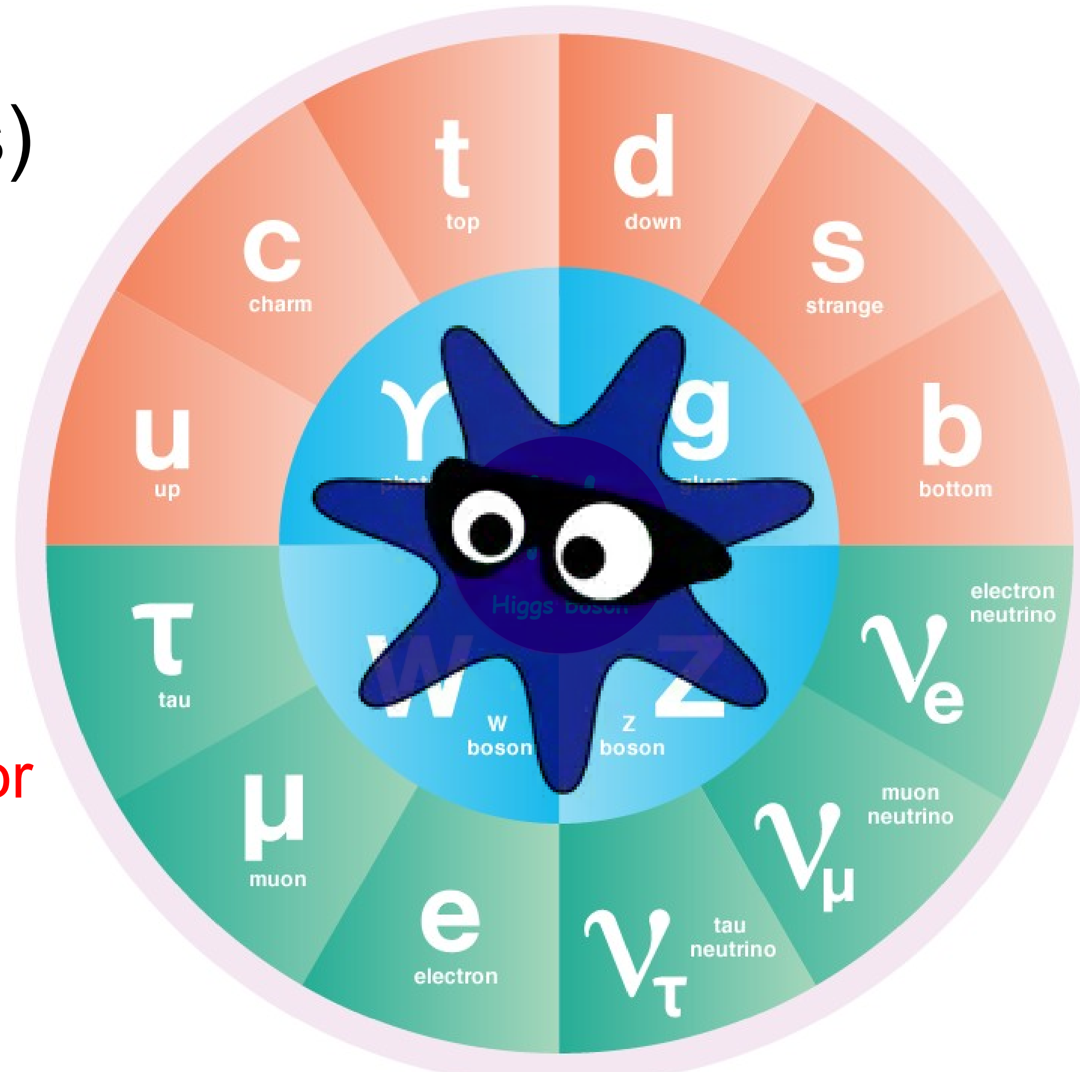
$$(e\overline{\psi}\gamma^\mu\psi)A_\mu -$$ Gauge interaction

Free boson $$\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\nu A_\nu$$

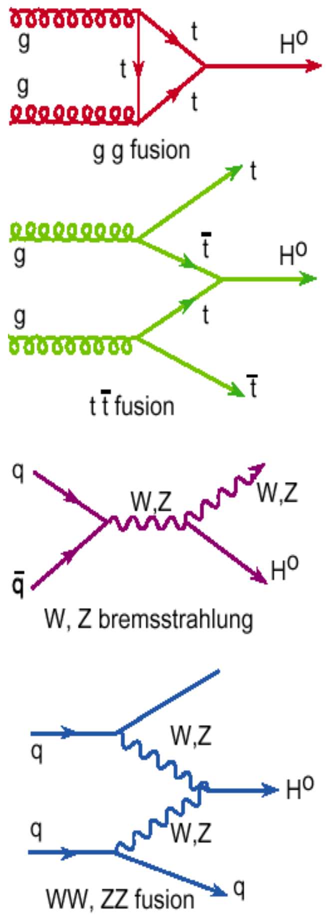
Simple Lagrangian formalism describes this very well but only for massless particles.

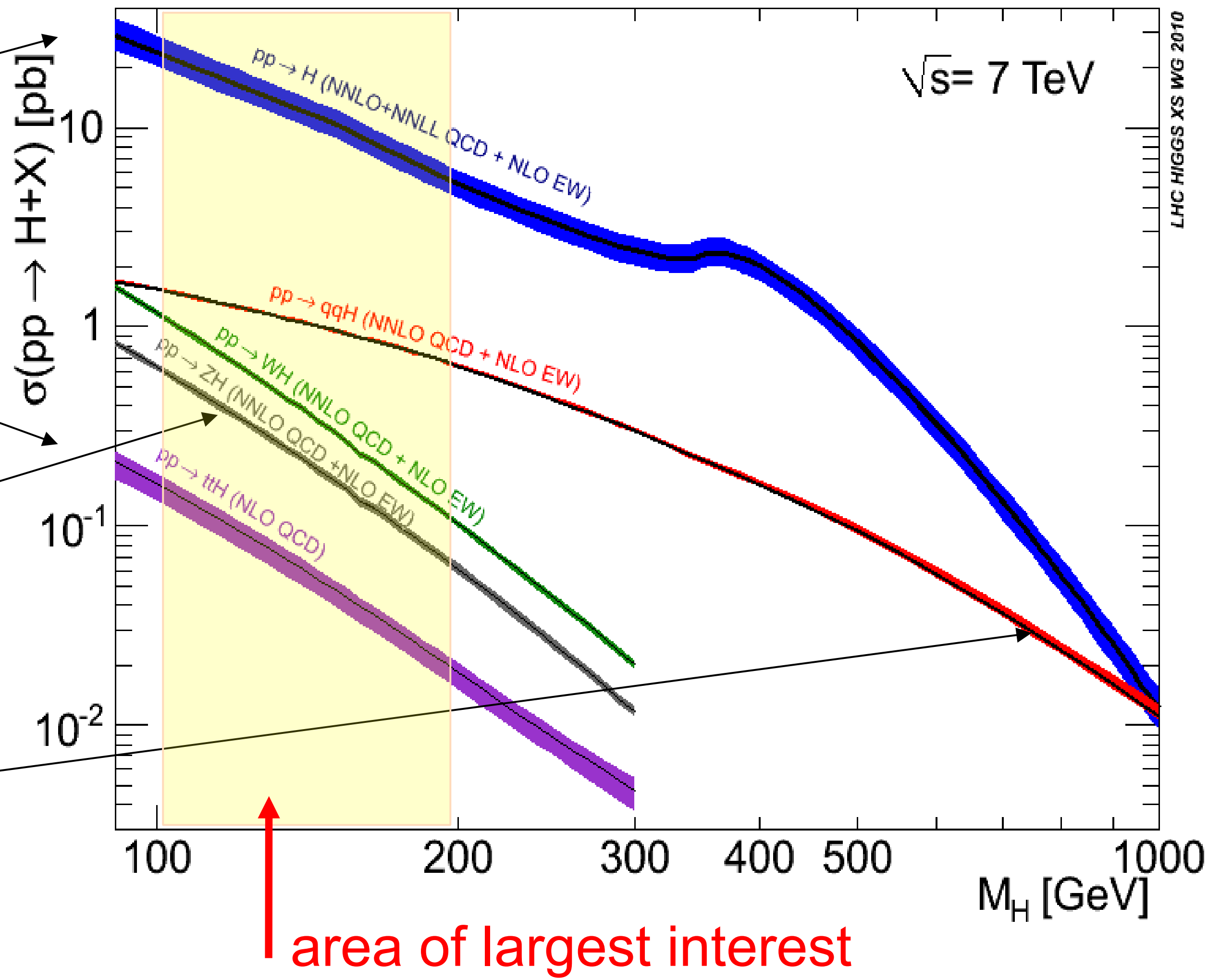
Local gauge invariance is violated

$$\psi \rightarrow \mathrm{e}^{i\theta(x)}\psi$$

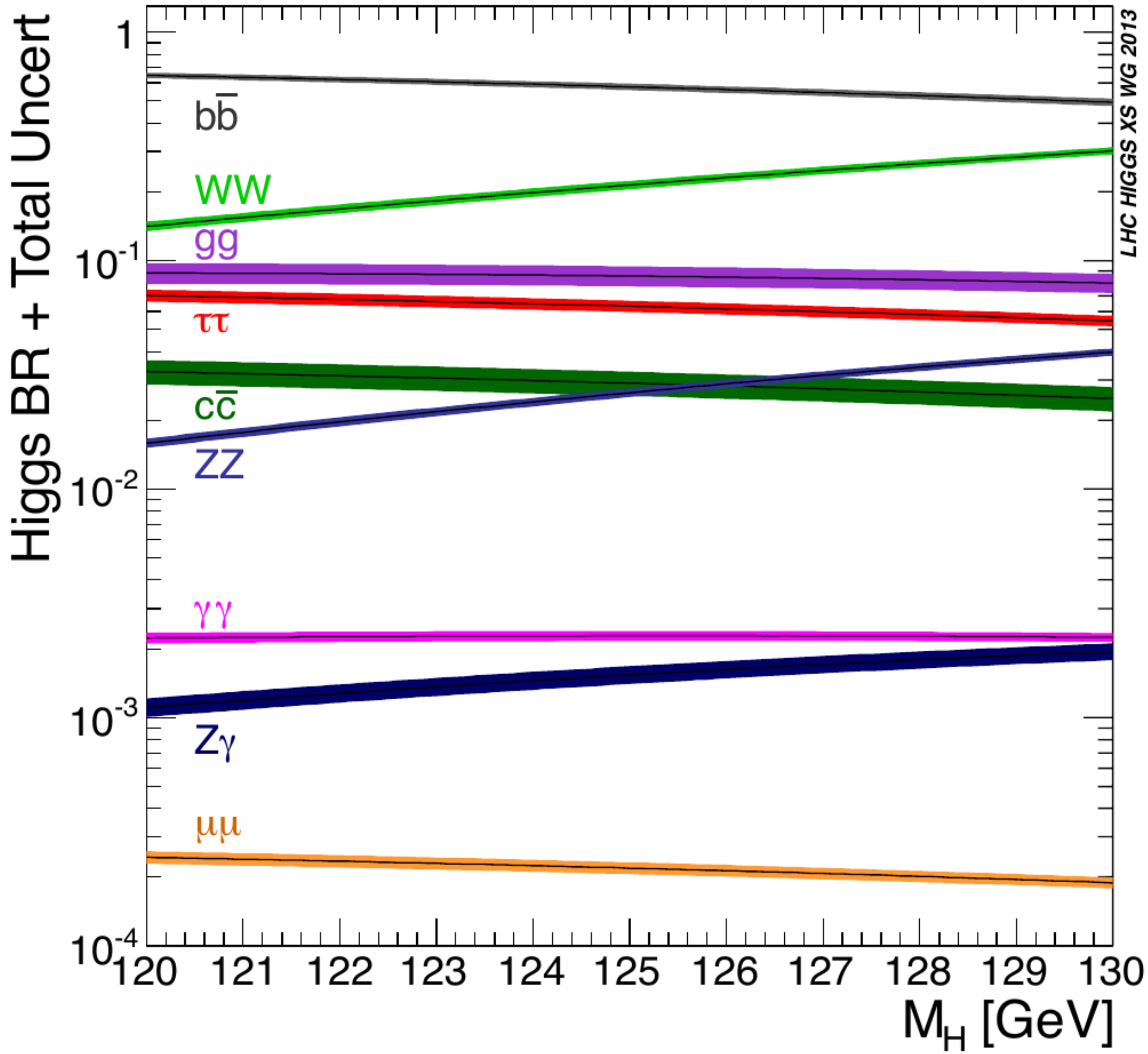


Higgs Production at the LHC





Higgs Decays



Decay	Branching Fraction [%]
bb	57
WW	22
tau tau	6.3
ZZ	3
γγ	0.2
	88.7

Table does not tell the full story

... but of course there is a message.

Higgs boson couples to mass

Messy: many channels, many subsequent decays *etc. etc.*

- common: leptons/photons essential for any early search
- 5 channels are most promising

What was known about the Higgs over 10 years ago?

'Obvious' bounds

Lower bound

- Require the 'mexican hat': *V(v)* < *V(0)* leads to

$$m_H > \sqrt{\frac{3(2m_W^2 + m_Z^4) - 4\sum m_\ell^4 - 12\sum m_q^4}{16\pi^2}} > 7\ \mathrm{GeV}$$

Mass of the Higgs Boson*

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 15 December 1975)

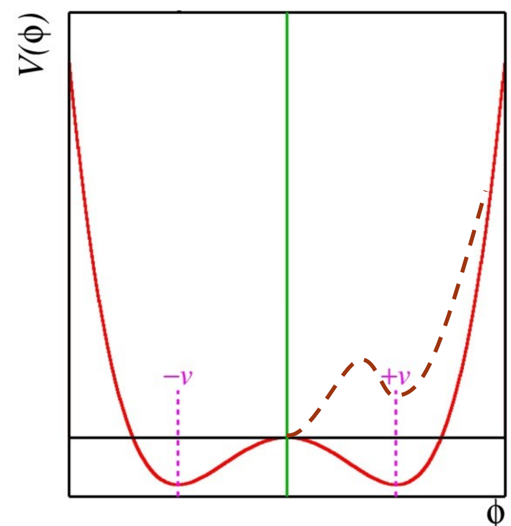
The stability of the vacuum sets a lower bound of order $\alpha G_F^{-1/2}$ on the Higgs-boson mass. For the simplest SU(2)⊗U(1) model, this lower bound is $1.738\alpha G_F^{-1/2}$, or 3.72 GeV.

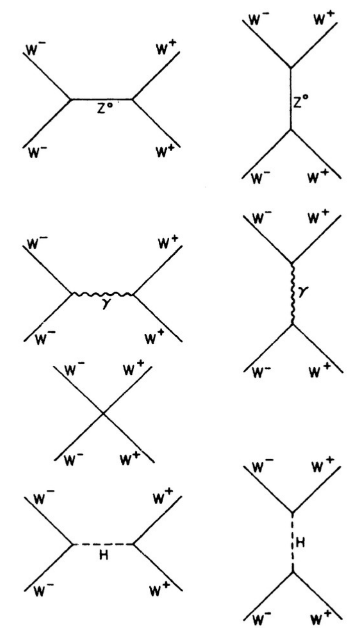
Also A. Linde, JETP Lett. 23 (1976) 64: > 5 GeV

Upper bound

- Triviality limit (unitarity)
- Higgs plays an essential role to maintain vector boson scattering finite

$$m_H < m_c = \sqrt{8\pi\sqrt{2}/3G_F} \approx 1\ \mathrm{TeV}$$





The precise meaning of the upper bound is that if m_H exceeds the critical value m_c, weak interactions will become strong in the TeV energy regime in the sense that **perturbation theory will cease to be a faithful representation of physics**.

Weak interactions at very high energies: The role of the Higgs-boson mass

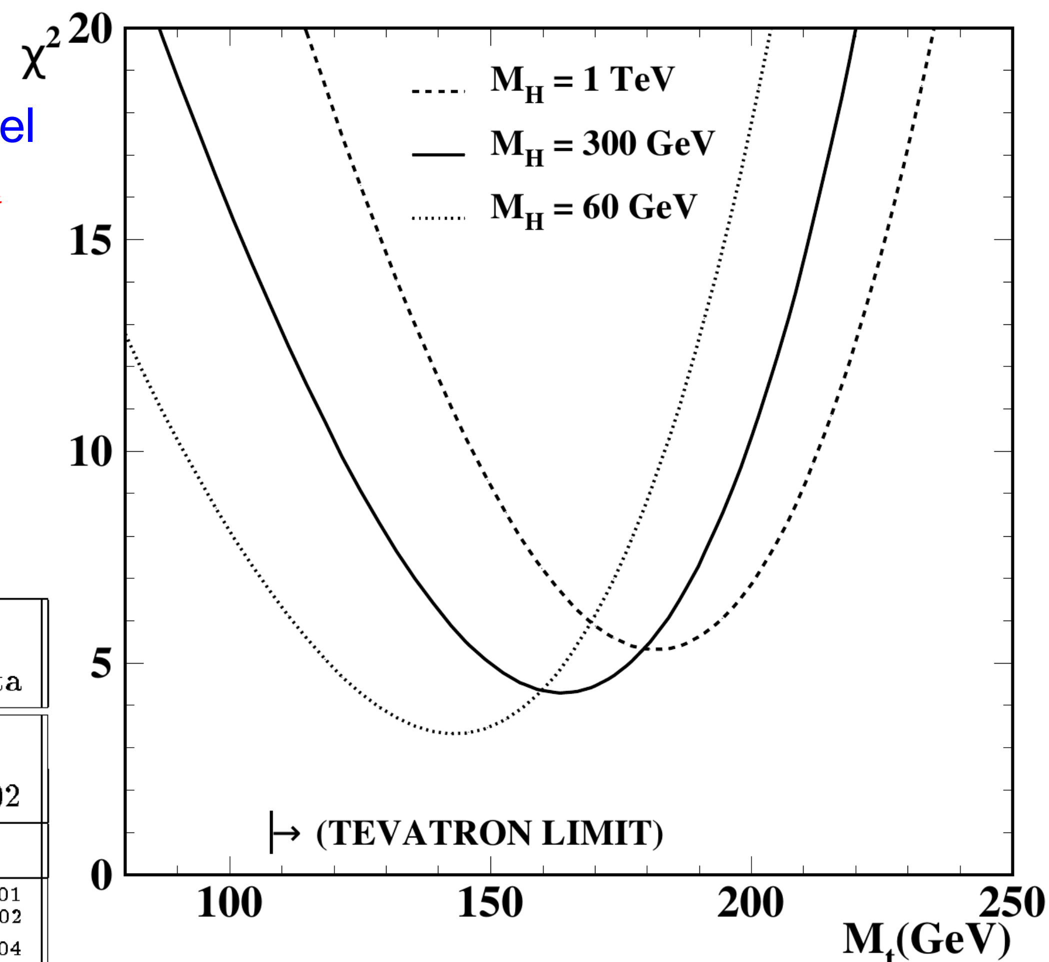
Benjamin W. Lee,* C. Quigg,† and H. B. Thacker
Fermi National Accelerator Laboratory,‡ Batavia, Illinois 60510
(Received 20 April 1977)

Constraints from Precision

Before the top discovery

- Missing pieces in *minimal* standard model calculations were parameters m_H and m_t
- Dependence (large $m_t \rightarrow$ large m_H): quadratic in m_t and logarithmic in m_H
- Prediction of m_t possible with *obvious constraints* on m_H
- No constraint on m_H

	LEP	LEP + Collider and ν data
M_t (GeV)	$166^{+17}_{-19}{}^{+19}_{-22}$	$164^{+16}_{-17}{}^{+18}_{-21}$
$\alpha_s(M_Z^2)$	$0.120 \pm 0.006 \pm 0.002$	$0.120 \pm 0.006 \pm 0.002$
$\chi^2/(d.o.f.)$	$3.5/8$	$4.4/11$
$\sin^2\theta_{eff}^{lept}$	$0.2324 \pm 0.0005\ ^{+0.0001}_{-0.0002}$	$0.2325 \pm 0.0005\ ^{+0.0001}_{-0.0002}$
$1 - M_W^2/M_Z^2$	$0.2255 \pm 0.0019\ ^{+0.0005}_{-0.0003}$	$0.2257 \pm 0.0017\ ^{+0.0004}_{-0.0003}$
M_W (GeV)	$80.25 \pm 0.10\ ^{+0.02}_{-0.03}$	$80.24 \pm 0.09\ ^{+0.01}_{-0.02}$



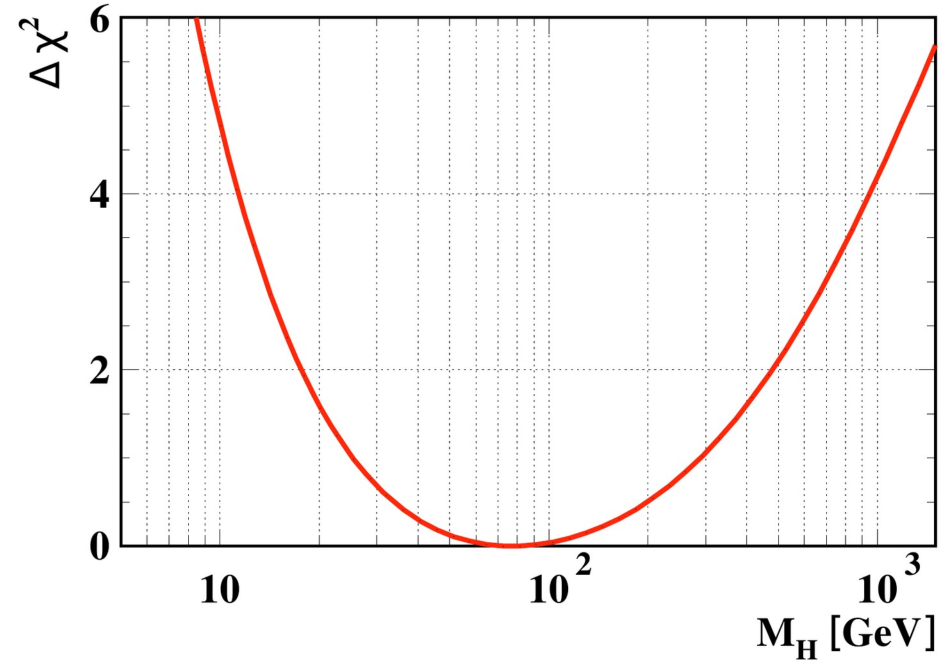
LEP Electroweak Working Group report
For EPS in Marseille 1993

CERN/PPE/93-157
26 August 1993

Constraints from Precision

After the top discovery

- Top quark was tied down enough* and all precision was brought to bear on the Higgs boson
- First plot indicated low Higgs boson mass but 10-1000 GeV still possible at 95% CL (note the log scale!)
- The blueprint for Higgs constraints from precision data



LEP Electroweak Working Group report
For ICHEP in Glasgow 1994

CERN/PPE/94-187
25 November 1994

* evidence from CDF in April 1994: $m_t = 174 \pm 10^{+13}_{-12}$ GeV

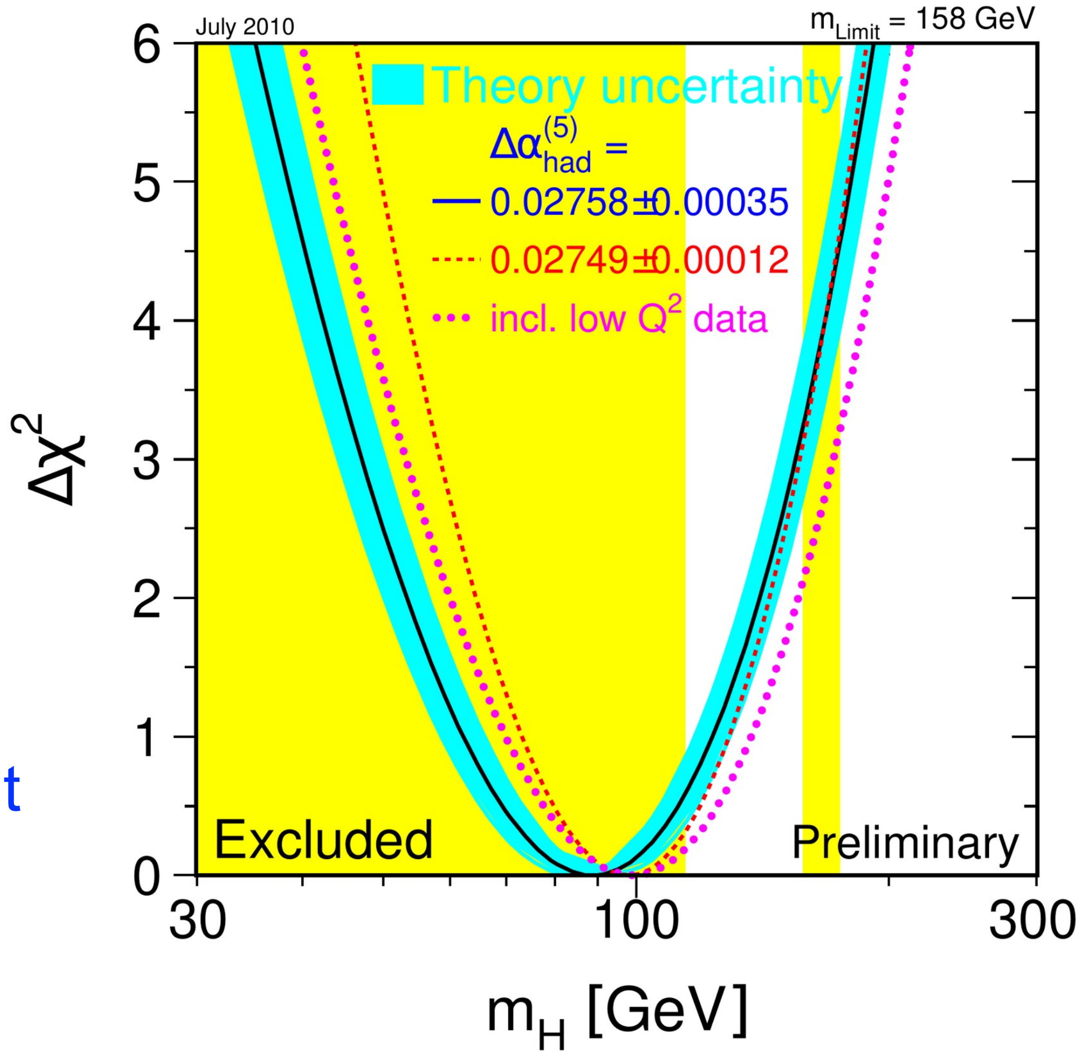
F. Abe *et al.*, Phys. Rev. Lett. 73 (1994) 225

The top discovery by CDF and D0 came in February 1995.

Constraints from Precision

After years of hard work

- Discovery of the top quark
- More precise data added at LEP and SLD
- Measurement of m_W at LEP and Tevatron
- Comparing to data from neutrinos and various low Q^2 experiments… all is consistent
- The Higgs should be below about 160 GeV



Final Electroweak Working Group report 2010: https://arxiv.org/pdf/1012.2367v2.pdf

Searches at Tevatron

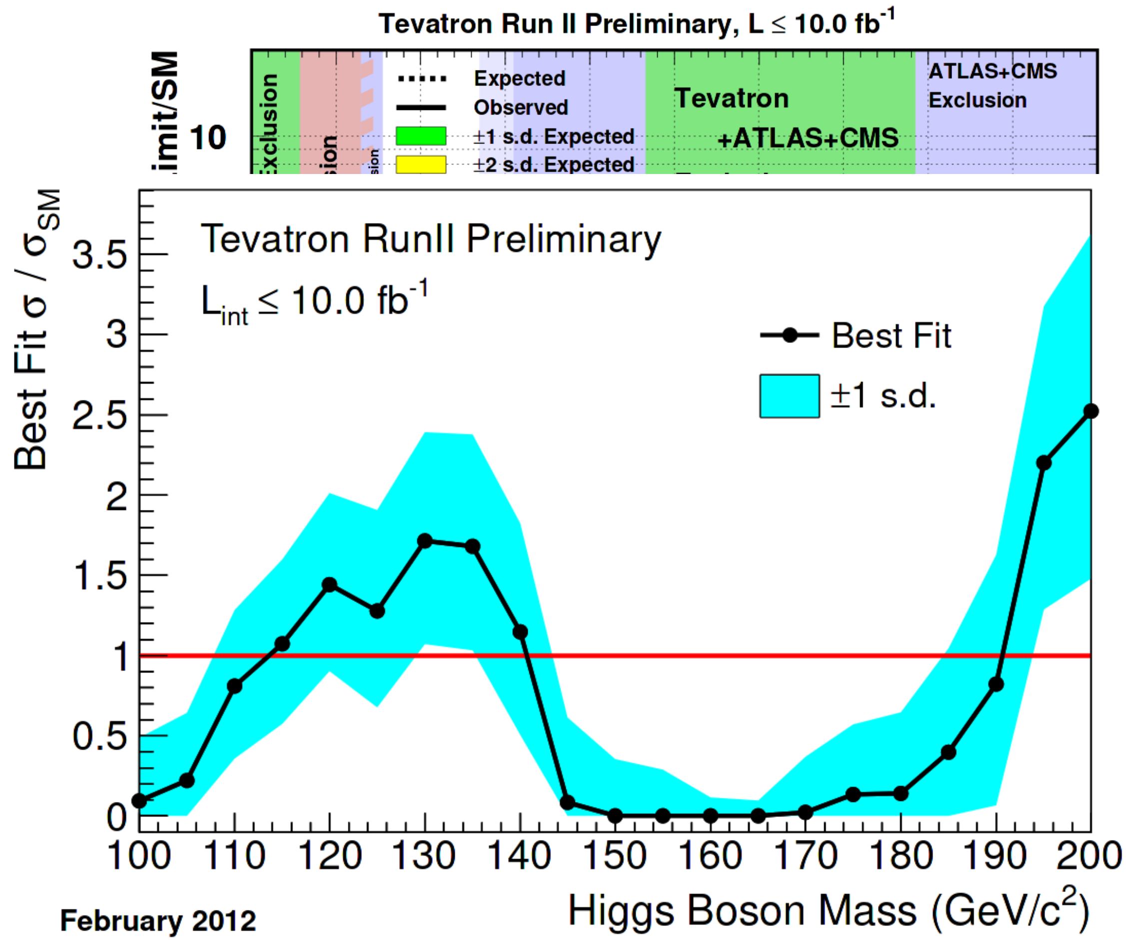
Main analyses: low mass

- Up to 125 GeV
- Higgs boson produced in associated production *VH*
- Higgs boson decay into b-quarks

Main analyses: high mass

- Beyond 125 GeV
- Higgs decaying to WW with subsequent leptonic decays
- All Higgs boson production modes contribute

http://arxiv.org/abs/1203.3774v1
by the TEVNPH Working Group



A broad excess is observed between $105 < m_H < 145$ GeV with a global significance of 2.2 standard deviations relative to the background-only hypothesis.

Preparing for the discovery

Analysis Process

Status at Moriond 2012

- There were hints and people wanted to jump to conclusions
- Collaborations decided to stay unbiased

Different but equally valid approaches applied

- ATLAS – conservative
  - No use of multivariate analysis (BDT/NN)
  - Froze analysis before 2012 data taking
  - Watching data roll in
- CMS – aggressive
  - Full scale multivariate (BDT/NN) analysis employed most on $H \rightarrow \gamma\gamma$
  - Analysis was still being optimized, but completely blinded
  - Unblinding in front of collaboration on June 15* – the most exciting event in my life ever (professionally speaking)

* YouTube video for CMS unblinding/discovery

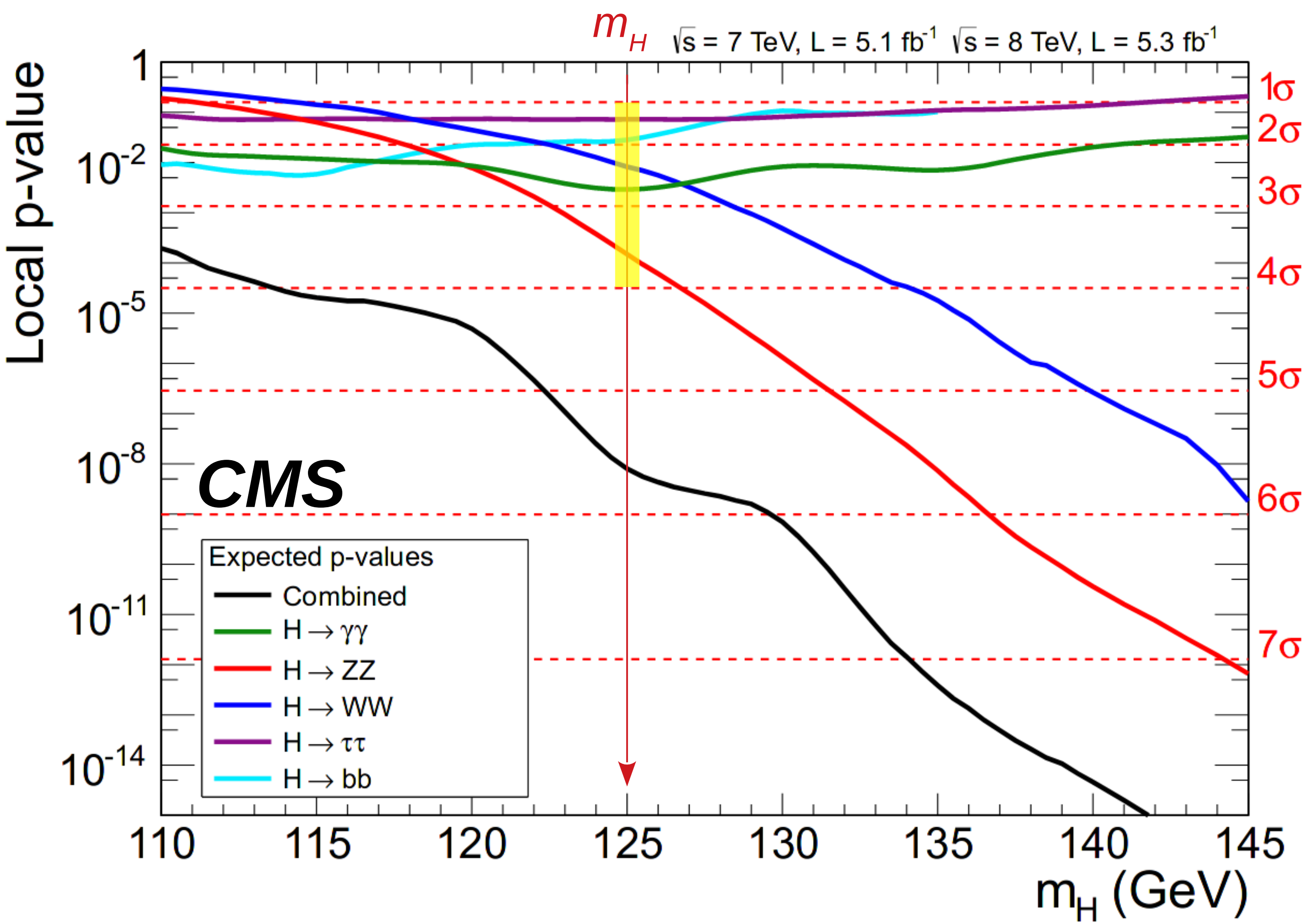

Higgs Hunting's
'Big Five'

Overview – Big Five

Channel	m_H resolution [%]	m_H range [GeV]	Data ATLAS (7+8 TeV)	Data CMS (7+8TeV)
H → ZZ → 4l	1-2	110-1000	5+5	5+5
H → gg	1-2	110-150	5+5	5+5
H → WW → 2l2v	20	110-660	5+5	5+5
H → tau tau	15	110-145	5+0	5+5
H → bb	10	110-135	5+0	5+5

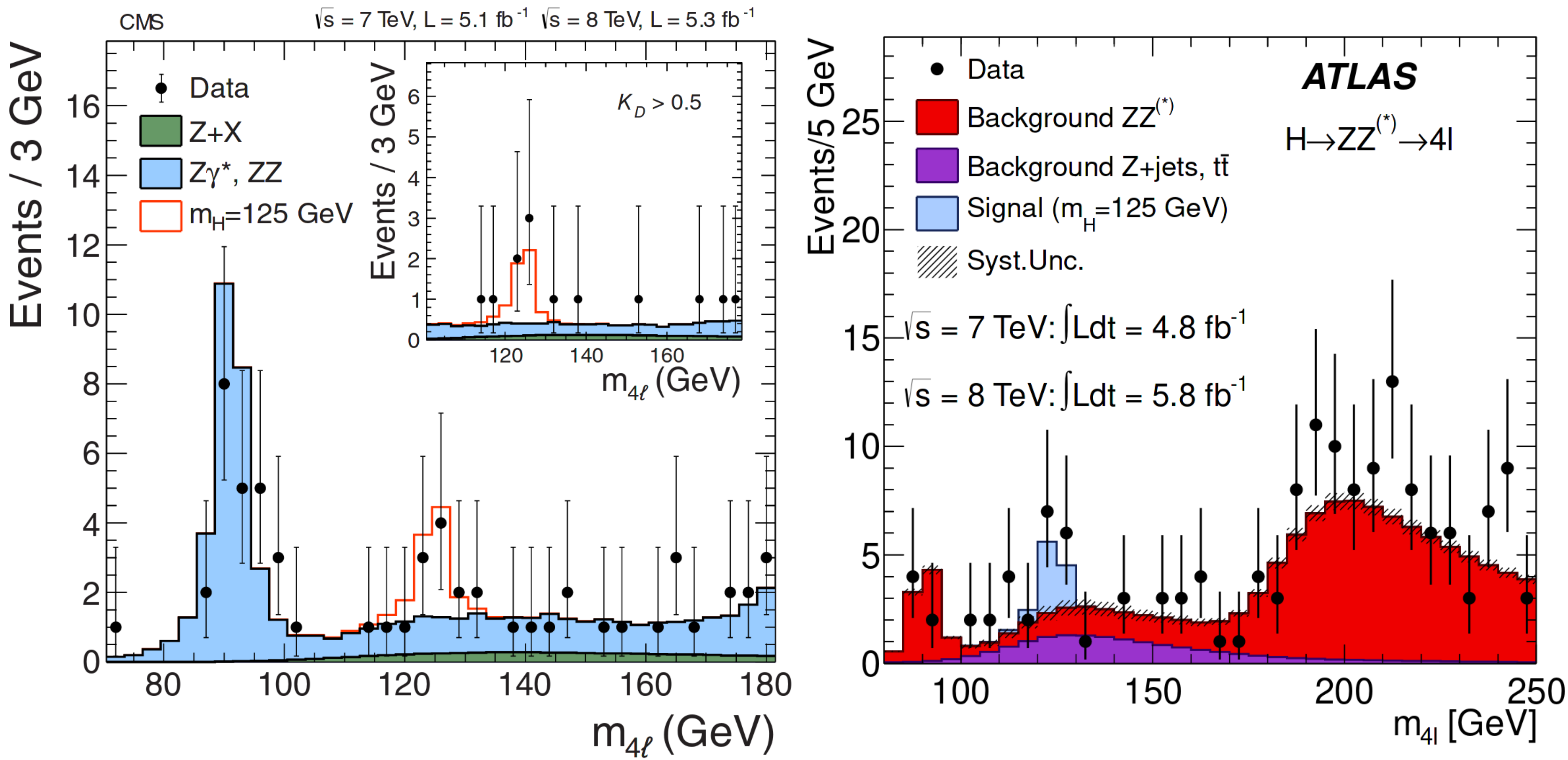
Data used in discovery paper

Big Five → Big Two or Three



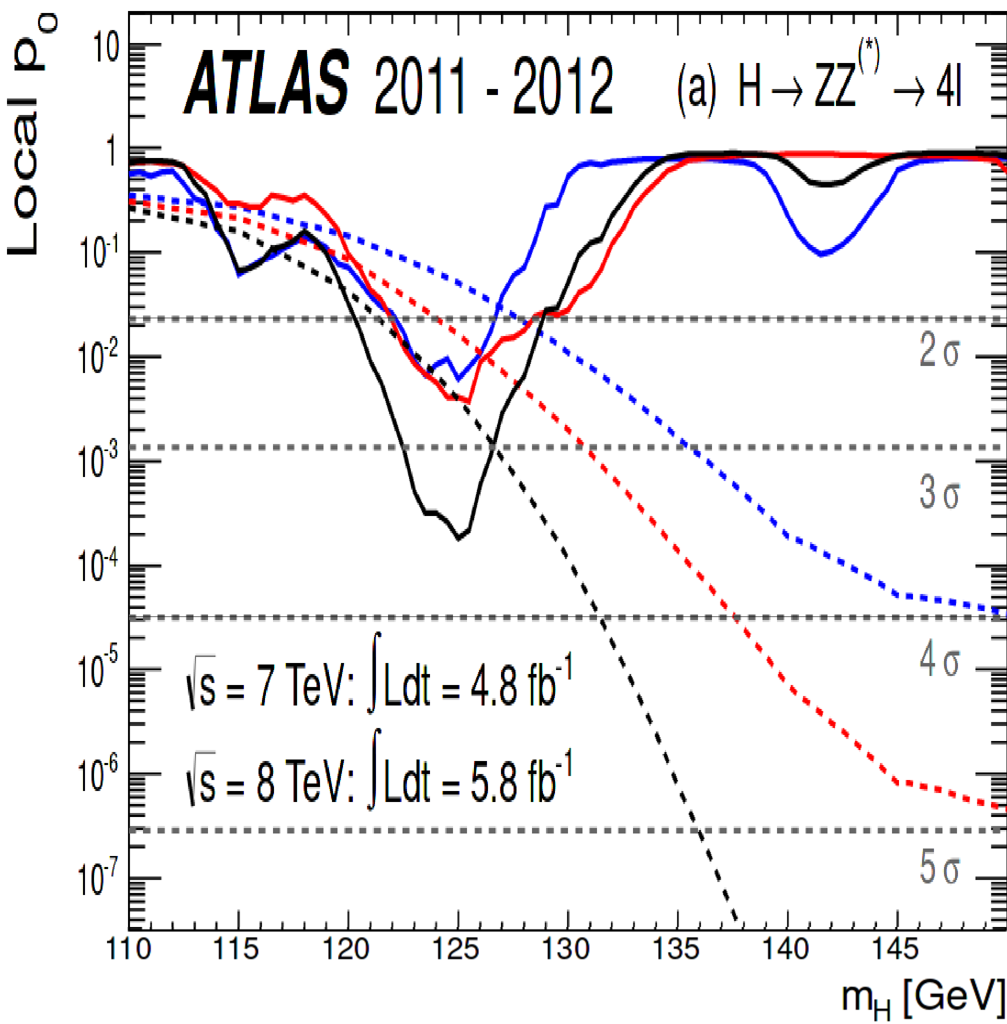
Retrospectively, there were really mainly two at best three channels that mattered

The Golden Mode: $H \rightarrow ZZ \rightarrow 4l$

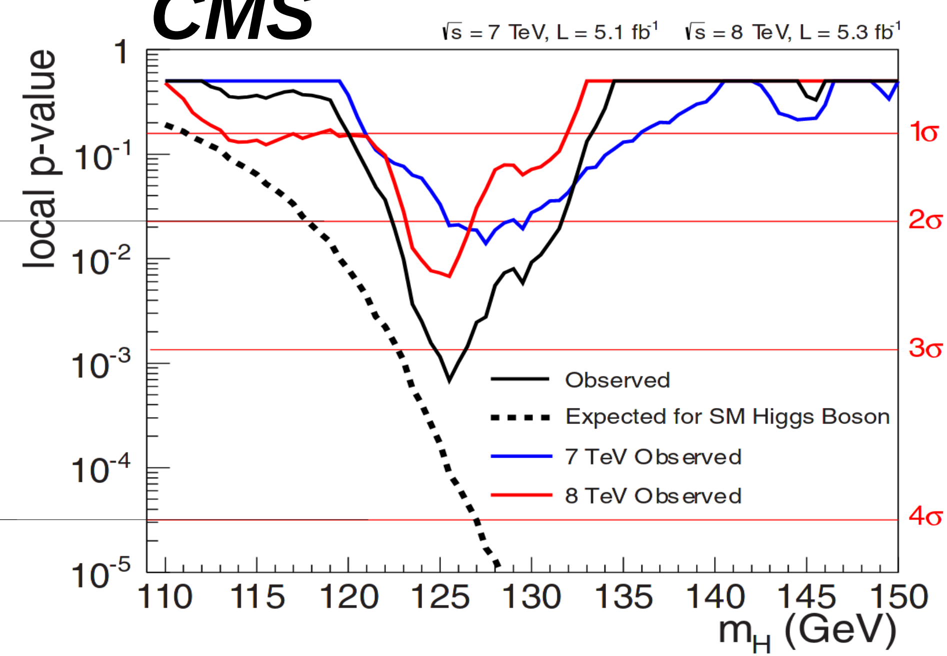


Peaks around 125 GeV

The Golden Mode: H → ZZ → 4l



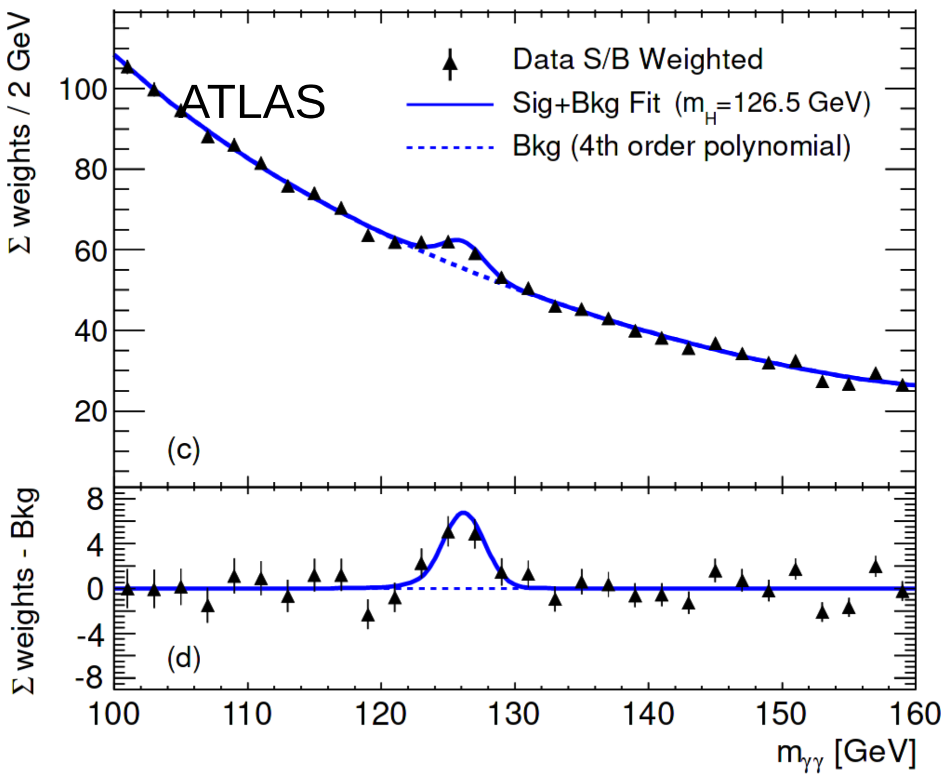
Excess evaluation

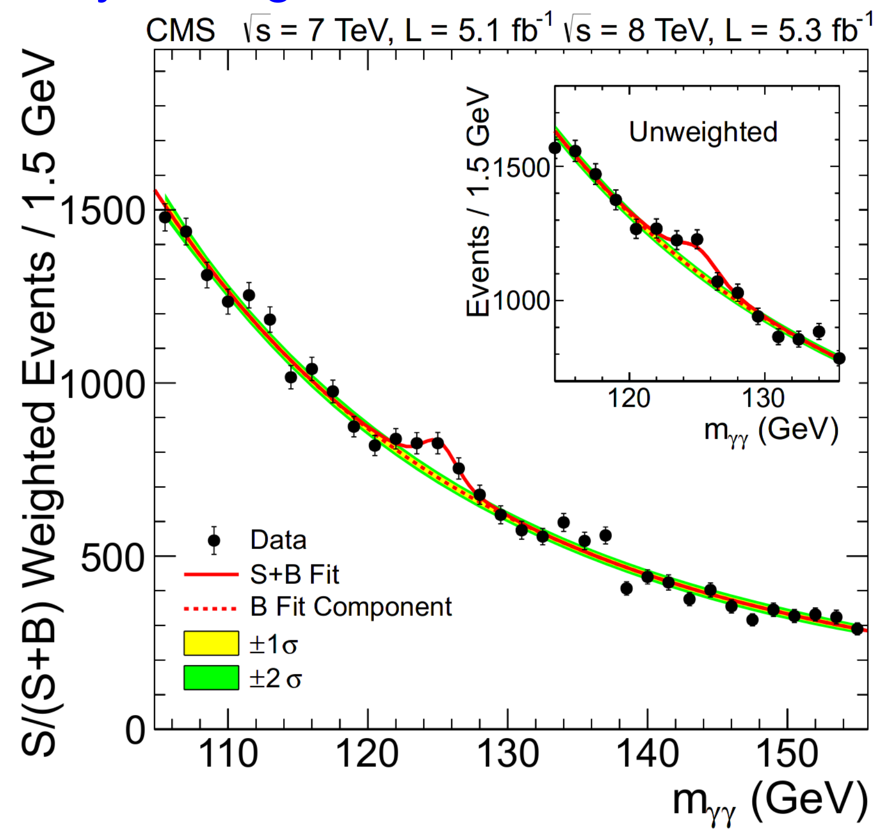


Low Mass Specialist: $H \rightarrow \gamma\gamma$

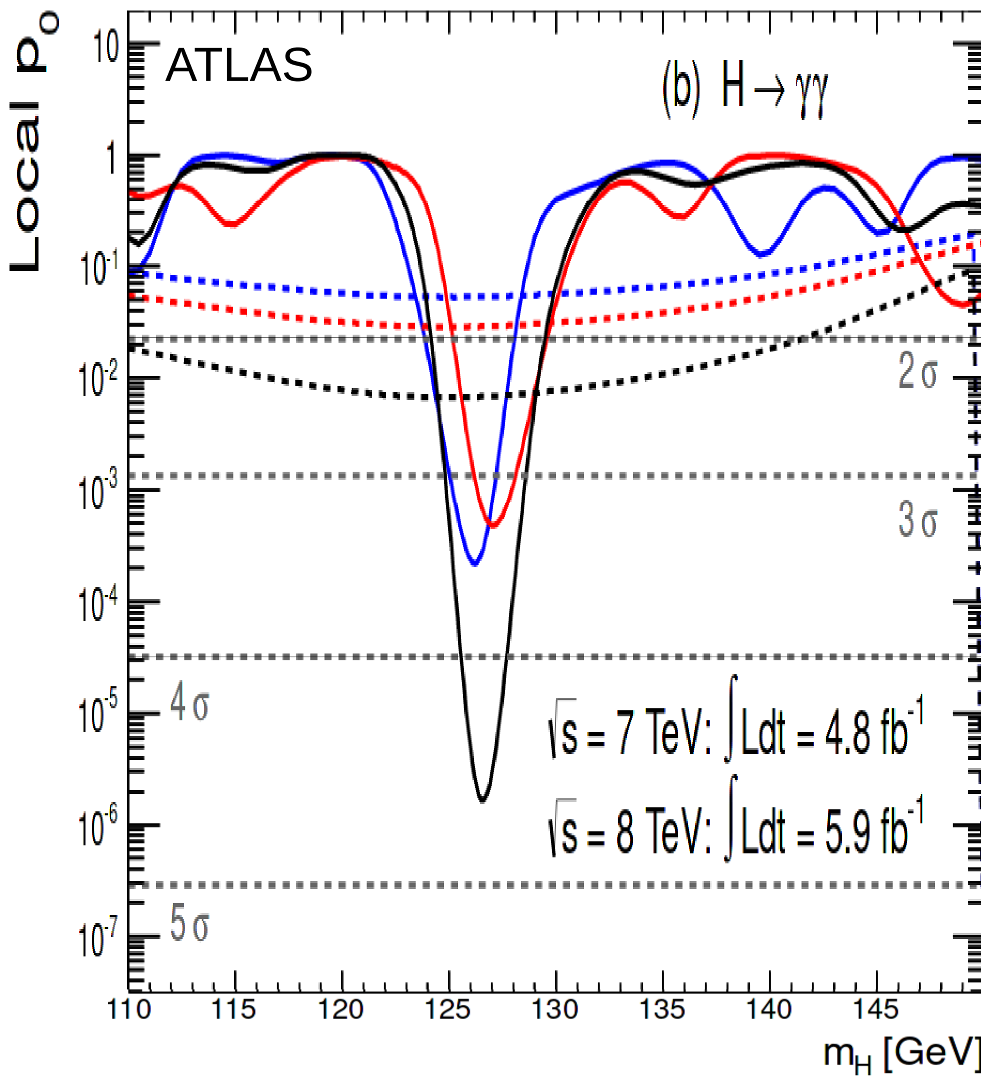
Diphoton mass plots from discovery papers

- Peak appears over continuous background
- Weighting needed to account for different quality of single events

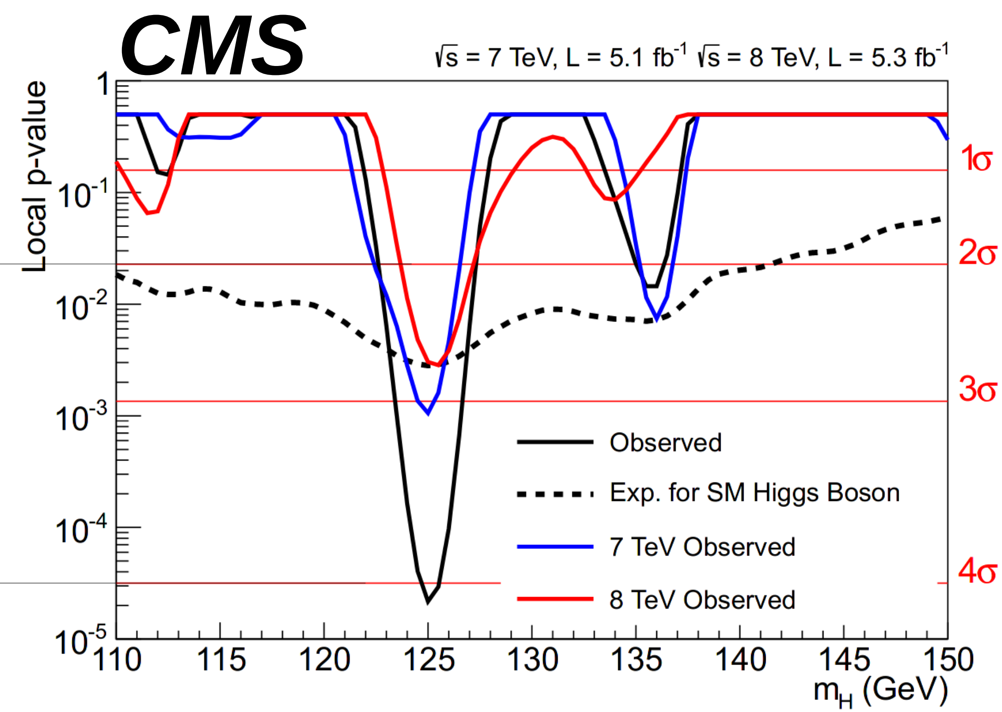




Low Mass Specialist: H → γγ



Excess evaluation



Discovery

Combine Channels per Experiment

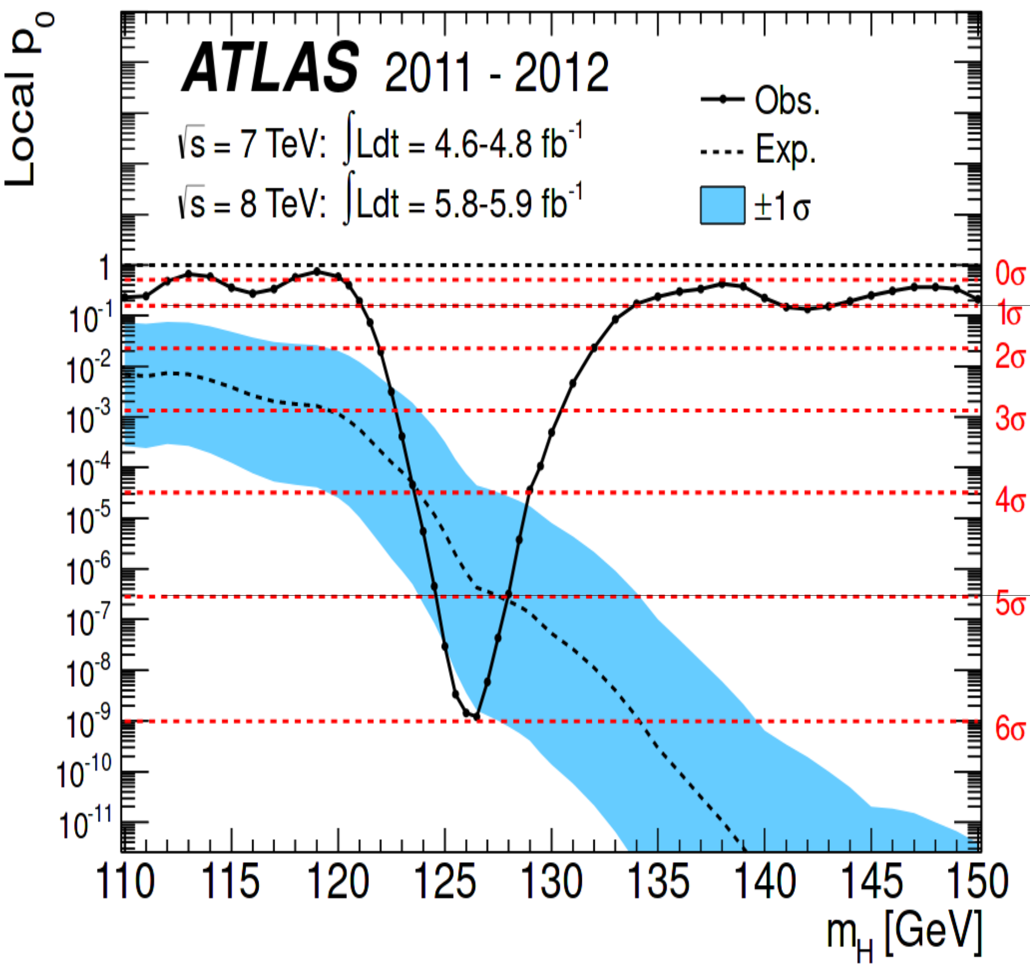
- H -> WW -> 2l2ν
- H -> γγ
- H -> ττ
- H -> bb
- H -> ZZ -> 4l

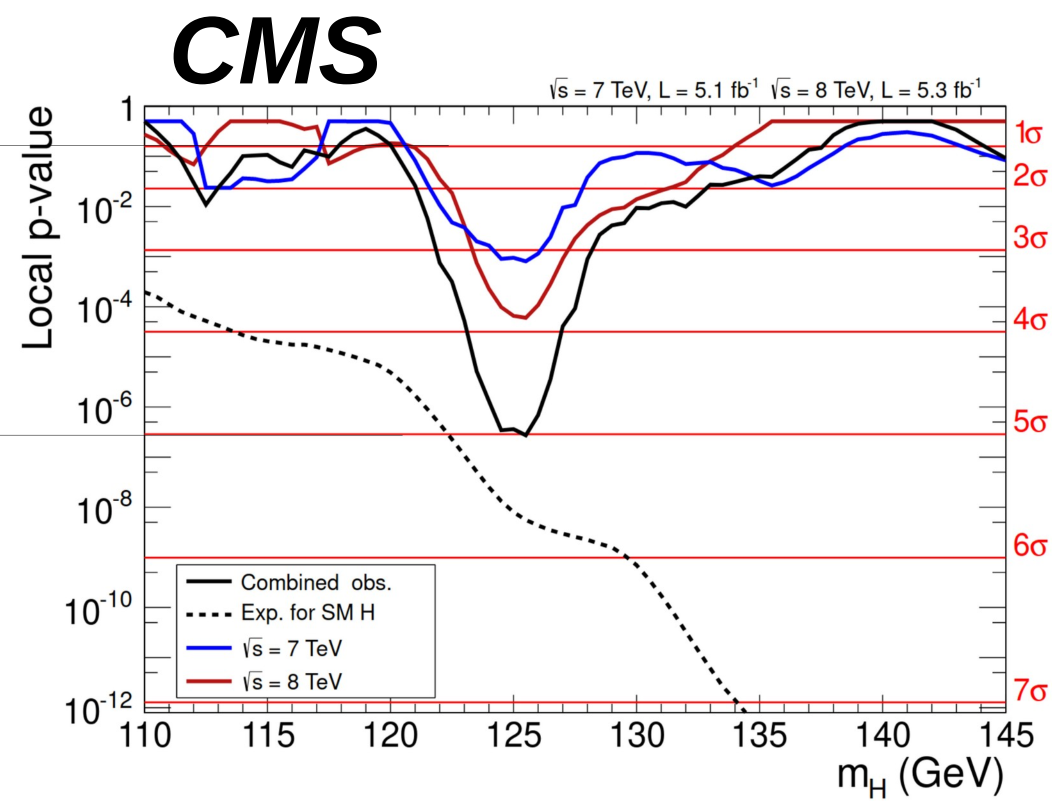
ATLAS and CMS use consistent, statistical tools.

Combined Channels Results

Comments

- ATLAS: 5.9 std obs (5.0 exp)
- CMS: 5.0 std obs (5.7 exp)





Historic Event: CERN–Melbourne

Rolf Heuer:

'We have it!'

4^{th} of July 2012 – new Higgs–like particle discovery

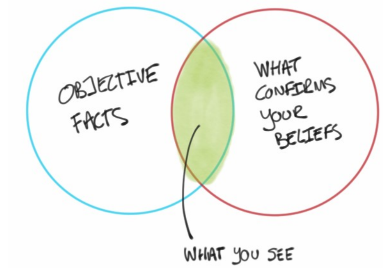
International Recognition

Two nobel theorists

Nobel prize in physics 2013

What now?

Lessons Learned



Real discoveries are hard

- There were a number of ‘non-discoveries’ until we found the ‘narrow resonance’ that turned out to be the Higgs boson
- At least two independent teams for each analysis (important errors were found)
- Define solid process that ensures unbiased/correct results
- Keep teams from different detectors separate

The LHC has two major general purpose detectors

- Independent confirmation of major results is essential in science
- Complementary detection techniques
- Also to double the luminosity

The narrow resonance

Discovery was stated conservatively, as it should

- Higgs couplings to bosons only (and top in the loop)
- Scientists: narrow resonance, spin 0 (2 photon decay) → Higgs-like
- The press: We found the Higgs boson

Next steps

- Measure the properties in depth and see whether it matches up with the Higgs boson we can predict so well (apart from its mass)
- Scientists needed to be convinced it really is the Higgs boson
- The beginning of a massive undertaking: compare this to the W and Z boson discoveries that were part of the motivation to build LEP

Milestones

from narrow resonance
to Higgs boson

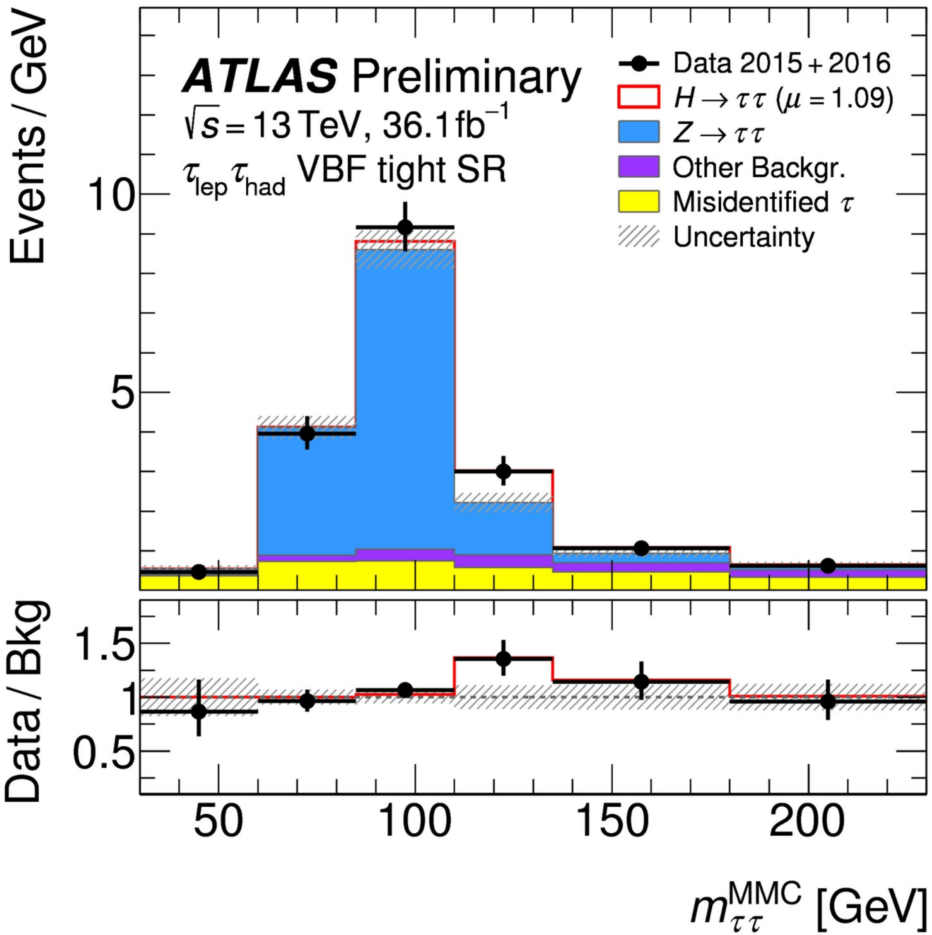
Yukawa Couplings

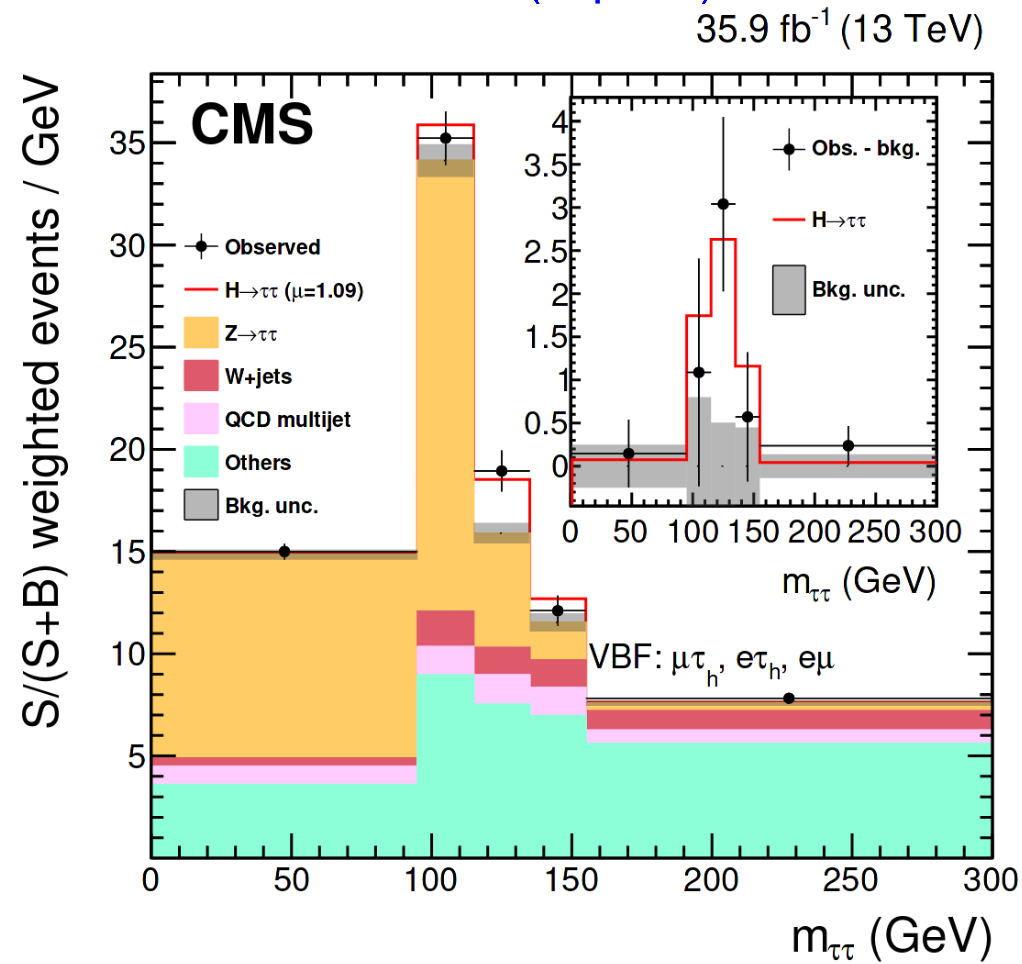
Tau-lepton b-quark	>	3rd generation
Muon	—	2nd generation

Observation of H→ ττ

Announced June, 2018

- ATLAS: 6.4 std observed (exp 5.4); CMS: 5.9 std observed (exp 5.9)

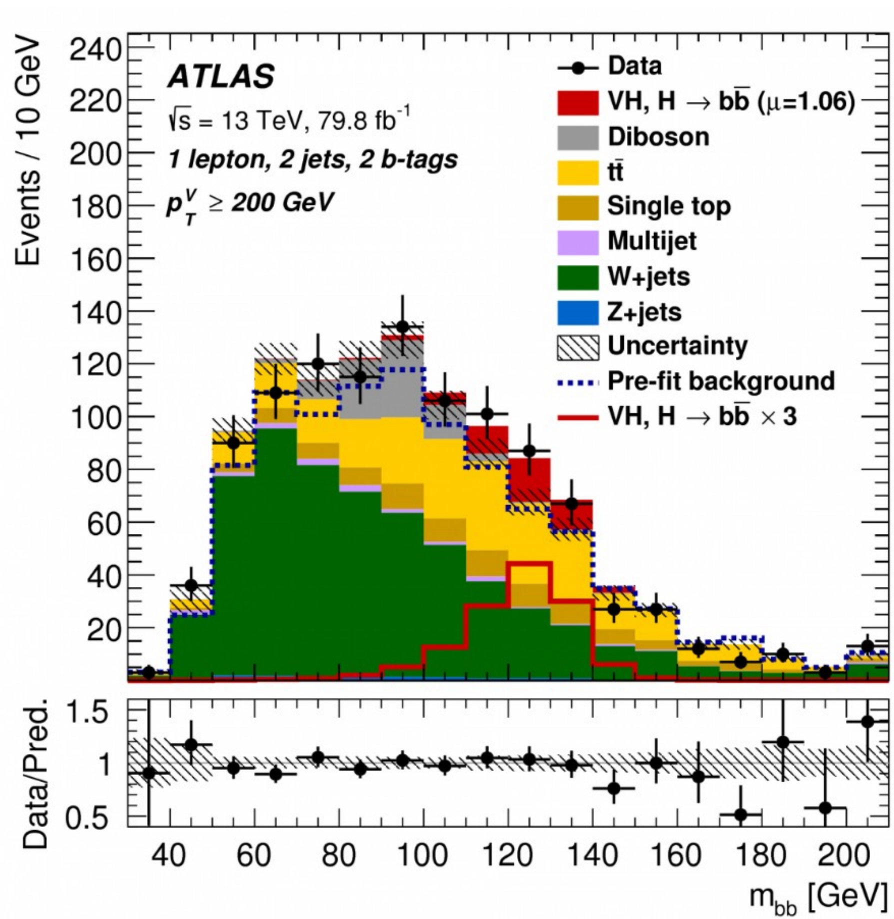


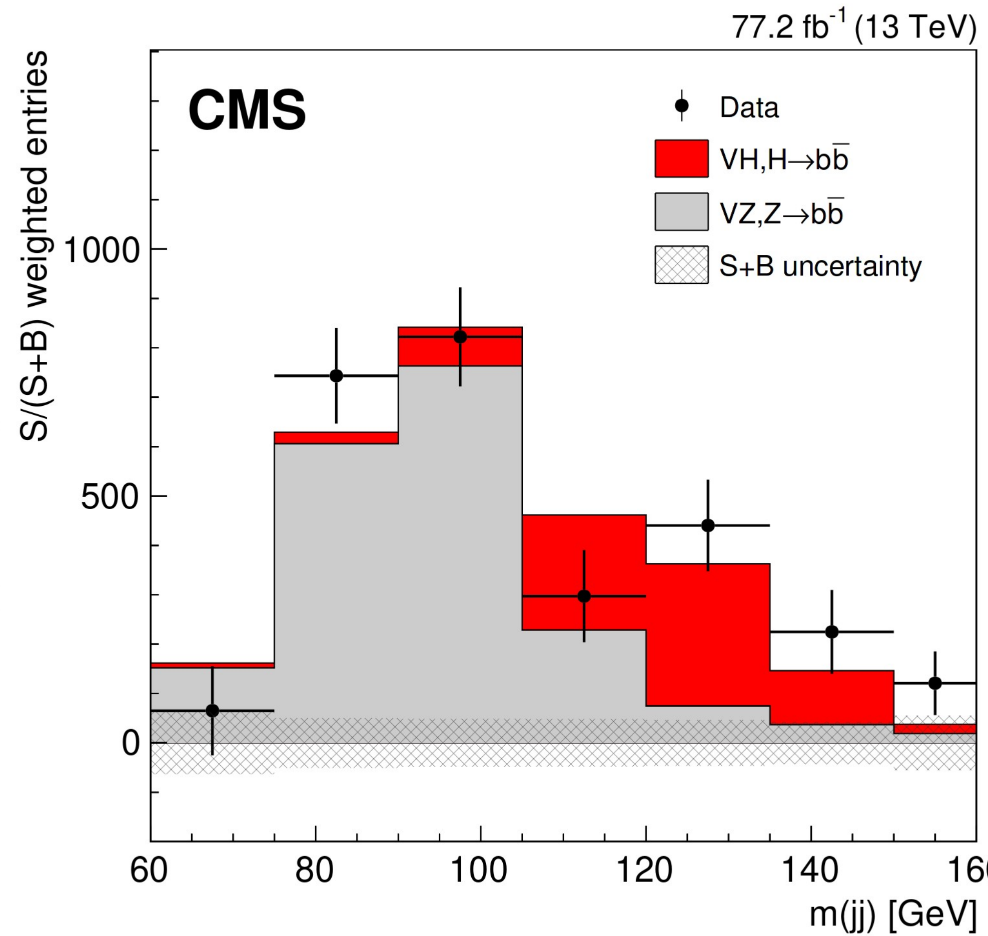


Observation of $H \rightarrow b\bar{b}$

Announced August, 2018

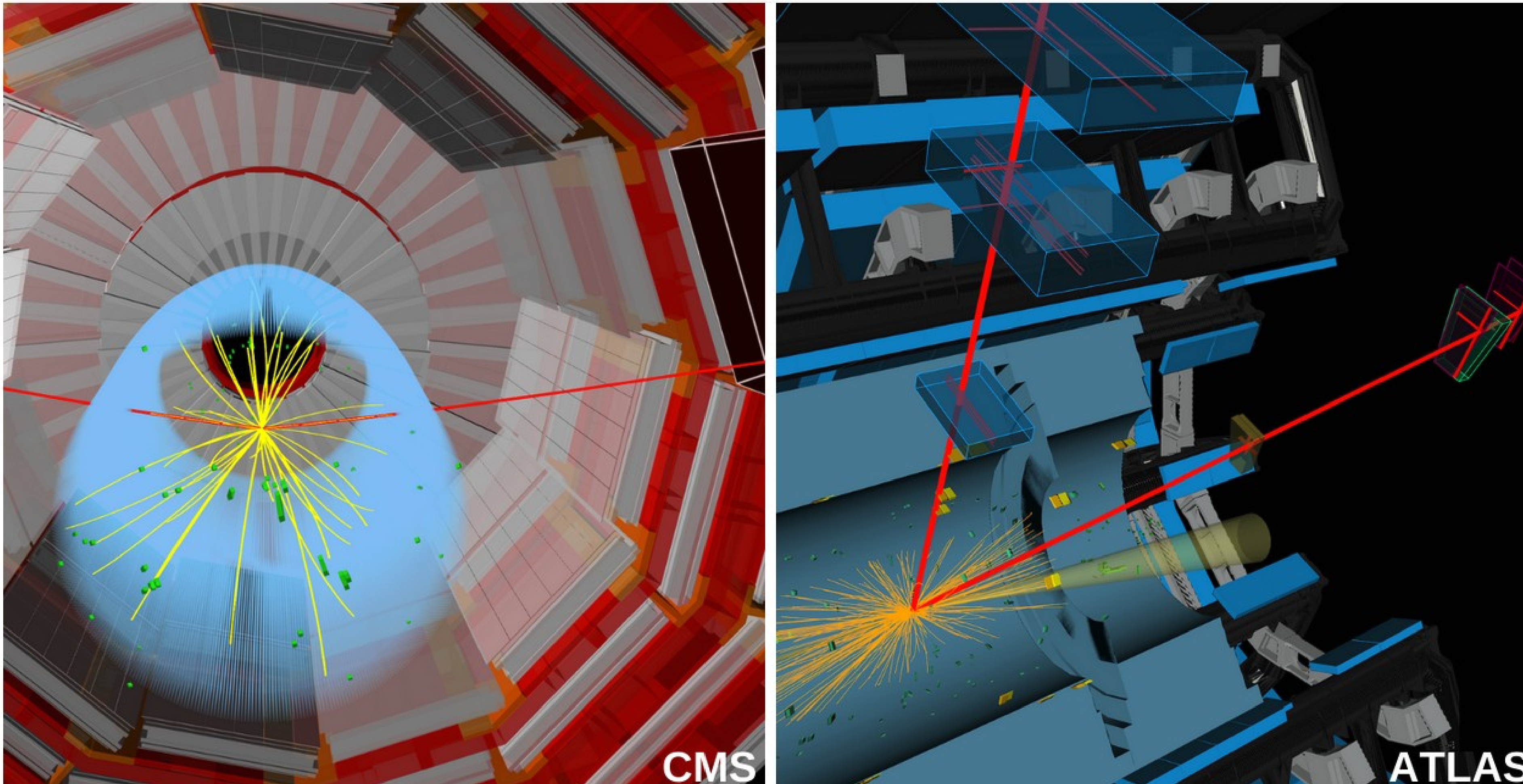
- ATLAS: 5.4 std observed (exp 5.5); CMS: 5.6 std observed (exp 5.5)





Evidence for $H \to \mu^+\mu^-$

August 2020

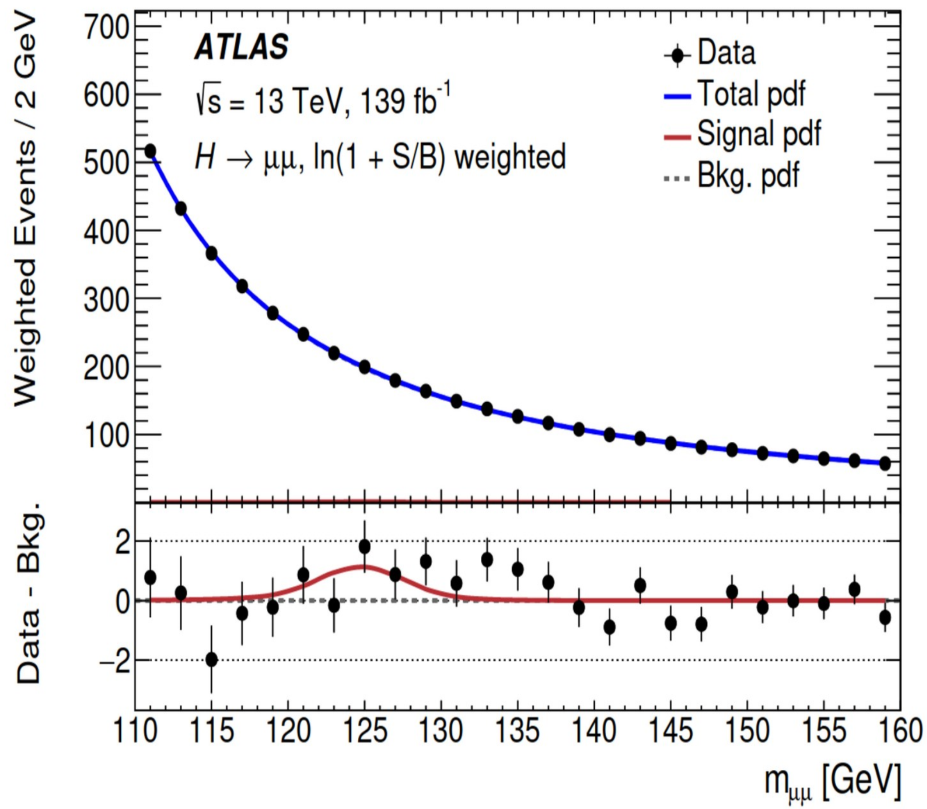


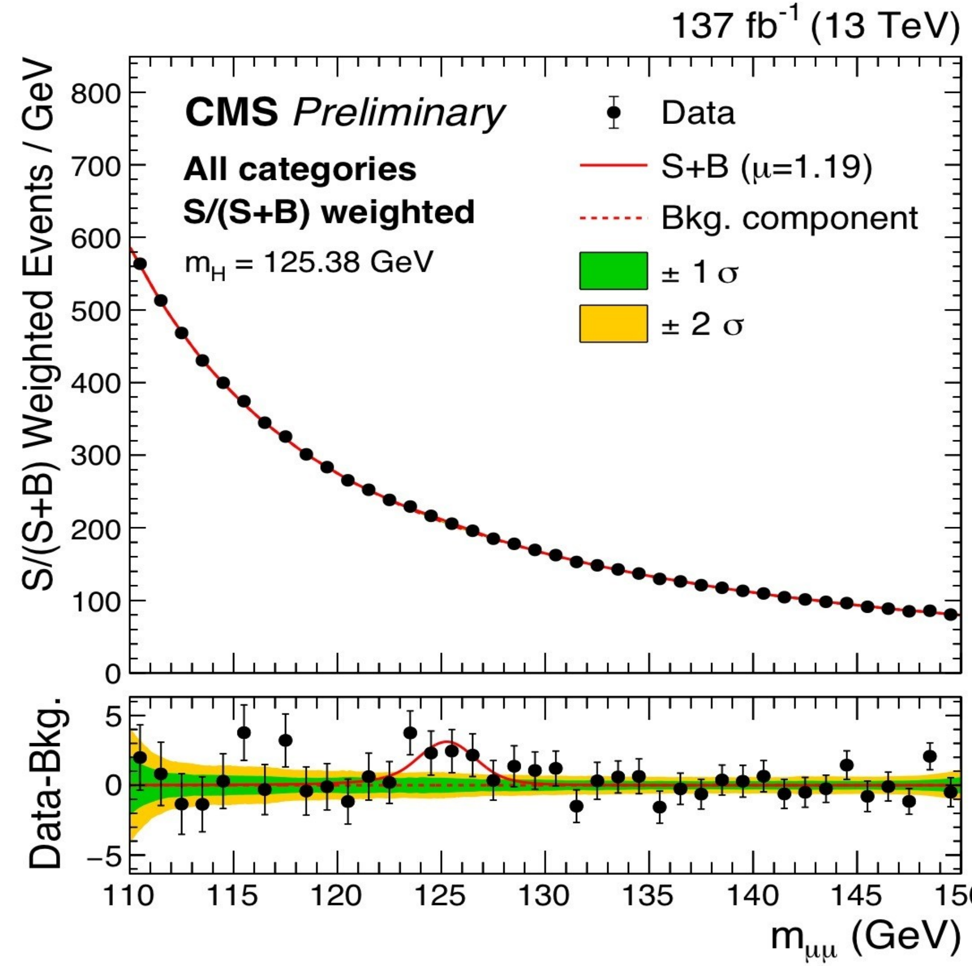
Candidate event displays of a Higgs boson decaying into two muons as recorded by CMS (left) and ATLAS (right). (Image: CERN)

Evidence for of $H \rightarrow \mu^+\mu^-$

Announced August, 2020

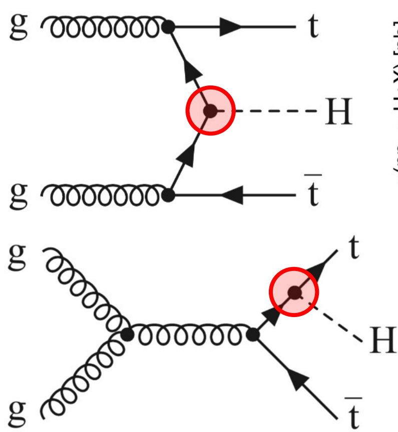
- ATLAS: 2.0 std observed (exp 1.7); CMS: 3.0 std observed (exp 2.5)

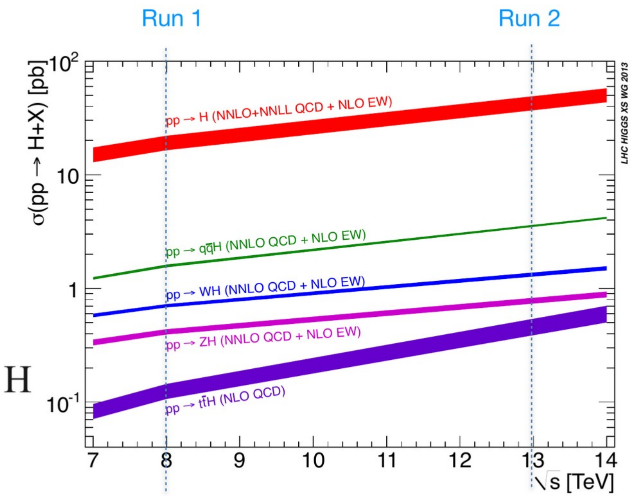




Rare Higgs Boson Production

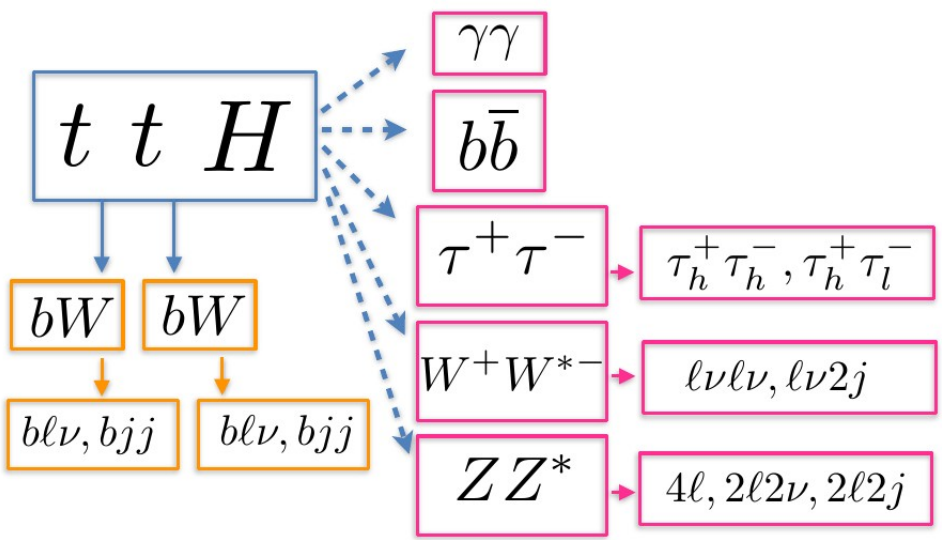
Higgs Boson Production ttH





Rare Production: ttH

- Direct probe of the top to Higgs coupling
- Close to two orders of magnitude below gluon fusion
- ... due to heavy tops is the big winner with increase in center-of-mass energy in Run 2



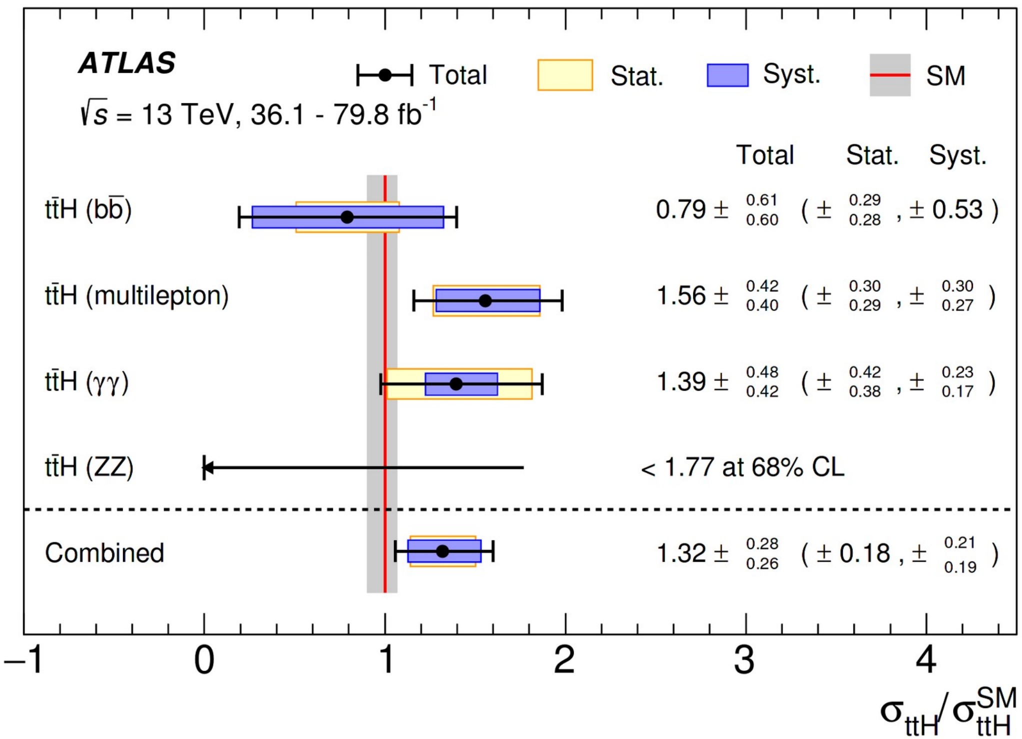
Analysis key ideas

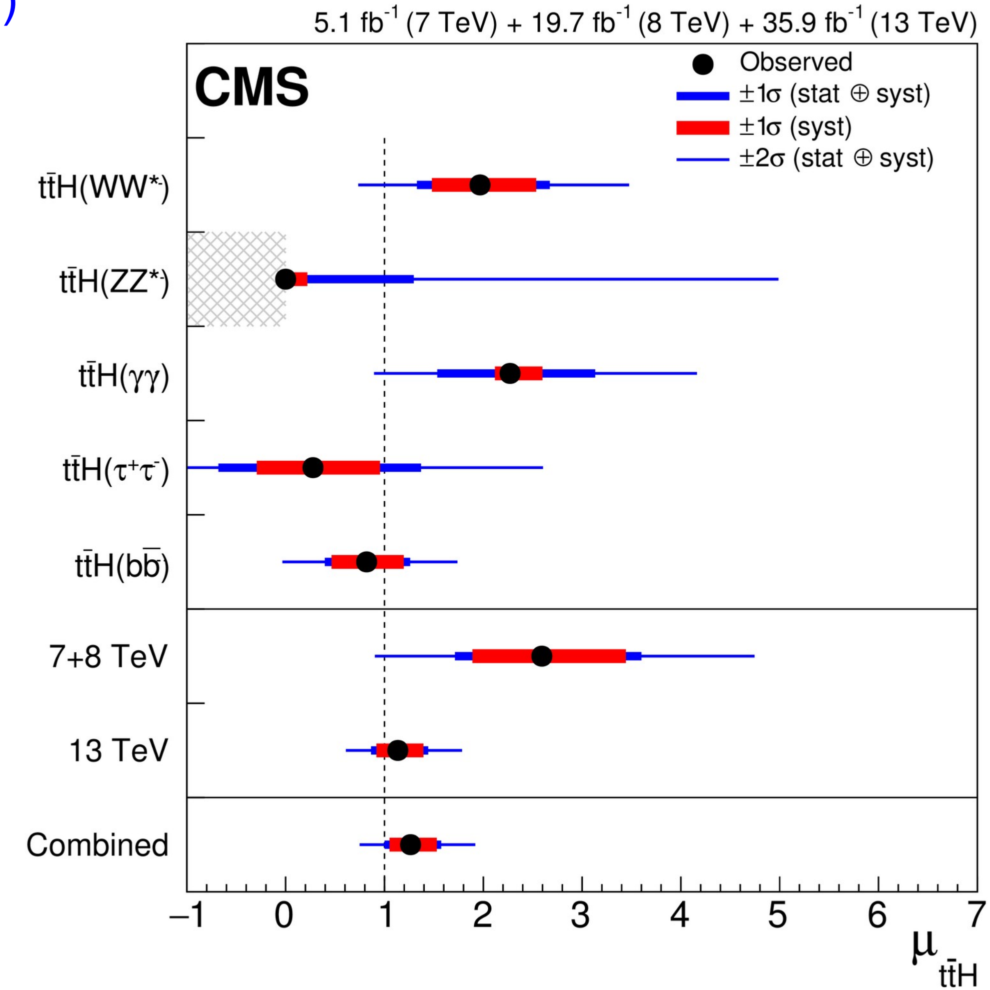
- The ditop pair offers the required handles
- The rest is 'just-the-usual-Higgs' analysis
- Very complex due to large number of objects in final state and high number of permutations

Higgs Boson Production ttH

Observed and (Expected) Excess analysis

- ATLAS: 6.3 standard deviations (expected 5.1)
- CMS: 5.2 standard deviations (expected: 4.2)
- Consistent with SM expectation





The narrow resonance looks, talks and walks like the Higgs boson.

Latest from Anniversary Papers

Overall Signal Strength

Signal strength modifiers, μ, scale production cross sections (initial state) or branching fraction (final state) of various channels

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \qquad \mu^f = \frac{\mathcal{B}^f}{\mathcal{B}^f_{\mathrm{SM}}} \qquad \mu_i^f = \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

- All main production modes observed and they agree with SM

Define overall signal strength, μ, to quantify overall agreement

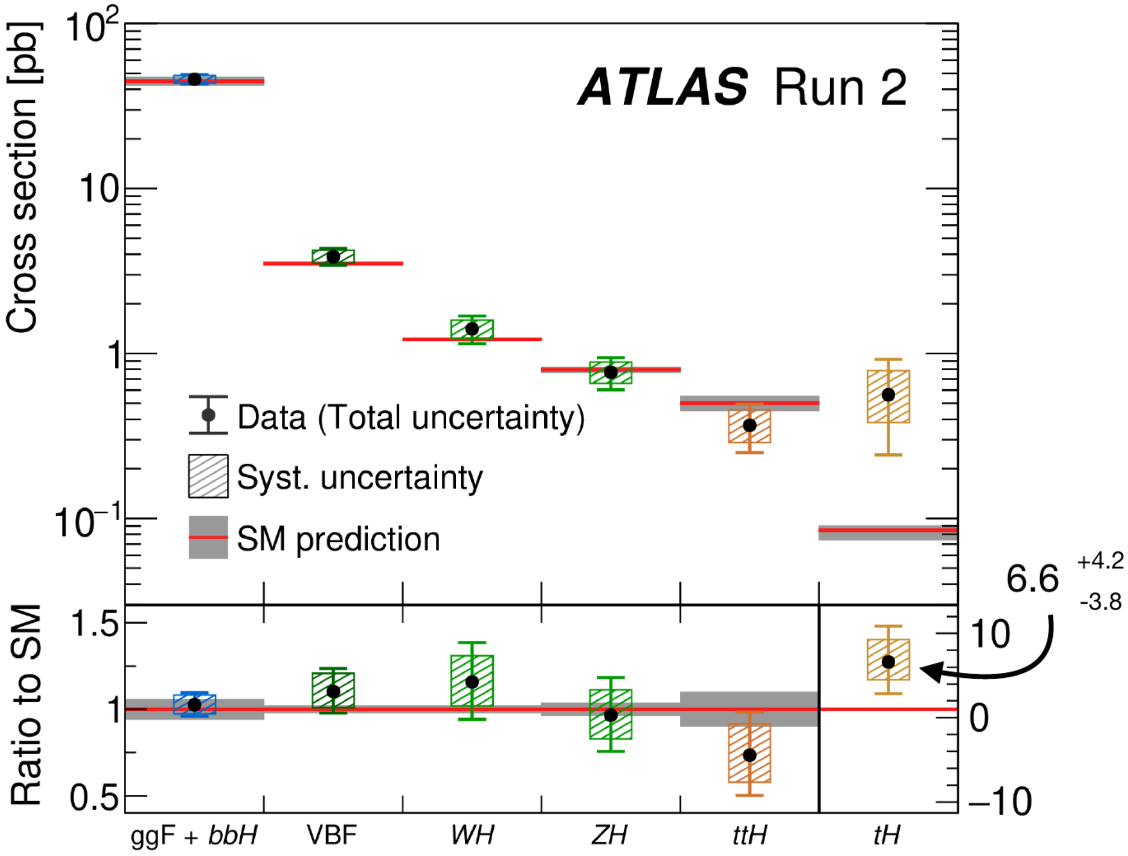
CMS μ = 1.002 ± 0.057 = 1.002 ± 0.036 (theo) ± 0.033 (syst) ± 0.029 (stat)
Nature 607 (2022) 60

ATLAS μ = 1.05 ± 0.06 = 1.05 ± 0.04 (theo) ± 0.03 (syst) ± 0.03 (stat)
Nature 607 (2022) 52

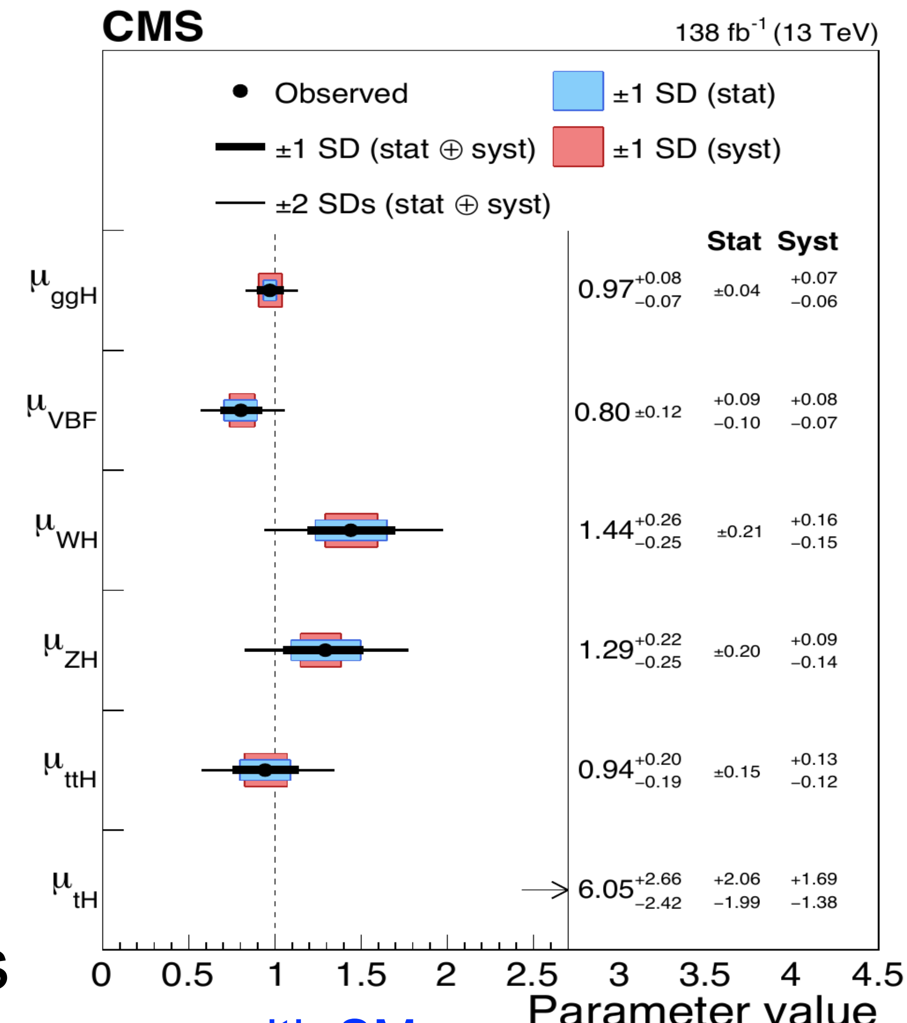
Comparing Run 1 and Run 2

- Theory uncertainty improved from 7% → 4%
- Experimental uncertainty improved from 14% → 6%

Versus Production Mechanism



Nature 607 (2022) 52

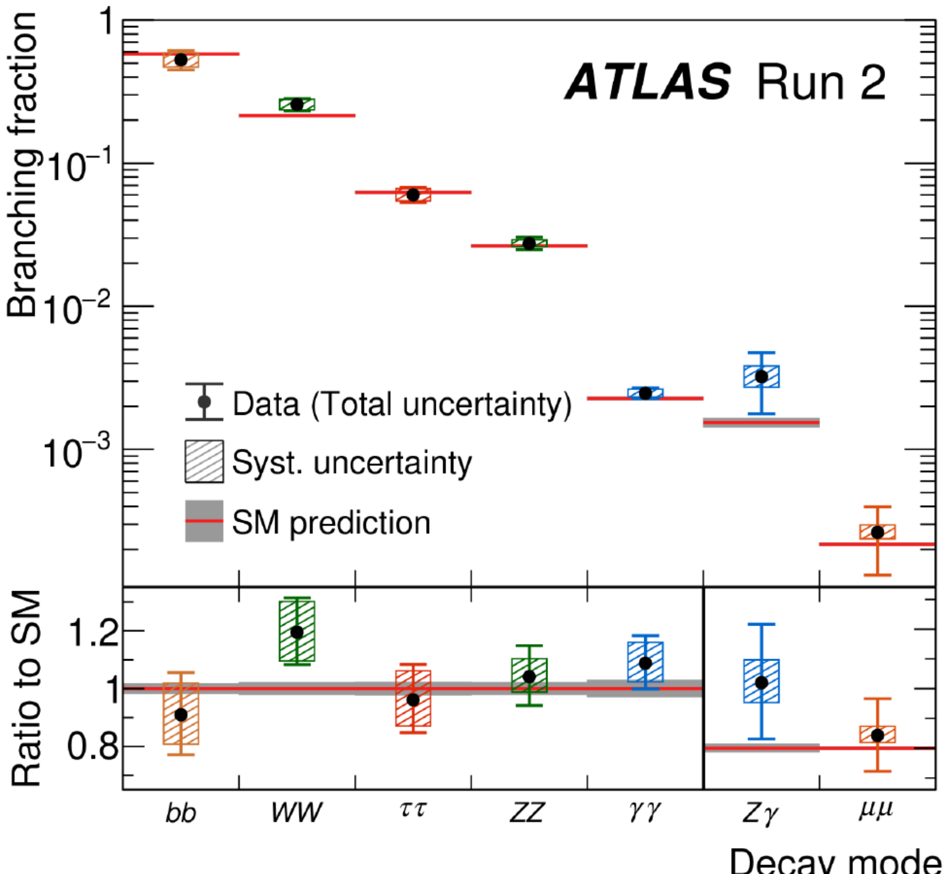


Nature 607 (2022) 60

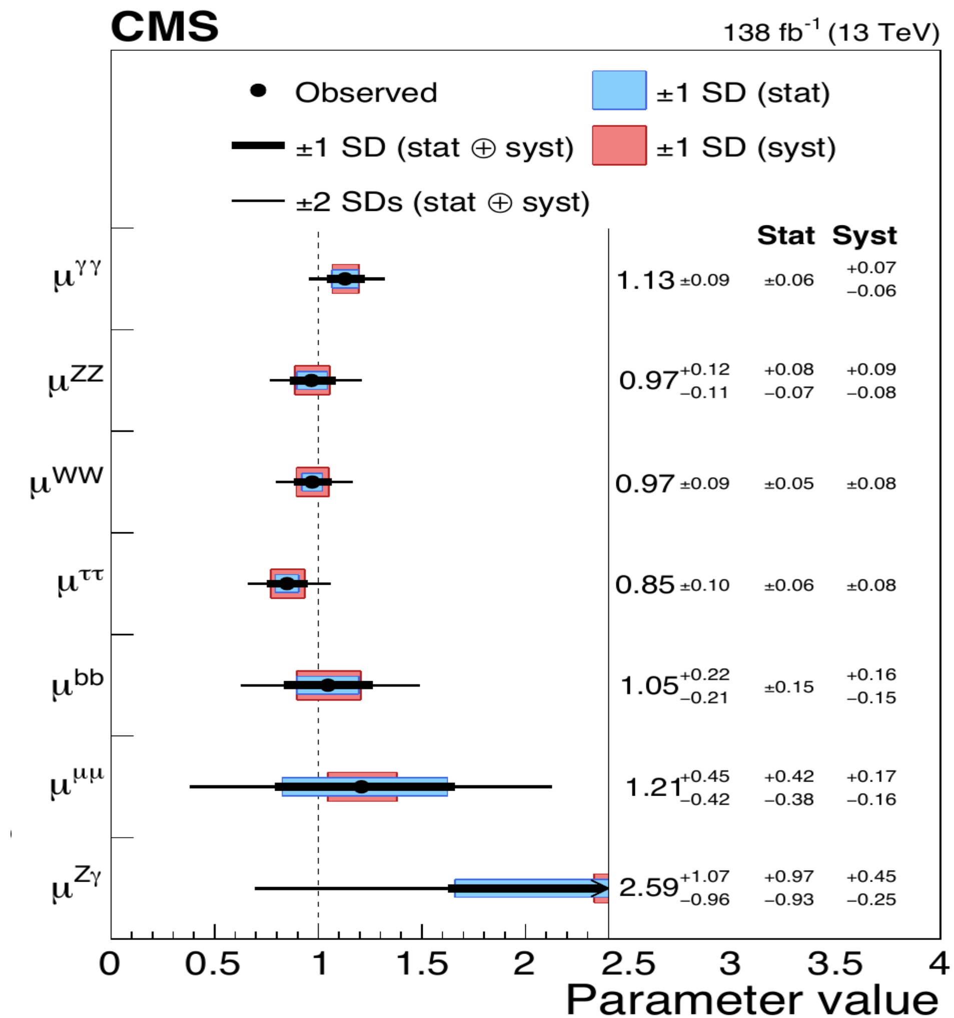
Higgs is produced in various ways

- All main production modes observed and they agree with SM

Versus Decay Mode



Nature 607 (2022) 52



Higgs decays in various ways

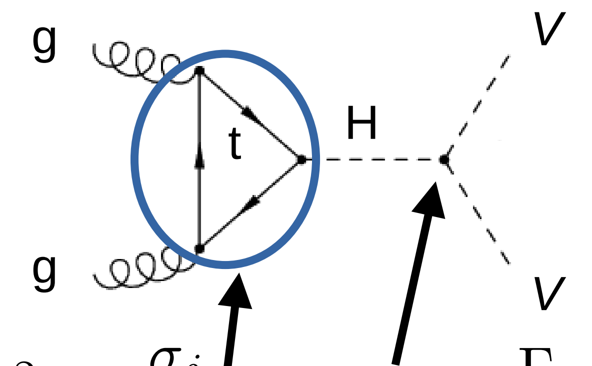
- All main decay modes observed, and they agree with SM

Nature 607 (2022) 60

Couplings Framework

Introduce modifier to the standard couplings production and decay rates

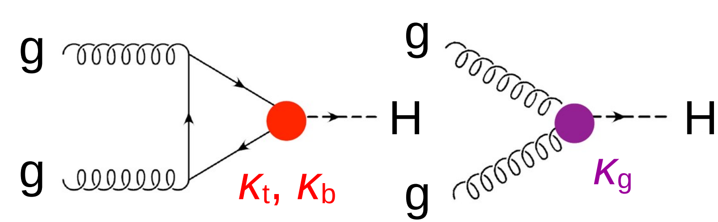
- Popular implementation is: κ-framework
- Loops at vertices can either be *joined* or *de-composed*



$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \qquad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}$$

Higgs width constraint from

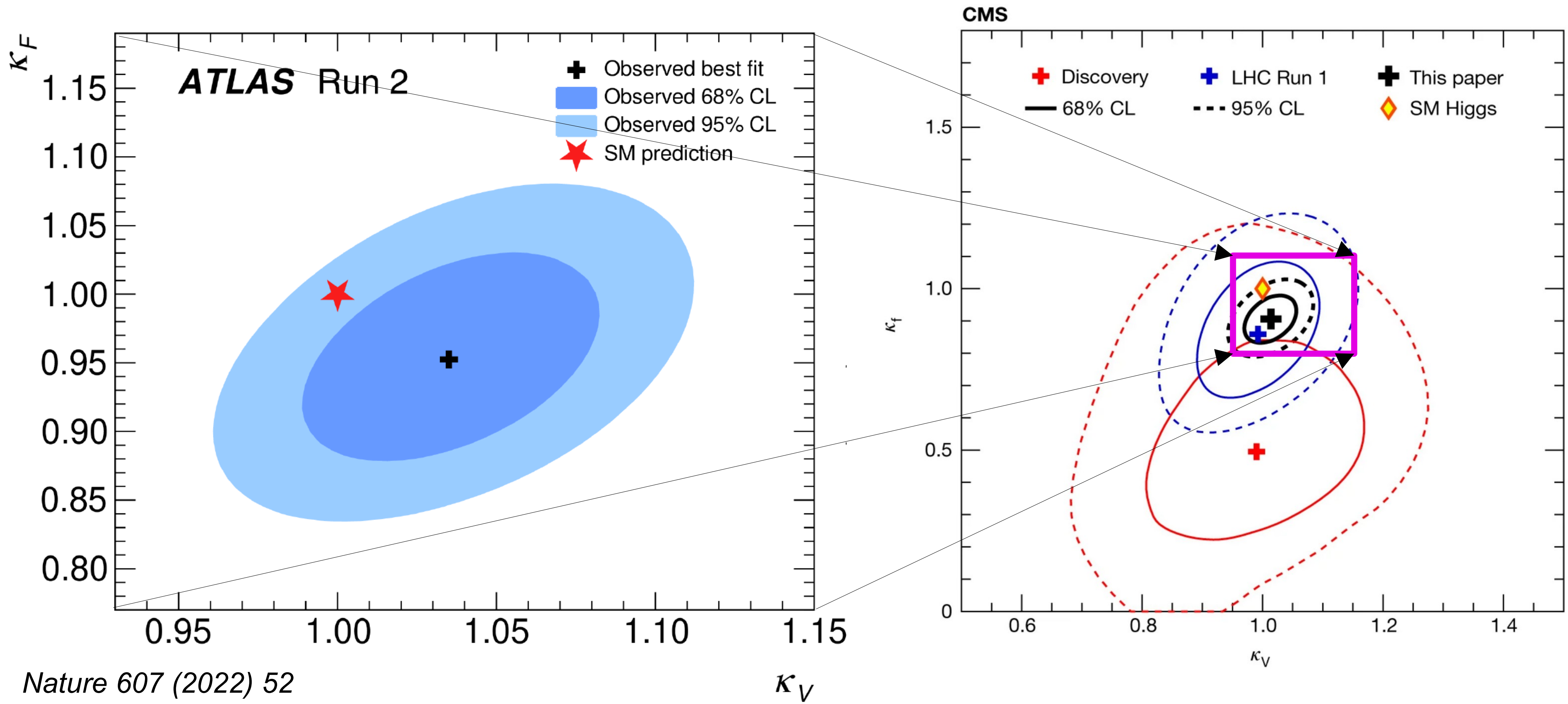
$$\frac{\Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \frac{\kappa_{\mathrm{H}}^2}{1 - \mathcal{B}_{\mathrm{inv}} - \mathcal{B}_{\mathrm{undet}}}$$



Objective of modifiers

- Identify the nature of possible discrepancy
- If discrepancy is found assumptions do not work but some indication of what is going on is useful

Couplings – VBosons/Fermions



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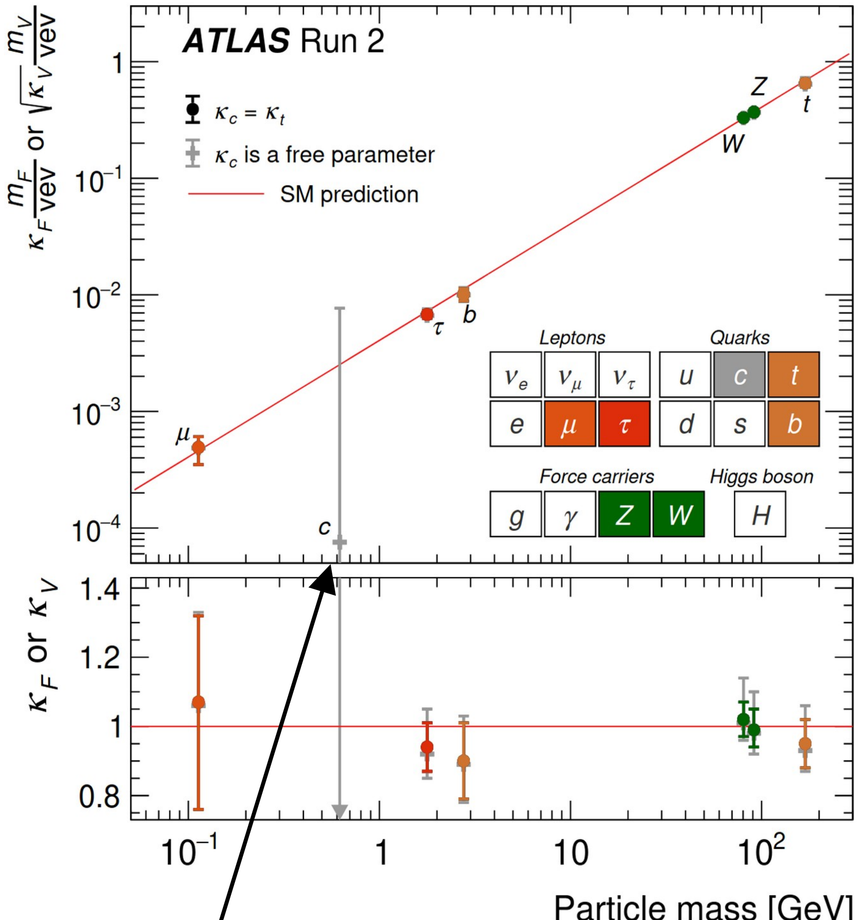
Coupling measurements improved a lot from Run 1 to Run 2

- Standard Model well within the two standard deviation range

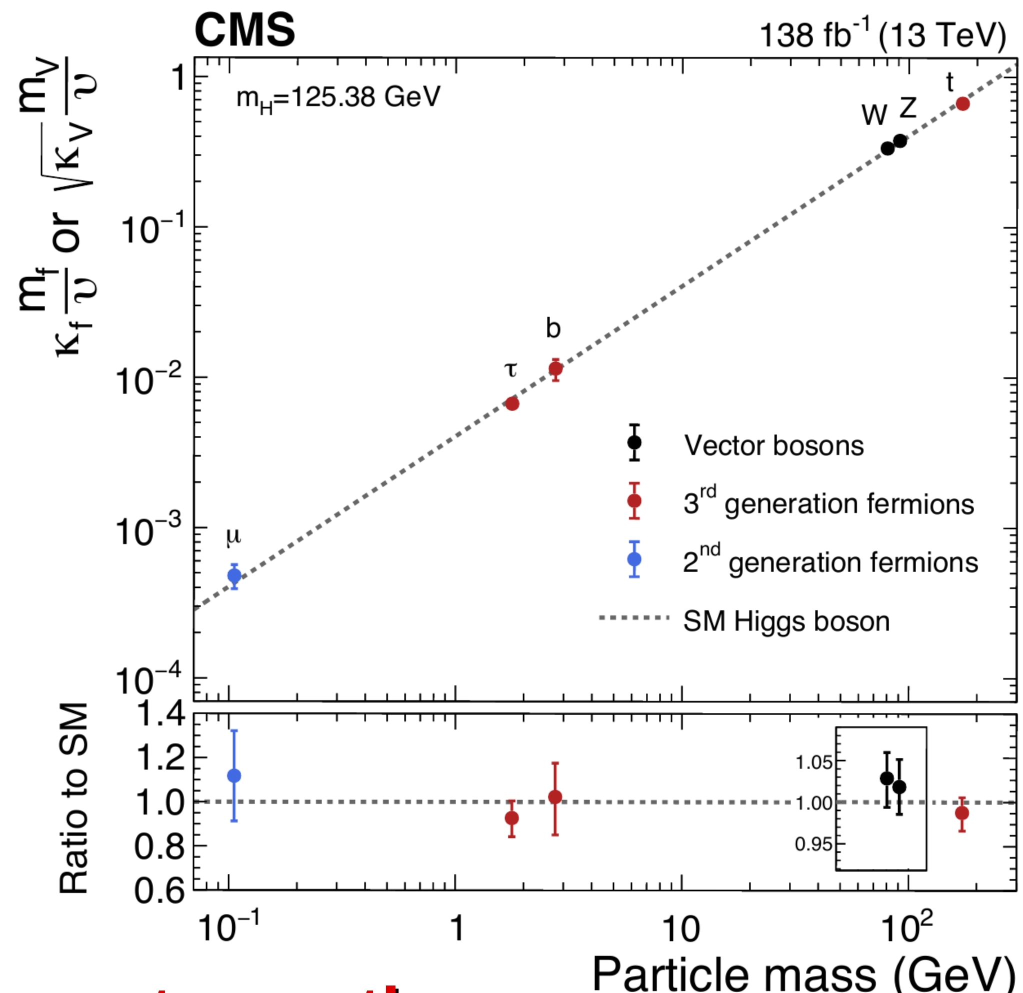
Nature 607 (2022) 60

Couplings versus Mass



Nature 607 (2022) 52

Charm quark coupling

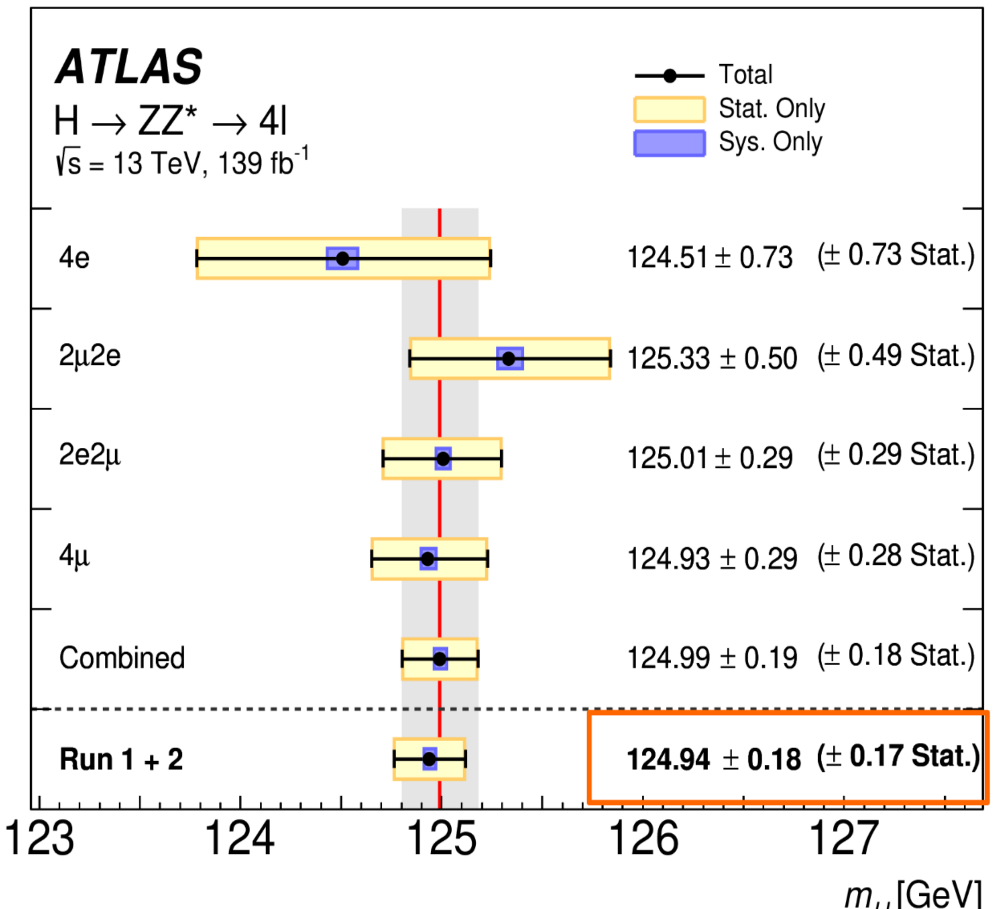


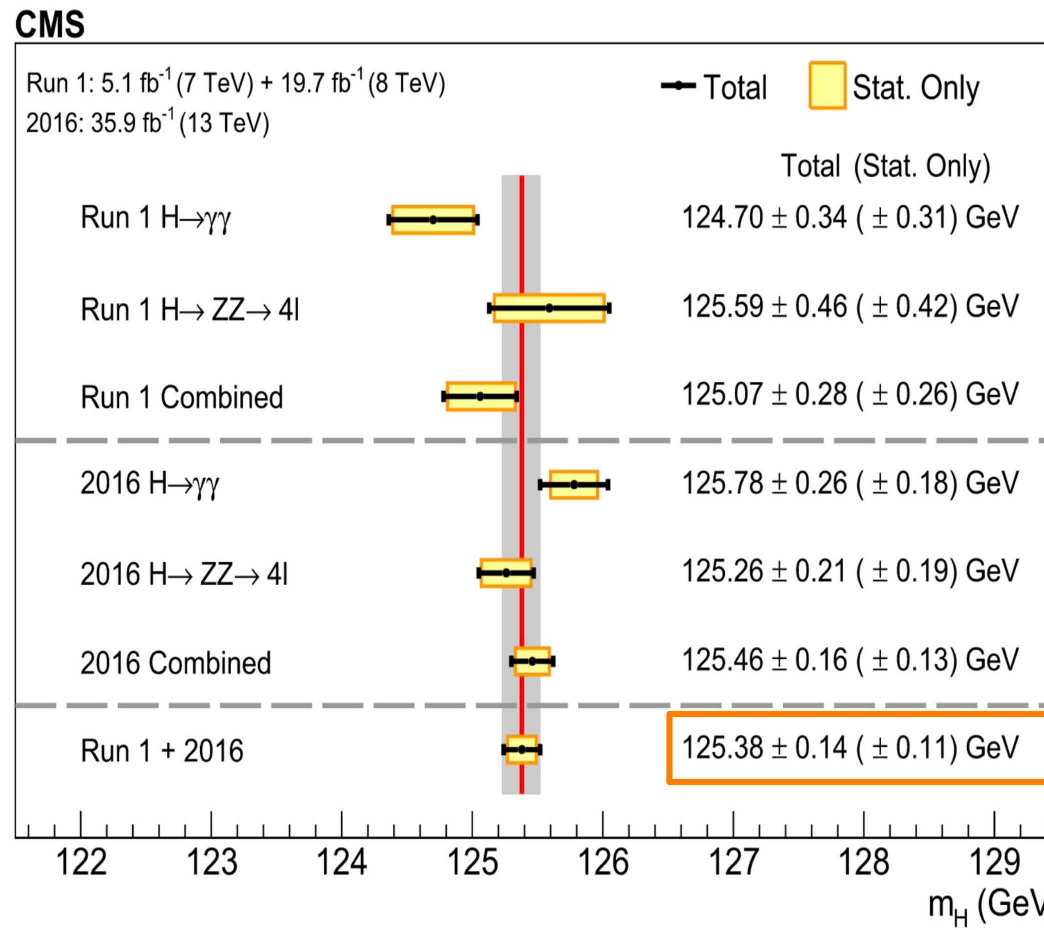
Agreement over three orders of magnitude.

Nature 607 (2022) 60

Higgs Mass

Two photon and 4 lepton channels determine Higgs mass: ~ 1‰

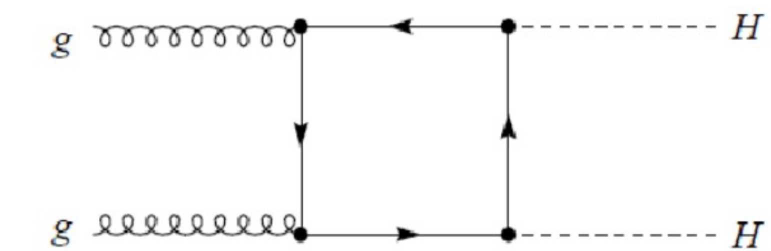




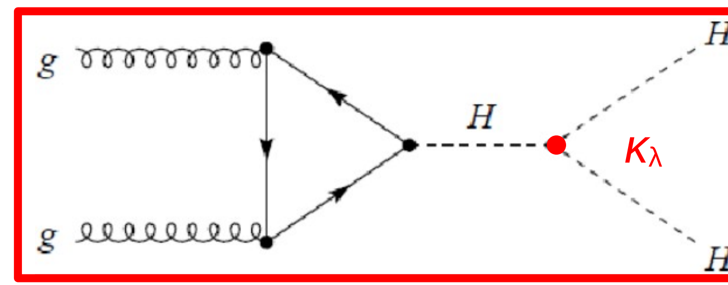
Higgs Self-Couplings

Higgs-boson pair production

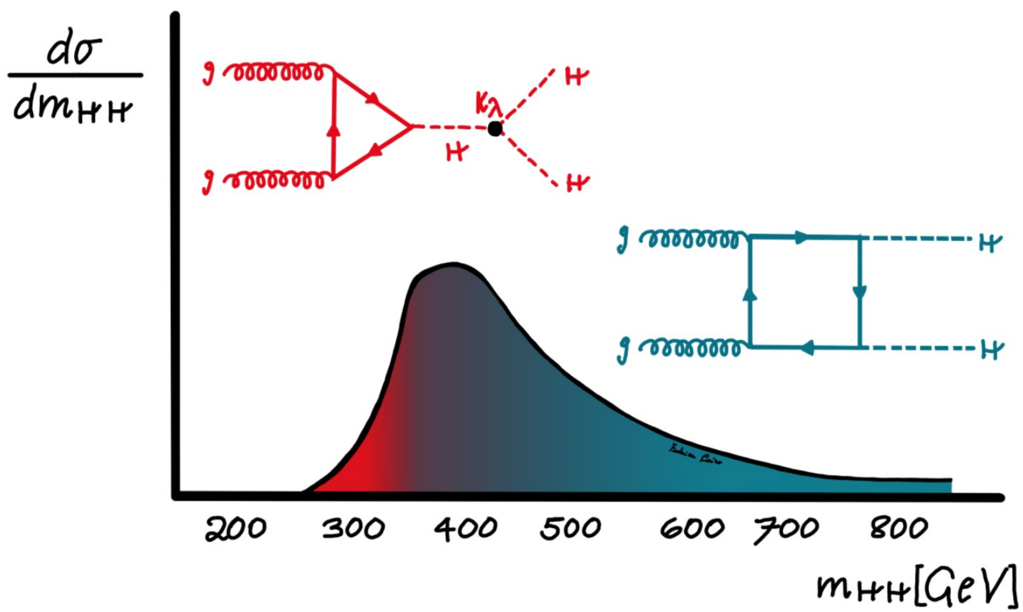
- Is non-resonant, because beyond Higgs mass, by definition.
- But triple Higgs vertex events are enriched at low mass



Not so interesting



Interesting

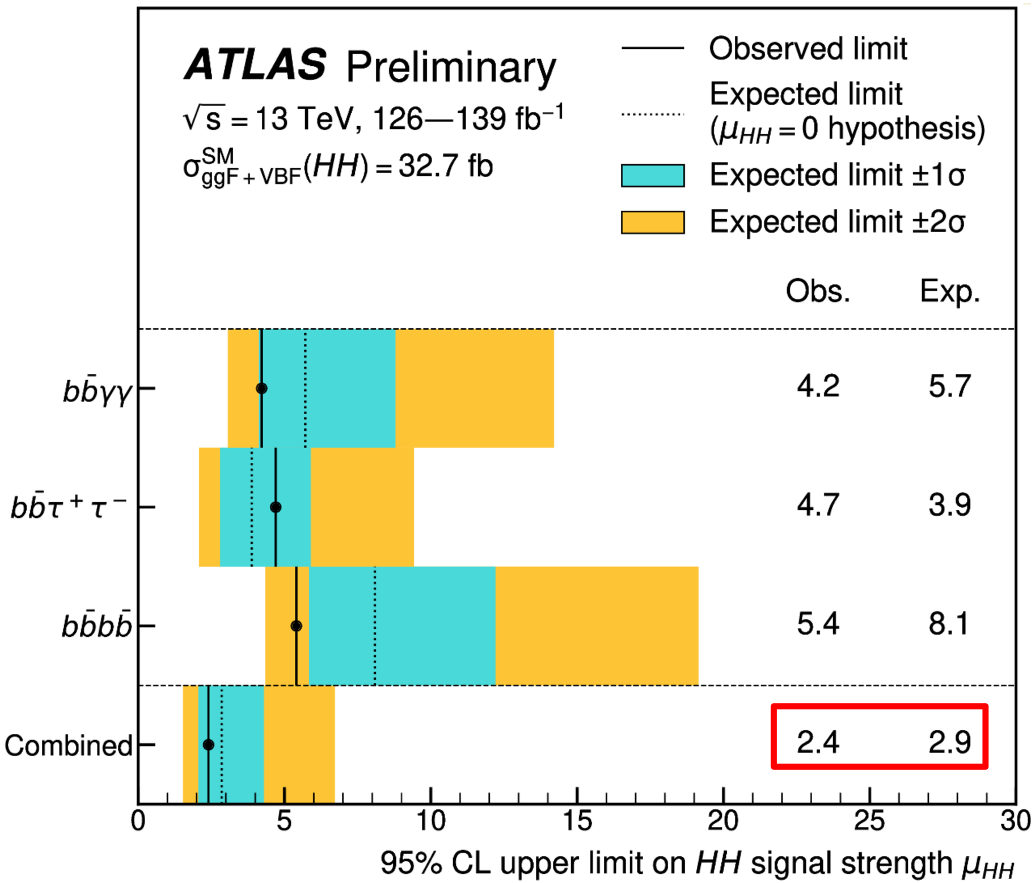


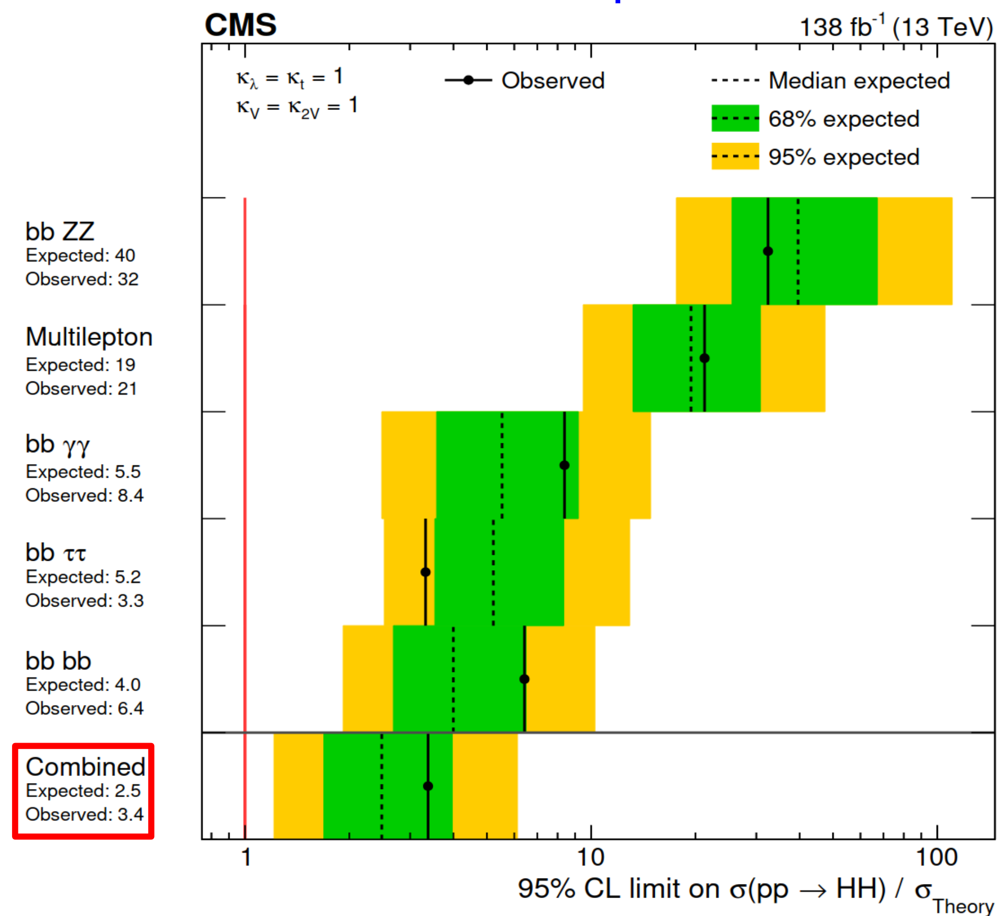
Similar diagrams for other production modes like Vector Boson Fusion but over a factor of 10 smaller.

Higgs Self-Couplings

No single winner…. many channels need to be combined

- Looks surprisingly good: ML techniques were essential to boost performance





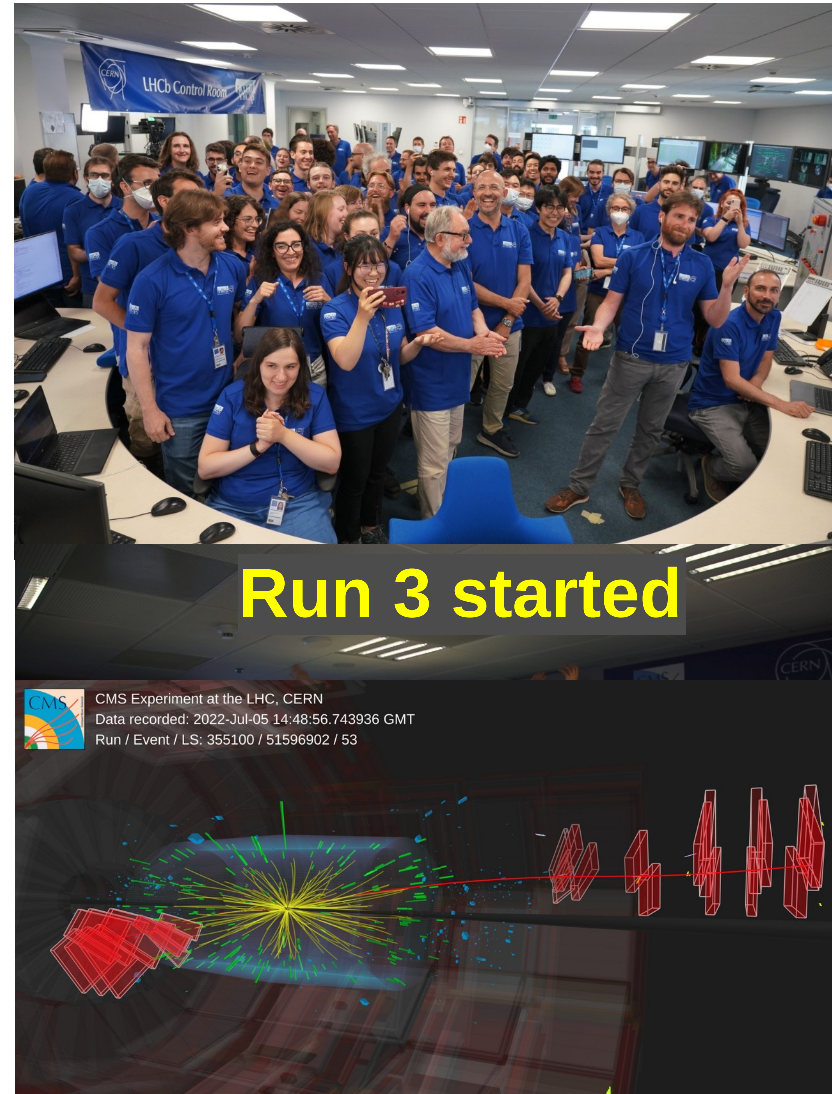
What the future holds

The parameters of Run 3

- Started just a week ago
- Duration: 2022-2025 (4 years)
- Adding about 200/fb

Things to look out for

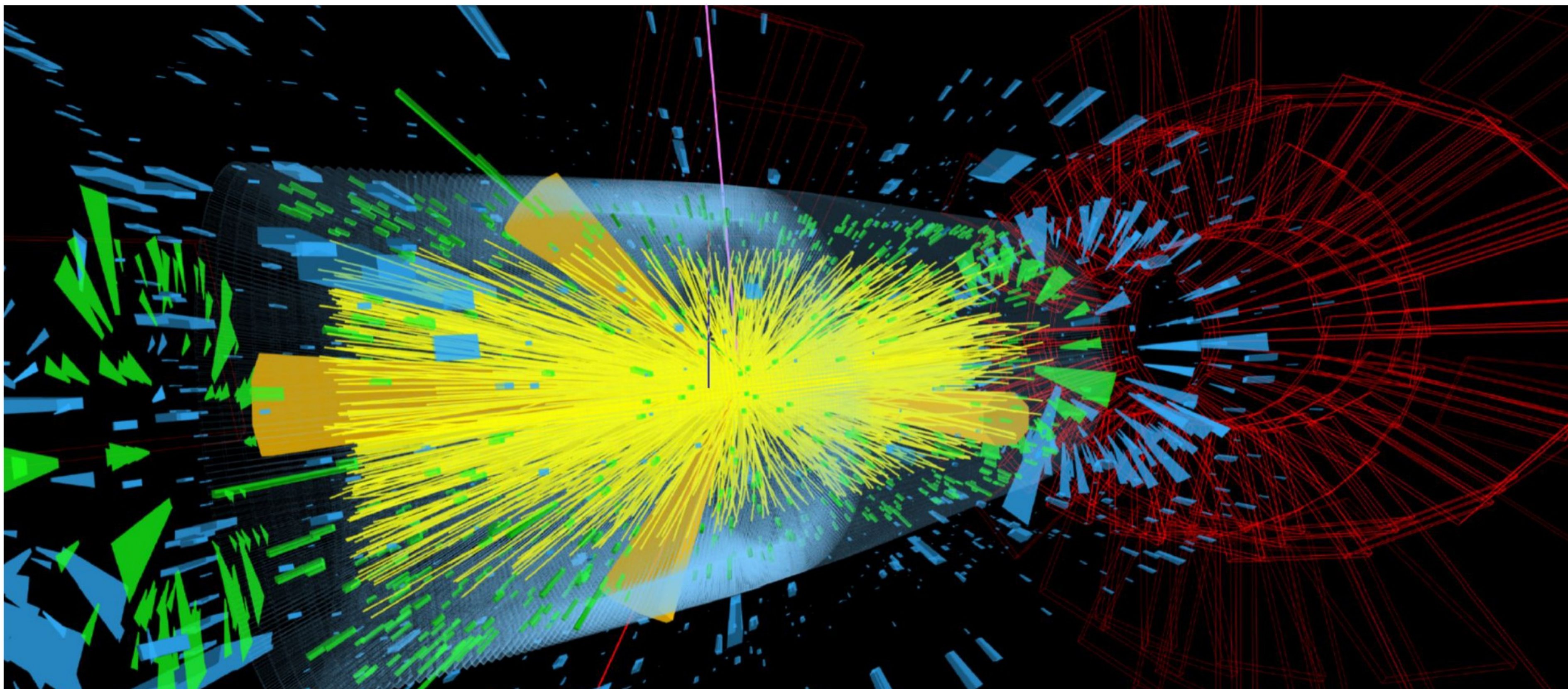
- Evidence for Higgs self coupling?
- Maybe see Higgs to dicharm?
- Everything is going to be come more precise
- There are analyses that win by much improved triggers



What the future holds

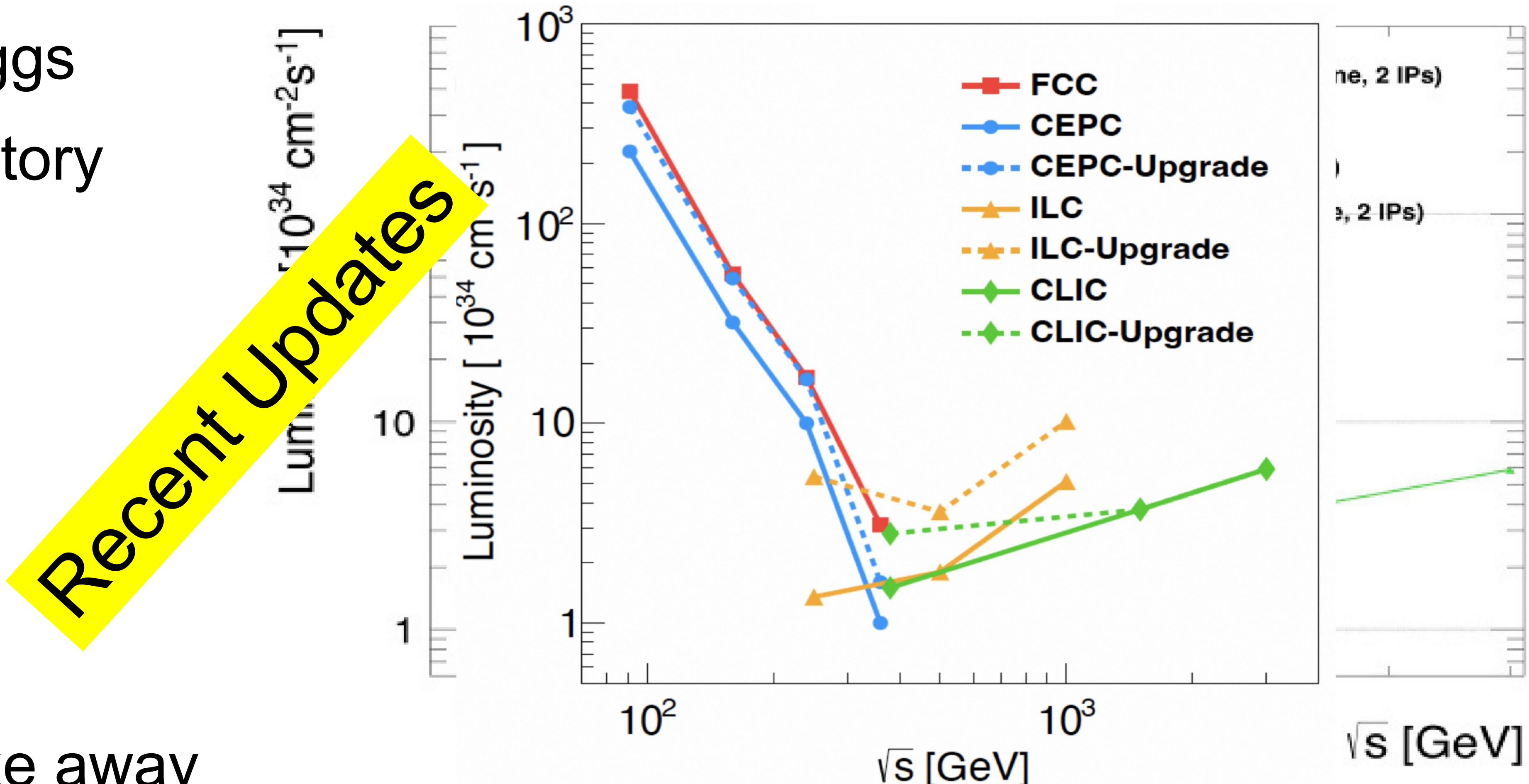
High Luminosity LHC (LHC on steroids)

- Better detectors, 10x more data; minimal goal: keep sensitivity



What the future holds

Higgs factory



Take away

- Highest luminosity in EW precision region: Z, WW, HZ, and tt area by a lot
- High E_{CM} do not work due to circular design → synchrotron radiation

What the future may hold...

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	$FCC\text{-}ee_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR_{EXO} (%)	SM	<1.7	<2.1	<1.6	<1.2	<1.2	<1.0	**<1.0**

Take-aways

- Precision of the HL-LHC (10xLHC) will be few percent range, Higgs self coupling observed
- FCC-ee most precise Higgs option (sub percent) and model independent total Higgs width

What the future may hold...

Advertisement: SnowMass and the future

- The deliberations of the SnowMass process will be held at the University of Washington in Seattle next week
- It is very important that the community finds its voice and makes smart decisions
- The future of High Energy Physics and the Energy Frontier are not obvious
- ...but we have great options and excellent physics we can do

Conclusions

The Higgs boson particle was discovered in 2012

- From 'A narrow resonance' to Higgs-boson like to Higgs boson
- An enormous effort by our community: theorists, accelerator physicists, detector builders and analyzers ….

Things we learned in the process ...

- It couples as expected: to bosons, to leptons and to quarks
- It passes all tests, but we have not yet asked all our questions

What does the future hold

- Run 3 will give us a bump to finish LHC, and HL-LHC will give us a factor of 10 and the future Higgs factories are looking good

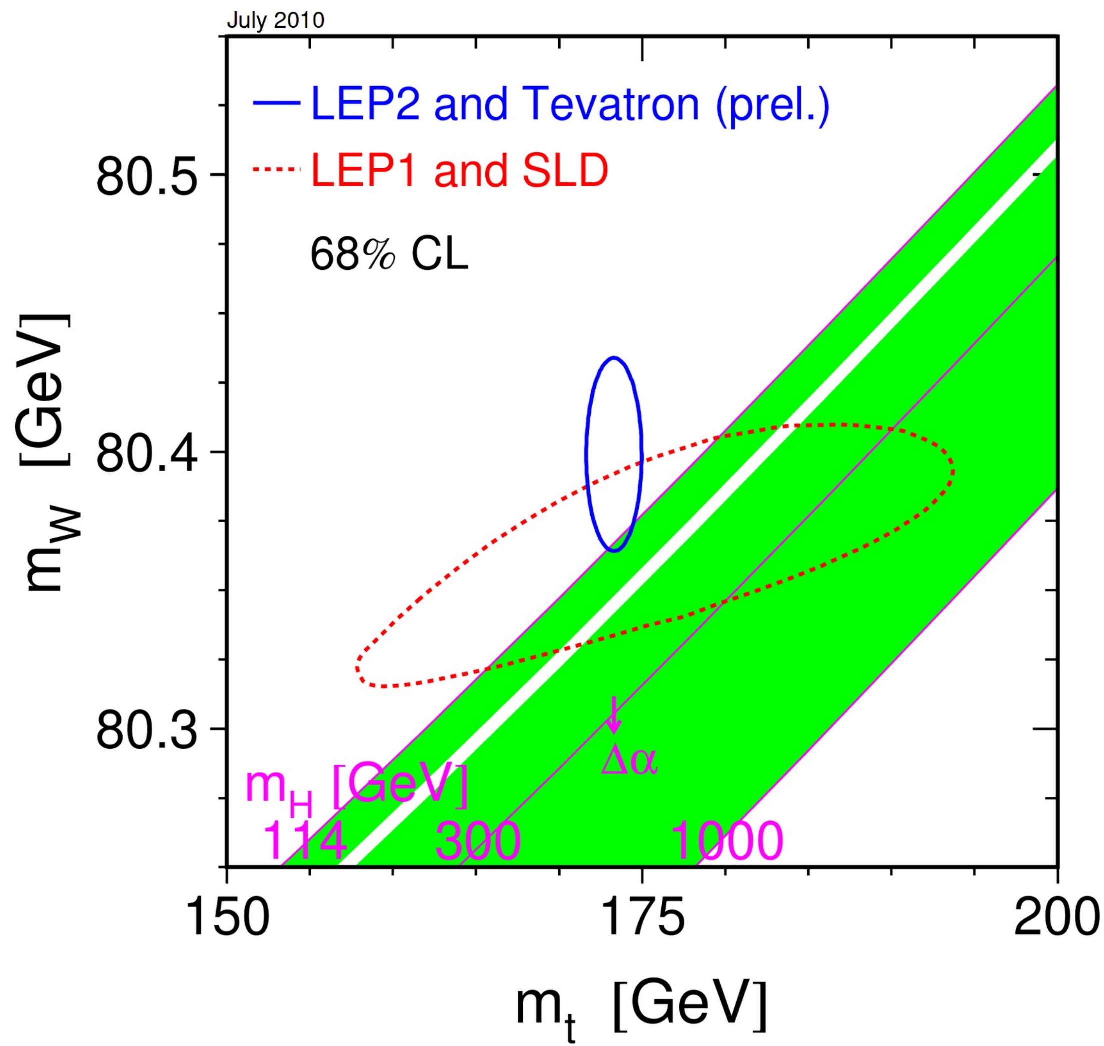
4.6% **LHC Status:** **Run 3 has resumed**

Extras

Comparing LEP1 and LEP2

Z *versus* W and top

- Very precise understanding of Z boson gives some constraints
- Including the top quark mass and the W boson mass makes a bigger dent



Final Electroweak Working Group report 2010: https://arxiv.org/pdf/1012.2367v2.pdf

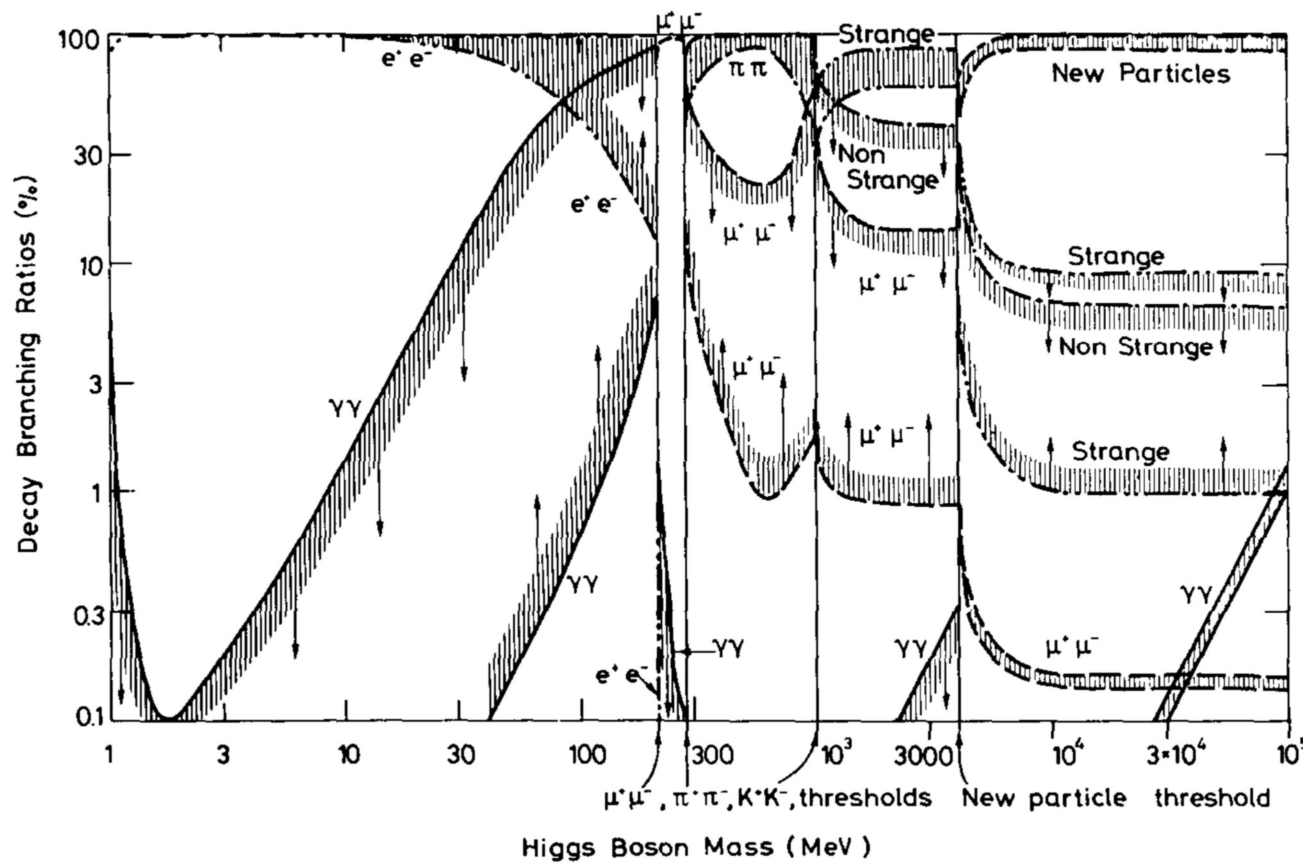
Searches before LHC

Early Searches

Starting low

- Scale on plot is MeV
- Interesting decay channels very different focus from the recent discovery time

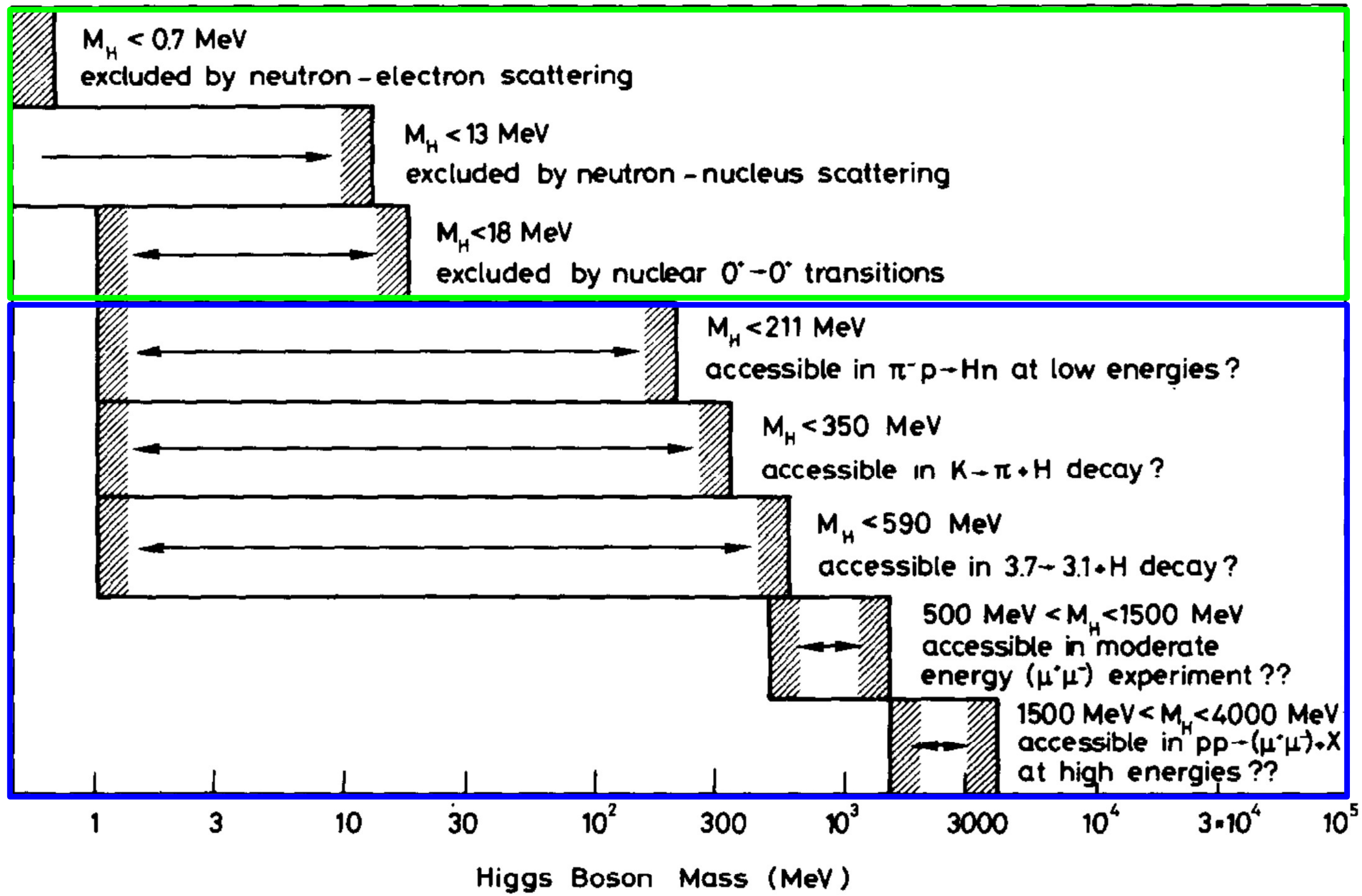
J. Ellis, M. Gaillard, D. Nanopoulos, Phys.B 106 (1976) 292
„A Phenomenological Profile of the Higgs Boson“



Early Searches

Starting low

- Used all existing experiments …
- Nuclear physics quickly ran out of gas
- Interesting to see what the planning was
- Higgs mass is outside of this early picture!!



J. Ellis, M. Gaillard, D. Nanopoulos, Phys.B 106 (1976) 292
„A Phenomenological Profile of the Higgs Boson“

Searches at LEP

At LEP 1 (Z peak)

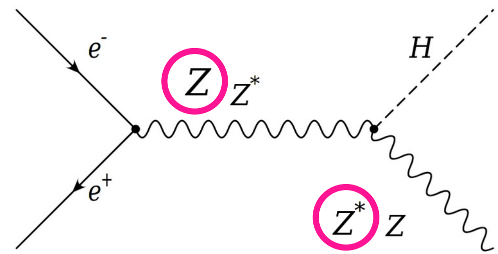
- m_Z ~ 91 GeV
- Main Z boson decay modes were dilepton (ee, μμ) and invisible decays to neutrinos
- Higgs decay into bb and ττ
- Reached limits up to about 60 GeV

At LEP 2 (WW threshold ++)

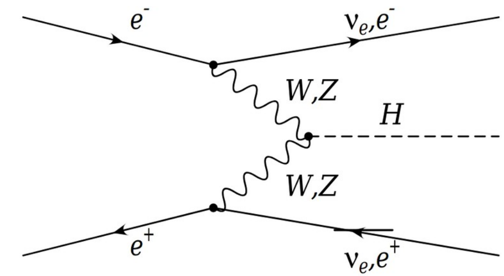
- 2^*m_W ~ 160 GeV
- All Z decays open
- Higgs decay into bb and ττ

Detectors

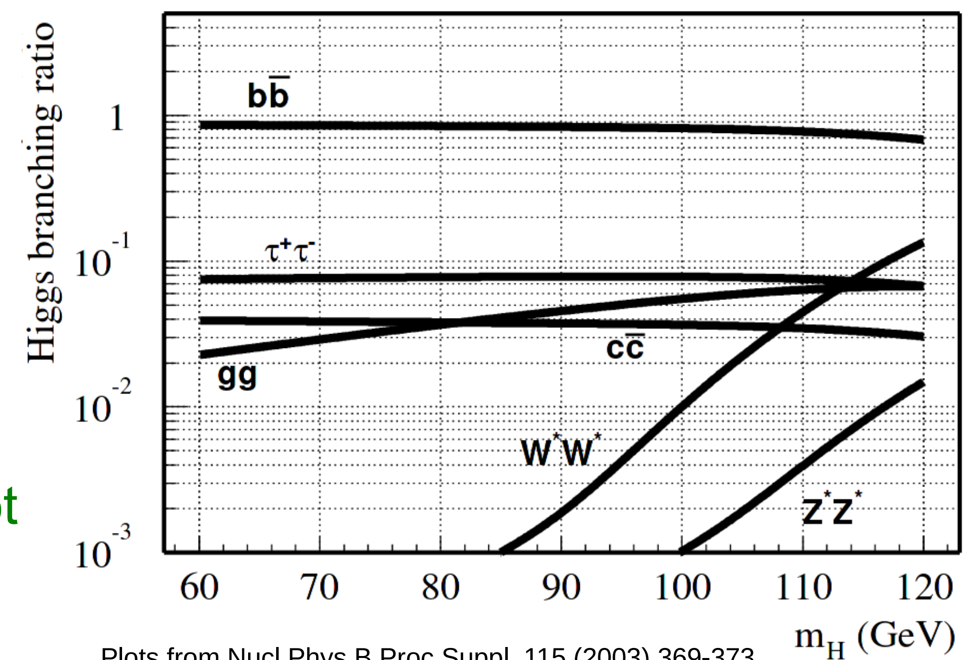
- Silicon vertex detectors became a hot commodity (2 and 3 layers)



Higgsstrahlung



Vector Boson Fusion



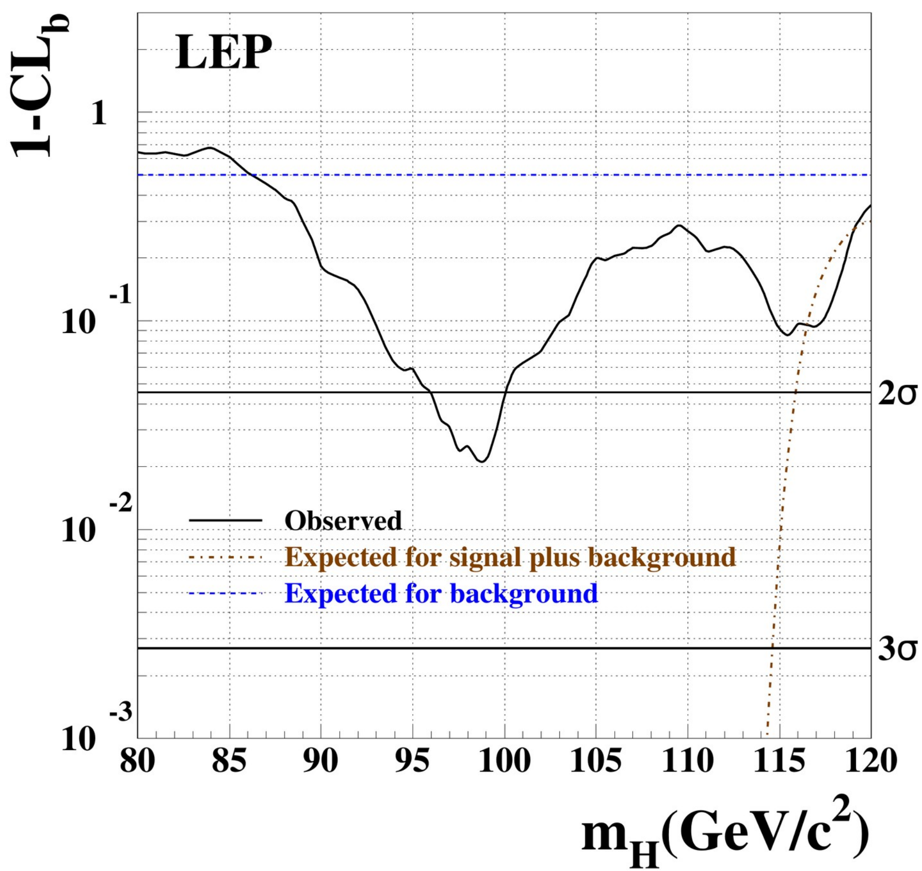
Plots from Nucl.Phys.B Proc.Suppl. 115 (2003) 369-373

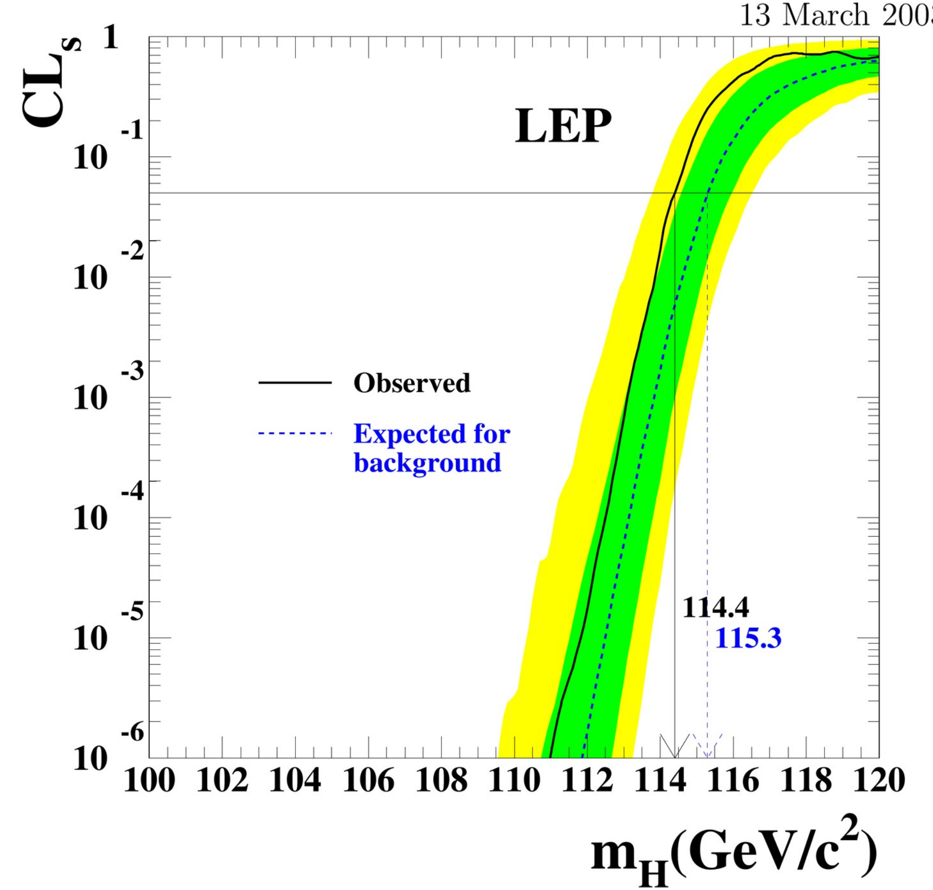
Searches at LEP 2

At LEP 2 (up to 209 GeV)

- Some tantalizing hints…. but no base for continuing the search

CERN-EP/2003-011
13 March 2003



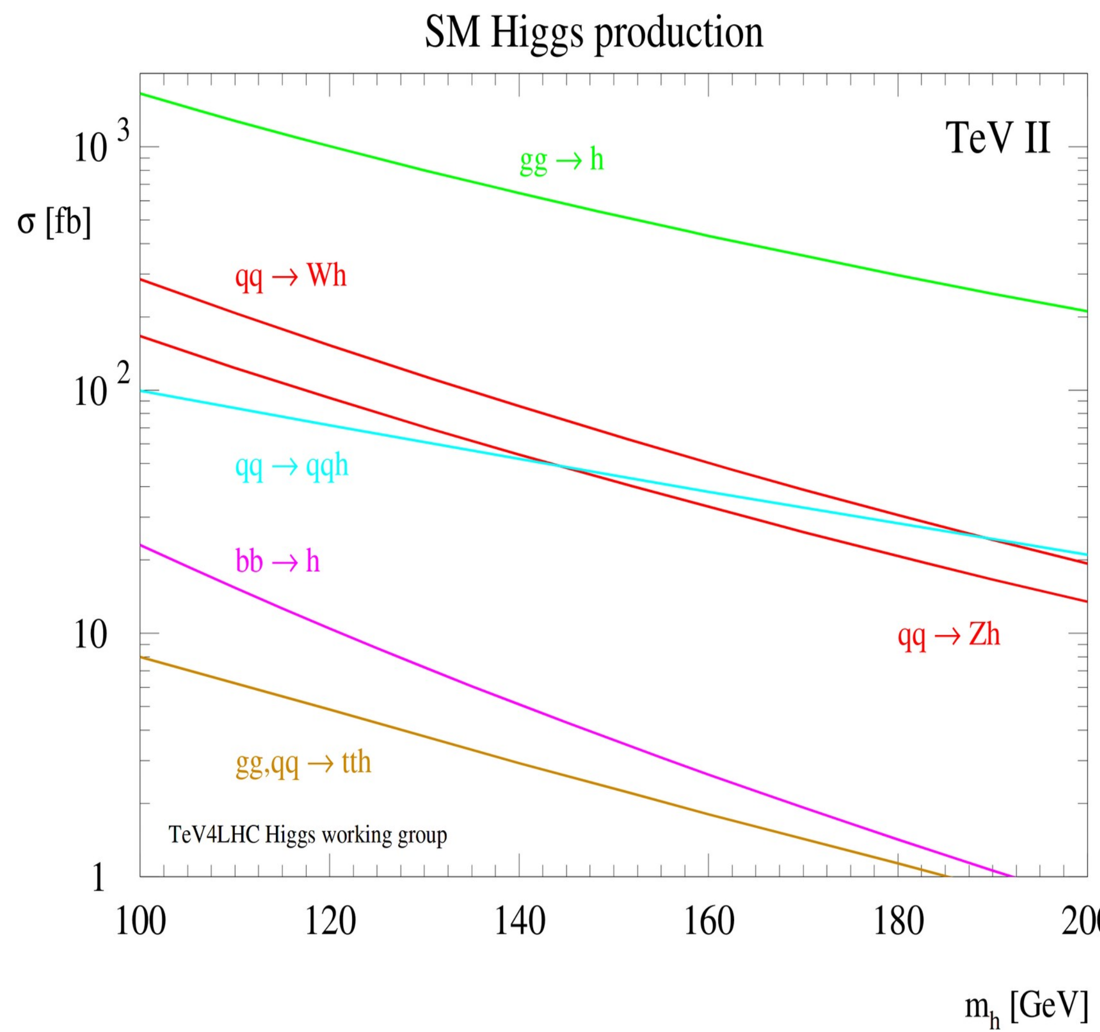


Plots from LEP Working group on Higgs Searches

Searches at Tevatron

Production and decay

- Dominant production is gg→H
- With proton-antiproton (q and qbar as valence quarks) collisions qq→ VH production large (associate production)
- Associate production can use W and Z bosons for powerful event cleanup
- Dominant searches in decays: H→bb and H→WW using associated production
- Other modes not really feasible due to small production and/or high background



Search setup at the LHC

Searches at the LHC

General ideas for the LHC

- Building two experiments is essential
- Not simply factor of two in luminosity
- Complementary designs and technologies: protect against potential failures and ensures *independent confirmation*

Analysis strategies *per experiment*

- At least two analyses instead of one, as independently as possible/reasonable → again *independent confirmation*
- Monte Carlo simulation is essential, but needs to be carefully tied to reality during the analysis process, aka *'data driven'*
- Make sure to *'blind'* the analysis …
- Searches use signal strength, μ, relative to SM: $\mu \equiv (\sigma \times BF)/(\sigma_{SM} \times BF_{SM})$
- Use sound statistical tools that are coherent between the experiments → allows for relevant comparison and facilitates the combination of results later

Searches at the LHC

Special for the *standard model Higgs boson*

- In its minimal implementation (see Occam's Razor) we knew everything* except for its mass
- Very precise MC simulations could be produced, for sufficient mass points separately to probe the continuous mass phase space
- Analyses were optimized for each mass point to get optimal results, for the SM Higgs boson

What if you find an excess?

- An excess of events is evaluated by the probability for a background fluctuation to be at least as large as the observed maximum excess: local *p*-value
- To obtain the global *p*-value the number of excesses that could have occurred in the phase space needs to be considered (LEE – look-elsewhere-effect)
- Global *p*-value is relevant to claim discovery, but is very difficult to define cleanly

* theorists had to work hard to make sure precise calculations were available

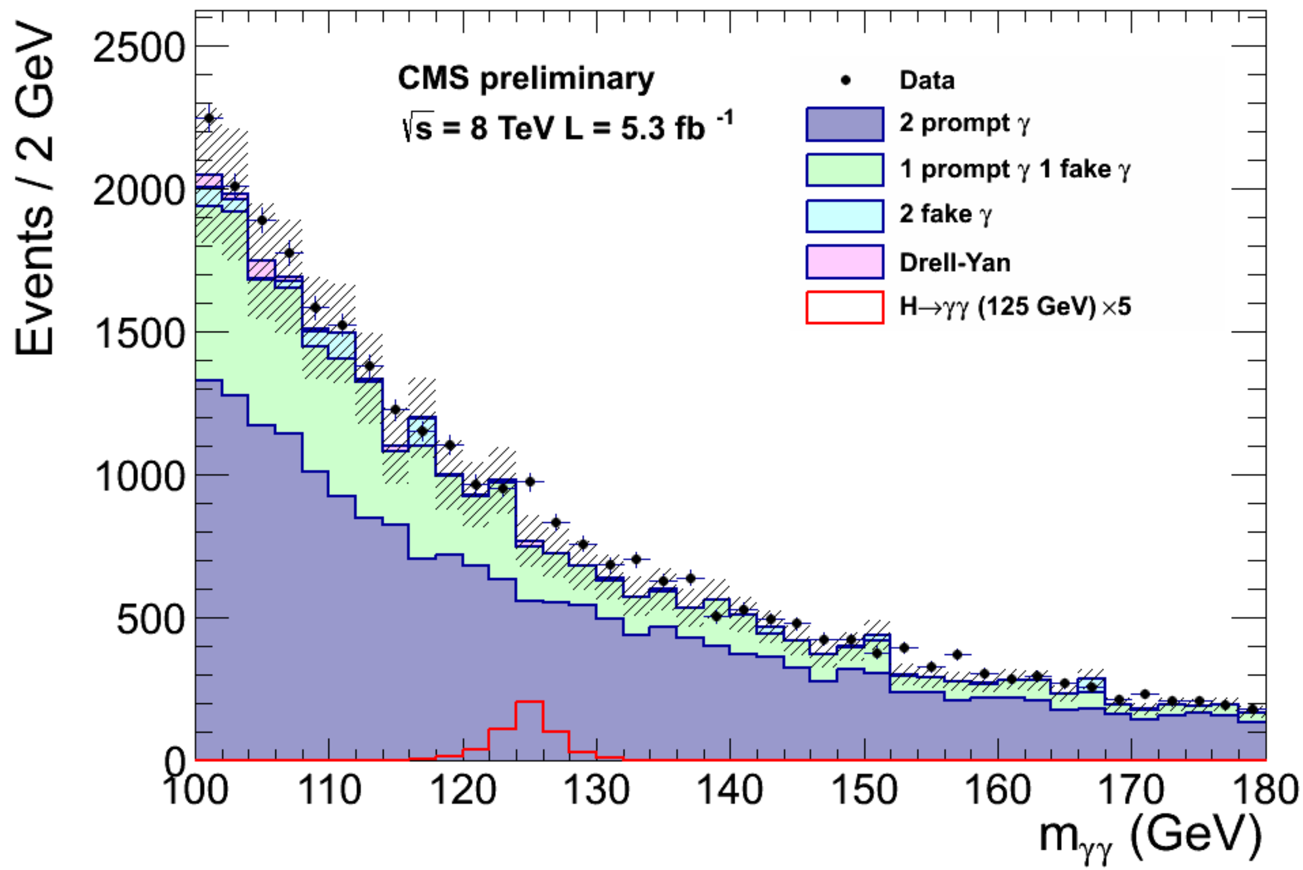
The Look-Elsewhere-Effect

Is relevant when you do not know where to look

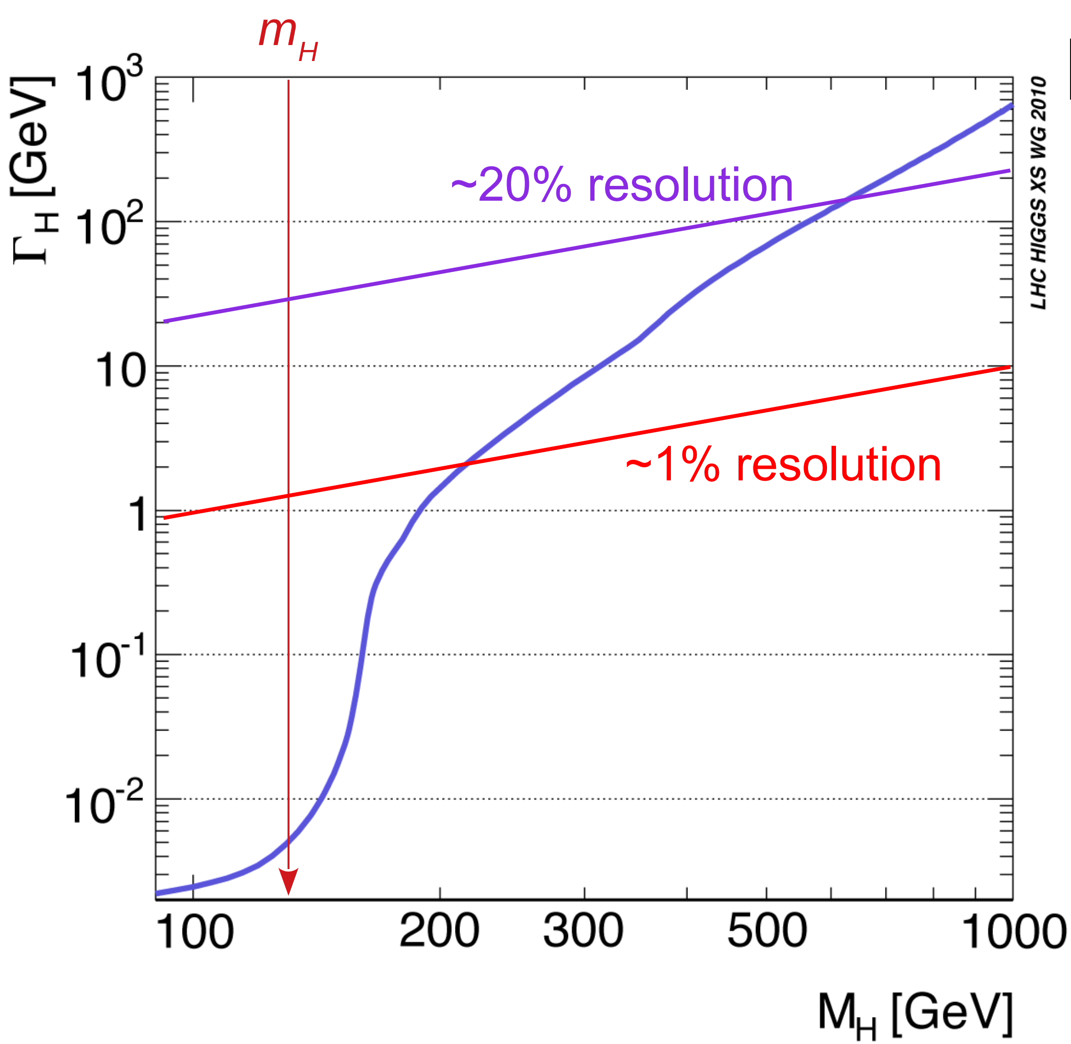
- Small intervall, small number of possible fluctuations
- Large interval, large number
- Applies generally of course

Forgotten art

- People only talk about this very close to a discovery….
- Because else it is not obvious that it is relevant



Higgs Natural Width



Higgs mass scenarios

- high masses (over ~300 GeV)
  - natural width is relevant
  - needs theory input in MC generators
  - Search sensitivity is affected
- low masses (below ~200 GeV)
  - natural width is irrelevant
  - detector resolution dictates the observed width of the mass peak
  - Search sensitivity unaffected

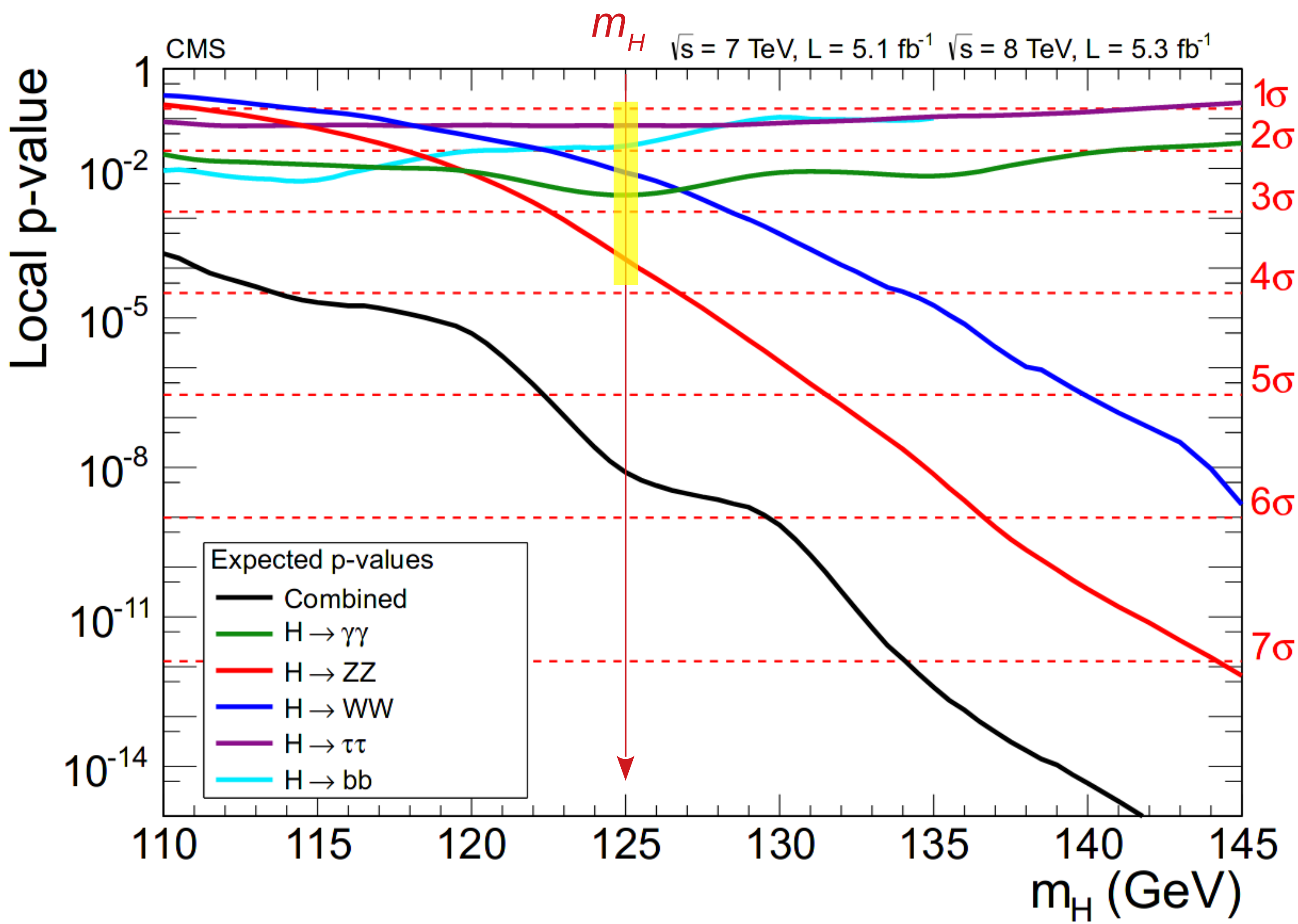

Higgs Hunting’s
’Big Five‘

Overview – Big Five

Channel	m_H *resolution* [%]	m_H range [GeV]	Data ATLAS (7+8 TeV)	Data CMS (7+8TeV)
H → ZZ → 4l	1-2	110-1000	5+5	5+5
H → gg	1-2	110-150	5+5	5+5
H → WW → 2l2v	20	110-660	5+5	5+5
H → tau tau	15	110-145	5+0	5+5
H → bb	10	110-135	5+0	5+5

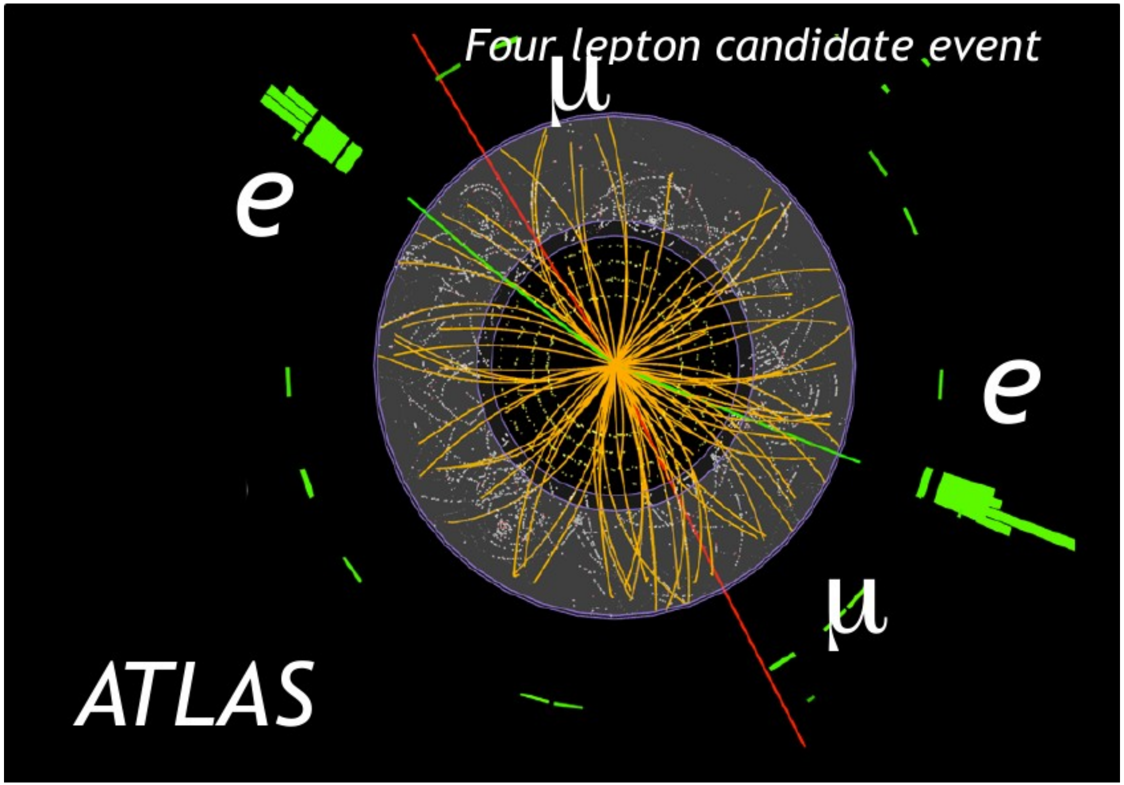
Data used in discovery paper

Big Five → Big Two or Three



Retrospectively, there were really mainly two at best three channels that mattered

The Golden Mode: H → ZZ → 4l



Analysis telegram

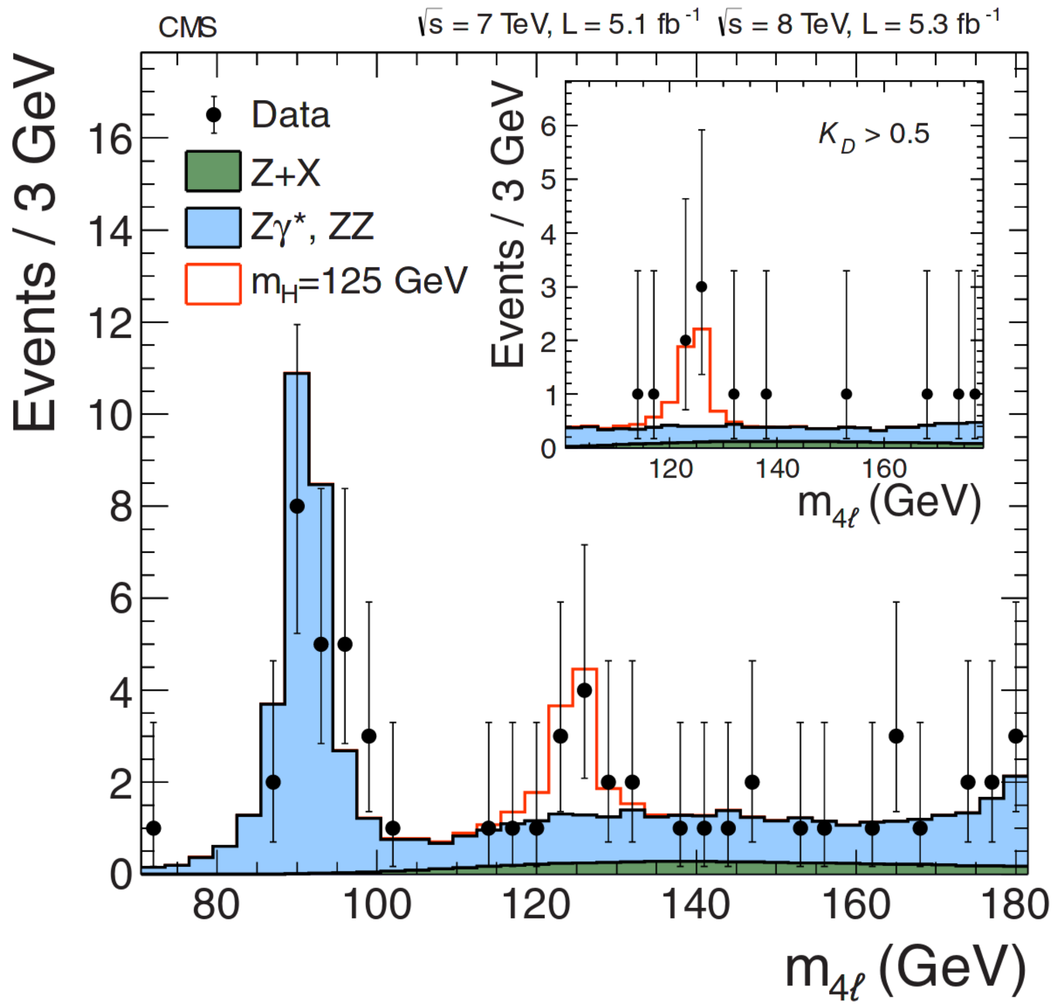
- 4 isolated high p_T leptons*
- consistent with *Z* decays
- from same vertex
- fit mass peak with resolution of 2-4 GeV
- little background, non-resonant *ZZ* production
- also *Zbb* and top (*2l2nu2b*)

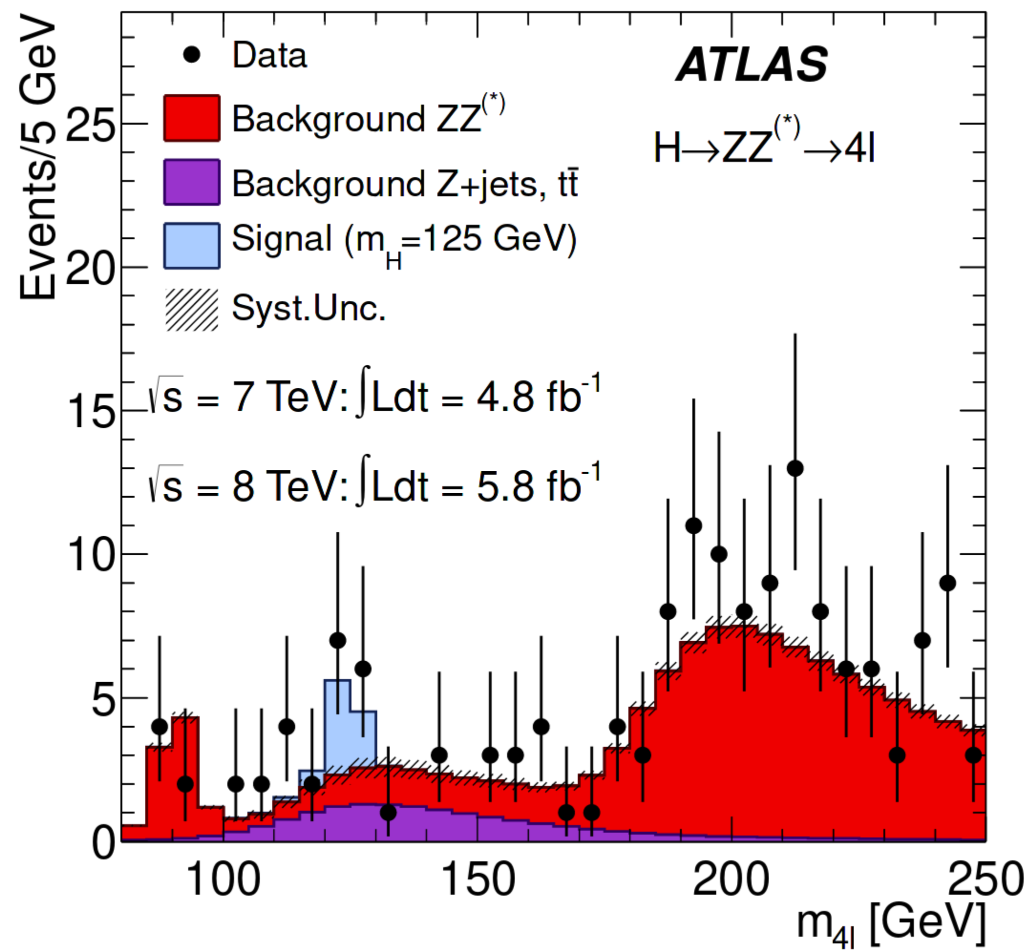
Background removal

- leptons from *b*-decays are non-isolated and displaced

* leptons here only muons and electrons

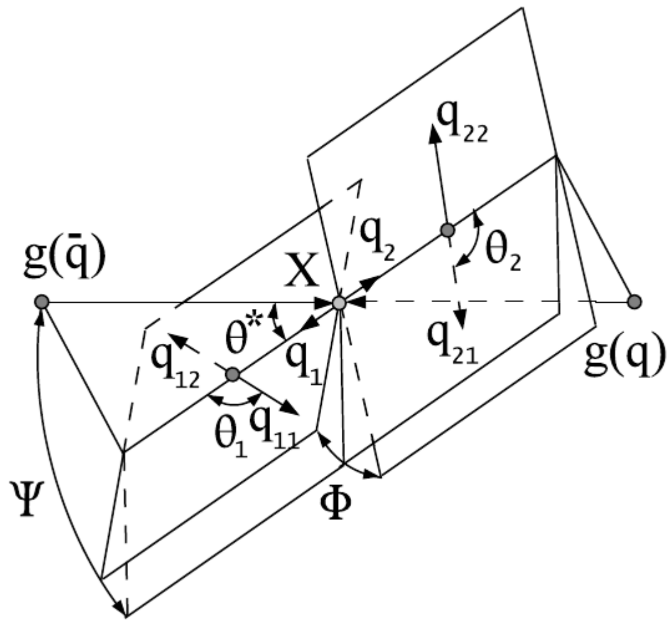
The Golden Mode: $H \to ZZ \to 4l$



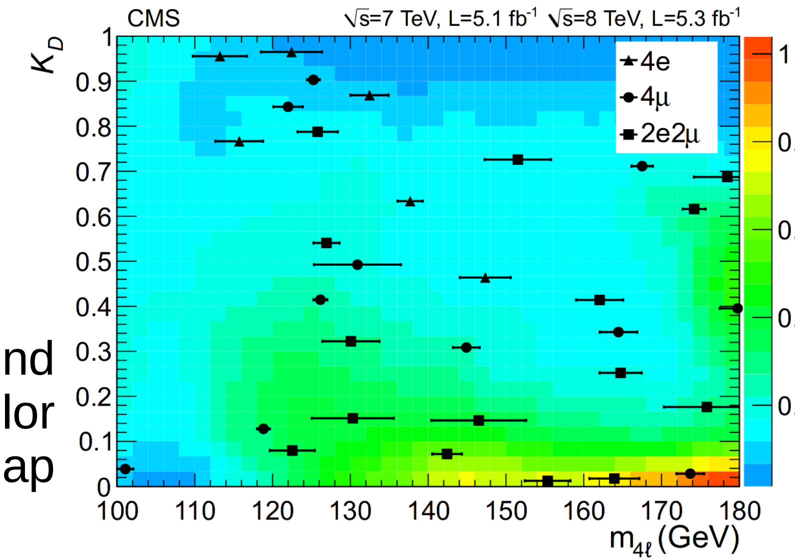


Peaks around 125 GeV

The Golden Mode: $H \rightarrow ZZ \rightarrow 4l$



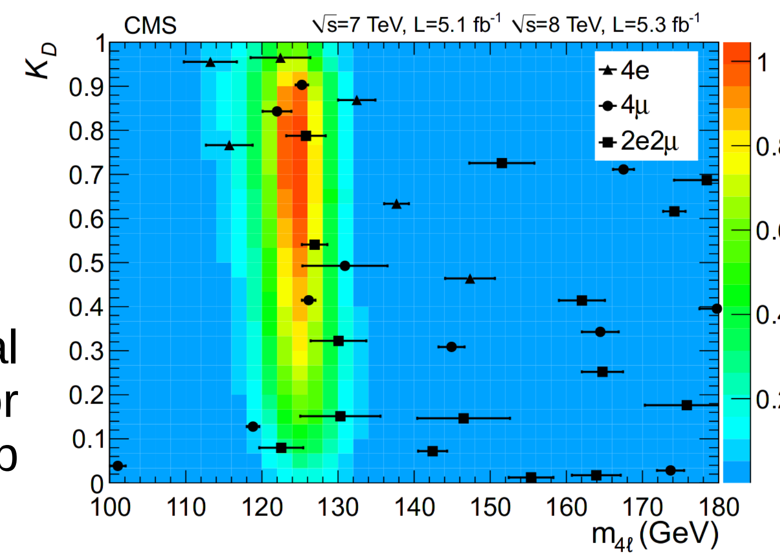
Background color map



Decay kinematics: angular analysis

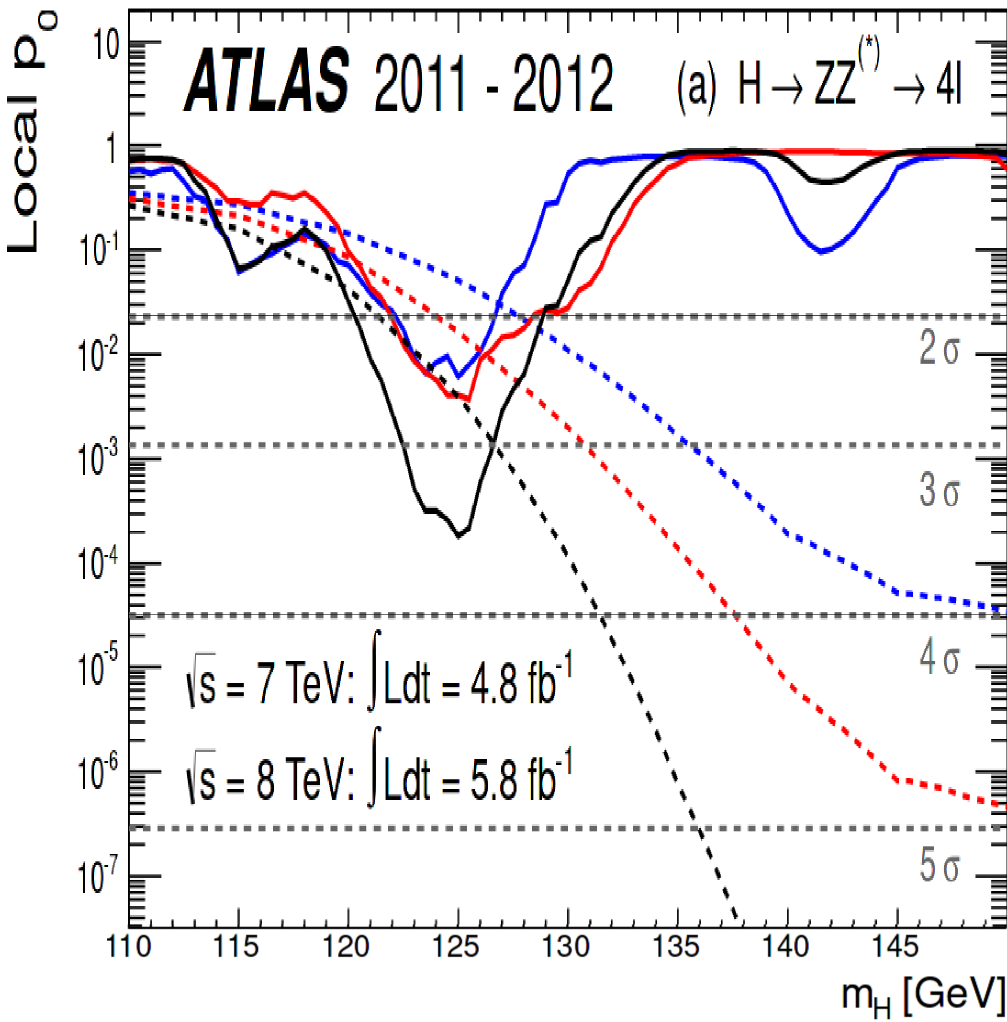
$$1/K_D = 1 + \frac{P_{bg}(m_1, m_2, \theta_1, \theta_2, \Psi, \Phi, \theta^*)}{P_{signal}(m_1, m_2, \theta_1, \theta_2, \Psi, \Phi, \theta^*)}$$

Signal color map

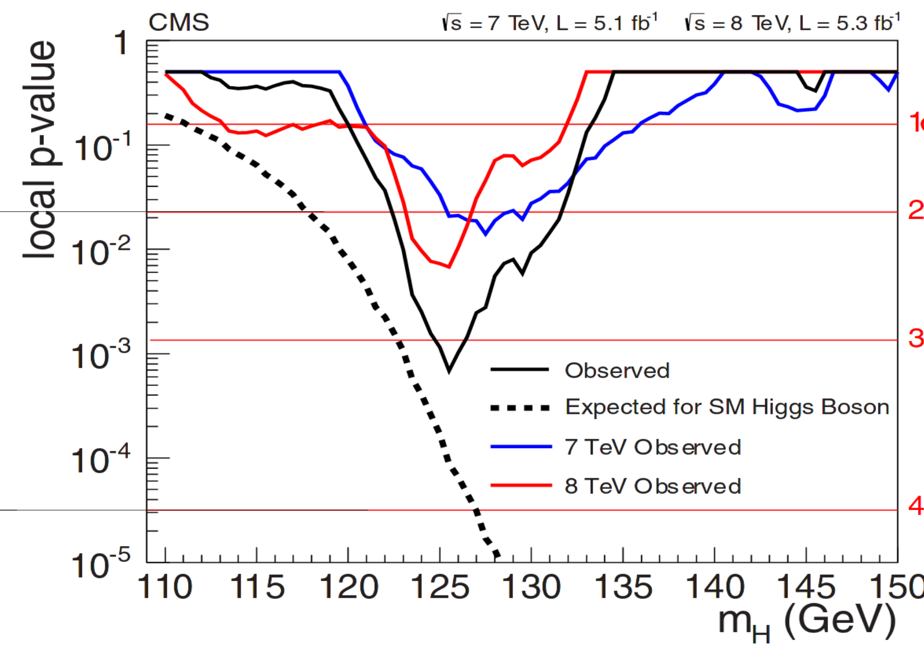


enhances analysis sensitivity

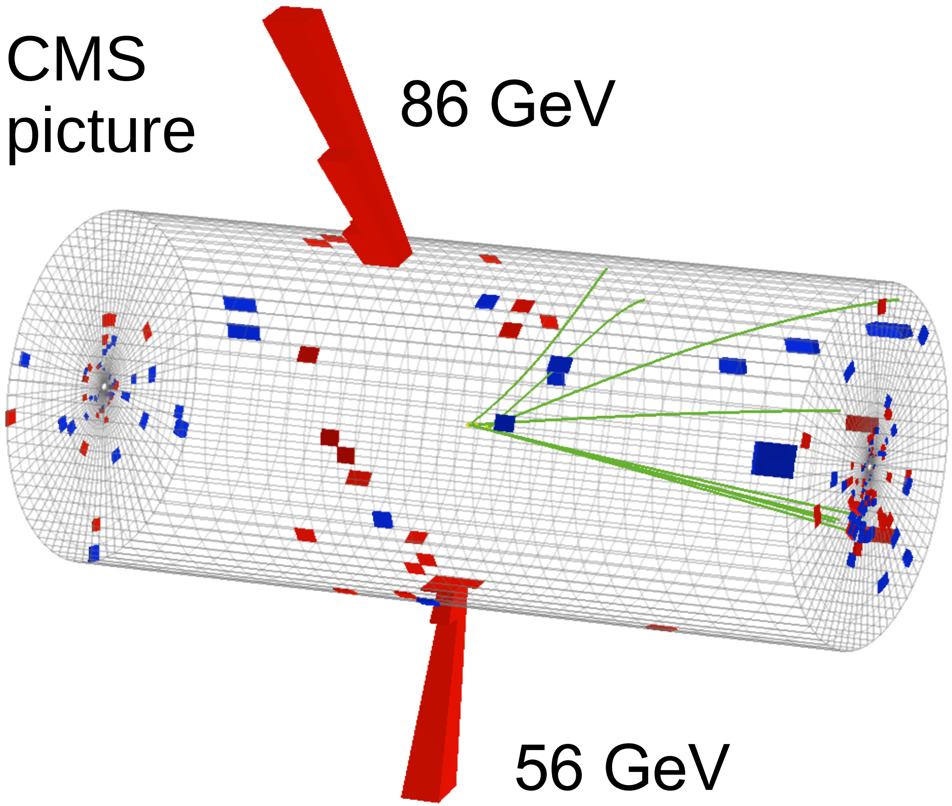
The Golden Mode: $H \rightarrow ZZ \rightarrow 4l$



Excess evaluation



Low Mass Specialist: $H \rightarrow \gamma\gamma$



Signature and background

- two high momentum photons
- low mass Higgs narrow
- two photon resolution excellent
- looking for narrow peak
- large irreducible background from direct two photons
- smaller fake photon background
- primary vertex finding is challenging

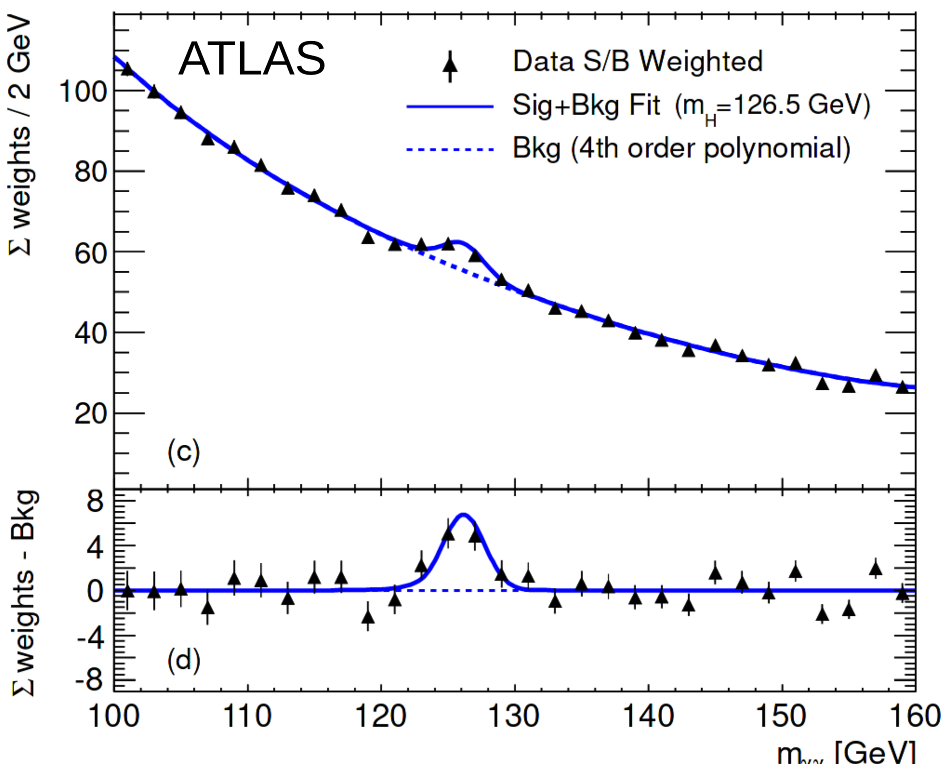
Key analysis features

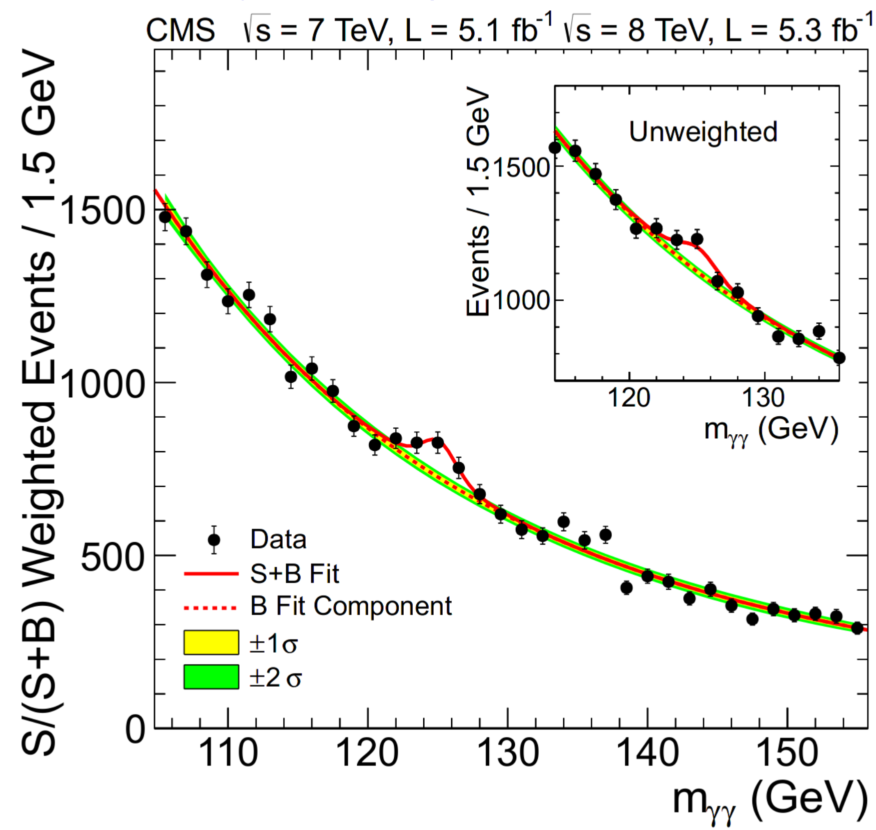
- energy resolution is almost everything: calibrate and optimize
- rejection of fake photons and optimized use of kinematics

Low Mass Specialist: H → γγ

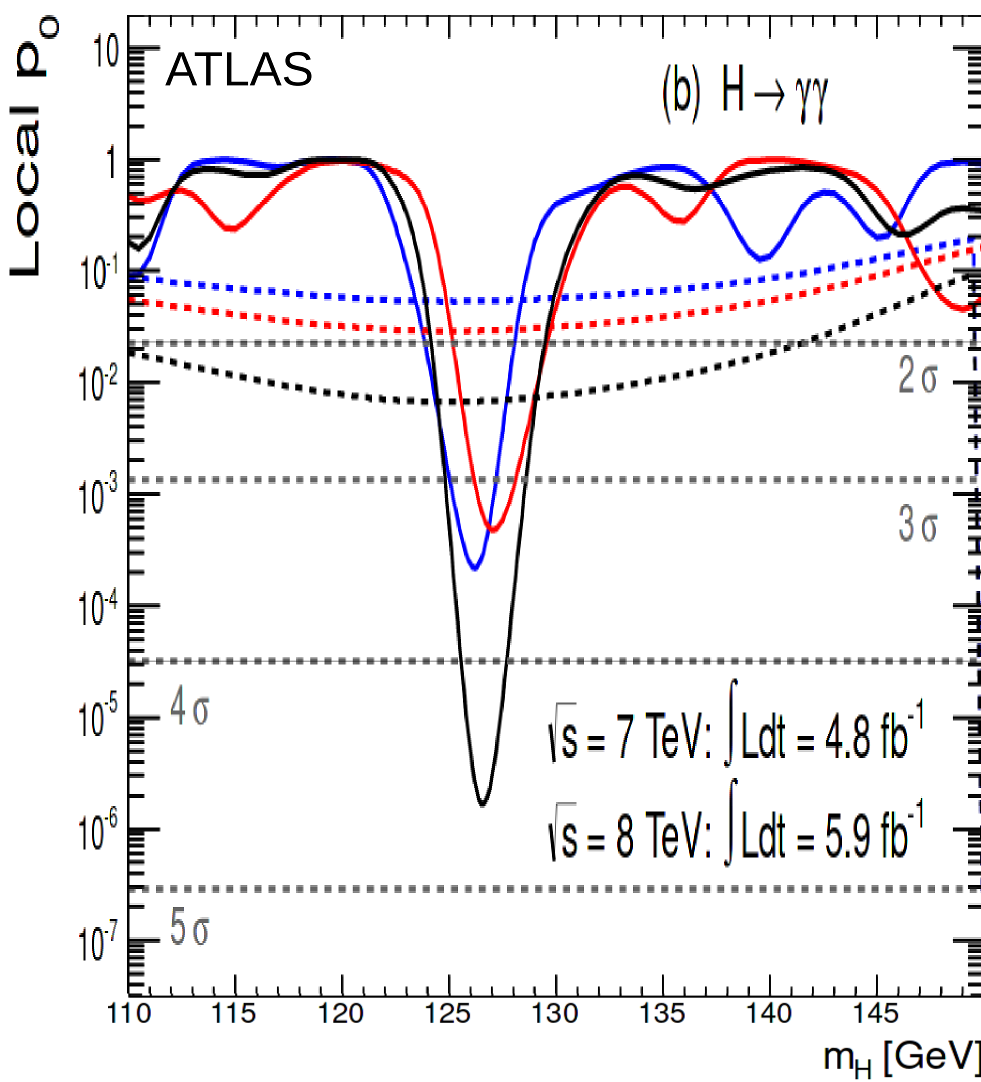
Diphoton mass plots from discovery papers

- Peak appears over continuous background
- Weighting needed to account for different quality of single events

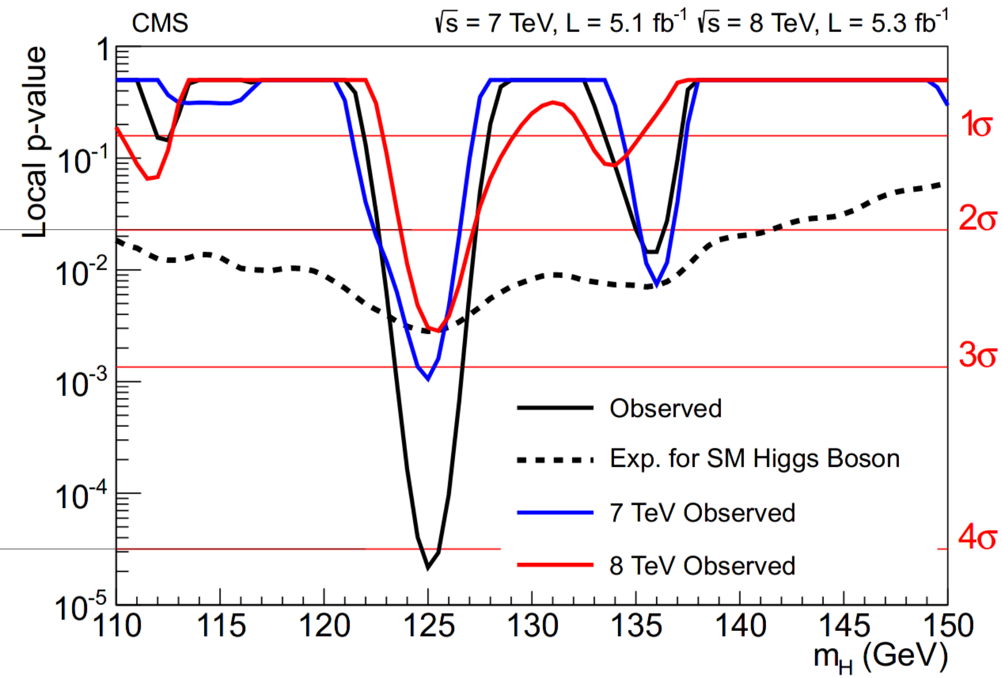




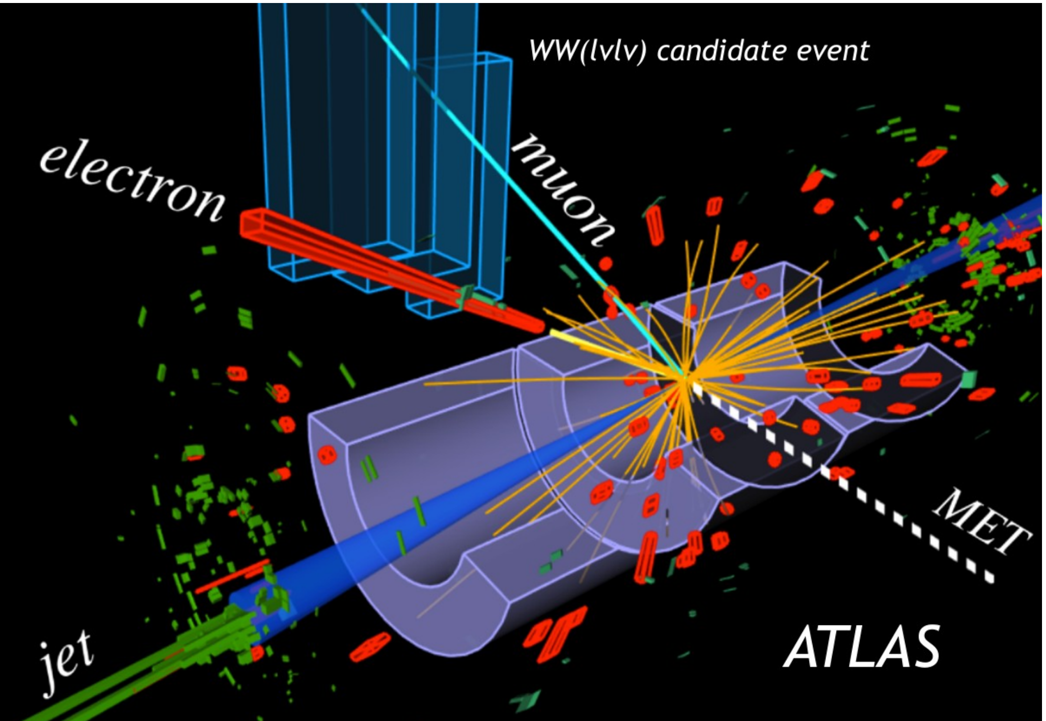
Low Mass Specialist: $H \rightarrow \gamma\gamma$

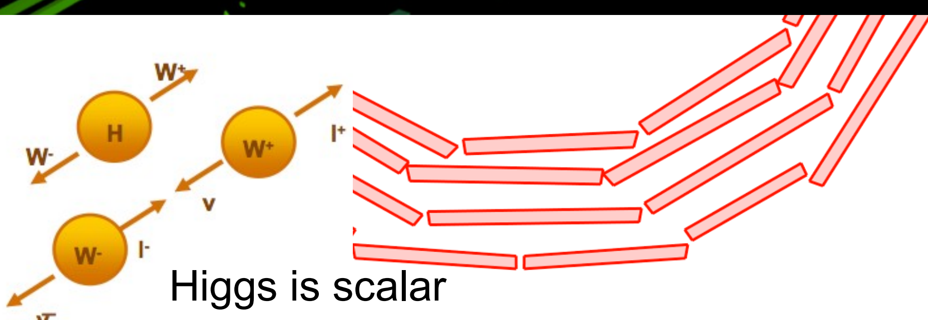


Excess evaluation



$H \rightarrow WW \rightarrow 2l\ 2\nu$





Higgs is scalar
so leptons are close

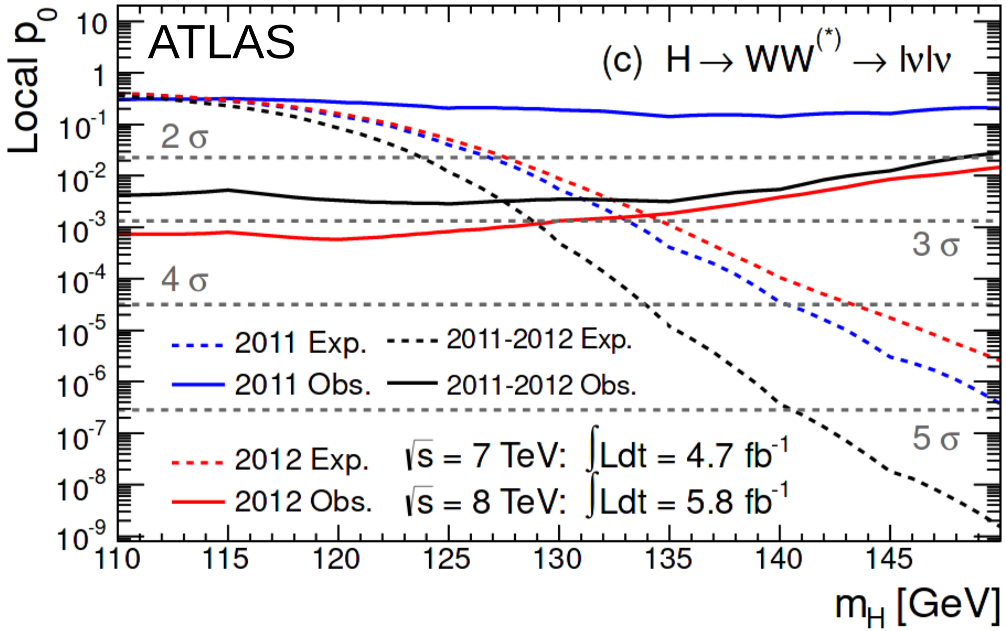
Signature

- 2 opposite charged leptons (leptons only *e*, *μ*)
- 2 neutrinos → missing transverse momentum (MET)
- no Higgs mass peak
- basically a counting analysis

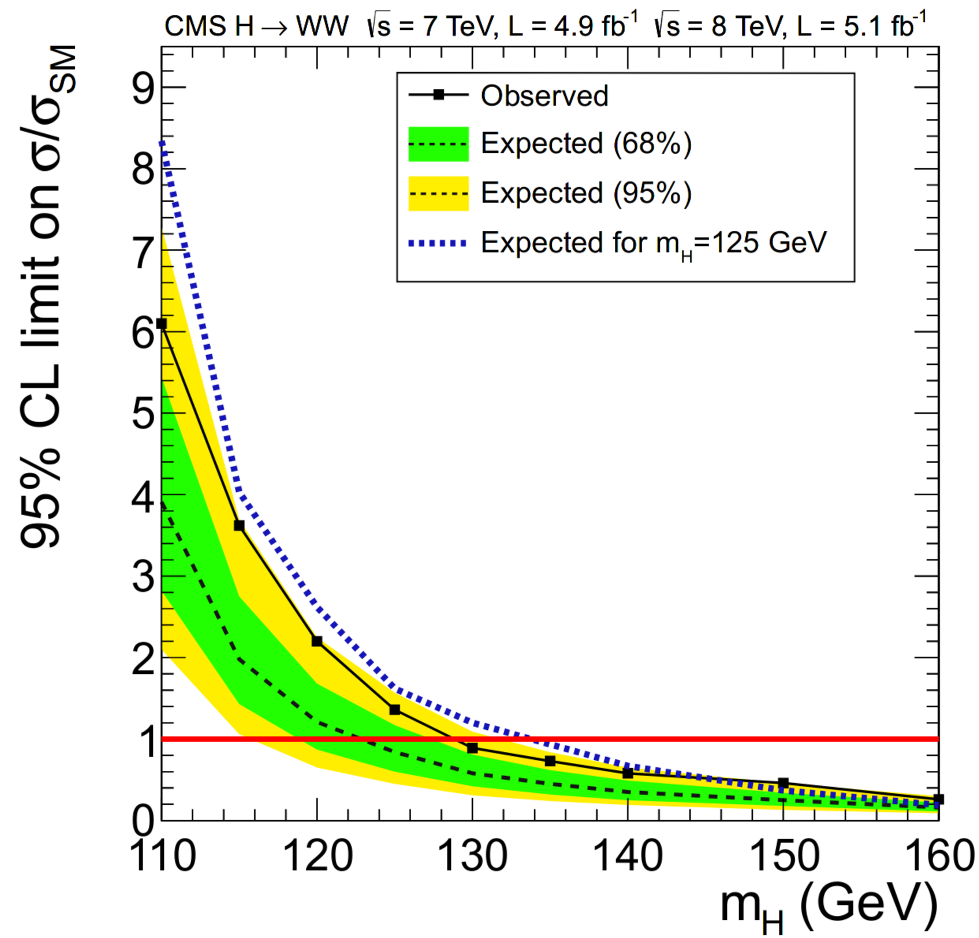
Analysis challenges

- understand backgrounds
- normalize to control regions
- backgrounds: WW, W+jets, top, DY

$H \rightarrow WW \rightarrow 2l\ 2\nu$



Excess evaluation



Different approach by CMS

- Instead of p-value derive limit
- See excess at about 2 standard deviations as expected

Discovery

Combine Channels per Experiment

H -> WW -> 2l2ν

H -> γγ

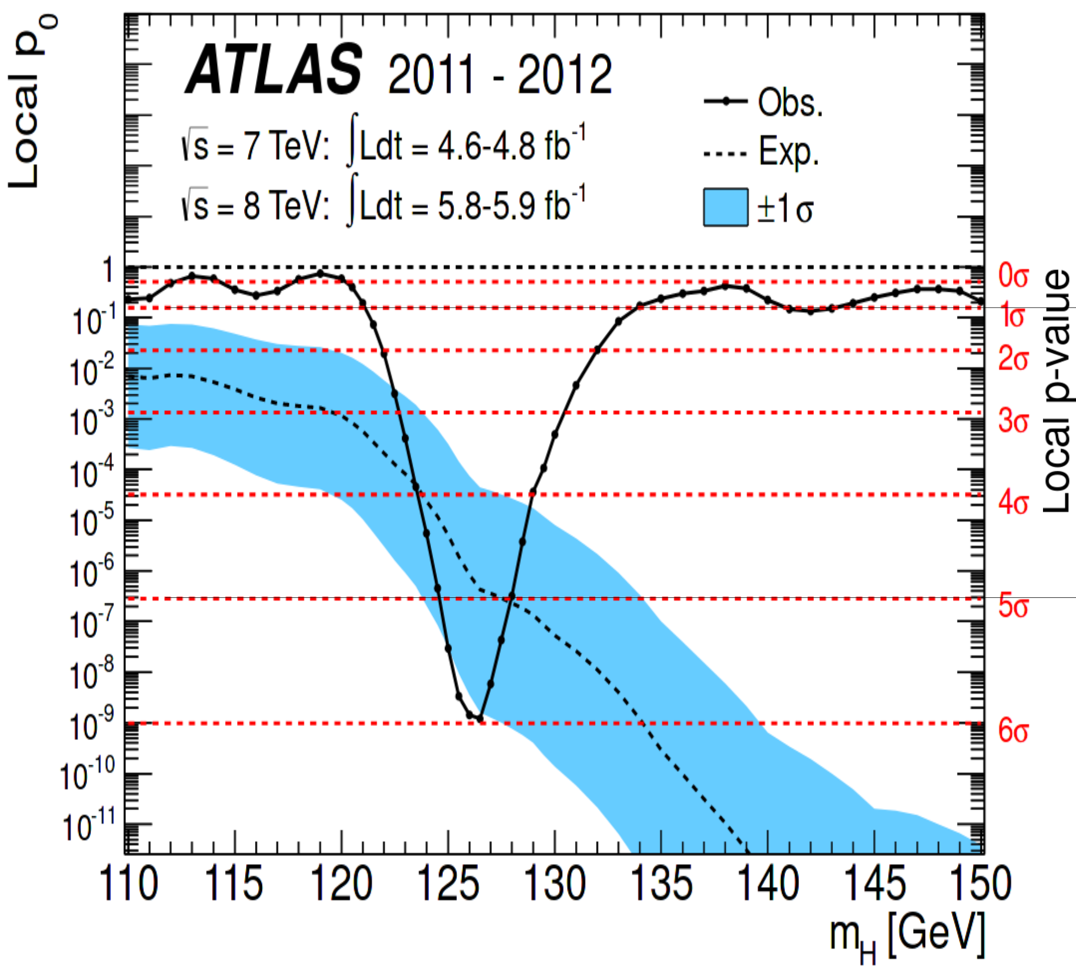
H -> ττ

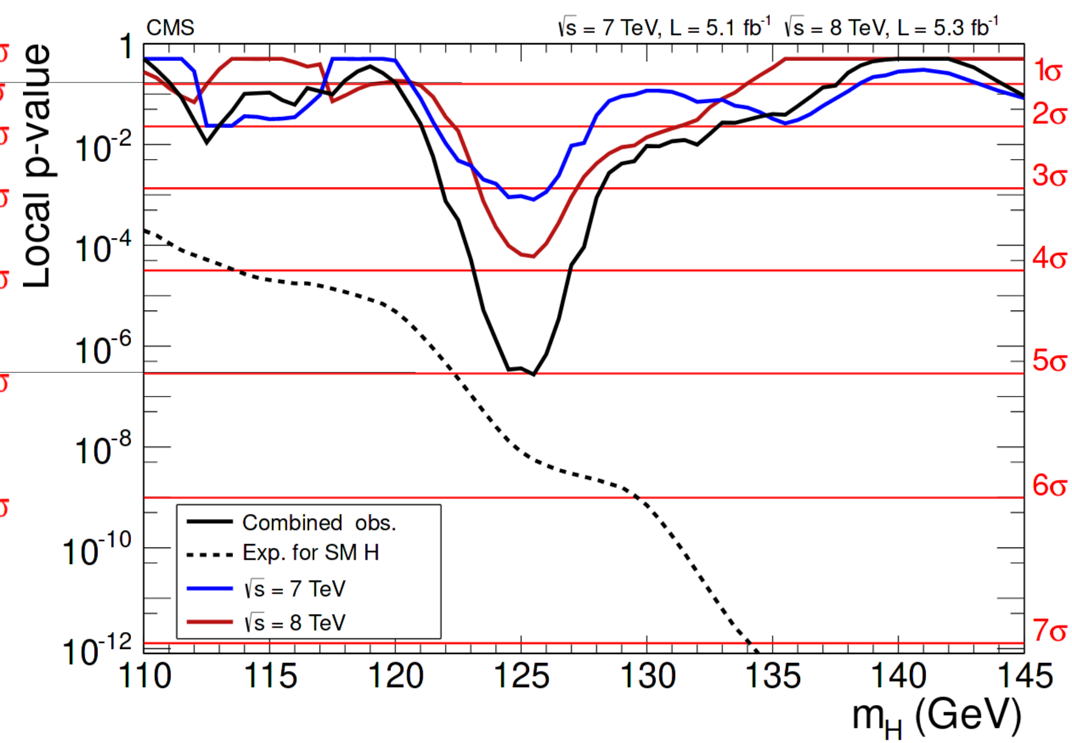
H -> bb

H -> ZZ -> 4l

ATLAS and CMS use consistent,
statistical tools.

Combined Channels Results





Historic Event: CERN–Melbourne

Rolf Heuer:

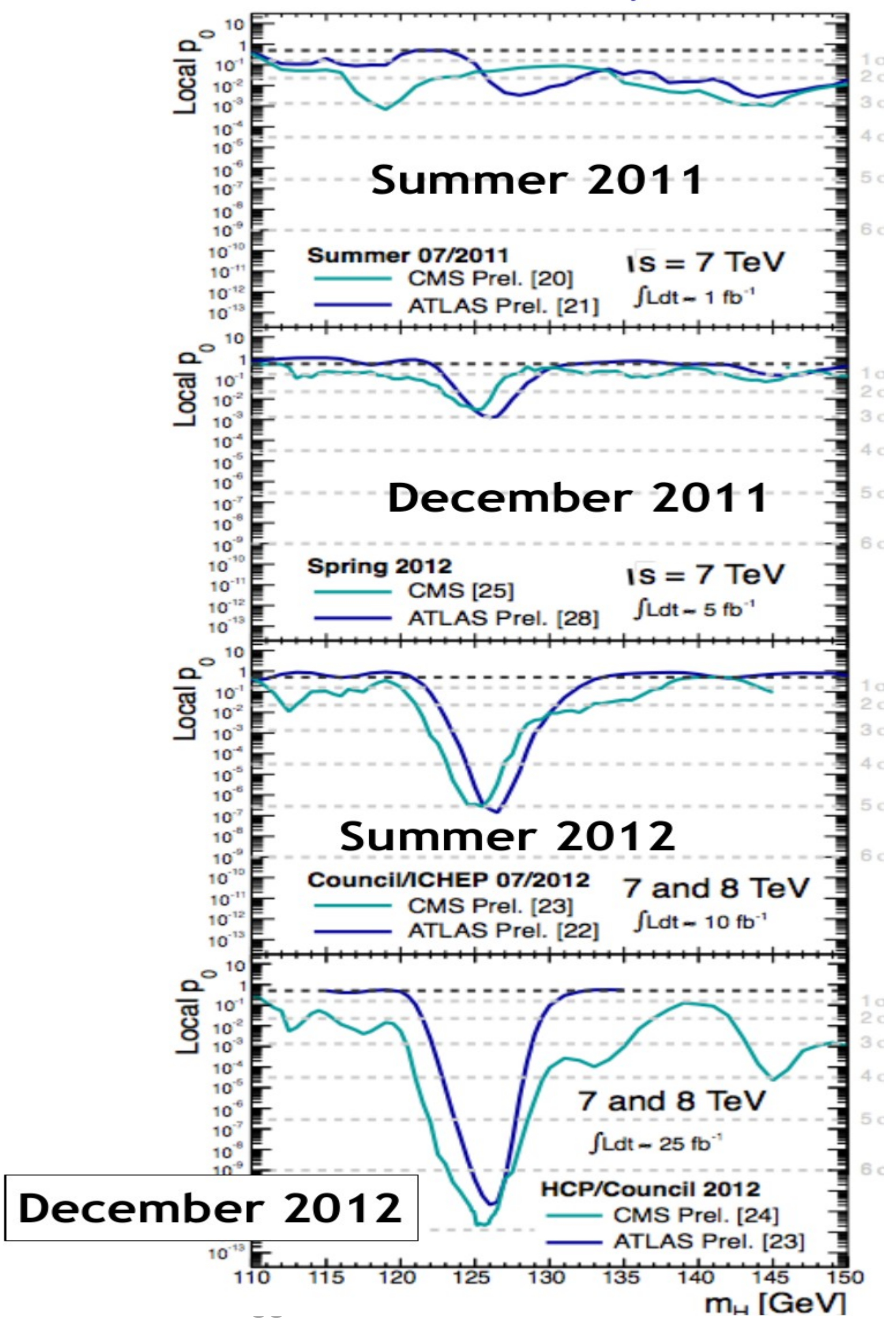
'We have it!'

4th of July 2012 – new Higgs–like particle discovery

International Recognition

Two nobel theorists

Nobel prize in physics 2013



Historic View

First exercise – Summer 2011

- Little data, last time with focus on limits

Building up – Winter 2011/2

- A small bump appears, but not enough for an observation

Discovery – Summer 2012

- The bump is confirmed in 8 TeV data: consistent between ATLAS/CMS
- Each experiment at 5 standard deviations
- New particle discovered

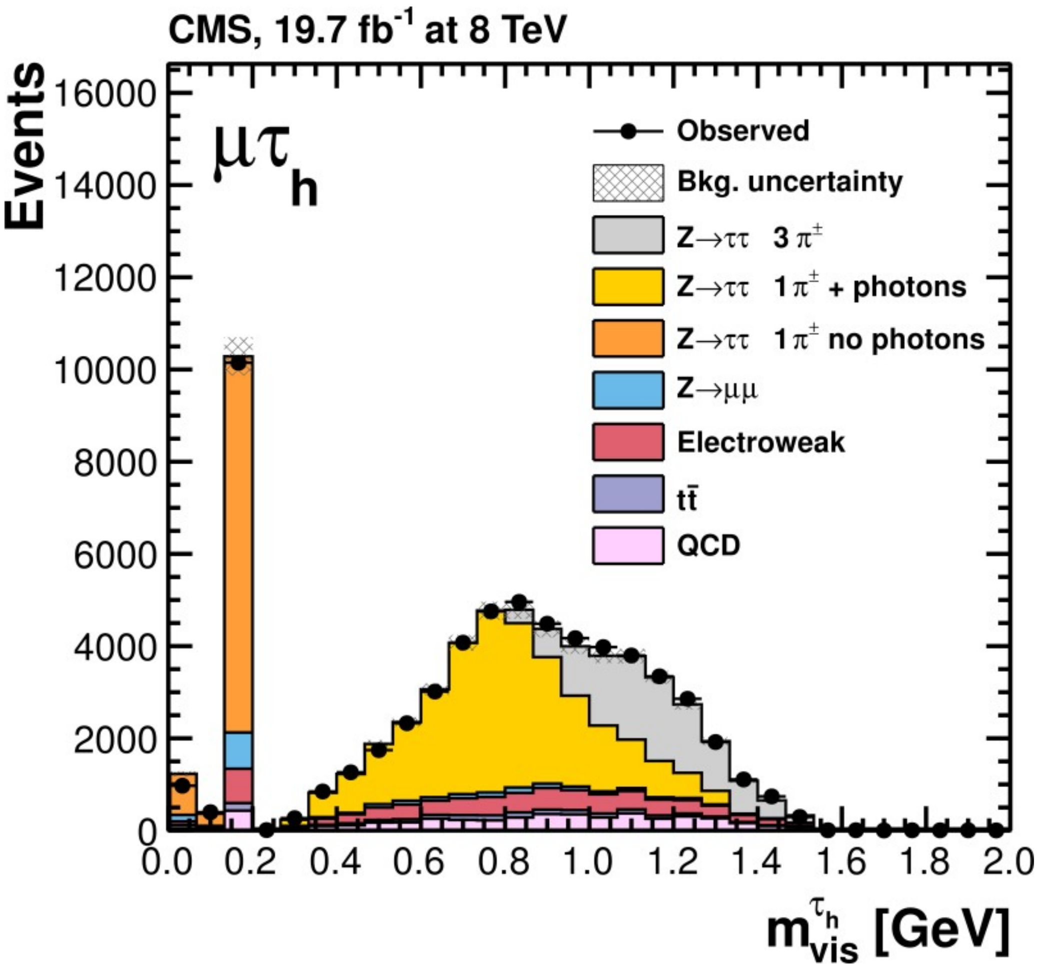
Measurements – December 2012

- Combined *p*-value plot becomes irrelevant
- Focus on measuring the new particle

Yukawa Couplings

Tau-lepton
b-quark
Muon

Higgs Coupling to Leptons?

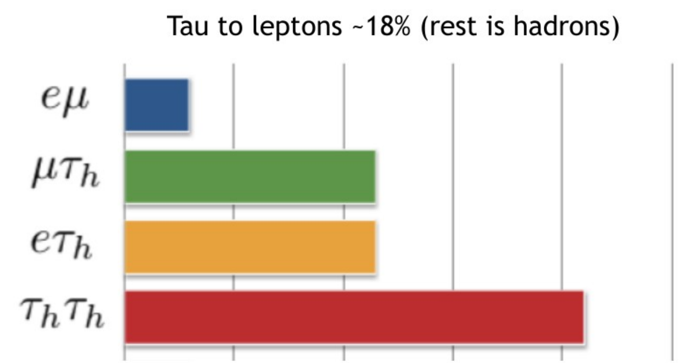


Decay: H→ ττ

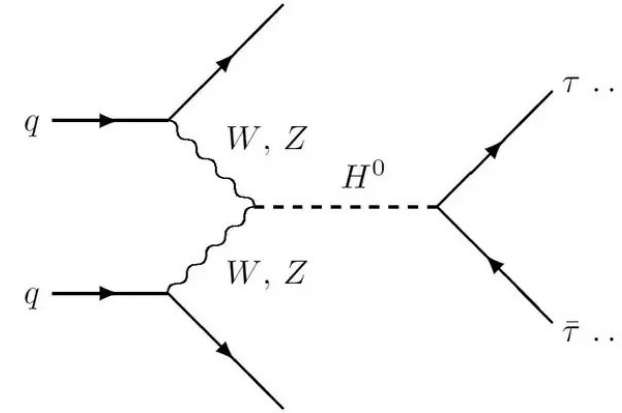
- Tau is heavy (good for Higgs), but also decays hadronically
- First channel probing Higgs to lepton couplings
- Good sensitive to some BSM models

Analysis challenges

- Tau identification is complex
- Always involves at least one neutrino
- Hadronically decaying taus can look like jets



VBF Production and $H \rightarrow \tau\tau$

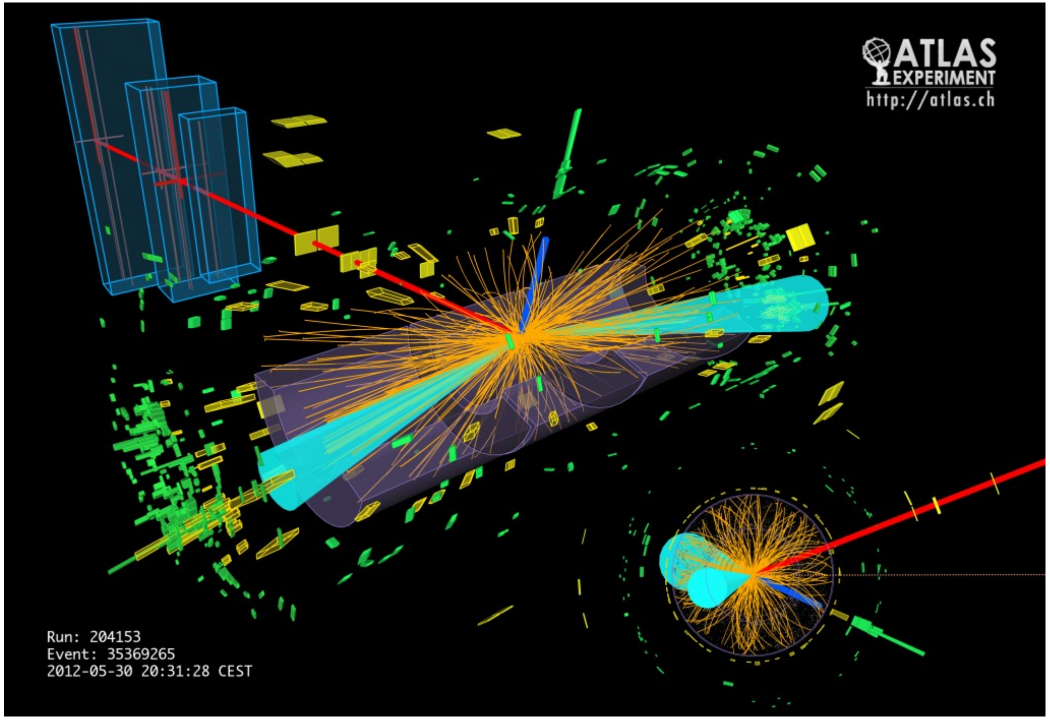


What helps with taus?

- Background is large and mass resolution is not great: neutrinos
- VBF production offers additional strong handles
- Two forward jets with large rapidity gap (color singlet exchange in t-channel)

Other things that help

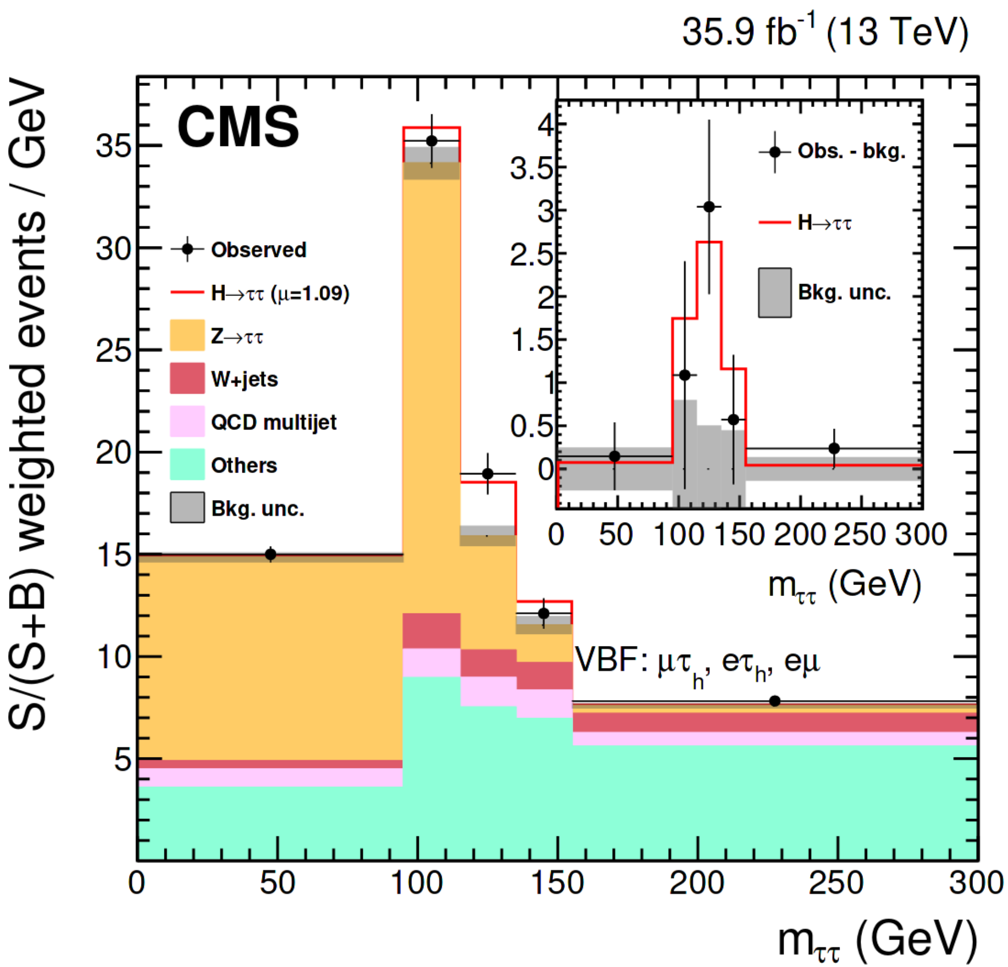
- Split gluon fusion production into categories splitting of boosted topologies → additional jet(s) in the event for boost
- Split into all possible categories to maximize sensitivity (0-jet, VBF, boosted) x ($e\mu$, $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$)
- This analysis is more complex

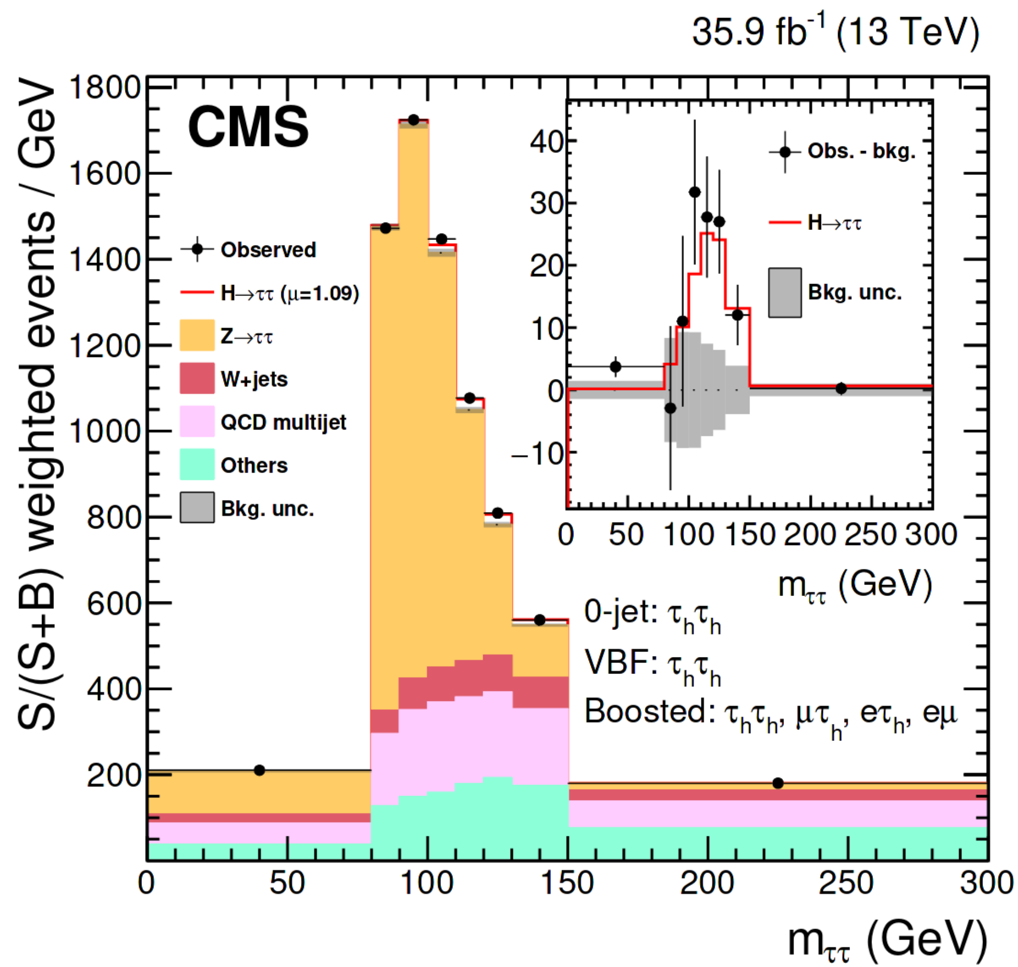


Observation of H→ ττ

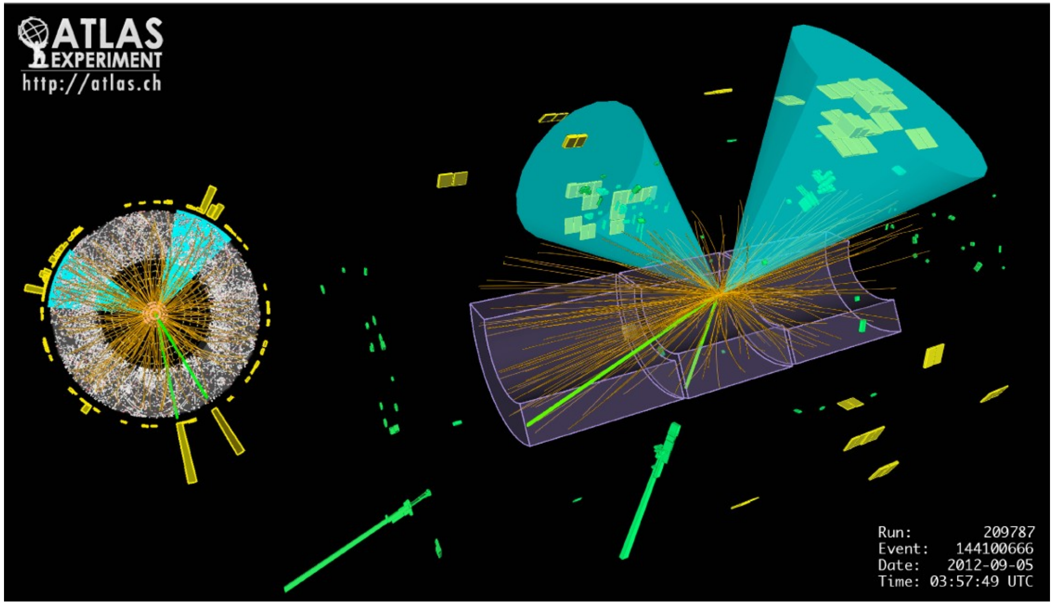
Evaluation of significance

- Observed excess corresponds to 5.9 standard deviations (expected 5.9)





Higgs Boson Decay to Quarks?



Decay: $H \rightarrow bb$

- b-quark is heavy (good for Higgs) largest branching fraction
- but also it is a hadron → jet, everything is a jet at hadron colliders
- Luckily b-hadrons are long lived and often produce displaced particle tracks
- But Z boson also decays to bb, and there are top production events and W+jets

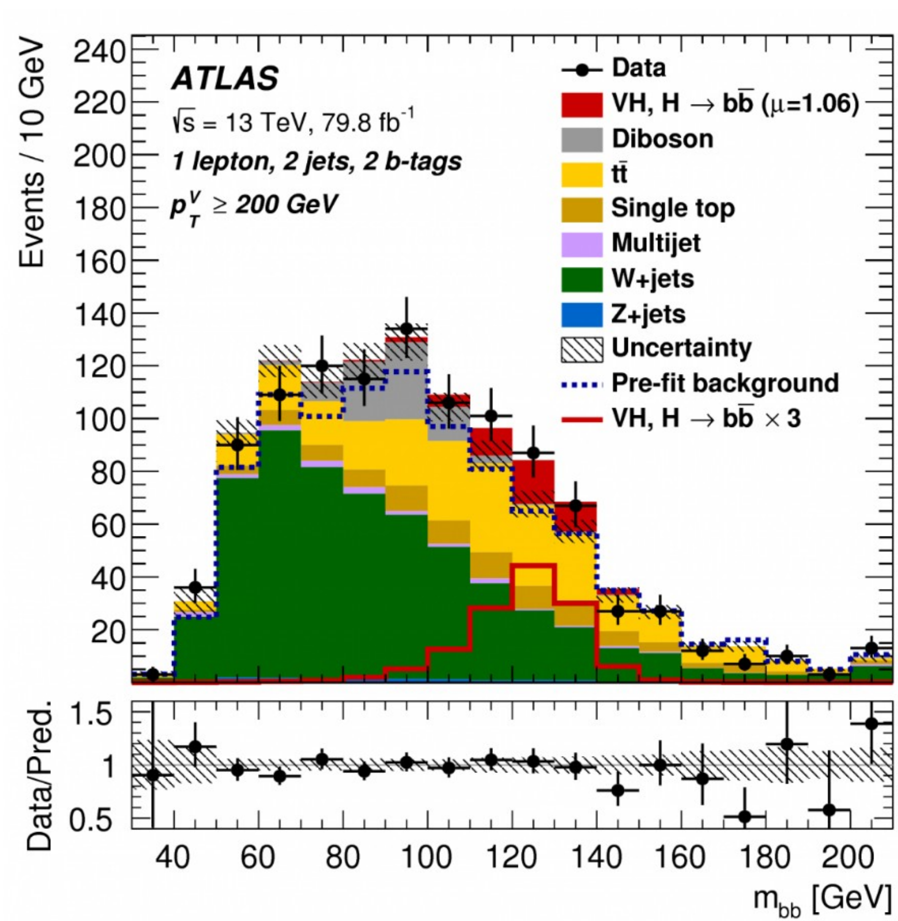
Analysis key idea

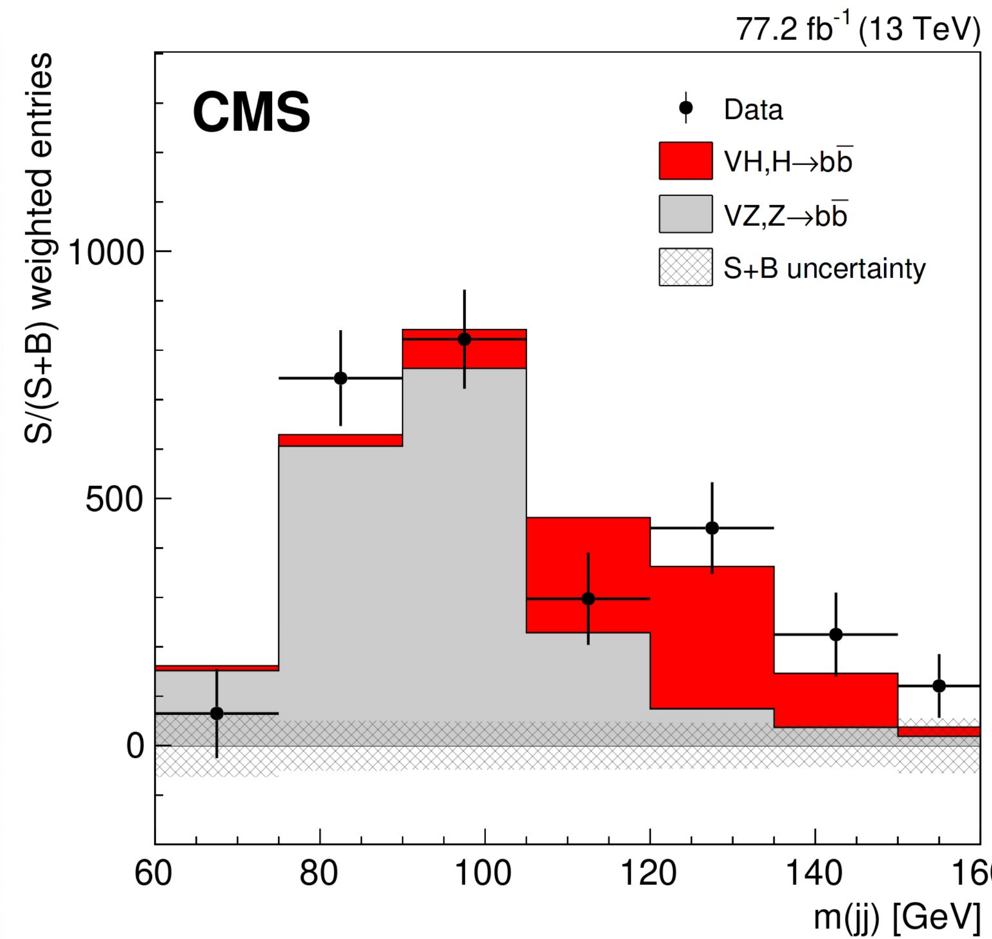
- Use associate production (*V*H) similar idea as with taus: *add handles to reduce background*
- *V* decays to leptons only (e, μ, ν)
- Categories are: zero ($Z \rightarrow \nu\nu$), one ($W \rightarrow l\nu$), or two ($Z \rightarrow ll$) charge leptons

Observation of H→ bb

Critical test

- Is the VZ(bb) described properly? Watch the W+jets background!

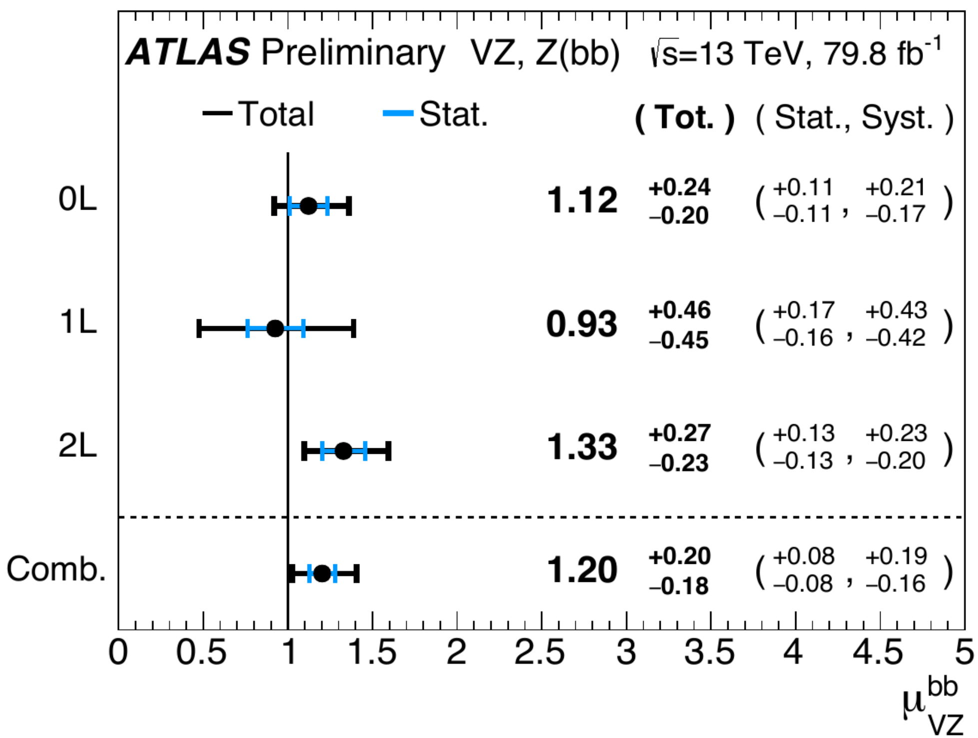


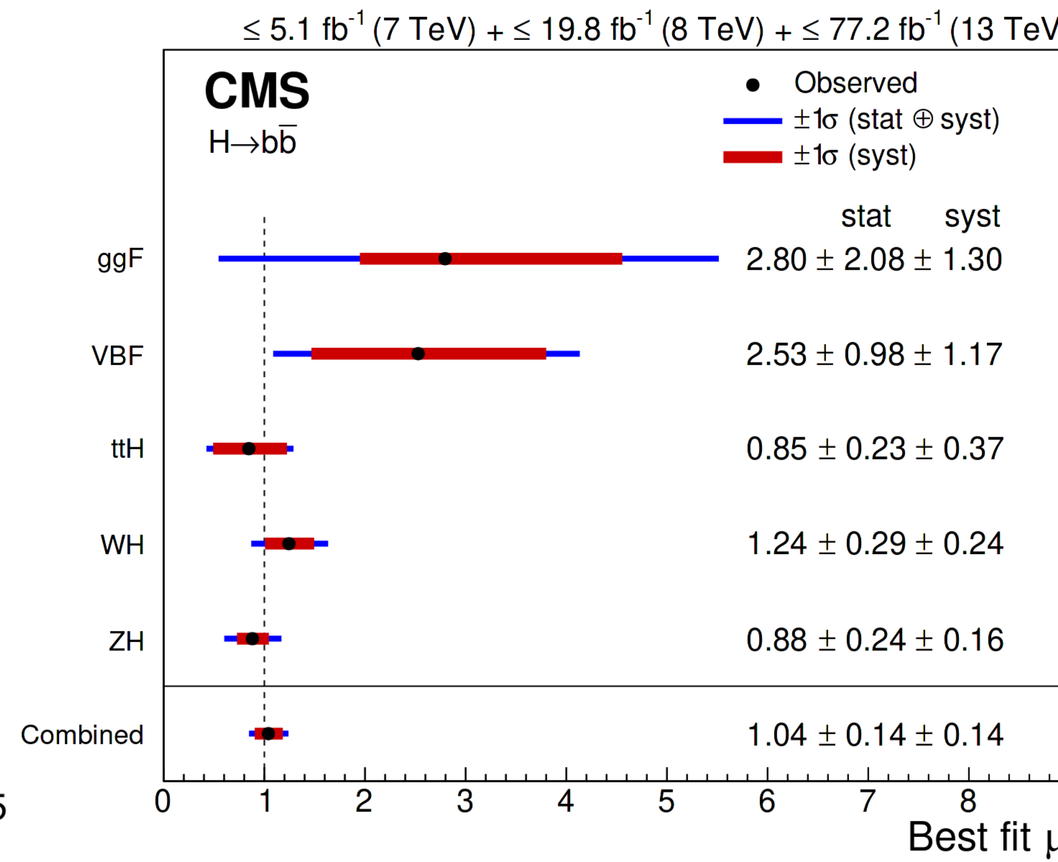


Observation of H→ bb

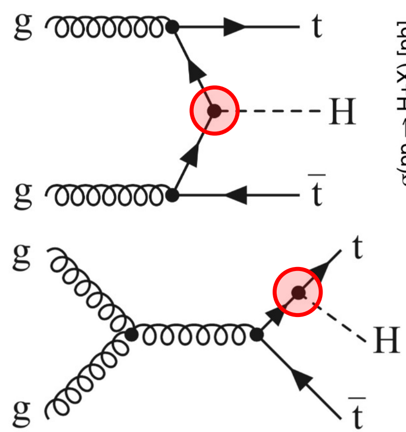
Observed and (Expected) Excess analysis

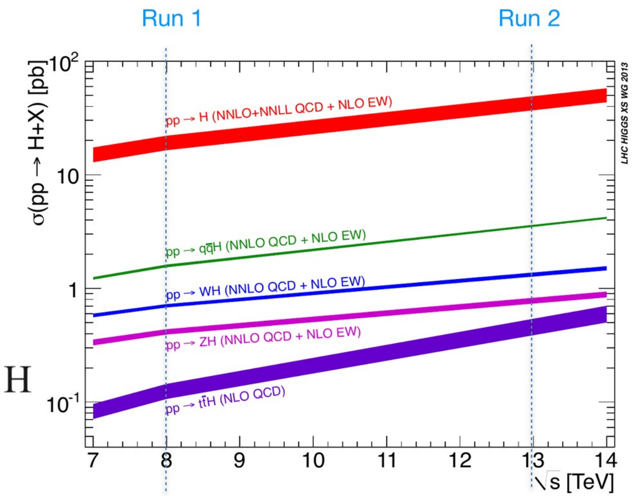
- ATLAS: 5.4 standard deviations (expected 5.5)
- CMS: 4.9 standard deviations (expected: 5.1)
- Consistent with SM expectation





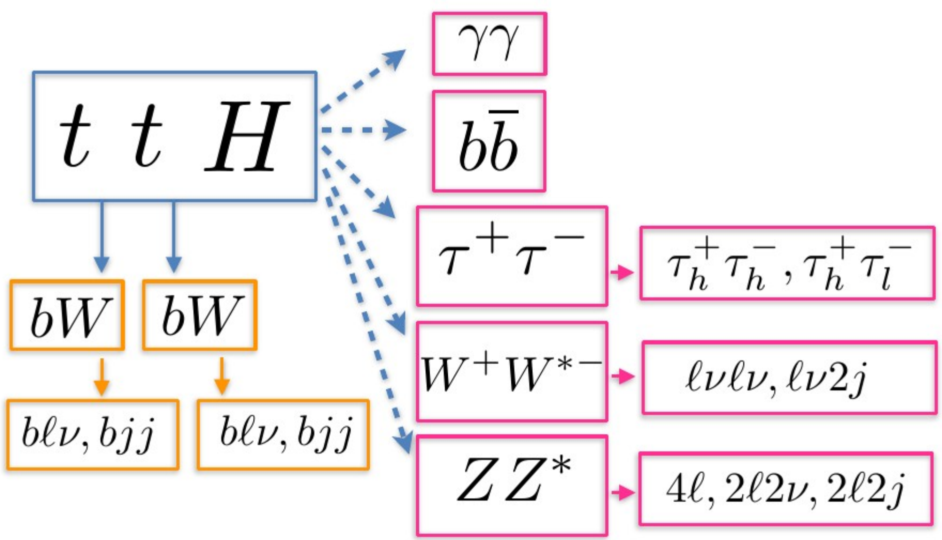
Higgs Boson Production ttH





Rare Production: ttH

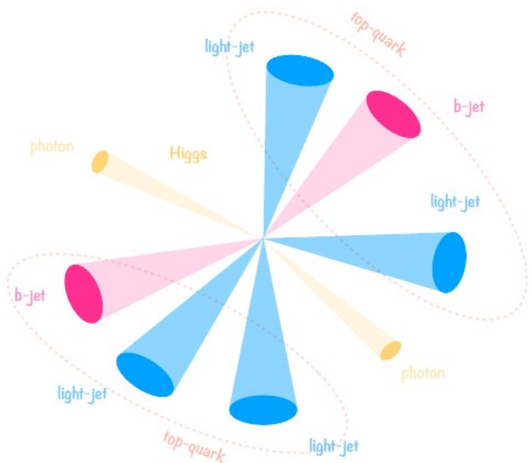
- Direct probe of the top to Higgs coupling
- Close to two orders of magnitude below gluon fusion
- ... due to heavy tops is the big winner with increase in center-of-mass energy in Run 2

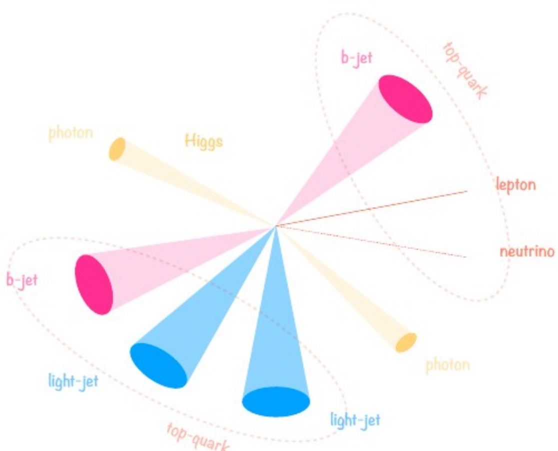


Analysis key ideas

- The ditop pair offers the required handles
- The rest is 'just-the-usual-Higgs' analysis
- Very complex due to large number of objects in final state and high number of permutations

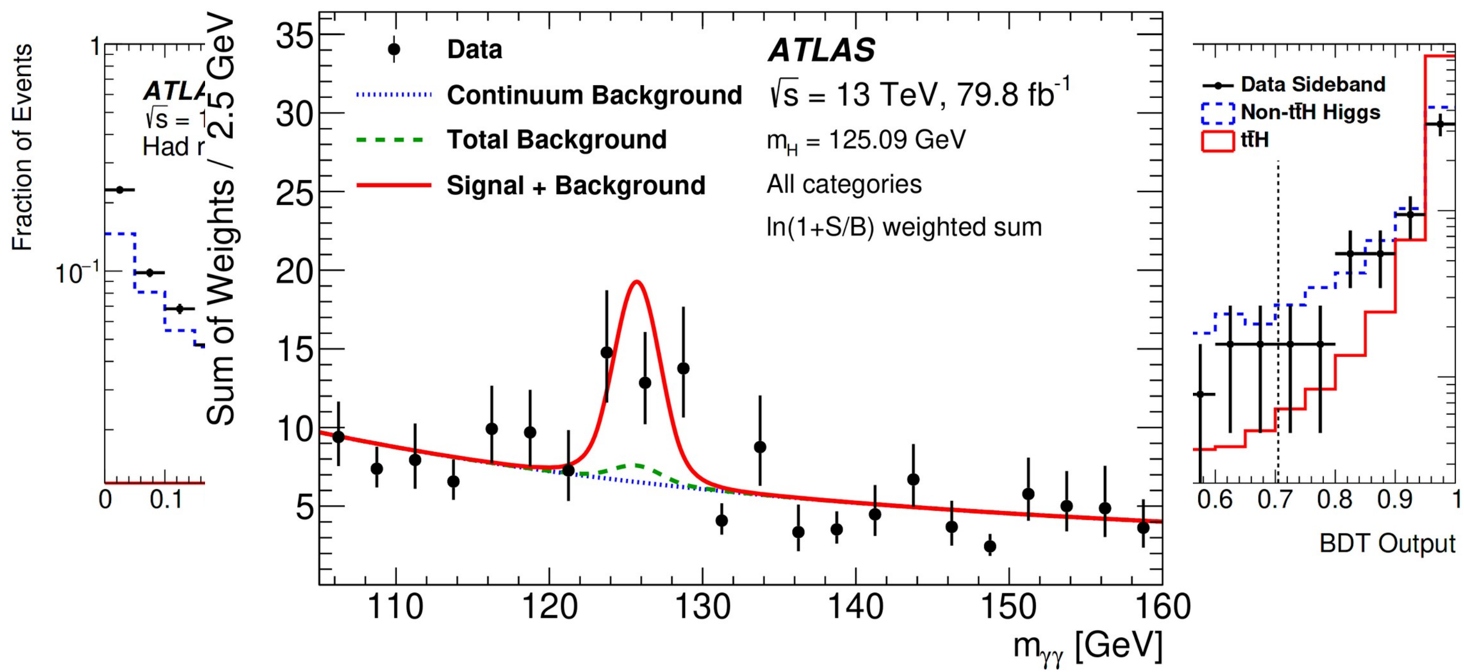
Higgs Boson Production ttH





ATLAS: ttH with H→γγ

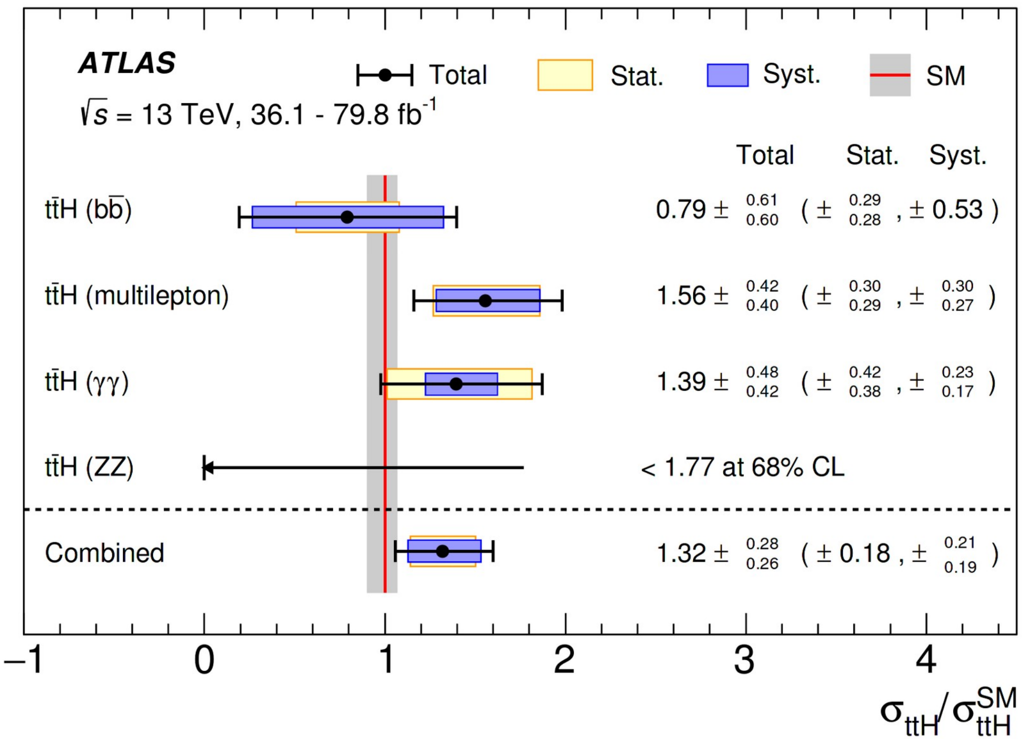
- Machine learning techniques come in handy
- Input four vectors of all analysis objects
- Train on signal MC and relevant backgrounds.
- Essential to have decent MC description

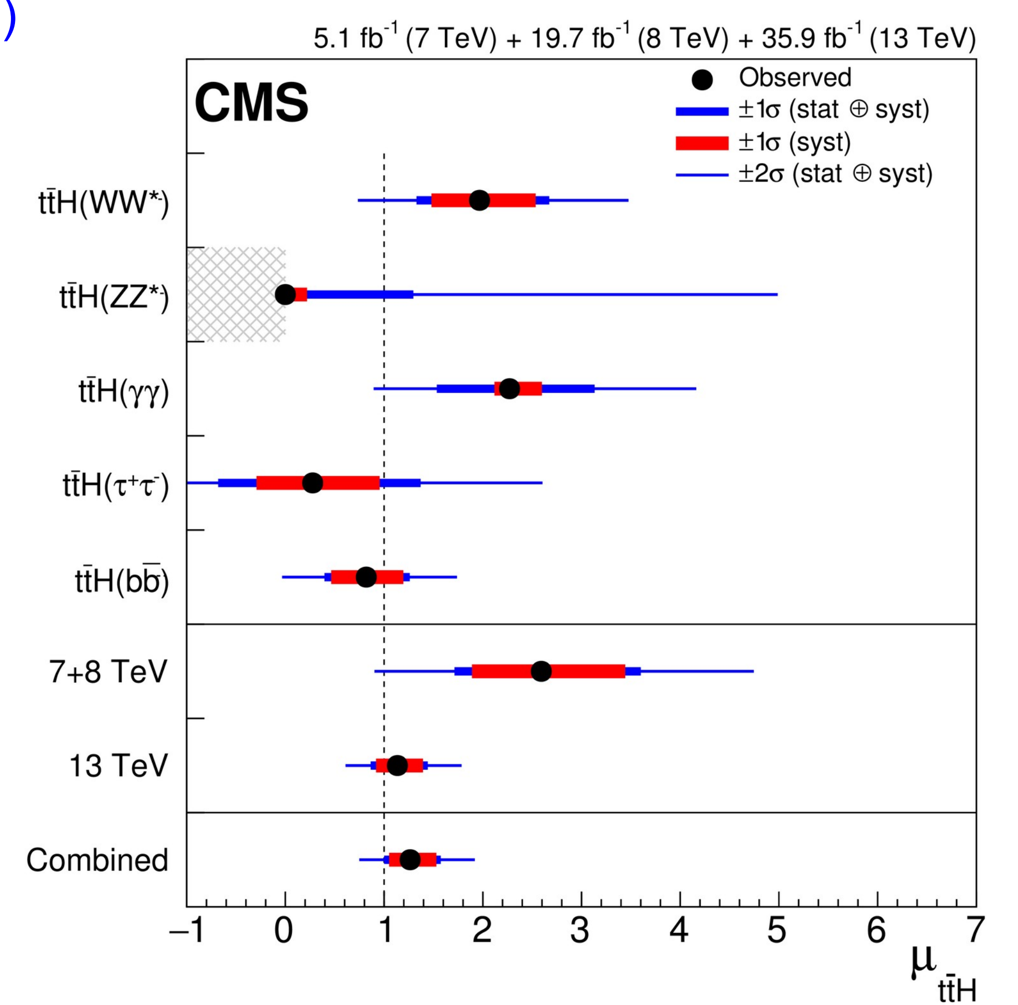


Higgs Boson Production ttH

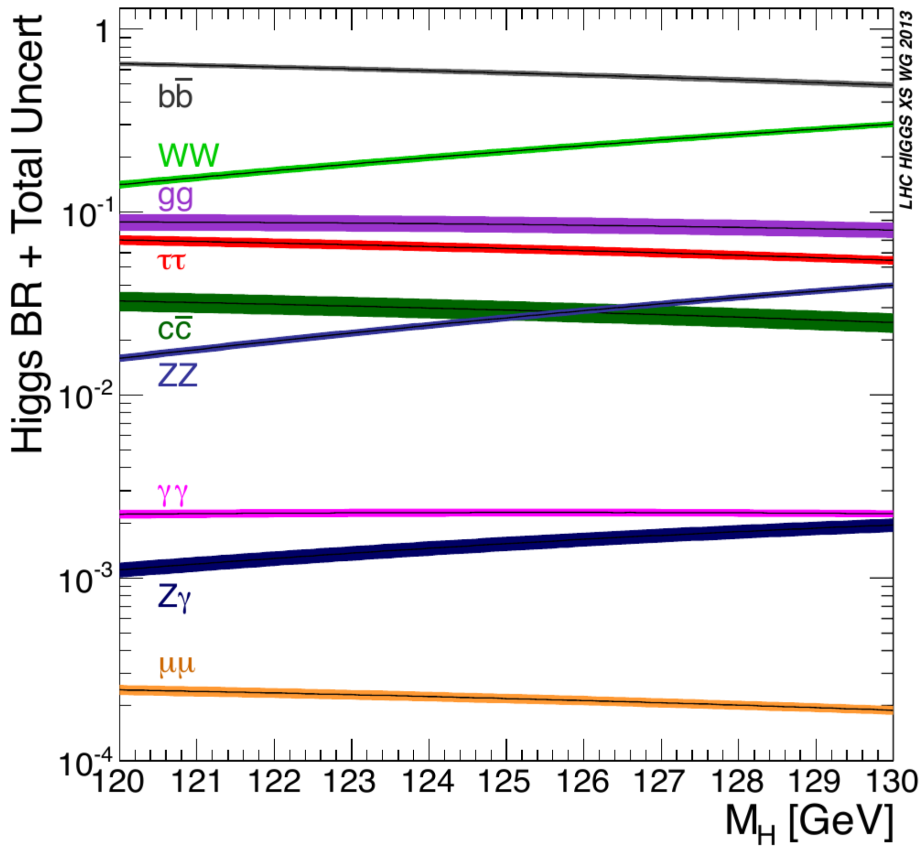
Observed and (Expected) Excess analysis

- ATLAS: 6.3 standard deviations (expected 5.1)
- CMS: 5.2 standard deviations (expected: 4.2)
- Consistent with SM expectation





Higgs Boson Coupling to 2nd generation?



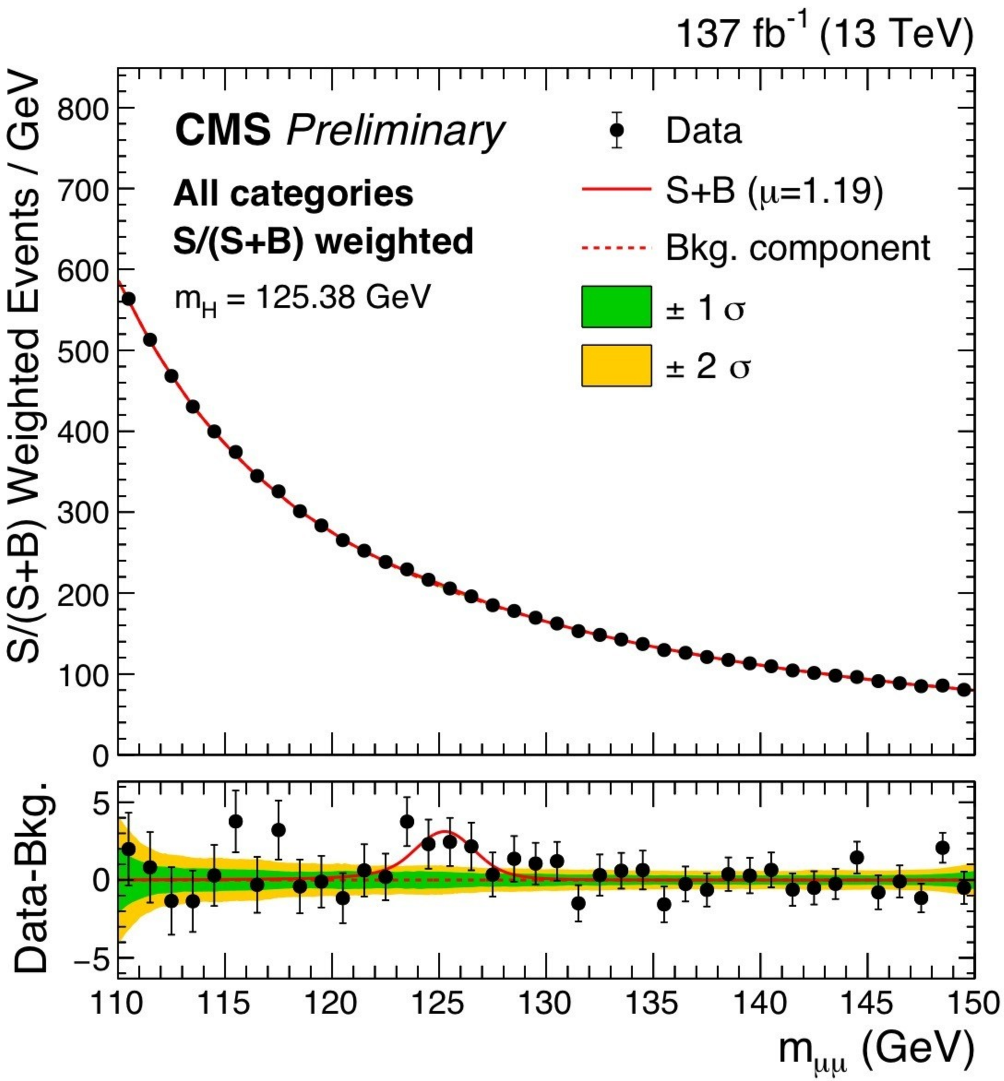
Decay: H→ μμ

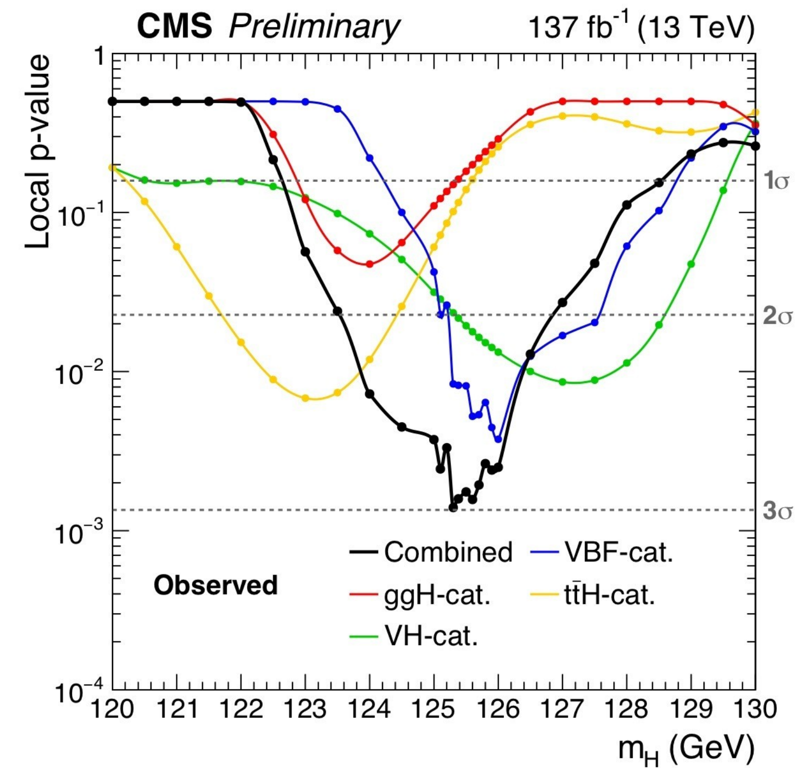
- Muon is lighter: m_μ = 105.6583755(23) MeV
- [Compare m_τ = 1776.86(12) MeV]
- Branching fraction: 0.02% (6.3% for ττ)

Analysis key idea

- We do know the Higgs mass ….
- Finding dimuon pair is straight forward but there are very few signal events and a continuous irreducible Drell-Yan background
- Some issues are similar to H→γγ but muons are much cleaner
- Scrape-the-barrel technique as for any search
- Include all production mechanisms and optimize each with full scale Deep Neural network

Evidence from CMS





Evidence: ≥3 standard deviations

- Signal model was studied in great detail
- Main contributor is VBF category

Very Similar for ATLAS

Excess seen

- Observed significance is 2.0 standard deviations, expected are 1.7
- Main contributor is also here the VBF category