Properties of the Higgs Boson

In the lecture, I will discuss the properties of the Higgs boson as predicted in the Standard Model and the comparison of these predictions to experiment. I will begin by discussing the various couplings of the Higgs boson and their implications for the pattern of Higgs boson decays. We will then turn to Higgs boson production at the LHC and ask how the Higgs boson can actually appear in the LHC data.

The story of the Higgs boson might be much more complicated that that provided by the Standard Model. But the Standard Model expectations are in any case an important reference point, and that will already give us quite a bit of material for this lecture.

The tree level couplings of the Higgs boson in Standard Model can be derived very simply. In unitarity gauge, we gauge away all components of the Higgs doublet field except for the the component that contains the vacuum expectation value. Then

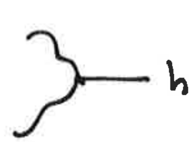
$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

From this formula, it is apparent that the coupling of the Higgs boson to any species is just

$$\delta\mathcal{L} = h \cdot \frac{\partial \mathcal{L}}{\partial v}$$

Thus,

fermion:  $= -i\,\frac{m_f}{v}$

gauge boson:  $= i\,\frac{2m_V^2}{v}\,g^{\mu\nu}$

Even for the Higgs boson itself, we find the self-coupling

Higgs boson  $= -3i \frac{m_h^2}{v}$

From these vertices, it would seem that the Higgs boson should decay dominantly to the heaviest particles of the Standard Model, the W and Z bosons and the top quark. However, reality is not so simple. The mass of the Higgs boson turns out to be about 125 GeV, a value small enough that none of the decays

$$h \to t\bar{t} \qquad h \to W^+W^- \qquad h \to ZZ$$

are allowed kinematicalliy. Instead, we have to take the next best options—Higgs decays into lighter (though still somewhat heavy) species, and Higgs decays into off-shell W, Z, and t. There are many processes in this category, leading to a large number of possible decay modes. This is in fact a good thing, since it will allow us to study a wide range of coupings of Standard Model particles to the Higgs boson.

Let us now go through the various possible types of Higgs boson decay processes. First, we have Higgs decays to quarks and leptons. For a light fermion, we can ignore the fermion mass except in the Higgs coupling. Then we can easily compute the matrix element using 2-component spinors. The matrix element for $h \to f_R \overline{f}_R$, for example, is

$$i\mathcal{M} = -i \frac{m_f}{v} u_R^\dagger v_R$$

$$= -i \frac{m_f}{v} 2p \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

$$= -i \frac{m_f m_h}{v}$$

Then

$$\Gamma(h \to f\bar{f}) = \frac{1}{2m_h}\frac{1}{8\pi}\frac{m_f^2 m_h^2}{v^2}\cdot 2 = \frac{m_f^2 m_h}{8\pi}\frac{1}{4m_W^2/g^2}$$

$$= \frac{\alpha_w}{8} m_h \frac{m_f^2}{m_W^2}$$

The Higgs decay to $f\bar{f}$ is actually in the P wave, so the more complete dependence on the fermion mass is

$$\Gamma(h \to f\bar{f}) = \frac{\alpha_w m_h}{8}\frac{m_f^2}{m_W^2}\left(1 - \frac{4m_f^2}{m_h^2}\right)^{3/2}$$

This would matter only for a heavier Higgs boson decaying to $t\bar{t}$.

For the decays to leptons, we can read off immediately

$$\Gamma(h \to \tau^+\tau^-) = 260 \text{ keV} \qquad \Gamma(h \to \mu^+\mu^-) = 9 \text{ keV}$$

For decays to quarks, QCD corrections are important. These are of two types. First, there is a color factor of 3 and a multiplicative correction from hard gluon radiation, as we saw in $W, Z \to q\bar{q}$. For the scalar decay, the effect is larger

$$3 \cdot \left(1 + \frac{17}{3\pi}\alpha_s(m_h) + \cdots\right) = 1.24$$

Second, the quark mass in the partial width formula should be the $\overline{MS}$ mass evaluated at the scale $Q = m_h$, which is related to the quark mass as usually quoted by the relation

$$m_f(m_h) = m_f(m_f)\cdot\left[\frac{\alpha_s(m_h)}{\alpha_s(m_f)}\right]^{4/b_0}(1 + \mathcal{O}(\alpha_s))$$

The quark masses at 125 GeV are

m_u	m_d	m_s	m_c	m_b
1.5	3	60	700	2800

MeV

so, for example,

$$\Gamma(h \to b\bar{b}) = \frac{\alpha_w}{8} \cdot \left(\frac{2.8}{m_W}\right)^2 (1.24) \cong 2.4 \text{ MeV}$$

As we will see, $h \to b\bar{b}$ is the dominant mode of decay for a 125 GeV Higgs boson, with a branching ratio of 58%. Scaling from this, the branching ratios for other fermion decays are

τ	c	s	μ
6.3%	3%	0.03%	0.02%

It is interesting that the τ mode is larger than the c mode. The larger τ mass (when evaluated at m_h) overcomes the QCD factors. The quoted 58% branching ratio for $h \to b\bar{b}$ implies a total width for the Higgs boson of 4.1 MeV.

Next, we turn to the Higgs decays to WW and ZZ. For on-shell W and Z, the matrix elements would be

$$i\mathcal{M}(h \to W^+W^-) = i\,\frac{2m_W^2}{v}\,\epsilon^*(+)\cdot\epsilon^*(-)$$

$$i\mathcal{M}(h \to ZZ) = i\,\frac{2m_Z^2}{v}\,\epsilon^*(1)\cdot\epsilon^*(2)$$

The product of longitudinal polarization vectors is

$$\epsilon^*(1)\cdot\epsilon^*(2) = \frac{p_1 p_2 + E_1 E_2}{m_Z^2} \sim \frac{m_h^2}{2m_Z^2}$$

The enhancement this provides is similar to that seen in the examples of the previous lecture. Since

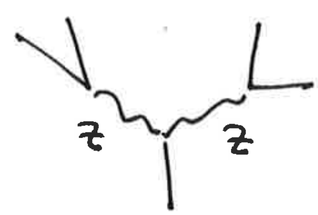
$$m_h = \sqrt{2\lambda}\, v$$

we have

$$\frac{2m_Z^2}{v} \cdot \frac{m_h^2}{2m_Z^2} = 2\lambda v$$

so also in this case the enhancement converts a gauge coupling into a Higgs field coupling strength.

Fior the actual situation of a 125 GeV Higgs boson, one or both of the W or Z bosons resulting from the decay must be off the mass shell. Then the Higgs boson decay is better represented as a decay to 4 fermions



The mass distributions of the virtual W and Z are shown in Figure 1.

The dynamics of the Higgs decay to ZZ can be thoroughly explored experimentally in the case in which both Z bosons decay to charged leptons. Unfortunately, this happens only in 0.2% of $h \to ZZ$ decays, both those events are readily gathered at the LHC and contain a great deal of information. With the hZZ coupling of the Standard Model, it is still true that the longitudinal vector boson polarization states dominate, so that the leptons are central in $\cos\theta$, and that the decay planes formed by the two leptonic decays tend to be parallel;

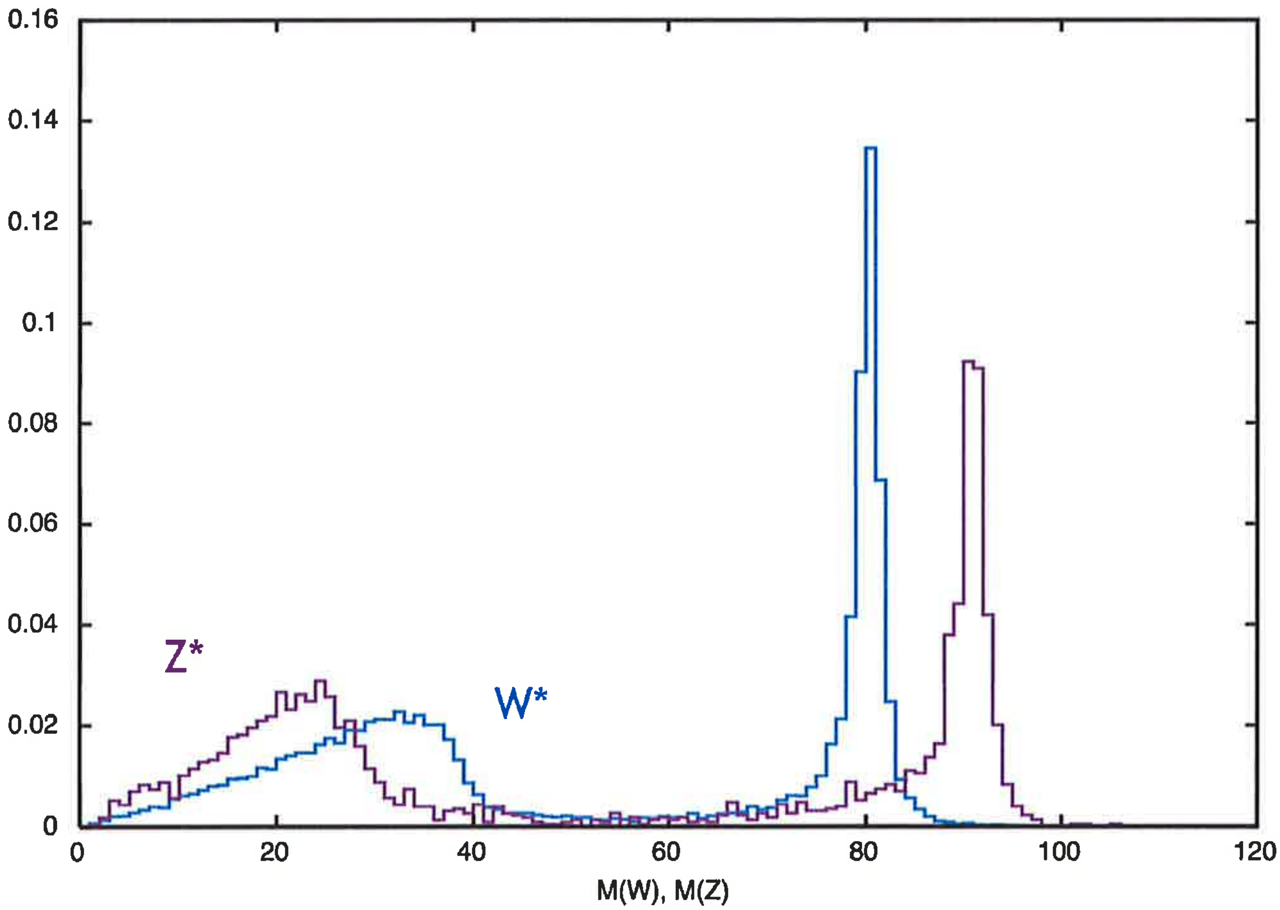


Fig. 1 Invariant mass distribution of the two vector bosons in $h \to WW^*$ and $h \to ZZ^*$, for $m_h = 120$ GeV.

This contrasts with the case of a pseudoscalar boson coupling to Z by

$$\Delta \mathcal{L} = C\, \varepsilon^{\mu\nu\lambda\sigma} F_{\mu\nu} F_{\lambda\sigma}$$

where $F_{\mu\nu}$ is the Z field strength. In this latter case, the Z polarizations will be transverse and the decay planes will be orthogonal. Even with the current very small sample of about 15 events per LHC experiment, the two cases can be discriminated at about 3 σ, with the data favoring the Standard Model form of the coupling.

Figure 2 shows tests of the Standard Model coupling hypothesis against hypotheses of other possible spin-parity assignments for the 125 GeV boson, as evaluated by the CMS collaboration. The hypothesis of spin 1 is also excluded by the observation of the decay $h \to \gamma\gamma$, to be discussed below. A spin 1 particle decaying in the S wave cannot decay to $\gamma\gamma$, since in this case only spins 0 and 2 are permitted.

Unsing Bose statistics, this conclusion can be extended to a decay in any partial wave, a result called the Landau-Yang theorem. The analysis shown in Figure 2 also excludes a number of specific forms of spin 2 couplings to ZZ.

Given that hte decay to WW and ZZ would be dominant for a Higgs boson with mass greater than 180 GeV, these modes are also still important for a boson of 125 GeV. The Standard Model predictions for the branching ratios are

$$WW^* \quad 22\% \qquad ZZ^* \quad 2.7\%$$

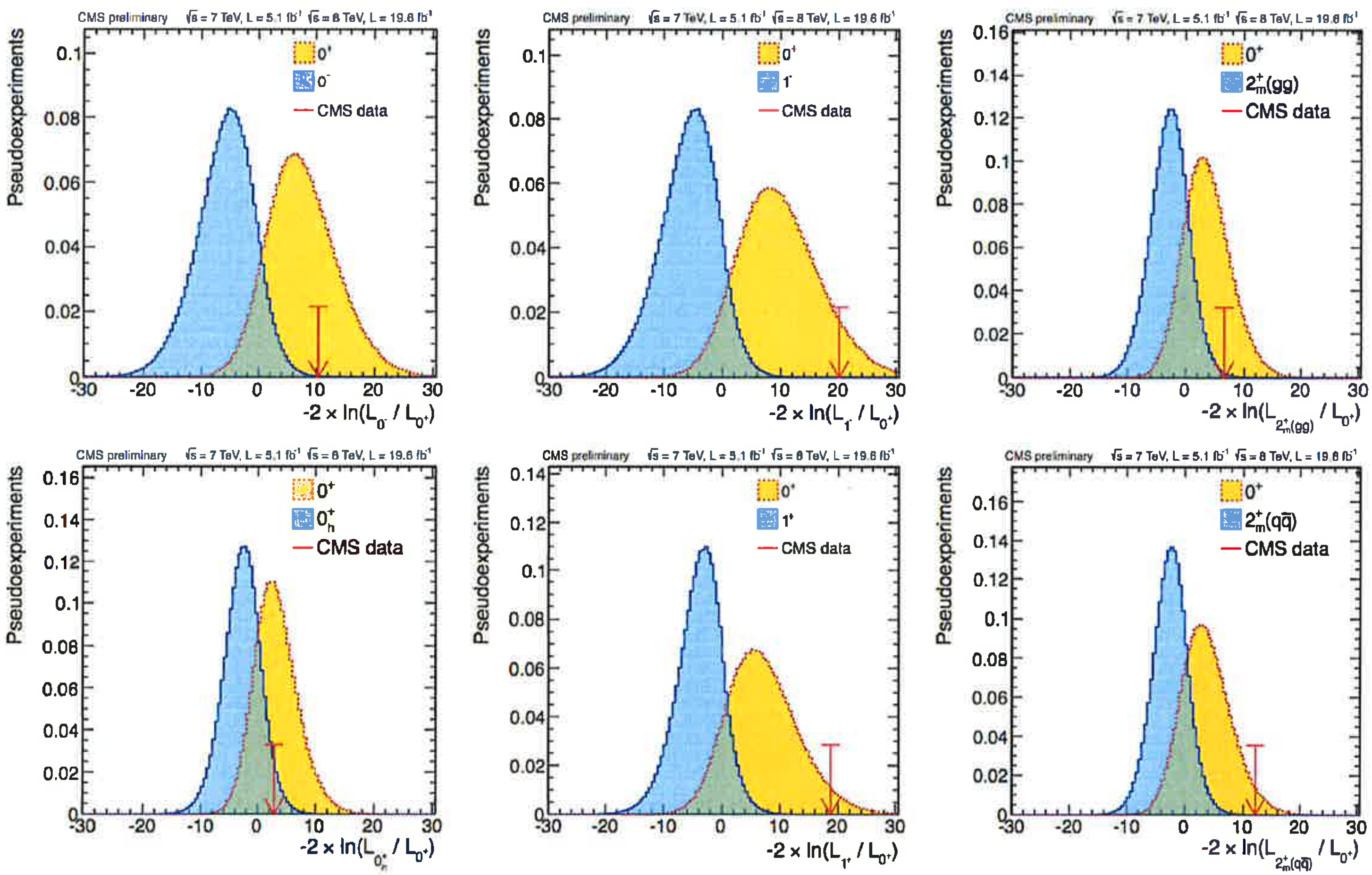


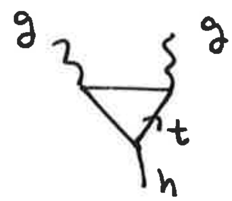
Fig. 2 Likelihood distributions for the hypothesis of the Standard Model hZZ coupling and for alternative spin-parity hypotheses, compared to data from the CMS experiment, from CMS-PAS-HIG-13-002 (2013)

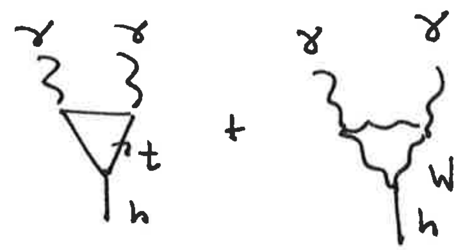
For observations at the LHC, these branching ratios must be multiplied by the branching ratios for leptonic decays of the W and Z. The predicted Higgs branching ratios depend very strongly on the precise mass of the Higgs boson

$$\frac{\Delta BR}{BR} \sim 14 \, \frac{\Delta m_h}{m_h}$$

For a prediciton with 1% uncertainty, the Higgs boson mass must be known to 100 MeV.

Finally, the Higgs boson can decay to massless vector bosons, $\gamma\gamma$ and gg. These particles have no direct coupling to the Higgs boson, but they can be connected to the Higgs through loop diagrams,



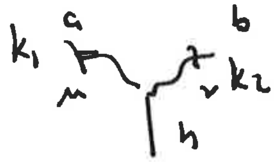


It is not so hard to compute these diagrams directly, but there is also a simple set of arguments to understand the values of these diagrams in the limit in which the Higgs mass is much lighter than those of the W and the t.

I will first discuss the case of $h \to gg$, for which only the t quark contributes. To understand the form of the coupling, represent it as an effective operator. This operator must be gauge-invariant, so the coupling of lowest dimension is

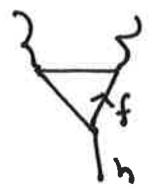
$$\Delta\mathcal{L} = \frac{A}{2}\, h \cdot F^a_{\mu\nu} F^{\mu\nu a}$$

This corresponds to a vertex



$$= -iA\,\delta^{ab}\left(k_1 \cdot k_2\, g^{\mu\nu} - k_1^\nu k_2^\mu\right)$$

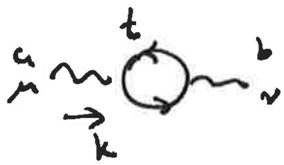
The coefficient A has the dimensions of $(\mathrm{mass})^{-1}$. In principle, any quark could contribute to A through a loop diagram. The size of this diagram would be



$$\sim \alpha_s \frac{m_f}{v} \cdot \frac{1}{M} \cdot \left(k_1 \cdot k_2\, g^{\mu\nu} - \dots\right)$$

where M is the momentum flowing in the loop, If $m_h > 2m_f$, we have $M \sim m_h$, and the diagram is suppressed by m_f/m_h. On the other hand, if $m_h < 2m_f$, then $M \sim 2m_f$ and the diagram is approximately independent of the quark mass. Oddly, only those quarks that are too heavy to appear in Higgs decays contribute to this amplitude.

To estimate the size of the contribution from the top quark, consider first the top quark vacuum polarization diagram



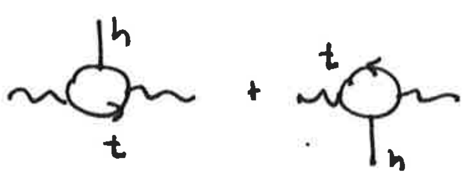
$$= i\left(k^2 g^{\mu\nu} - k^\mu k^\nu\right) \mathrm{tr}(t^a t^b) \frac{\alpha_s}{3\pi} \log \Lambda^2/m_t^2$$

$$= i\left(k^2 g^{\mu\nu} - k^\mu k^\nu\right) \delta^{ab} \frac{\alpha_s}{6\pi} \log \Lambda^2/m_t^2$$

Now

$$m_t^2 = \frac{y_t^2 v^2}{2}$$

and, since the coupling of the Higgs field is entirely account by $v \to v+h$, the coupling of a zero-momentum Higgs boson to two gluons is given by



$$= i\left(k^2 g^{\mu\nu} - k^\mu k^\nu\right) \delta^{ab} \frac{\alpha_s}{3\pi} \frac{1}{v}$$

Then

$$A = \frac{\alpha_s}{3\pi v} = \frac{g\,\alpha_s}{6\pi m_W}$$

The partial width for $h \to gg$ in the limit $m_h \ll 2m_t$ is then

$$\Gamma(h \to gg) = \frac{\alpha_w \alpha_s^2}{72\pi^2} \frac{m_h^3}{m_W^2}$$

The exact 1-loop expression is

$$\Gamma(h \to gg) = \frac{\alpha_w \alpha_s^2}{72\pi^2} \frac{m_h^3}{m_W^2} \cdot \left| \frac{3}{2} \tau \left[1 - (\tau - 1)\left(\sin^{-1} \frac{1}{\sqrt{\tau}}\right)^2 \right] \right|^2$$

where

$$\tau = \frac{4m_t^2}{m_h^2}$$

It is interesting that the amplitude for $h \to gg$ is related to the top quark contribution to the QCD β function. If the coupling constants of the Standard Model did not run, we could consider all of the mass scales of the Standard Model to be set by v. The Higgs field, which is a fluctuation of v, would be the Goldstone boson of spontaneously broken scale invariance. In the real Standard Model, scale invariance is also explicitly broken by the running of couping constants, and this effect provides zero-momentum couplings for this Goldstone boson.

A similar argument gives the Higgs boson couplings to $\gamma\gamma$. The top quark contribution to the electromagnetic vacuum polarization is

$$= i(k^2 g^{\mu\nu} - k^\mu k^\nu) \frac{3 Q_f^2 \alpha}{3\pi} \log \Lambda^2 / m_t^2$$

The contribution of W bosons to this vacuum polarization is proportional to the vector contribution to the β function of an $SU(2)$ gauge theory; in particular, it has the opposite sign from the fermionic contribution.

W


$$= i(k^2 g^{\mu\nu} - k^\mu k^\nu)\,\frac{\alpha}{4\pi}\left(-\frac{22}{3}\right) \log \Lambda^2/m_W^2$$

Finally, we must include the contribution to the β function from the Higgs field that is eaten by the W boson when it gets mass. The complete vacuum polarization amplitude is

$$= i(k^2 g^{\mu\nu} - k^\mu k^\nu)\,\frac{\alpha}{4\pi}\Big[\underset{W^+}{-\frac{22}{3}} + \underset{\pi^+}{\frac{1}{3}} + \underset{t}{\frac{4}{3}\cdot 3\cdot\left(\frac{2}{3}\right)^2}\Big] \log\frac{\Lambda^2}{v^2}$$

$$= i(k^2 g^{\mu\nu} - k^\mu k^\nu)\left(-\frac{\alpha}{3\pi}\right)\left[\frac{21}{4} - \frac{4}{3}\right] \log\frac{\Lambda^2}{v^2}$$

Then we find for the partial width, in the limit $m_h \ll 2m_W, 2m_t$,

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha_w \alpha^2}{144\pi^2}\,\frac{m_h^3}{m_W^2}\left|\frac{21}{4} - \frac{4}{3}\right|^2$$

Careful evaluation, including QCD corrections to the $h \to gg$ width, gives

$$BR(h \to gg) = 8.6\% \qquad BR(h \to \gamma\gamma) = 0.23\%$$

The complete pattern of Standard Model Higgs branching ratios is shown as a function of the Higgs boson mass in Figure 3.

To study the Higgs boson couplings at the LHC, we must address two more issues. First, we need to understand the processes by which the Higgs boson is produced at the LHC. Second, we need to understand the prospects for actually observing the Higgs boson in each decay mode among the various products of LHC reactions.

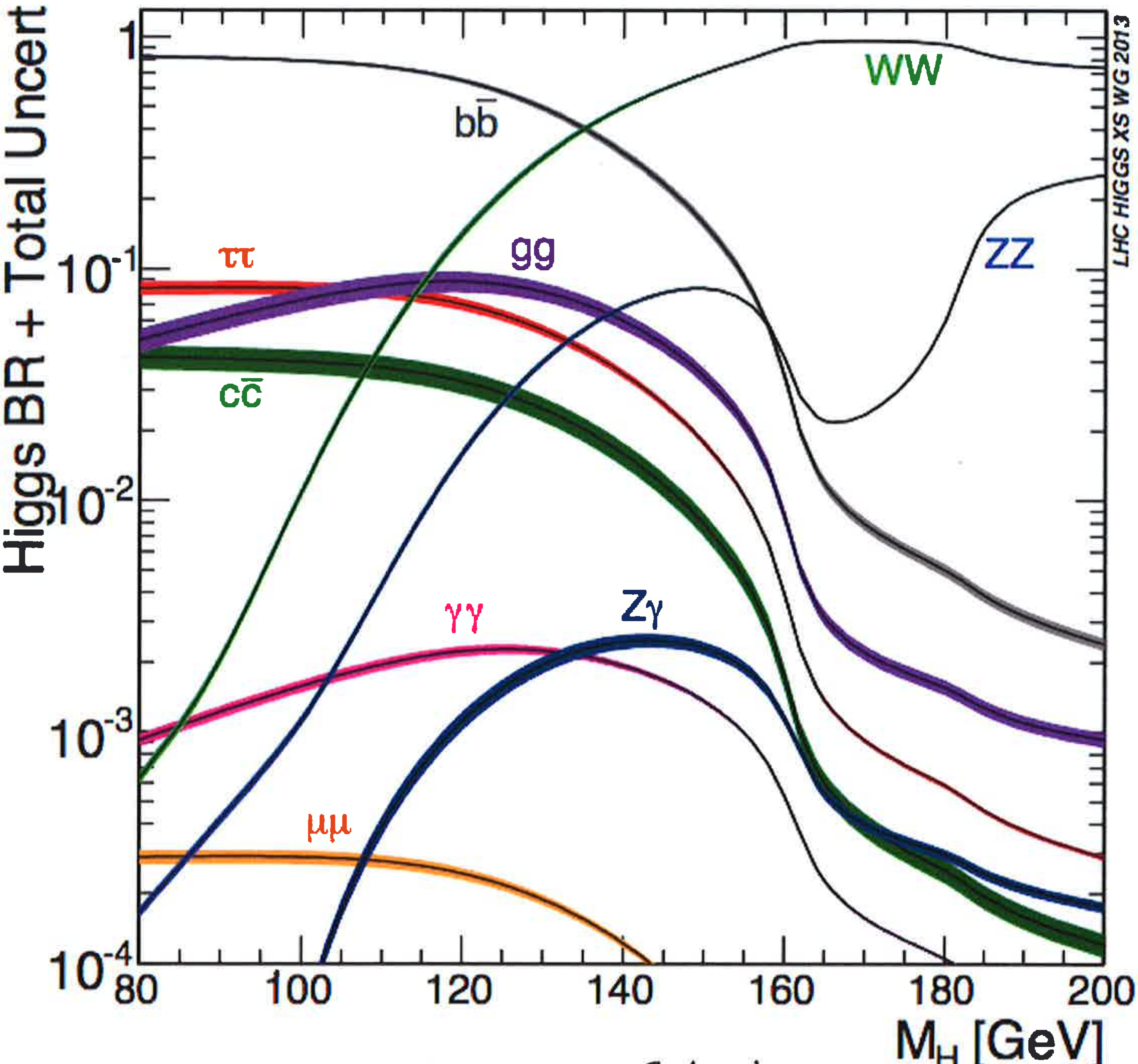
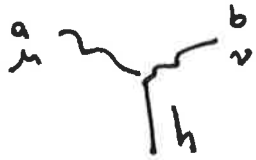


Fig. 3 Standard Model predictions for the Higgs boson branching ratios as a function of m_H, from LHC Higgs Cross Section Working Group, arXiv: 1307.1347

I will first discuss the production processes. We have just conputed the Higgs boson decay amplitude to gg. If we turn this process around, we obtain the process

$$gg \to h$$

which turns out to be the Higgs production process with the largest cross section. The matrix element we computed above has the form



$$i\, A^{\mu\nu}\, \epsilon^*_\mu(1) \cdot \epsilon^*_\nu(2) \cdot \delta^{ab}$$

and gives a decay rate

$$\Gamma(h \to gg) = \frac{1}{2m_h}\, \frac{1}{8\pi} \cdot \frac{1}{2} \cdot 8 \cdot \sum_{pol.} \left| A^{\mu\nu} \epsilon^*_\mu(1)\, \epsilon^*_\nu(2) \right|^2$$

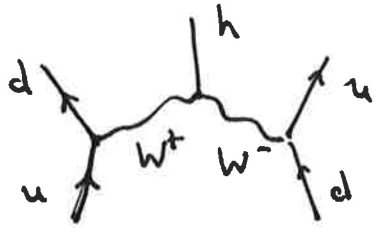
The same matrix element predicts a Higgs production rate, using the 1-body phase space explained in lecture 2,

$$\sigma(gg \to h) = \frac{1}{2} \cdot \frac{1}{2} \cdot \frac{1}{8} \sum_{pol.} \frac{1}{2s}\, 2\pi\, \delta(\hat{s} - m_h^2) \left| A^{\mu\nu} \epsilon_\mu(1)\, \epsilon_\nu(2) \right|^2$$

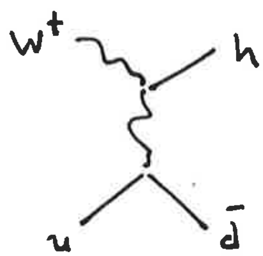
Comparing these expressions, we find

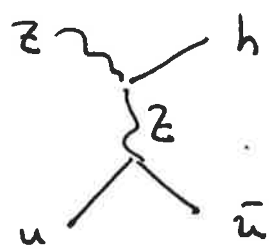
$$\sigma(gg \to h) = \frac{\pi^2}{8}\, \frac{\Gamma(h \to gg)}{m_h}\, \delta(\hat{s} - m_h^2)$$

Other production processes for the Higgs boson are vector boson fusion, analyzed in the previous lecture

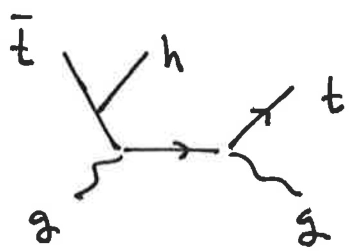


associated production with a W or Z boson





and radiation from a top quark



The predicted values of the four cross sections in pp collisions, as functions of center of mass energy, is shown in Figure 4.

Though the $gg \to h$ cross section is the largest at the LHC, it is not always the preferable one for studies of the Higgs boson. If the Higgs boson does not stand out among other Standard Model reaction products, we need to go to other reactions in which the Higgs boson is produced with other objects that tag its presence. In the cases of vector boson fusion or associated production, we would use the hard forward jets or leptonic W and Z decays to enhance the probability that a given event actually includes Higgs boson production. And, since the top quark does not appear in Higgs decays, we must study the associate production with top if we wish to measure the $ht\bar{t}$ coupling.

Among the various Higgs decays, there are only two in which the Higgs appears as a characteristic and full reconstructable object at the LHC. These are

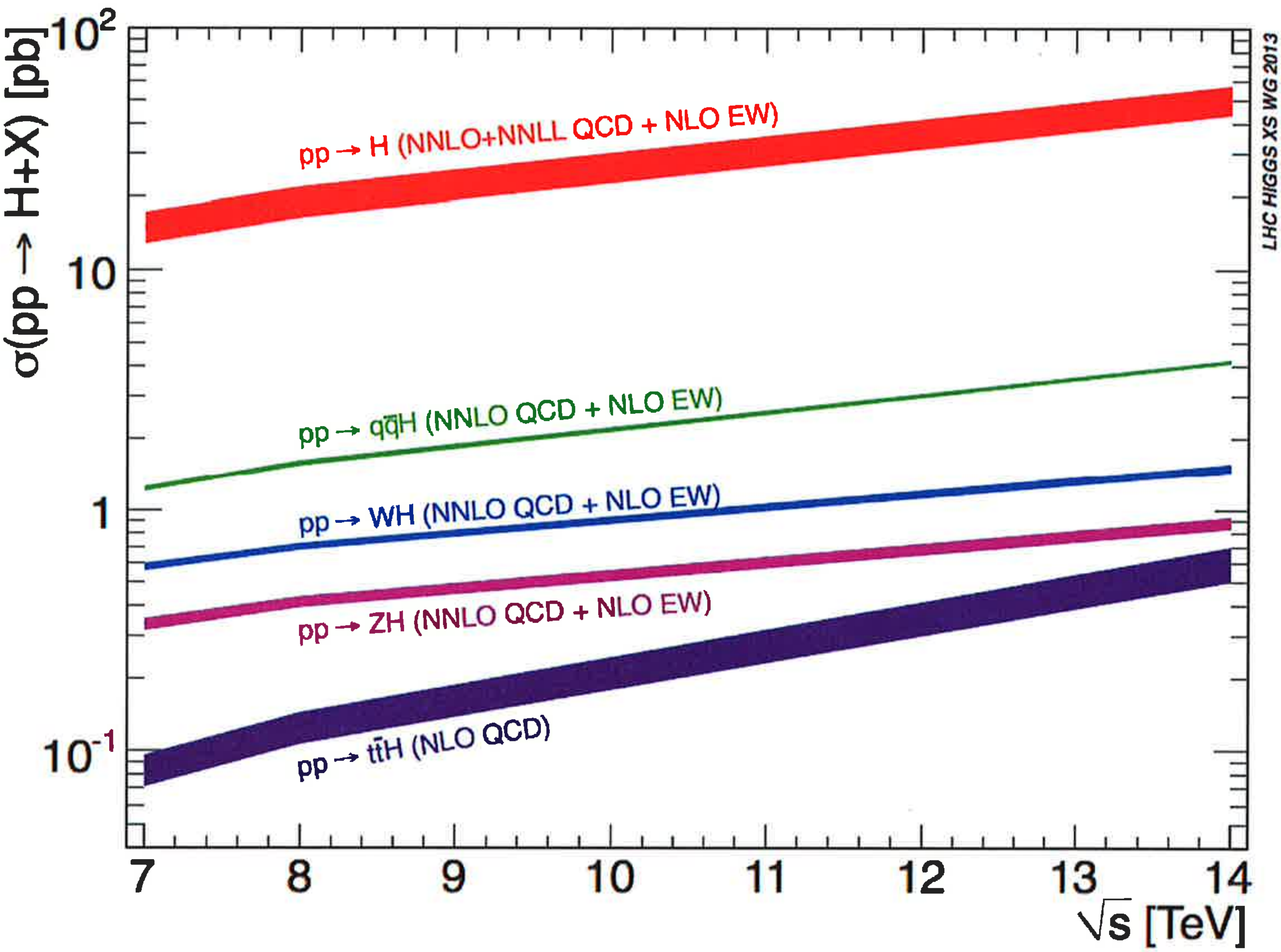


Fig. 4 Higgs boson production cross sections in the Standard Model, as a function of pp center of mass energy, from the Particle Data Group review of Higgs properties, pdg.lbl.gov

$$h \to \gamma\gamma \qquad BR = 0.23\%$$

$$h \to ZZ^* \to 4\ell \qquad BR = 1 \times 10^{-4}$$

These are the only cases in which the decay products of the Higgs are leptonic or electromagnetic particles, in which the backgrounds are moderate, and in which all decay products of the Higgs boson are observed. In these modes, the Higgs boson appears as a significant resonance in an appropriate distribution. These are the modes in which the Higgs boson was original discovered. Figure 5 shows the current $\gamma\gamma$ invariant mass distribution from the CMS experiment. Events are collected in a variety of signal categories and appear in the plot weighted by the probably of $\gamma\gamma$ signal, as opposed to background, events in each category. Figure 6 shown the current 4 lepton invariant mass distribution for the ATLAS experiment. Both plots, and the corresponding plots from the other experiments, show clear evidence fo rthe presence of a resonance near 125 GeV. Figure 7 shows an event display from ATLAS of a candidate

$$pp \to h \to ZZ^* \to e^+e^- \mu^+\mu^-$$

event.

Higgs identification in the other decay modes is much more difficult. A Higgs decay to WW^* appears as

$$pp \to h \to WW^* \to \ell^+\nu \, \ell^-\bar{\nu}$$

that is, as a pair of leptons plus $\not{E}_T$. This is no obvious reconstructable mass peak. The process

$$pp \to W^+W^- \to \ell^+\nu \, \ell^-\bar{\nu}$$

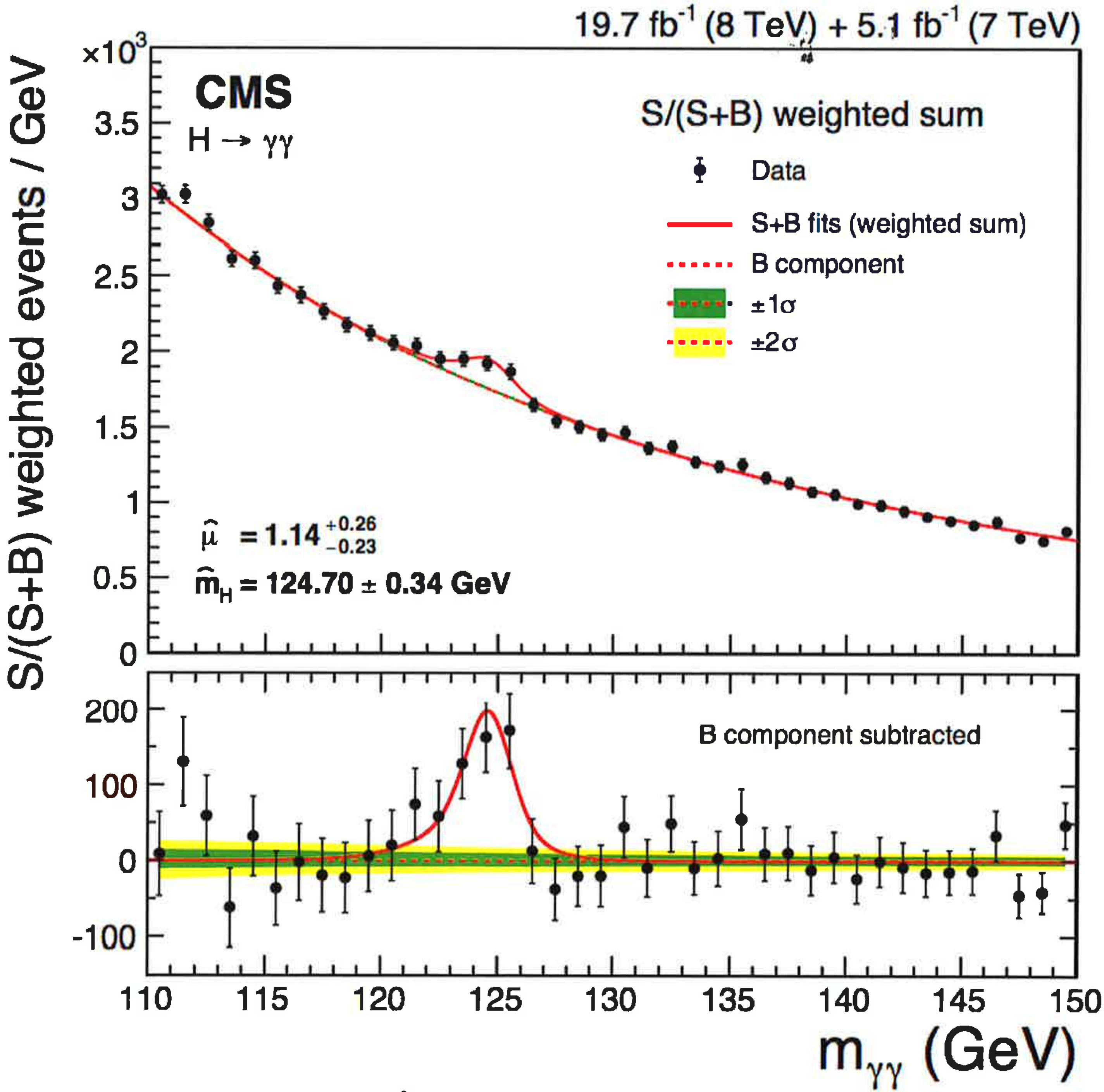


Fig. 5 Distribution of $pp \rightarrow \gamma\gamma + X$ events as a function of the $\gamma\gamma$ invariant mass, from the CMS experiments. Events are weighted by the signal/background ratio in each event class. From arXiv: 1407.0558 Eur. Phys. J C 74, 10 (2014).

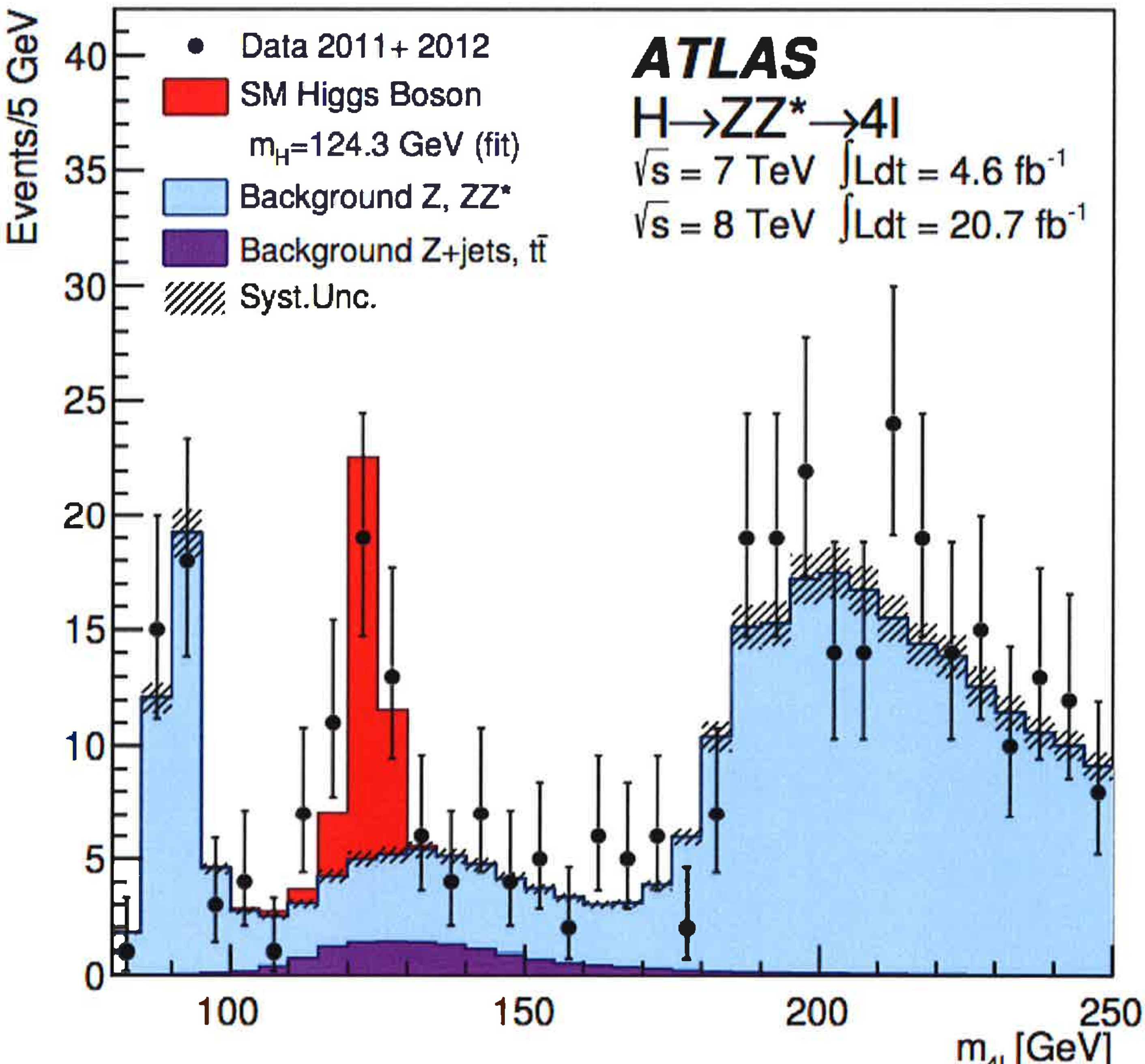


Fig. 6 Distribution of $pp \to 4l$ events as a function of the 4-lepton invariant mass, from the ATLAS experiment, arXiv: 1307.1427, Phys Lett. B726, 88 (2013)

$$h^0 \to Z^0 Z^0 \to \mu^+ \mu^- e^+ e^-$$

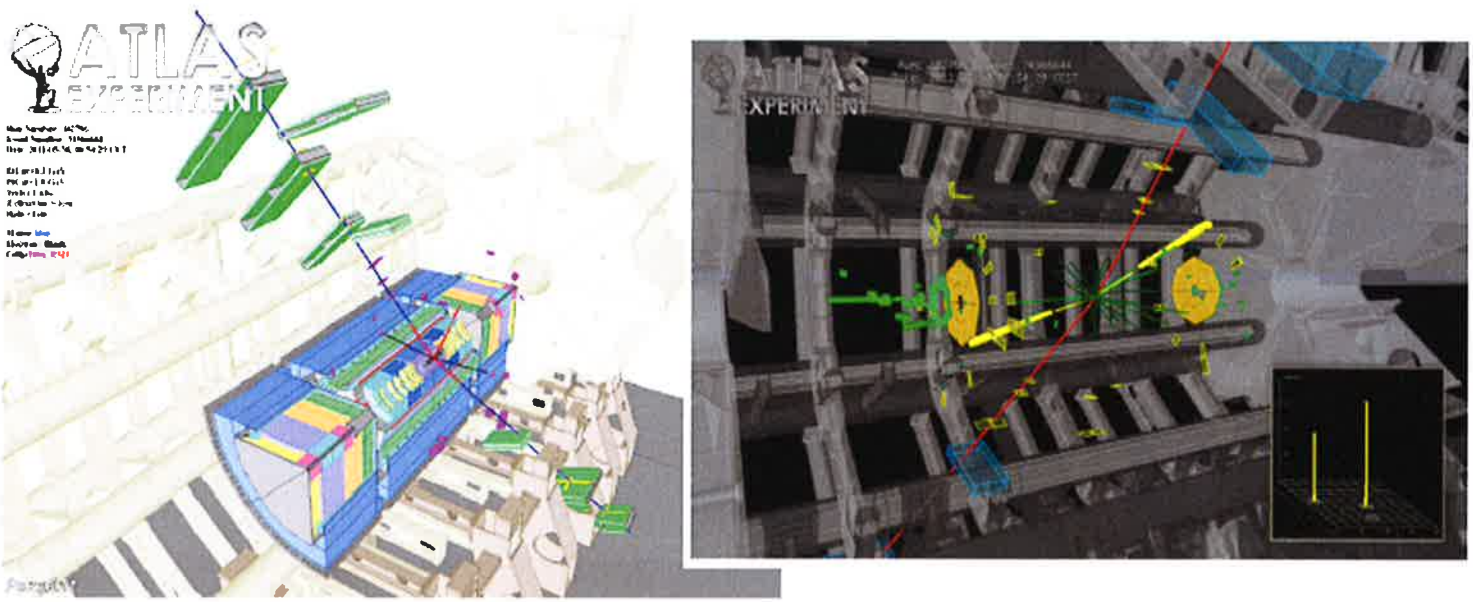
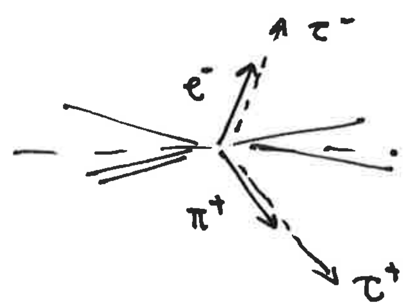


Fig. 7 Candidate $h \to$ 4 lepton event from the ATLAS experiment.

provides an obvious background. In addition, $t\bar{t}$ production with leptonic decays on both sides gives a background. For this reason, the analyses of $h \to WW^*$ at the LHC apply a restriction to event with 0 or 1 high-p_T jets. The evidence for the appearance of the Higgs boson is an excess of signal over background. For example, Figure 8 shows the evidence from the ATLAS experiment, with event samples plotted as a function of the $\ell^+\ell^-$ invariant mass. The dark blue band shows the contribution to the signal region from $pp \to WW$; the yellow band show the contribution from $t\bar{t}$.

The decay $h \to \tau^+\tau^-$ is very difficult to identify in a generic sample of LHC events. The τ appears at the LHC as a single electron or muon accompanied by $\not{E}_T$, or as a single hadronic track or a group of three tracks of very small angular separation. The hadronic decays can be faked by QCD jets. The strongest evidence for $h \to \tau^+\tau^-$ comes from a search for Higgs production in vector boson fusion, using the forward jets produced in this reaction as additional tags. A candidate event of this type from ATLAS, with an isolated electron, an isolated muon, and two forward jets, is shown in Figure 9.

Since the τ lepton always decays to an unobserved ν_τ, it is not possible to directly reconstruct the mass of the $\tau^+\tau^-$ system. However, there is a nice trick that can be used. The τ has very low mass, so for a high-momentum τ, the decay products will be almost collinear. We can make the approximation that the decay products are exactly collinear, or that the τ momentum is parallel to the momentum of the observed isolated track. Then an event with $\tau^+\tau^-$ emission has the form



with the energies of the two τ leptons considered as unknowns. These two unknowns can be determined by two equations if we impose p_T balance in the event. The technique gives the $\tau^+\tau^-$ mass with a resolution of about 15 GeV.

There are significant backgrounds to the Higgs signal. The Z boson can also be produced in WW fusion, so

$$pp \to j + j + Z^0 \ , \qquad Z^0 \to \tau^+\tau^-$$

is an irreducible background, with a $\tau^+\tau^-$ mass peak near m_Z rather than at 125 GeV.

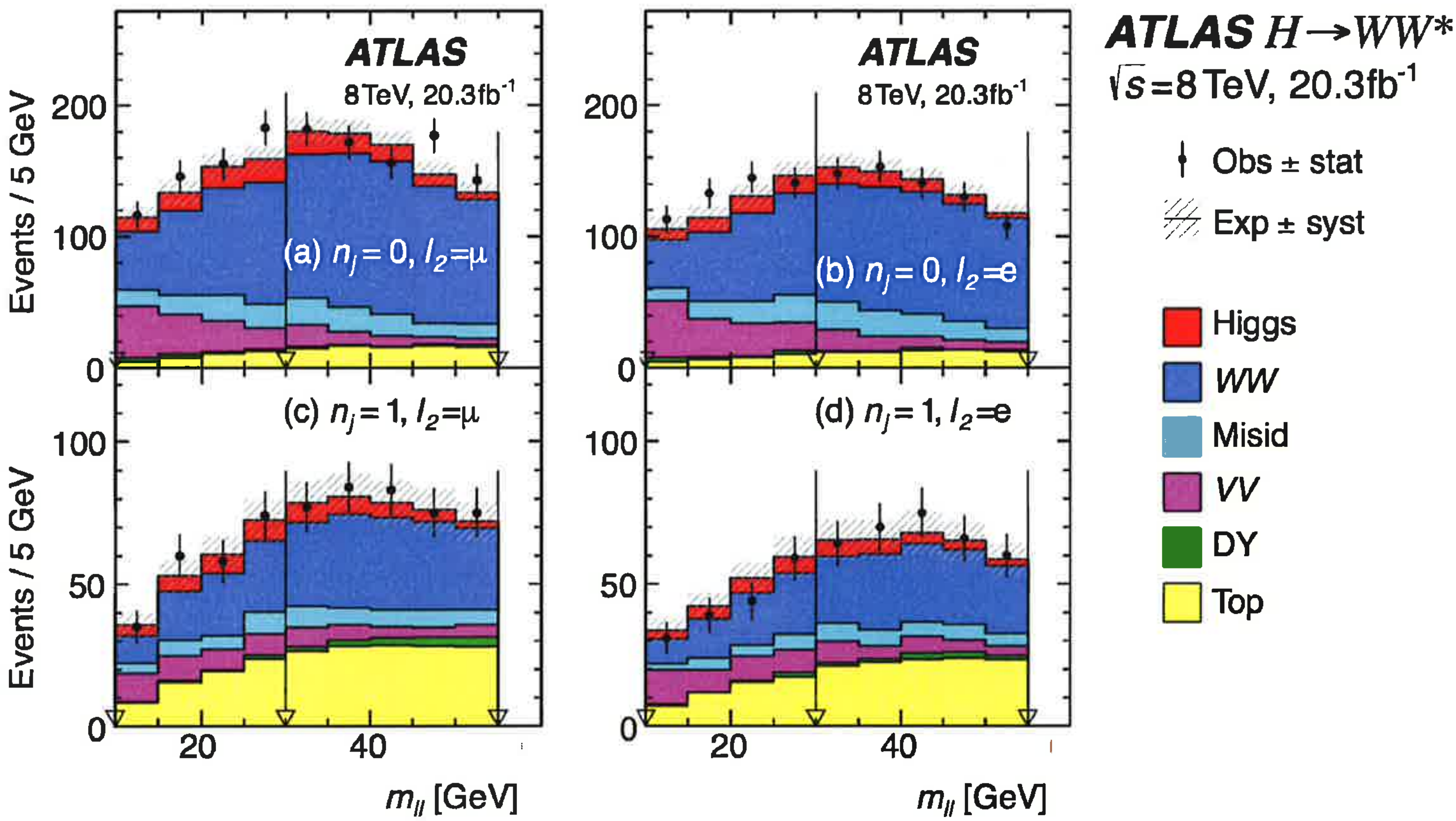


Fig. 8 Dilepton invariant mass distribution in the sample of candidate $pp \to h \to WW^* \to l\nu l\nu$ events collected by the ATLAS experiment, from arXiv: 1412.2641. top: 0-jet events, bottom: 1 jet events.

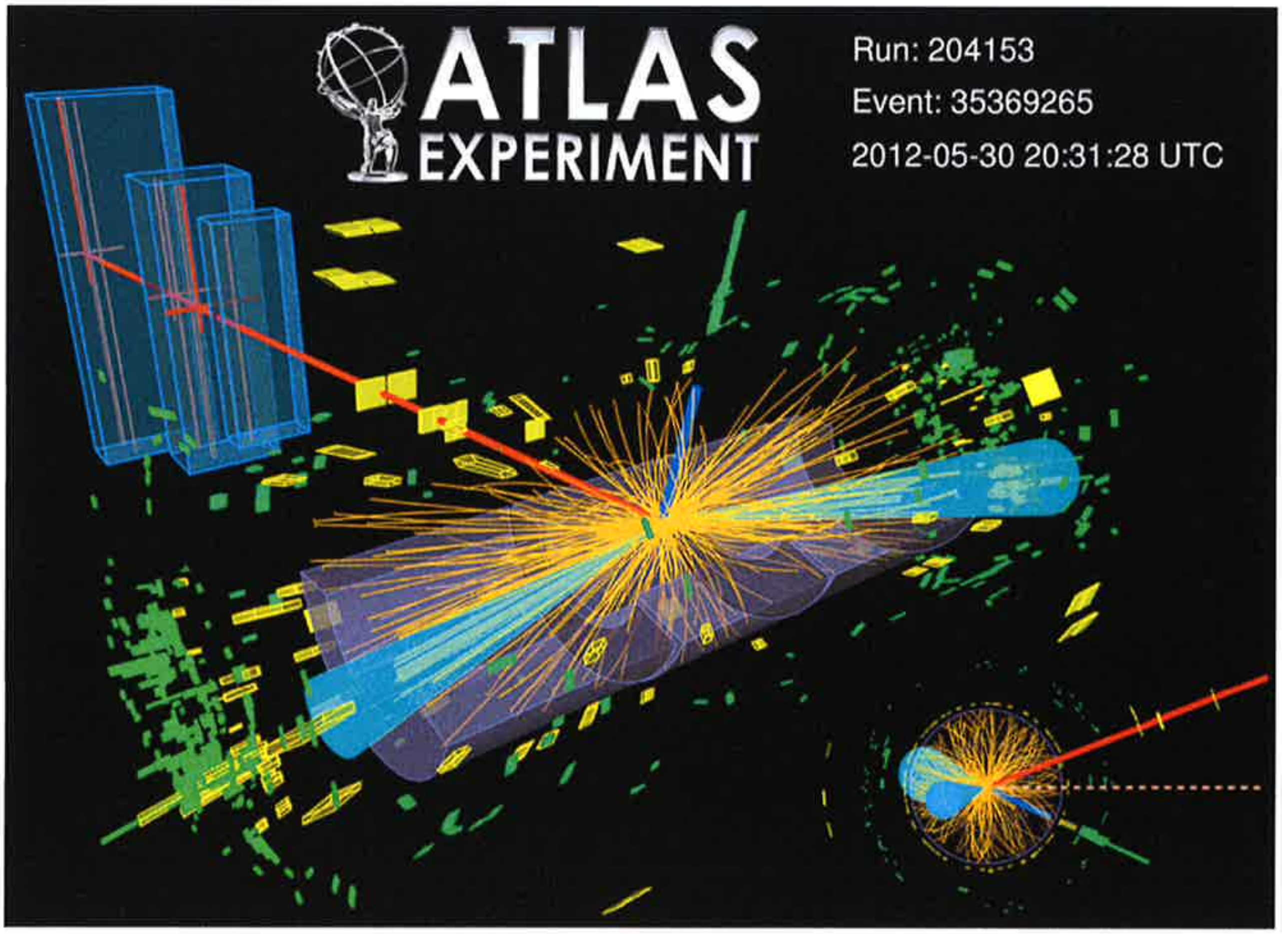


Fig. 9 Event display for a candidate $pp \to jjh$, $h \to \tau^+\tau^-$ event from the ATLAS experiment

The size of this background can be measured using $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ events. The process

$$pp \to W^+W^- \to \ell + jj + \not{E}_T$$

is also an important background, over a very broad range in the reconstructed $\tau^+\tau^-$ mass. The data from the CMS experiment is shown in Figure 10. The two background processes account for most of the event sample, with, however, a small but significant excess between 100 and 130 GeV.

The decay $h \to b\bar{b}$ is even more difficult. Recall that, at 8 TeV, the QCD process

$$gg \to b\bar{b}$$

has a cross section of about 1 mb. Even restricting to $b\bar{b}$ invariant masses near 100 GeV, the QCD cross section is of the order of 10 μb, compared to a Higgs production cross section of 20 pb. Some help is needed.

First, we need to look at a process with leptoins, to suppress the contribution from QCD production of $b\bar{b}$. ATLAS and CMS use the associated production with a vector boson

$$pp \to Wh\ , \ Zh$$

with W, Z decaying leptonically. There is still a substantial background from

$$pp \to W \text{ or } Z + \text{jets}$$

especially with gluon splitting to $b\bar{b}$,

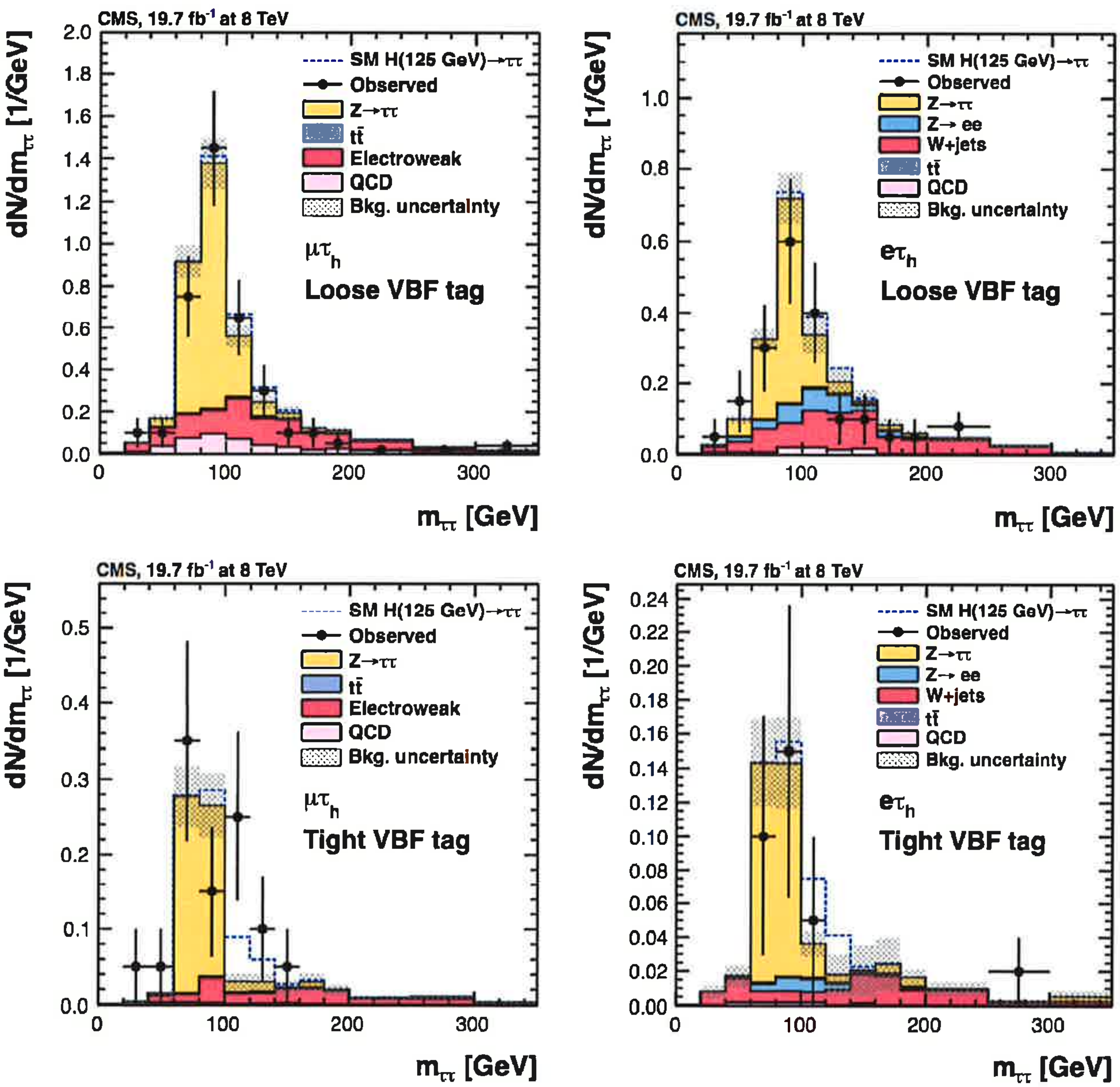


Fig. 10 Analysis of candidate $pp \to h \to \tau^+\tau^-$ events from vector boson fusion, from the CMS collaboration, arXiv: 1401.5041, JHEP 1405, 104 (2014)

$$pp \to W + g \,, \quad g \to b\bar{b}$$

and also from two vector boson production, for example,

$$pp \to W + Z \qquad Z \to b\bar{b}$$

The expeirments try to take advantage of small differences between the detailed properties of events in these classes to find evidence of the $h \to b\bar{b}$ signal.

A summary of the LHC measurements of Higgs production and decay in the various modes is shown in Figure 11. The measurements are quoted in terms of the "signal strength" μ, defined by

$$\mu = \frac{\sigma(pp \to h \to A\bar{A})}{(\text{Standard Model Expectation})}$$

A signal strength of 1 corresponds to agreement with the Standard Model; a signal strength of 0 corresponds to no evidence for the appearance of the Higgs boson. The signal strength does not have a simple dependence on the Higgs couplings. Consider, for example, the measurement of the rate for the process

$$pp \to h \to \gamma\gamma$$

For this reaction,

$$\mu \sim \sigma(gg \to h) \cdot BR(h \to \gamma\gamma)$$

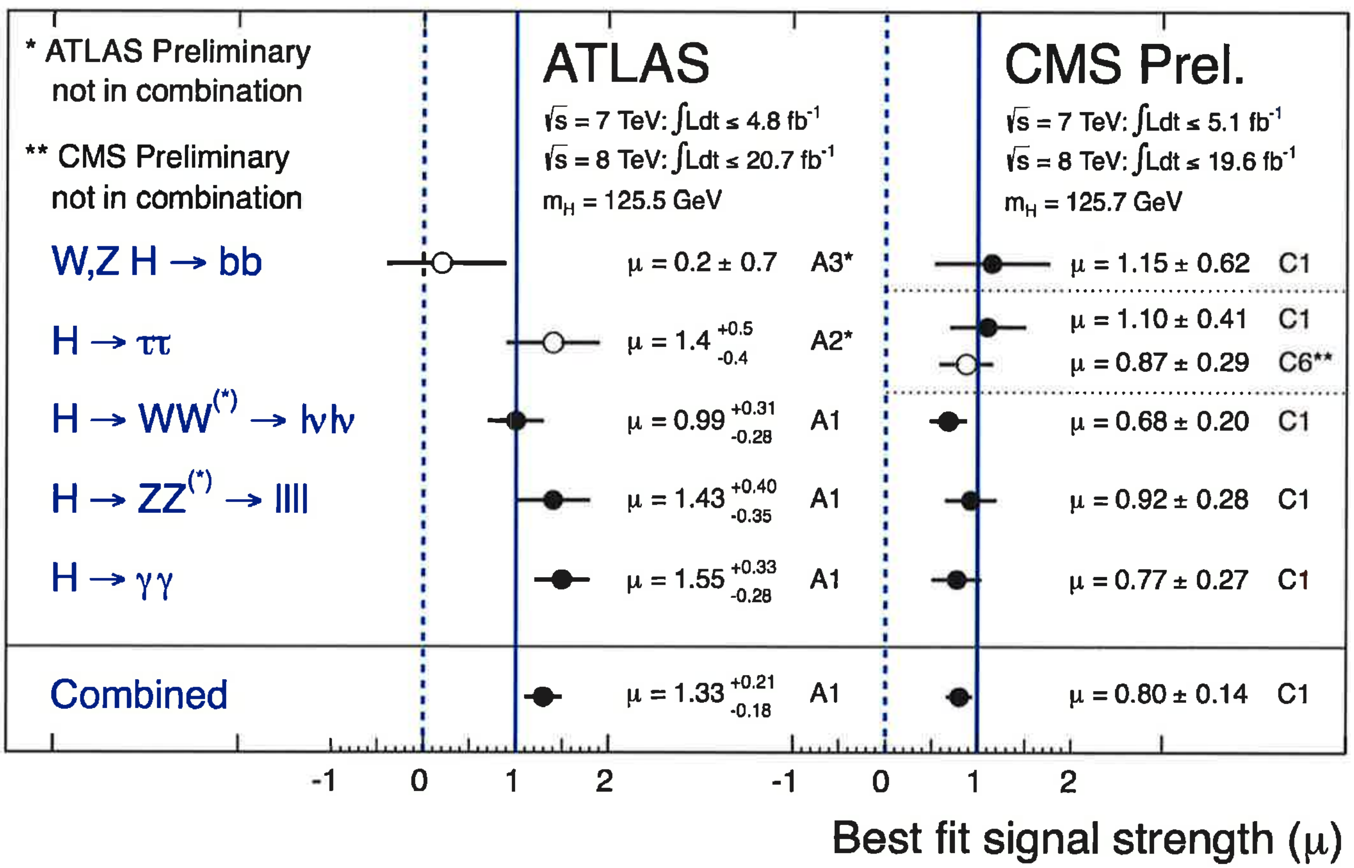


Fig. 11 Measured signal strengths for Higgs boson production and decay, compiled by the Particle Data Group, from the Higgs boson review, pdg.lbl.gov

which is proportional to

$$\frac{\Gamma(h\to gg)\,\Gamma(h\to\gamma\gamma)}{\Gamma_{tot}}$$

where Γ_{tot} is the total Higgs decay width. The quantity Γ_{tot} includes all Higgs couplings. So, if the signal strength for this reaction is larger than 1, this might be because

$$\Gamma(h\to gg) \quad \text{or} \quad \Gamma(h\to\gamma\gamma)$$

are greater than their Standard Model values, or because Γ_{tot}, dominated by the $hb\bar{b}$ coupling, is smaller than its Standard Model value. It is very difficult to disentangle the set of μ measurements to provide estimates of the specific Higgs couplings to different species. This is especially true in the current situation in which the signal strength for $h\to b\bar{b}$ processes is very uncertain.

Nevertheless, the picture shown in the figure is quite promising. All of the signal strengths are consistent with their Standard Model values within the errors, and most are measured, already at this early stage in the LHC program, to better than 30% accuracy. The accuracies will improve greatly in the 13 TeV run of the LHC.

I hope very much that, in the future, we will also have higher precision measurements of the HIggs boson couplings in e^+e^- annihilation experiments. The proposed International Linear Collider should constrain the Higgs boson couplings to the 1% level.

Will the Standard Model picture of the Higgs boson hold up under such close scrutiny. Very likely, it will not. This program of experiments gives a powerful way to explore for new physics beyond the Standard Model.