Off-shell Interpretations TF
Theory uncertainties from ATLAS

Martina Javurkova[1], Rafael Coelho Lopes de Sá[1], Lailin Xu[2]

[1]University of Massachusetts-Amherst

[2] Brookhaven National Laboratory

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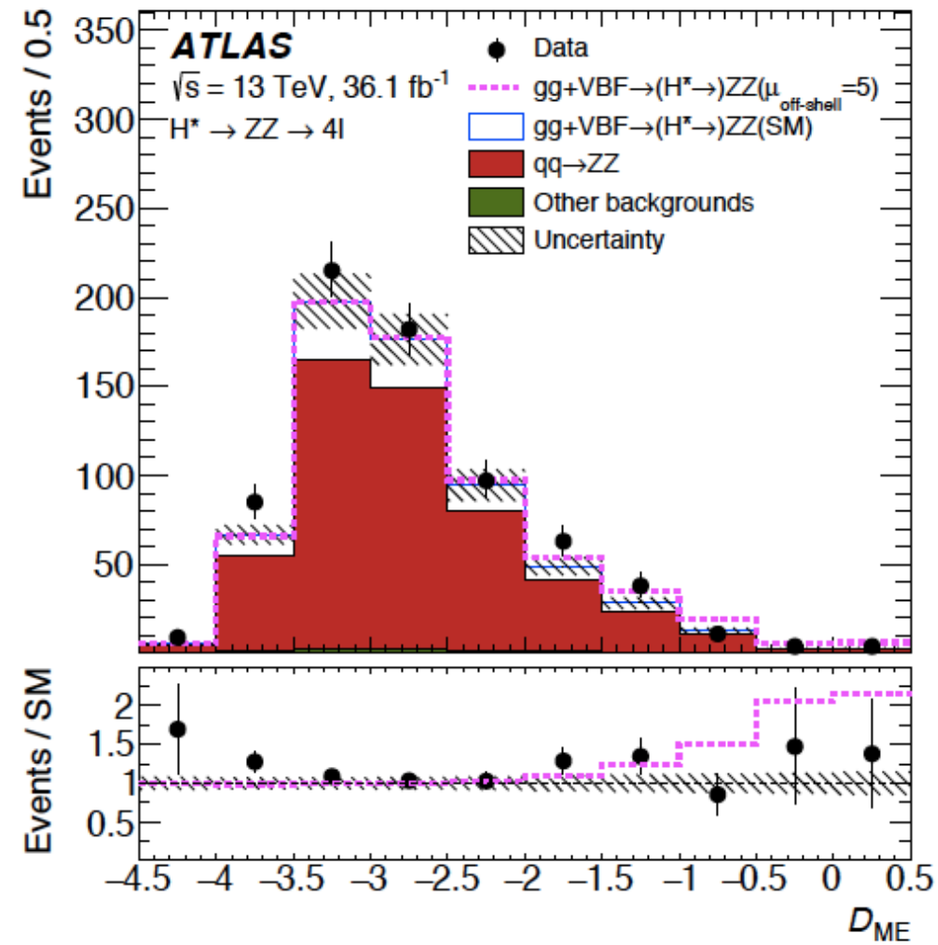
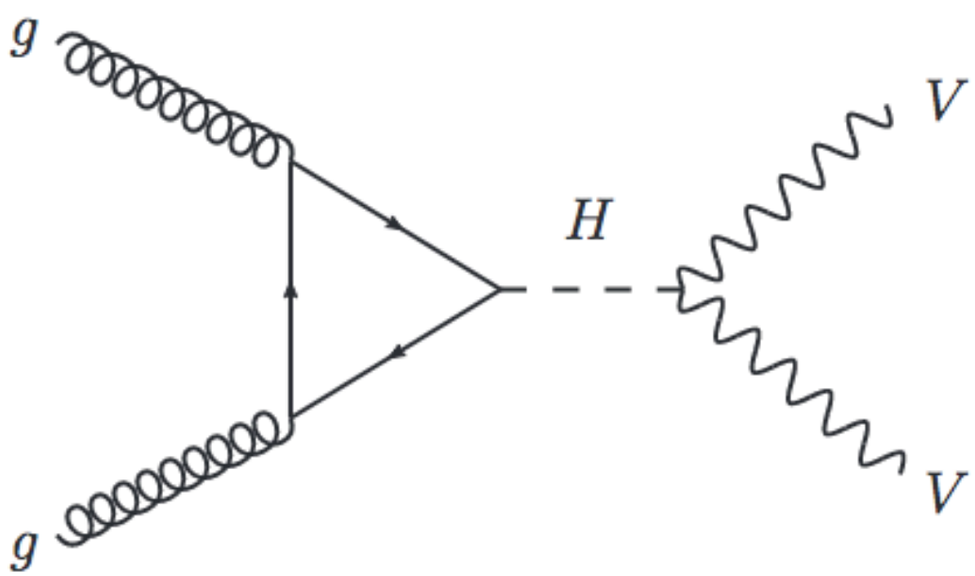
Off-shell analysis overview

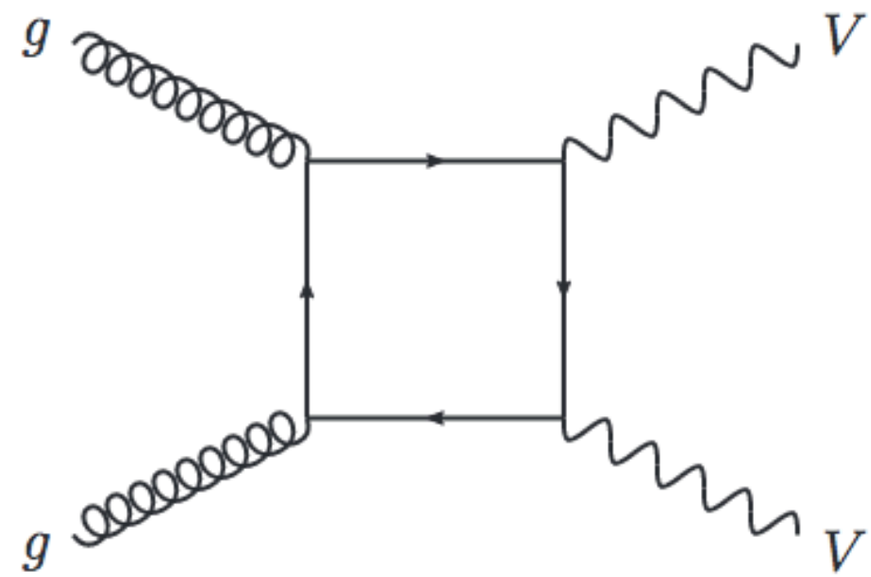
Measurement of off-shell Higgs boson production in the $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$ decay channels at $\sqrt{s} = 13$ TeV with the data of $36.1\ \mathrm{fb}^{-1}$ [Latest ATLAS paper]

- **Main event selections**
  - $ZZ \to 4\ell$: 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
  - $ZZ \to 2\ell 2\nu$: exactly two opposite-charge leptons of the same flavour, $E_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV, $m_Z \in [76,106]$
- **Example of the analysis strategy for $ZZ \to 4\ell$**
  - ME-based discriminant computed at LO is constructed to enhance the separation between the $gg \to H^* \to ZZ$ signal and the $gg \to ZZ$ and $qq \to ZZ$ backgrounds
  - This discriminant is subsequently used in a binned maximum-likelihood fit for the final result



$gg \to (H^* \to)ZZ$ process





MC simulation

- $gg \to (H^* \to)ZZ$
  - Include the SM Higgs boson signal, $gg \to H^* \to ZZ$, the continuum background, $gg \to ZZ$, 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 $m_{ZZ}/2$

1.The LO $gg \to ZZ$ process is part of the NNLO calculation for $pp \to ZZ$

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

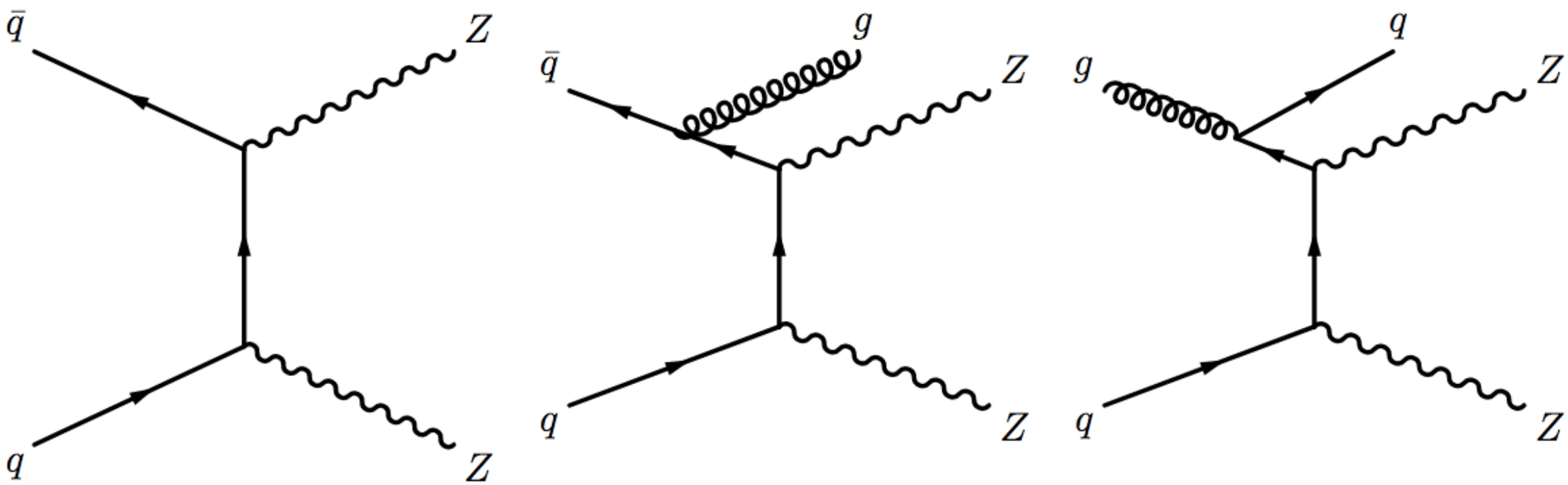
Theory uncertainties due to higher-order QCD corrections

- 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 $p_{\mathrm{T}}^{\mathrm{jet}} > 150$ 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

$q\bar{q} \to ZZ$ 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 $\rho = |\sum_i \vec{\ell}_{i,\mathrm{T}} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}|/(\sum_i |\vec{\ell}_{i,\mathrm{T}}| + |\vec{E}_{\mathrm{T}}^{\mathrm{miss}}|)$ (following the recipe from the theory paper)
  - $\underline{\rho < 0.3}$: 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
  - $\underline{\rho > 0.3}$: 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

Conclusion

- The largest systematic uncertainties for the off-shell analysis arise from the theoretical uncertainties in the gg-initiated ZZ processes and the $q\bar{q} \to ZZ$ background process

Systematic uncertainty	95% CL upper limit on $\mu_{\text{off-shell}}$		
	$ZZ \to 4\ell$	$ZZ \to 2\ell 2\nu$	Combined
QCD scale $q\bar{q} \to ZZ$	4.2	3.9	3.2
QCD scale $gg \to (H^* \to)ZZ$	4.2	3.6	3.1
Luminosity	4.1	3.5	3.1
Remaining systematic uncertainties	4.1	3.5	3.0
All systematic uncertainties	4.3	4.4	3.4
No systematic uncertainties	4.0	3.4	3.0

Possible improvements

- $q\bar{q} \to ZZ$ 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

Backup