Offshell couplings and Higgs width in ATLAS and CMS

Roberto Di Nardo
on behalf of ATLAS and CMS collaborations

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Why study the Higgs boson off-shell production?

- High mass region of $H \rightarrow VV$ above the $2m_V$ threshold sensitive to the Higgs boson production through off-shell and background interference effects
  - characterize the properties of the Higgs boson through off-shell signal strength and off-shell Higgs boson couplings
  - Sensitivity to new physics that change interaction between the Higgs and SM particles in this region
- Unique way to probe New Physics in the Higgs domain at large momenta

Why the width? ($\Gamma_{H,SM}=4.2$ MeV)

- @ LHC only $\sigma \cdot BR$ can be measured
  - $\Gamma_H$ cannot be estimated from the Higgs boson rates
- Direct and indirect approaches to constrain the Higgs width are nevertheless available
  - Worth investigating the HL-LHC (and experiment upgrades) potential to exploit all of them!
- Off-shell to on-shell cross section ratio \( \sim 8\% \) in the SM
- In the high mass region off-shell Higgs production and non resonant \( gg\rightarrow VV \) background (box diagram)

- Interference sizable and negative in SM
- Similar for \( qq\rightarrow VV+2j \) and VBF production
- Possible to obtain a sample with an arbitrary value of \( \mu_{\text{off-shell}} \) combining the SM expectations for \( gg\rightarrow (H^*)\rightarrow ZZ \), \( gg\rightarrow H^*\rightarrow ZZ \) and \( gg\rightarrow ZZ \)

\[
MC_{gg\rightarrow (H^*)\rightarrow ZZ}(\mu_{\text{off-shell}}) = \left( \frac{K_{H^*}(m_{ZZ})}{K_{gg}(m_{ZZ})} \cdot \frac{K_{gg}^{H^*}(m_{ZZ})}{\mu_{\text{off-shell}}} \right) \cdot MC_{SM}^{gg\rightarrow H^*\rightarrow ZZ}
\]

- LO (gg2VV/MCFFM) generator used for run1 results
- Large \( k \)-factors (when known) at NNLO
Offshell couplings

- Run1 results: combination of $WW \to l\nu l\nu$ and $ZZ \to 4l/l\nu l\nu$
  - Similar sensitivity for 4l and l\nu l\nu
  - Matrix Element discriminant exploited in the 4l, $m_T$ used for l\nu l\nu
  - Channels with MET might be more challenging in HL environment
- $qq \to ZZ$ dominant bkg for driving channels
  - High precision needed for its prediction
- Systematics dominated by the theoretical uncertainties
  - QCD scales and PDF for $qq \to ZZ$ and $gg \to (H) \to ZZ$
    - experimental uncertainty subdominant
- Limits also on anomalous off-shell coupling

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With the increase in statistics, it will be crucial to have the most accurate possible theoretical predictions.

- To reduce the dominant theoretical uncertainties on cross sections and shapes of the different components.
- Essential to move from LO to NLO MC development for \( gg \rightarrow (H^*) \rightarrow VV \) and \( gg \rightarrow VV \) processes (for less "QCDinclusive" analysis).
  - \( gg \rightarrow VV \) exact NLO available \(< 2m_t \), above approximate.

- Equally important is to improve precision of MC generators (and predictions) for the main \( qq \rightarrow VV \) background.
  - \( pp \rightarrow WW/ZZ \) at NNLO cross sections and NNLO MC development (+EW corrections).

- At HL-LHC \( \mu_{\text{offshell}} \) measurement sensitivity @ 20% without theoretical systematic uncertainties (ATLAS).

- HE-LHC will increase even more the relative contribution of the \( gg \) compared to \( qq \) at high \( m_{4l} \).
Higgs boson width: direct constraint

- Direct measurement using $m_{4l}$ and $m_{WW}$ spectra
  - Very few assumptions, lower precision, limited by experimental resolution (~1-2%)

- Exploited using Run1 and Run2 data to obtain upper limit on $\Gamma_H$
  - CMS:
    - upper limit on $\Gamma_H$ combining $H\rightarrow ZZ\rightarrow 4l$ and $H\rightarrow WW$ : $\Gamma_H < 1.7 \text{ GeV}$ at 95% CL (exp. 2.3 GeV)
    - Run2 (35.9/fb) using 4l : $\Gamma_H < 1.1 \text{ GeV}$ at 95% CL (exp. 1.6 GeV)
  - ATLAS
    - Run1 $H\rightarrow ZZ\rightarrow 4l$ : $\Gamma_H < 2.6 \text{ GeV}$ at 95% CL (exp. 3.5 GeV for $\mu = \bar{\mu}$), similar limits using $H\rightarrow WW$

- >250 times larger wrt SM prediction
  - At HL-LHC a limiting factor will be the uncertainties on the resolution
  - Some caveats for $WW$ due to interference with the bkg
Lower bound on $\Gamma_H$

- Possible to set a direct lower bound on the Higgs width using its lifetime
- In the SM the $\tau_H \sim 4.8 \times 10^{-8} \mu$m (far from experimental sensitivity)

- $H \to ZZ \to 4l$ suitable channel to extract the lifetime from the flight distance
  - Displacement between production (PV) and decay (4l) vertex

- Current Run1 limit (CMS)
  - $c\tau_H < 57 \mu$m at the 95% CL $\Rightarrow \Gamma_H > 3.5 \times 10^{-3} \text{eV}$ at 95% CL
- No extrapolation study available at the moment
  - Impossible to measure SM value also with 3/ab, nevertheless possible to improve sensitivity from highly boosted Higgs
  - Precise identification of the PV despite the high-pileup expected
Probing the Higgs width with Hyy

- $gg \to H \to yy$ and the continuum irreducible background $gg \to yy$ interfere
  - The imaginary component reduces the total yield by 2-3%
  - The real part is responsible for a non negligible mass shift, depending on $\Gamma_H$.
- Measuring this shift allows to indirectly constraint the total Higgs width.
  - Estimation of $\Delta m_H = -35 \pm 9$ MeV for Run1 ATLAS measurement ($\Gamma_H=4$MeV) - ATL-PHYS-PUB-2016-009
  - same categorization and detector response as used in the Run1 mass measurement.

2 Possible way to approach the measurement (linked to the reference mass)

- Use $m_{H,ZZ}$ as reference value
  - Shift in this channel negligible ($ggZZ$ small)
  - Drawback is detector calibration uncertainty from ZZ as well
  - Needed sensitivity down to $\sim 70$MeV
    - Strong reduction of photon scale uncertainty needed
    - Stat sensitivity to $\Delta m_H$ $\sim 40$ MeV at HL-LHC
Probing the Higgs width with H->γγ

- Use the $p_{TH}$ dependency of the shift
  - Constrained within the yy channel alone
  - Partial cancellation of calibration systematic uncertainties (energy scale)

- ATL-PHYS-PUB-2013-014
  - Evaluate the mass difference between $p_{TH} \leftrightarrow 30$ GeV
  - Systematics on the difference roughly estimated to be $<100$ MeV
  - Stat dominated, if in presence of SM width, limit on $\Gamma_H \sim <40-50 \Gamma_{SM}$

- An alternative could be the usage of the mass difference wrt pp->H+2j
- Presented in Phys. Rev. D 92, 013004, no projection study performed at the moment
  - H(->yy)+2jet provide good reference mass since cancellation between GGF and VBF
Indirect constraint on $\Gamma_H$ from offshell production

- $\sigma_{\text{offshell}} \sim g_g^2 g_V^2$ does not depend on the total width $\Gamma_H$, $\sigma_{\text{onshell}}$ does
  - In terms of coupling modifiers
    \[
    \frac{\sigma_{\text{off-shell}}}{\sigma_{\text{on-shell}}} = \mu_{\text{off-shell}} = k_{g,\text{off-shell}} \cdot k_{V,\text{off-shell}}
    \]
    \[
    \frac{\sigma_{\text{on-shell}}}{\sigma_{\text{on-shell}, \text{SM}}} = \mu_{\text{on-shell}} = \frac{k_{g,\text{on-shell}}^2 \cdot k_{V,\text{on-shell}}^2}{\Gamma_H / \Gamma_H^{\text{SM}}}
    \]

- Under the assumption of equal on-peak and off-peak coupling modifiers, limit on $\mu_{\text{off-shell}}$ can be reinterpreted, combined with $\mu_{\text{on-shell}}$, as limit on $\Gamma_H$
  - Strong assumption, $k_g(s)$ sensitive to possible new physics at higher mass scales
  - New physics which modify off-shell signal strength do not change bkg predictions
    \[
    \kappa_{g,\text{on-shell}}^2 \leq \kappa_{g,\text{off-shell}}^2 \kappa_{V,\text{on-shell}}^2 \]

- Latest experimental results (WW+ZZ in Run1 for ATLAS and CMS, 4l Run2 CMS):
  - $\Gamma_H < 22.7$ MeV @ 95%CL (<33 MeV exp.)
  - $\Gamma_H < 13$ MeV @ 95%CL (<26 MeV exp.)
    CMS Run1 JHEP 09 (2016) 051
  - 4l: $\Gamma_H < 4.1$ MeV @ 95%CL (<32 MeV exp.)
    CMS Run2, 12.9 fb$^{-1}$ CMS PAS HIG-16-033

- For HL-LHC most of the consideration done for $\mu_{\text{off-shell}}$ valid here as well
  - In this interpretation, the uncertainty on $\mu_{\text{off-shell}}$ dominates
    - $\sim 5\%$ precision achievable for $\mu_{\text{on-shell}}$ ZZ
  - Estimate using 4l alone by ATLAS (10% syst on $R_{H^*}^B$)
    \[
    \Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV
    \]
    ATL-PHYS-PUB-2015-024
Conclusions

- With Run1 data, both CMS and ATLAS set first limits on the Higgs boson width and offshell production
  - First results using Run2 data also available

- For the Higgs width exploited both direct and indirect methods
  - Direct measurement will be challenging also with RUN2 and HL-LHC statistics
  - Indirect methods (under well-defined assumptions) provide already today limits @ 3 times the SM width
  - For several of the presented measurements, also limitations from the detector performances
    - Key point is to keep the performances at the same level as today (or better) also in a high pileup environment

- Off-shell production of the Higgs boson gives interesting extra information about the coupling structure of the Higgs boson
  - Very interesting measurement to perform @ HL-LHC
  - $\mu_{\text{offshell}}$ measurement sensitivity @ 20% level with 3000fb\(^{-1}\) (no theoretical uncertainties)
  - Very important the theoretical knowledge of the $gg\to(H^*)\toVV$ process and the backgrounds at higher orders in QCD
  - $m_{ZZ}$ differential cross section measurement might be used as well, at the price of reduced sensitivity

- Will be interesting to explore also the reach for HE-LHC
Backup