## HIGGS PROPERTIES



After the discovery of a scalar particle which strongly resembles the Higgs boson predicted by the SM, it became very important to study its properties, e.g. couplings and spin/CP. Several studies have already been carried out with the LHC Run 1 data.

The first property that can be measured quite precisely is the Higgs boson mass $m_H$, which is obtained from the invariant mass distribution in the $\gamma\gamma$ and $4\ell$ channels.

The ATLAS and CMS combination obtained from RUN 1 is $m_H = 125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})$ GeV with an uncertainty which is already at the permille level.

The other important quantity to describe the Higgs boson profile is the Higgs width $\Gamma_H$, which, for $m_H \sim 125$ GeV, in the SM is $\Gamma_H \sim 4$ MeV, and is too small to be directly measured at the LHC. The direct upper bound on $\Gamma_H$ that ATLAS and CMS can put is of the order of about 1 GeV. The indirect method that could be used in $e^+e^-$ colliders from the missing mass distribution in ZH production cannot be used at the LHC because at hadron colliders the partonic centre-of-mass energy is not constant.

Recently, a new proposal has been made (Caola, Melnikov, 2013) to indirectly obtain the Higgs boson width from off peak measurements of ZZ and WW production.

Let us focus on ZZ. The production of a Higgs boson in this channel can be written as

$$\frac{d\sigma}{dm_{ZZ}^2} \sim g_{gg}^2(m_{ZZ})\, g_{ZZ}^2 \, \frac{F(m_{ZZ})}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

where $m_{ZZ}$ is the ZZ invariant mass and $g_{gg}(m_Z)$ and $g_{ZZ}$ are effective couplings of the gluons ~~and~~ and of the Z bosons to the Higgs. It turns out that the invariant mass distribution remains quite flat in the high mass tail, due to the tail of the Breit-Wigner and to the increased phase space. The off shell rate $(m_{ZZ} - m_H \gg \Gamma_H)$ is independent of the Higgs boson width $\sigma_{\text{offshell}} \sim \text{const}$. On the other hand the on shell cross section $(|m_{ZZ} - m_H| \lesssim \Gamma_H)$ is inversely proportional to the width

$\sigma_{\text{onshell}} \sim \dfrac{1}{\Gamma_H}$ $\Rightarrow$ the ratio $\dfrac{\sigma_{\text{offshell}}}{\sigma_{\text{onshell}}}$ is proportional to the width!

However this conclusion is model dependent: it assumes that the Higgs couplings can be extrapolated from the on shell to the off shell region. The function $F(m_{ZZ})$ depends on the Spin/CP nature of the Higgs, and also relatively light BSM particles could affect the off shell cross section. With some assumptions, however, ATLAS and CMS have obtained interesting constraints on $\Gamma_H$.

Higgs couplings

As repeatedly stated in this course, by fixing the Higgs boson mass, the Higgs sector is completely specified in the SM, and the couplings to fermions and gauge bosons follow. To measure (small) deviations from the SM, a working framework has been defined for these studies at the Run 1, which is based on the following hypothesis:

- the signals observed in the different channels originate from a single narrow resonance with mass $m_H \sim 125$ GeV.
- the zero width approximation is used, such that $\sigma(ii \to H \to ff) = \dfrac{\sigma_{ii}\Gamma_{ff}}{\Gamma_H}$
- only modifications of coupling strengths are considered: the tensor structure of the Lagrangian is assumed to remain the same (this implies in particular that the observed state is a CP even scalar)

With these hypotheses modifications of the coupling strengths of the Higgs are introduced, by rescaling (some of) the couplings with appropriate scaling factors $K_i$. The SM cross sections and decay rates are recovered in the limit $K_i \to 1$. For example, using this notation, and defining $k_H$ as the scale factor to rescale the width, the cross section for $gg \to H \to \gamma\gamma$ can be written as

$$\sigma \cdot Br(gg \to H \to \gamma\gamma) = \sigma \cdot Br(gg \to H \to \gamma\gamma)\Big|_{SM} \cdot \frac{k_g^2 k_\gamma^2}{k_H^2}$$

This procedure leads to different benchmark scenarios, depending on which couplings are actually rescaled. The simplest scenario is the one in which all couplings are scaled by the same common factor. In this case $\sigma \cdot BR \to \frac{k^2 k^2}{k^2} = k^2$ and this is equivalent to leave the overall signal strength as a free parameter.

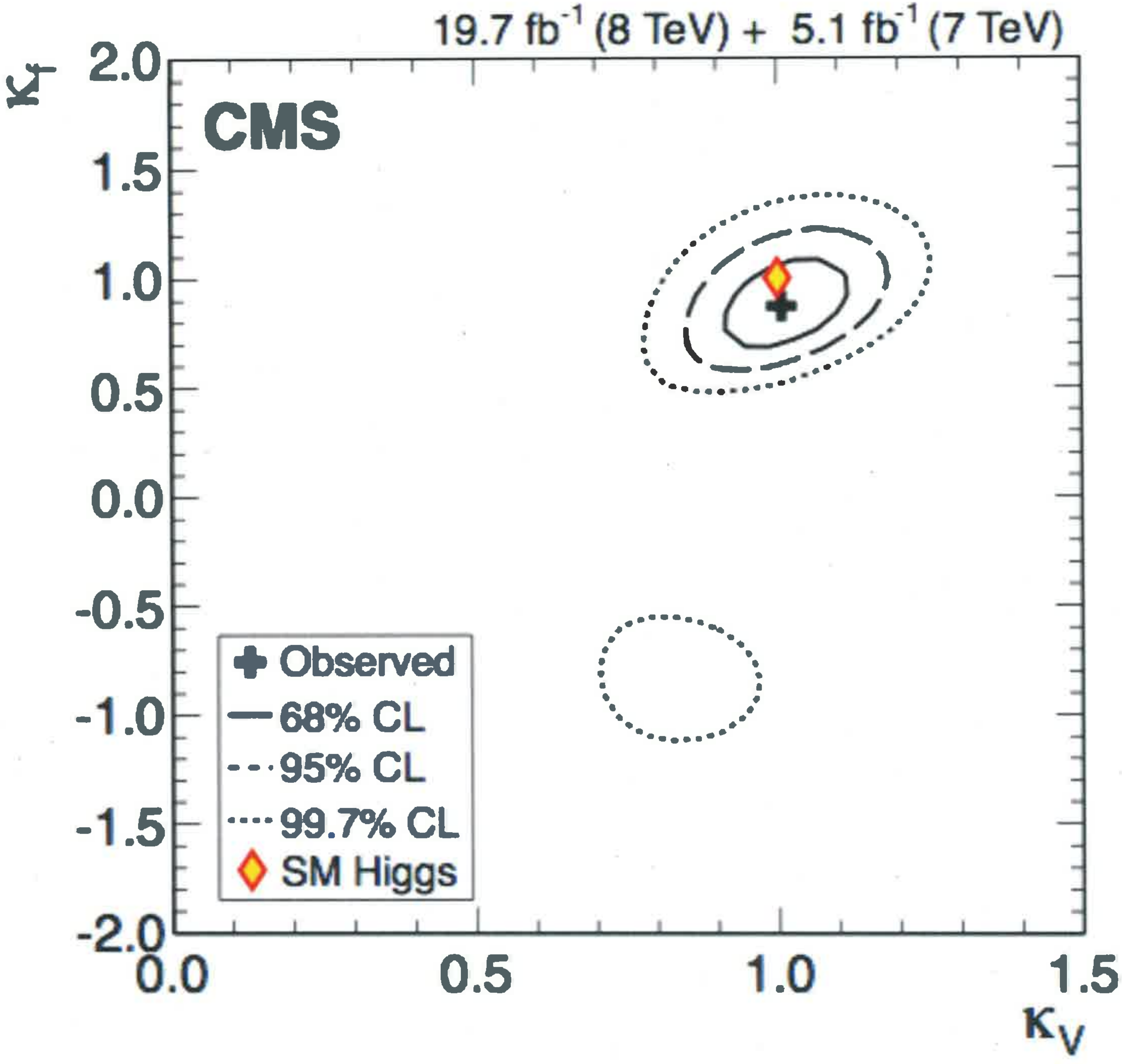
These fits lead to the most precise results, but have obvious shortcomings, as it treats all the particles that couple with the Higgs boson on the same footing. The next to simplest possibility is to scale the couplings of vector bosons and fermions with two independent factors $K_V$ and $K_F$. Adding more independent parameters makes the parametrization more complete, but also more difficult to test with a relatively low integrated luminosity.

It is important to stress that this strategy does not correspond to a specific BSM scenario, but it is more an effective way of parametrizing small deviations from the SM picture. When high luminosity will be accumulated, this framework should be complemented by more general (and rigorous) approaches.

One possibility is the so called Effective Field Theory (EFT) approach which implies that the SM Lagrangian is augmented with a set of higher dimensional operators

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i c_i O_i$$

This approach provides a consistent framework to study small deviations from the SM picture induced by new physics sitting at a scale $\Lambda$ relatively higher than the Higgs mass.



19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
CMS
κf
κV
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0.0
0.5
1.0
1.5
Observed
68% CL
95% CL
99.7% CL
SM Higgs

## Spin/CP

We now move to discuss the spin/CP properties of the Higgs boson. The observation in the decay modes $H \to \gamma\gamma$, $H \to ZZ$, $H \to WW$ allows us multiple tests of these properties. We start our discussion from the Landau-Yang theorem, which states that a spin 1 particle cannot decay in a $\gamma\gamma$ pair.

### Landau Yang theorem

Consider the Higgs boson at rest decaying in two photons travelling along the z direction. Let $m(M \to h_1, h_2)$ be the decay amplitude for an initial state with $J_z = M$ decay in the two photons with helicities $h_1$ and $h_2$. Angular momentum conservation implies $M = h_1 - h_2$ so, limiting ourselves to consider spin 0 or spin 1 particles, the only possibilities are $m_1 = m(0 \to 1, 1)$ and $m_{-1} = m(0, -1, -1)$. A rotation $R_y(\pi)$ around the y axis leads for a spin J particle to $R_y(\pi)|J_z=0\rangle = (-1)^J |J_z=0\rangle$, so the initial state gets a phase factor $(-1)^J$. However, since the photon are identical and have the same helicity, the final state is unchanged $\Rightarrow$ This implies that the J=1 amplitude must vanish. Note that if we assume that the Higgs sector is C conserving, this fixes $C = +1$ for the Higgs ( ~~...~~ $C = -1$ for the photon).

The possibility that the discovered Higgs resonance has spin 2 was considered from the beginning very challenging. Indeed no theoretical model has been formulated that can consistently account for this possibility, and typical models have an intrinsic cut-off of the order of the particle mass!

The ideal channel to study the spin/CP properties of the Higgs was $H \to ZZ^* \to 4\ell$. This channel offers two important variables that are very sensitive to spin and parity: the azimuthal angle between the decay planes of the ~~Z~~ bosons $\phi$ and the invariant mass of the off-shell Z.

In the SM the $\phi$ distribution is

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\phi} = \left(1 + a_1 \cos\phi + a_2 \cos 2\phi\right)\frac{1}{2\pi}$$

where $a_1$ is the parity violating amplitude, which is strongly suppressed.

Neglecting this contribution we have

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\phi} = \frac{1}{2\pi}\left(1 + m_H \,\xi \cos 2\phi\right) \qquad \xi > 0$$

where $m_H = (-1)^J P$ $\Rightarrow$ THE SIGN OF $\phi$ MODULATION IS COMPLETELY DETERMINED BY $m_H$ (opposite for pseudoscalar)

The other important variable is the invariant mass $m^*$ of the off shell boson.

Defining the momentum of the $Z(Z^*)$ in the H rest frame in units of $m_H$

we have $$\beta^2 \equiv \left(1 - (m_Z+m_x)^2/m_H^2\right)\left(1 - (m_Z-m_x)^2/m_H^2\right)$$

In the SM we have $$\frac{d\Gamma}{dm_x^2} \sim \beta \sim \sqrt{(m_H-m_Z)^2 - m_x^2}$$

and this behavior is driven by the phase space (the amplitude goes like $\beta^0$)

In the general case the HZZ amplitude is a tensor that can be written as $T_{\mu\nu\beta_1\cdots\beta_J}$

The behavior of the amplitude can be determined by counting the momenta in each term of the tensor $T_{\mu\nu\beta_1\cdots\beta_J}$

Z polarization

Higgs polarization

For example, for a vector $1^-$ the tensor must contain at least one power of $\beta$

$$\Rightarrow \quad \frac{d\Gamma}{dm_x^2} \sim \beta^3$$

For a $2^+$ a term $g^{\mu\beta_1}g^{\nu\beta_2}$ can be present and would lead to $\frac{d\Gamma}{dm_x^2} \sim \beta$

excluding this term we get $\frac{d\Gamma}{dm_x^2} \sim \beta^5$ !

By using this variable one can clearly distinguish from the SM many possible cases except <u>$1^+$ and $2^+$</u> for which one can exploit angular correlations.

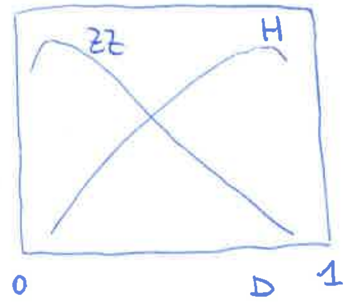
The variables we have discussed are very useful, but the best results are obtained by exploiting the full kinematical information on the event by using the

<u>MATRIX ELEMENT METHOD</u>

$$D = \left[ 1 + \frac{P_{bkg}(\Omega)}{P_{sig}(\Omega)} \right]^{-1}$$

MELA:

kinematic discriminant constructed from the ratio of probabilities for signal and background




In this way one can distinguish the signal from the background hypothesis.

However the method can also be used to distinguish two different Spin/CP hypothesis.

<u>CP EVEN / CP ODD MIXING</u>

The most general vertex for a spinless particle coupling to Z bosons is

$$V^{\mu\nu}_{HZZ} = \frac{i g m_Z}{\cos\theta_W} \left[ a g^{\mu\nu} + b \frac{p^\mu p^\nu}{m_Z^2} + c\, \varepsilon^{\mu\nu\rho\sigma} \frac{p_\rho p_\sigma}{m_Z^2} \right]$$

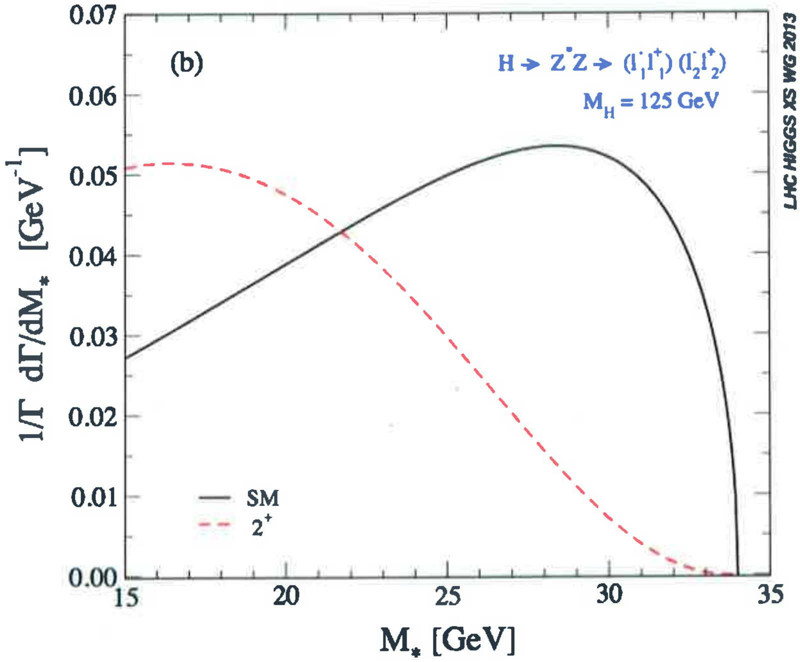
the SM corresponds to $a=1$, $b=c=0$

In the case $a \neq 0$ $b=0$ $c \neq 0$ we have a mixture of CP even and CP odd states

Note that typically the AZZ coupling is not present at lowest order

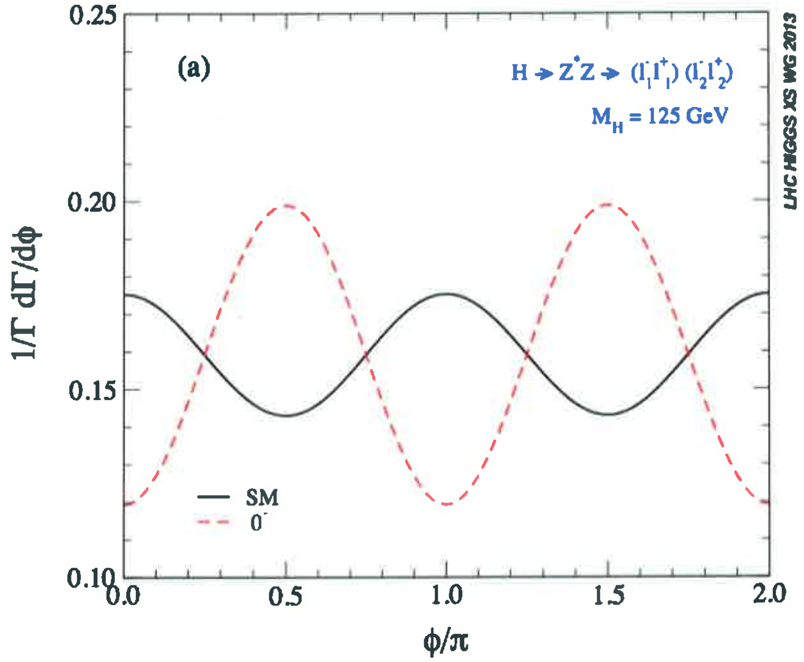
It requires a dimension 5 operator $\mathcal{L}_{AVV} \sim \frac{c_V}{\Lambda} A V^{\mu\nu} \tilde{V}_{\mu\nu}$

$\Rightarrow$ angular distributions will not provide discrimination against a possible small CP odd component.




$2^+$ without the term $T^{\mu\nu\beta_1\beta_2} \sim g^{\mu\beta_1}g^{\nu\beta_2} + g^{\mu\beta_2}g^{\nu\beta_1}$ (no momentum dependence)

$\Rightarrow$ falls off as $(\beta^2)^2\beta = \beta^5$ contrary to what happens in the SM!




$$\frac{1}{\Gamma}\frac{d\Gamma}{d\phi} \approx \frac{1}{2\pi}\left[1 + \eta_H\, \xi \cos 2\phi\right] \qquad \eta_H = P(-1)^J$$

in the SM $\quad \xi = \frac{1}{2}\frac{1}{\gamma^4+2} \qquad \gamma^2 = \frac{m_H^2 - m_*^2 - m_Z^2}{2 m_* m_Z}$

## DOUBLE HIGGS PRODUCTION

$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$ $\Rightarrow$ trilinear Higgs coupling uniquely determined

$\lambda_{HHH} = \frac{\lambda}{4} v h^3$ $\qquad m_H^2 = 2\lambda v^2$

$= \frac{\lambda}{8} \frac{m_H^2}{v}$

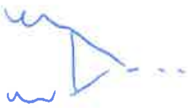
only accessible through double Higgs production

PRODUCE OFF SHELL HIGGS $H^* \to HH$

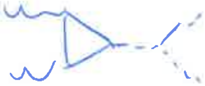

$b\bar{b}\, WW$

$b\bar{b}\, \gamma\gamma$

NOT ALL THE DIAGRAMS ARE SENSITIVE TO $\lambda_{HHH}$!



pb ;



fb ; $\Rightarrow$ POSSIBLE AT HIGH LUMINOSITY LHC (1000 times smaller than single Higgs production)

ab !

$HH \to b\bar{b}\gamma\gamma$ 50 signal events $\sqrt{s} = 14\,\mathrm{TeV}$ $\int \mathcal{L} = 3000\, fb^{-1}$

$HH \to b\bar{b}\tau\tau$ 300 signal events

$\Rightarrow$ expected accuracy on $\lambda_{HHH}$ $\Rightarrow$ 30-50 %

$K_{NLO} \sim 2$

NNLO ~ 20% wrt NLO

$\mathcal{L} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} \left( c_H \frac{H}{v} - c_{HH} \frac{H^2}{v^2} \right)$