Constraining total width of Higgs boson at the LHC

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Introduction

• After the discovery in 2012, the principal job has been to identify the nature of the resonance through multiple measurements with holistic attitude. This includes
  - Observation in boson channels
  - Evidence in fermion channels
  - Precise determination of mass
  - Combined fits to couplings assuming minimal spin-0 structure
  - Kinematics in bosonic channels to test the structure of the couplings
  - Constraint on Higgs boson width

• Since the mass resolution in the best decay channels ~ 2-3 GeV, it is impossible to directly measure Standard Model Higgs width $\Gamma_H \sim 4.2$ MeV ($m_H=125$ GeV)

• Experimental limit from global fit of CMS data $\Rightarrow \Gamma_H < 3.4$ GeV @ 95% CL~$1000* \Gamma_H^{SM}$

• Recently a novel way to constrain $\Gamma_H$ has been suggested
  Kauer, Passarino JHEP 1208 (2012) 116
  Campbell et al, JEHP 1404 (2014) 060
Estimation of the width using Higgs interferometry

In narrow width approximation, on-shell Higgs production+decay depends on
i) the strengths of the couplings of Higgs boson in production and decay
vertices, $g_{xx}$ and $g_{yy}$

$$\sigma \cdot \text{Br} \propto \frac{g_{xx}^2 g_{yy}^2}{\Gamma_H}$$

ii) the total width $\Gamma_H$

- If we rescaling all the couplings by the same factor, say $\xi$ and the total width by $\xi^4$
  the on-shell production rate remains same $\Rightarrow$ there is some degeneracy.

- Naively, since $\Gamma_H / m_H \sim 10^{-5}$, resonance peak is very narrow
  $\Rightarrow$ there is no off-shell cross section to measure! However this is not true!

Mass dependence of $gg \rightarrow H \rightarrow ZZ$ cross section,

$$\frac{d\sigma_{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}^2} \propto g_{ggH}^2 g_{HZZ}^2 \frac{F(m_{ZZ})}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

$F(m_{ZZ})$ depends on virtual Higgs and Z decay dynamics

At resonance $\Rightarrow$

$$\sigma_{\text{on-peak}}_{gg \rightarrow H \rightarrow ZZ} \propto \frac{g_{ggH}^2 g_{HZZ}^2}{\Gamma_H}$$

Utilization of Higgs propagator structure

$\Rightarrow$ Ratio of on-peak/off-peak $\sim \Gamma_H$

Off-shell part $\Rightarrow$

$$\sigma_{\text{off-peak}}_{gg \rightarrow H \rightarrow ZZ} \propto g_{ggH}^2 g_{HZZ}^2$$

Similar considerations for VBF production
Practical considerations for $ZZ \rightarrow 4$ lepton final state

Possibilities for $ZZ \rightarrow 4$ fermion production at LHC
(a) gluon pair initiated signal
(b) gluon pair initiated background
(c) qq initiated dominant background

Usual classification of signal and background contributions in analyses “neglects” interference effect between (a) and (b) which affects total cross section.

Invariant mass distribution of 4 leptons:
- Continuum background due to $qq \rightarrow ZZ$ large in most regions.
- Destructive interference at high mass $M_{ZZ} \gg 2M_Z$.

3 regions of spectrum peak, off-shell (low) off-shell (high)
Estimating Higgs width from $H \rightarrow WW$ decay

Gluon fusion for H production  SM bkg.

Vector boson fusion for H production  SM bkg.

Effect of large $\Gamma_H$

S, C, and SCI
Strategy for experimental analysis

Do not assume standard model Higgs → introduce scaling factors for couplings and such that

\[ \kappa_g = \frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} \quad \kappa_Z = \frac{\sigma_{HZZ}}{\sigma_{HZZ}^{SM}} \]

\[ \sigma_{\text{on-peak}}^{gg\to H\to ZZ} = \frac{\kappa_g^2 \kappa_Z^2}{r} (\sigma \cdot B)_{\text{SM}} \equiv \mu (\sigma \cdot B)_{\text{SM}} \]

\[ \mu = 1 \Rightarrow \text{SM} \]

These relations are true for pure Higgs boson signal

Data has signal(S), background (B) and their interference(I)

In the off-shell region, \( M_{ZZ} > 2M_Z \), the shape of mass spectrum has 3 components:

\[ \mathcal{P}_{\text{tot}} = \mu r \mathcal{P}_{\text{sig}} + \sqrt{\mu r} \mathcal{P}_{\text{int}} + \mathcal{P}_{\text{bkg}} \]

\( \mathcal{P} \) s are templates obtained from monte carlo or derived from data.

Use \( \mu \) value derived from data and fit \( r \).

- \( \mu \) can be constrained from independent measurement, to estimate \( r \)
- Or, simultaneous fit of off-shell and on-shell regions can determine \( r \)
Templates and event distribution

- Signal, background, interference templates are not available separately.
- Generate total amplitudes with 3 values of $r$, say, $r = 1, 9, 25$
- Extract 3 components from matrix eqn.

\[
\begin{pmatrix}
S \\
I \\
B \\
p_1 \\
p_9 \\
p_25 \\
\end{pmatrix} = A^{-1} \cdot \begin{pmatrix}
S \\
I \\
B \\
p_1 \\
p_9 \\
p_25 \\
\end{pmatrix} \\
A = \begin{pmatrix}
1 & 1 & 1 \\
9 & 3 & 1 \\
25 & 5 & 1 \\
\end{pmatrix}
\]

- Selected event can be from gluon fusion ($ggH + ttH + \text{background}$) type, or, vector boson fusion ($VBF + WH + ZH + \text{bkg.}$) type or, dominant $qq$ initiated backgrounds process.

\[
\mathcal{L}_i = N_{gg \rightarrow ZZ} \left[ \mu r \times \mathcal{P}^{gg}_{\text{sig}} + \sqrt{\mu r} \times \mathcal{P}^{gg}_{\text{int}} + \mathcal{P}^{gg}_{\text{bkg}} \right] + N_{VBF} \left[ \mu r \times \mathcal{P}^{VBF}_{\text{sig}} + \sqrt{\mu r} \times \mathcal{P}^{VBF}_{\text{int}} + \mathcal{P}^{VBF}_{\text{bkg}} \right] + N_{qq \rightarrow ZZ} \mathcal{P}^{qq}_{\text{bkg}} + ...
\]

Probability distribution for on-shell region

\[
\mathcal{P}_{\text{tot}}^{\text{on-shell}}(\vec{x}) = \mu ggH \times \left[ \mathcal{P}^{gg}_{\text{sig}}(\vec{x}) + \mathcal{P}^{ttH}_{\text{sig}}(\vec{x}) \right] + \mu VBF \times \left[ \mathcal{P}^{VBF}_{\text{sig}}(\vec{x}) + \mathcal{P}^{VH}_{\text{sig}}(\vec{x}) \right] + \mathcal{P}^{qq}_{\text{bkg}}(\vec{x}) + \mathcal{P}^{gg}_{\text{bkg}}(\vec{x}) + ...
\]

Probability distribution for off-shell region

\[
\mathcal{P}_{\text{tot}}^{\text{off-shell}}(\vec{x}) = \left[ \mu ggH \times (\Gamma_H/\Gamma_0) \times \mathcal{P}^{gg}_{\text{sig}}(\vec{x}) + \sqrt{\mu ggH \times (\Gamma_H/\Gamma_0)} \times \mathcal{P}^{gg}_{\text{int}}(\vec{x}) + \mathcal{P}^{gg}_{\text{bkg}}(\vec{x}) \right] + \left[ \mu VBF \times (\Gamma_H/\Gamma_0) \times \mathcal{P}^{VBF}_{\text{sig}}(\vec{x}) + \sqrt{\mu VBF \times (\Gamma_H/\Gamma_0)} \times \mathcal{P}^{VBF}_{\text{int}}(\vec{x}) + \mathcal{P}^{VBF}_{\text{bkg}}(\vec{x}) \right] + \mathcal{P}^{qq}_{\text{bkg}}(\vec{x}) + ...
\]

$\Gamma_H / \Gamma_0 = \text{scale factor } r$
Extraction of S, B, I

- Analysis based on main selection criteria for \( H \rightarrow ZZ \rightarrow 4l \) and \( H \rightarrow ZZ \rightarrow 2l \ 2\nu \), produced in gluon fusion and vector boson fusion processes mainly needs template distributions for signal, background and interference terms.

- Define a discriminant for signal selection based on matrix element method approach where likelihood of signal is defined on event-by-event basis based on kinematics.

- Discriminant threshold studied using distribution of kinematic variables from matrix element based JHUGEN package.

\[
\mathcal{D}_{gg} = \frac{\mathcal{P}_{gg}}{\mathcal{P}_{gg} + \mathcal{P}_{qq}} = \left[ 1 + \frac{\mathcal{P}_{bkg}^{qq}}{a \times \mathcal{P}_{sig}^{gg} + \sqrt{a} \times \mathcal{P}_{int}^{gg} + \mathcal{P}_{bkg}^{gg}} \right]^{-1}
\]

- \( a \): relative weight of signal in the likelihood ratio.
- Since expected exclusion is \( r \sim 10 \), use \( a = 10 \)

- Templates for gluon fusion are obtained from MCFM, gg2VV packages. PHANTOM for VBF
- Corrections which have been taken into account:
  - k-factors for higher order QCD in \( gg \rightarrow ZZ \) continuum
  - Electroweak effect in \( qq \rightarrow ZZ \)
  - Higher orders in \( M_{ZZ} \) spectrum
Results

- Use $ZZ \rightarrow 4l$ (for 7 and 8 TeV data) and $ZZ \rightarrow 2l2\nu$ (for 8 TeV data).
- Assume tree level HVV coupling.
  Anomalous HVV coupling would enhance off-shell contribution.

For $M_{4l}$ distribution from $ZZ \rightarrow 4l$, consider off-shell region > 330 GeV
For $M_T$ distribution from $ZZ \rightarrow 2l2\nu$, consider region > 350 GeV
- Fit with 3 floating parameters: $\Gamma_H$, $\mu_{ggH}$, $\mu_{VBF}$
  ➔ use independent contributions of gg fusion and vector boson fusion contributions for H production in the on-shell region.

At 95% CL upper limit from CMS analysis on $\Gamma_H$: $22 \text{ MeV} \sim 5* \Gamma_H^{SM}$

arXiv: 1405.3455
Constrain on Higgs boson width from ATLAS data

Similar analyses from ATLAS collaboration

→ Combines signal strength in 2 regions: on shell and off-shell to constrain $\Gamma_H$
  • Assume that couplings do not depend on $M_{4l}$ or subprocess energy

• Background level due to $gg \rightarrow ZZ$ has large uncertainty, results presented as a fn. of k-factor ratio between $gg \rightarrow ZZ$ continuum background and signal $gg \rightarrow H^* \rightarrow ZZ$

• Used $ZZ \rightarrow 2e2\mu$ and $2l2\nu$ final states

Depending on k-factor for $gg \rightarrow ZZ$, $\Gamma_H < 20-32$ MeV or $(4.8 - 7.7)\Gamma_H^{SM}$
Conclusion

• Using the structure of Higgs propagator, the mass distribution of a pair of vector bosons (ZZ and WW) at LHC, at high enough values beyond on-shell diboson mass, is used to constrain the total width of Higgs boson, $\Gamma_H$.

• The key idea is the dependence of cross section at resonance on $\Gamma_H$ in narrow width approximation while the off-shell Higgs production is independent of $\Gamma_H$.

• CMS analyses used ZZ to 4 leptons and 2 leptons + 2 neutrinos final state, for gluon fusion and vector boson fusion production.

• At 95% confidence, upper limit is $\Gamma_H < 22$ MeV, which is about 5 times larger than the width expected from standard model $\Gamma_H^{SM}$ for a Higgs boson of mass 125 GeV.

• Similar strategy is being followed for using $H \rightarrow WW$ decay.

• ATLAS experiment has compared the signal strengths for $ZZ \rightarrow 2e2\mu$ and $2l2\nu$ final states in Higgs boson on-shell and off-shell regions.

• Taking into account the uncertainty in the estimation for the continuum background $gg \rightarrow ZZ$, the upper limit is $\Gamma_H < 20-32$ MeV or $(4.8 – 7.7)\Gamma_H^{SM}$. 
Backup
Constraining Higgs width using $H \rightarrow \gamma\gamma$ final state

The real part of the interference due to 2 states of diagrams for diphoton final state causes significant mass shift in invariant mass of 2 photons $\sim 50-100$ MeV for inclusive selection.

Mass shift at NLO can be used for determination of width.

Much smaller shift for $H+2$ jet final state:
- VBF shifts towards lower mass
- GF shifts towards higher mass
Knowledge of total width is extremely important to derive the couplings

Fixing the total width

Not fixing the total width