Off-shell Interpretations TF
Theory uncertainties from ATLAS

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Off-shell analysis overview

Measurement of off-shell Higgs boson production in the $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$ decay channels at $\sqrt{s} = 13$ TeV with the data of 36.1 fb$^{-1}$ [Latest ATLAS paper]

- **Main event selections**
  - $ZZ \rightarrow 4\ell$: four-lepton candidates are formed by selecting a lepton-quadruplet made out of two same-flavour, opposite-sign lepton pairs, $m_{4\ell} > 220$ GeV, $m_{Z1} \in [50,106]$ GeV, $m_{Z2} \in [50,115]$ GeV
  - $ZZ \rightarrow 2\ell 2\nu$: exactly two opposite-charge leptons of the same flavour, $E_T^{\text{miss}} > 120$ GeV, $m_Z \in [76,106]$ GeV

- **Example of the analysis strategy for $ZZ \rightarrow 4\ell$**
  - ME-based discriminant computed at LO is constructed to enhance the separation between the $gg \rightarrow H^* \rightarrow ZZ$ signal and the $gg \rightarrow ZZ$ and $qq \rightarrow ZZ$ backgrounds
  - This discriminant is subsequently used in a binned maximum-likelihood fit for the final result
$gg \rightarrow (H^* \rightarrow )ZZ$ process
MC simulation

- \( gg \rightarrow (H^* \rightarrow ZZ) \)

- Include the SM Higgs boson signal, \( gg \rightarrow H^* \rightarrow ZZ \), the continuum background, \( gg \rightarrow ZZ \), and the signal–background interference contribution

- Generated with the MC generator Sherpa v2.2.2+OpenLoops [Ref]

- Matrix elements calculated for 0-jets and 1-jet at LO and merged with the Sherpa parton shower

- NNPDF30NNLO PDF set used\(^1\)

- QCD renormalisation and factorisation scales set to \( m_{ZZ}/2 \)

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\(^1\)The LO \( gg \rightarrow ZZ \) process is part of the NNLO calculation for \( pp \rightarrow ZZ \)
Higher-order theory corrections

- **NLO QCD** corrections [Caola, Melnikov, Röntsch, & Tancredi, 2015] [Caola et al., 2016]
  - Available for the full process $gg \to (H^* \to ZZ$
  - Allowing $m_{ZZ}$ differential K-factors to be calculated with an expansion in the inverse top mass below $2m_t$, and assuming a massless-quark approximation above this threshold
  - Used to correct all three components with separate NLO/LO K-factors computed for the signal $K^S(m_{ZZ})$, the background $K^B(m_{ZZ})$ and the interference $K^I(m_{ZZ})$

- **NNLO QCD** corrections [Passarino], [Handbook of LHC Higgs Cross Sections]
  - Available only for the signal process $gg \to H^* \to ZZ$ as a function of $m_{ZZ}$
  - Overall correction is applied by scaling the differential NLO QCD reweighted cross section by an additional flat NNLO/NLO K-factor of 1.2, which is assumed to be the same for the signal, the background and the interference
Theory uncertainties due to higher-order QCD corrections

- Uncertainty on the NLO K-factors due to the **QCD scale uncertainty** (estimated by varying the renormalisation and factorisation scales independently, ranging from a factor of one-half to two) is **10–20%** as a function of $m_{ZZ}$

- Assumed that it covers the uncertainties in the 1.2 scale factor estimated only for the NNLO/NLO signal correction but also applied to the background and interference components

- **Below $2m_t$:** the default scale uncertainty doubled for events with $p_T^{\text{jet}} > 150$ GeV (following the recipe from the theory paper)
  - Higher-order corrections are computed with a maximum jet transverse momentum of 150 GeV to ensure a good description by the $1/m_t$ expansion

- **Around $2m_t$:** the default scale uncertainty increased by 50%
  - Possible effects on the K-factor which were not estimated as the top quark moves on-shell

- **Above $2m_t$:** Assumed that the scale uncertainty covers the assumption of massless loops

- These recipes discussed with theorists at a previous HXSWG meeting (Feb 2018, [link](#))
Other theory uncertainties

• PDF uncertainty

  • Corresponds to the 68% CL variations of the nominal PDF set NNPDF30NNLO as well as the difference from alternative PDF sets (CT10NNLO and MMHT2014NNLO)

  • Found to be about 3%

• Parton-shower modelling uncertainty

  • Evaluated by varying parameters in parton-shower tunes

  • Found to be 2–3% in normalisation

• Off
$q \bar{q} \rightarrow ZZ$ process
MC simulation and higher-order theory corrections

- Simulated with Sherpa v2.2.2

- **NLO QCD** accuracy is achieved in the matrix-element calculation for 0- and 1-jet final states and **LO QCD** accuracy for 2- and 3-jet final states

- Merging with the Sherpa parton shower was performed using the MePs@NLO prescription

- NNPDF30NNLO PDF set for the hard-scattering process

- **NLO EW** corrections are applied as a function of the particle-level $m_{ZZ}$
  [Biedermann, Denner, Dittmaier, Hofer, & Jäger, 01/2016] [Biedermann et al., 11/2016]
Theory uncertainties due to higher-order corrections

- **QCD scale uncertainty**
  - Estimated by varying the renormalisation and factorisation scales independently, ranging from a factor of one-half to two
  - Found to be **5–10%** and parametrised as function of $m_{4\ell}$

- **EW correction uncertainty**
  - EW corrections computed at LO QCD because the mixed QCD–EW corrections have not yet been calculated, therefore an additional systematic uncertainty is considered by studying
    \[
    \rho = \left| \sum_i \vec{\ell}_{i,T} + \vec{E}_{T}^{\text{miss}} \right| / \left( \sum_i \left| \vec{\ell}_{i,T} \right| + \left| \vec{E}_{T}^{\text{miss}} \right| \right)
    \]
    (following the recipe from the theory paper)
  - $\rho < 0.3$: the NLO QCD event kinematics resembles the LO event kinematics in being dominated by recoiling vector bosons, the corrections are thus applicable without extra uncertainty
  - $\rho > 0.3$: the correction is applied with a 100% systematic uncertainty to account for the missing mixed QCD–EW corrections which are expected to be of the same order of magnitude
  - Its impact is estimated to be about **1%**
Other theory uncertainties

- PDF uncertainty
  - Corresponds to the 68% CL variations of the nominal PDF set NNPDF30NNLO as well as the difference from alternative PDF sets (CT10NNLO and MMHT2014NNLO)
  - Found to be about 3%

- Parton-shower modelling uncertainty
  - Evaluated by varying parameters in parton-shower tunes
  - Found to be 2–3% in normalisation
The largest systematic uncertainties for the off-shell analysis arise from the theoretical uncertainties in the $gg$-initiated $ZZ$ processes and the $q\bar{q} \rightarrow ZZ$ background process.

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>$95%$ CL upper limit on $ZZ \rightarrow 4\ell$</th>
<th>$ZZ \rightarrow 2\ell2\nu$</th>
<th>$\mu_{\text{off-shell}}$</th>
<th>Combined</th>
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</thead>
<tbody>
<tr>
<td>QCD scale $q\bar{q} \rightarrow ZZ$</td>
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<td>3.9</td>
<td>3.2</td>
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<tr>
<td>QCD scale $gg \rightarrow (H^* \rightarrow)ZZ$</td>
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<td>Luminosity</td>
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<td>3.4</td>
<td>3.0</td>
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</tr>
</tbody>
</table>
Possible improvements

• $q\bar{q} \rightarrow ZZ$ process

  • Use a control region and extrapolate to the signal region

  • Use the most recent NNLO QCD+NLO EW calculations from MATRIX+OpenLoops

• $gg$-initiated $ZZ$ processes

  • Looking forward to the implementation of loop-induced processes at NLO in MC tools, mainly MadGraph and Sherpa

  • One alternative solution would be to generate LO 0j+1j sample (or even 0+1+2j) using MadGraph and CKKW merging