CMS analysis approaches to gluon fusion K factors

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on behalf of the CMS Collaboration

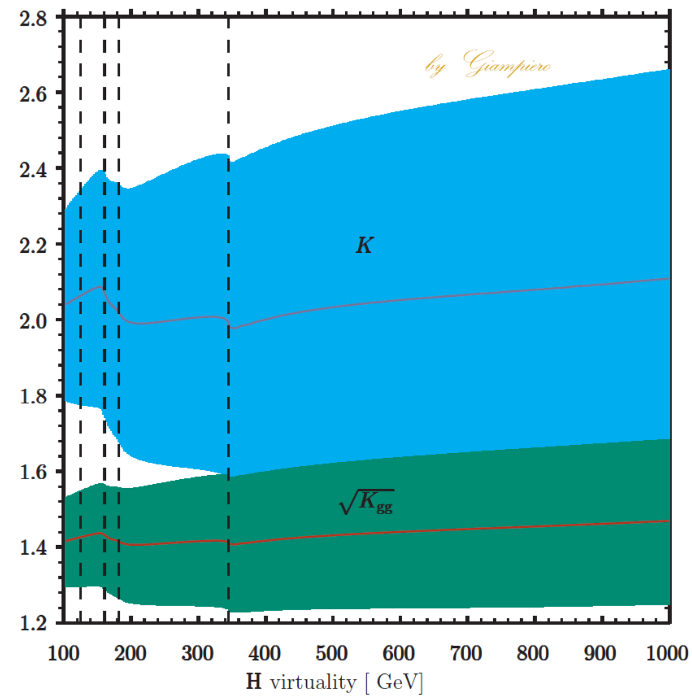
LHCHXSWG off-shell subgroup – 22.02.2018

Run-I overview

- In Run-I off-shell analysis, CMS relied on the parameterizations provided by G. Passarino for $\sqrt{s} = 7$ and 8 TeV.
  → There was K_{sig} and an approximated K_{bkg} provided, but we observed $K_{bkg} \cong K_{sig}$
  → Motivated the discussion of whether $K_{sig} = K_{bkg}$ is a good enough approximation
  → Consulted with theorists (F. Caola, K. Melnikov), and conclusion was that under soft-gluon approximation, they should be similar.

- Work by Li et al. (arxiv 1504.02388) on ZZ, and by Bonvini et al. (arxiv 1304.3053) on WW also illustrated the similarity of K_{int} to K_{sig} under the soft-gluon approximation

  → Conclusion was that a 10% additional uncertainty on bkg., and a related uncertainty on interference, is enough to cover the differences.



G. Passarino, Higgs CAT, arxiv 1312.2397

Run-II landscape

- Strategy in CMS is guided by the need to know the full invariant mass shape + kinematics of final particles due to analysis needs:

  → Need to evaluate associated particles and uncertainties related

  → Better access to different production modes

  → Categorization for VBF events is also important at high mass, VBF or VH events at low mass, so need to understand associated jet behavior from gluon fusion, a dominant background in these categories

  → Spin-0 high mass and off-shell width/spin-parity analyses are affected by mass parameterization and need to apply mass-dependent uncertainties

  → Different sources of uncertainty affecting different regions in a mass-dependent way (i.e. QCD scale dominant at the lower parts of high mass, PDF choice above 2 TeV)

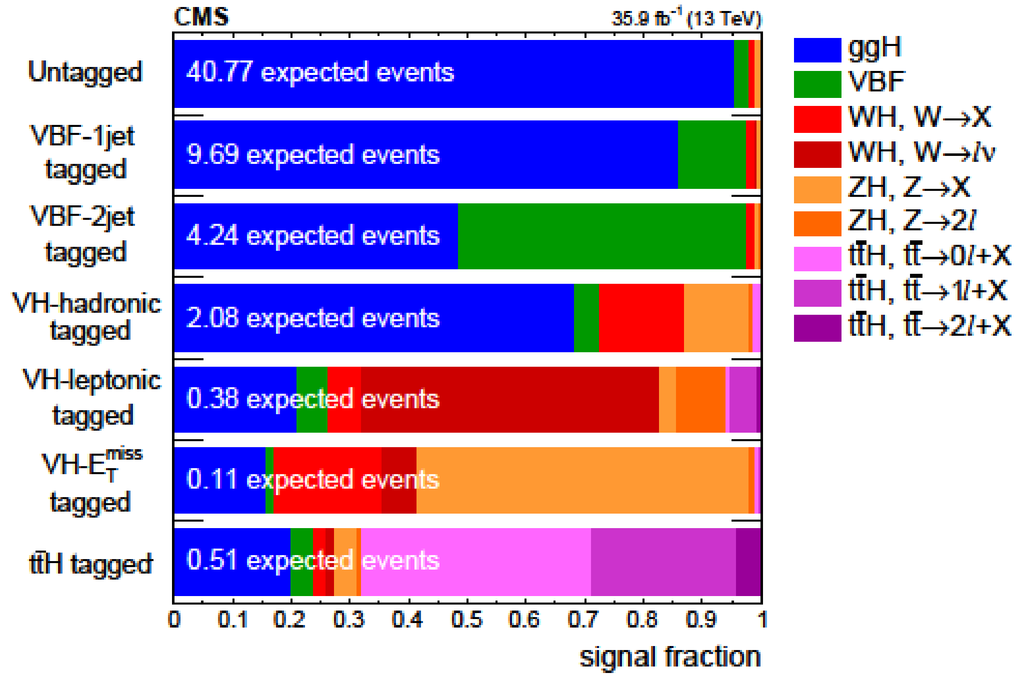
  → Need to find reliable signal, background and interference parameterizations

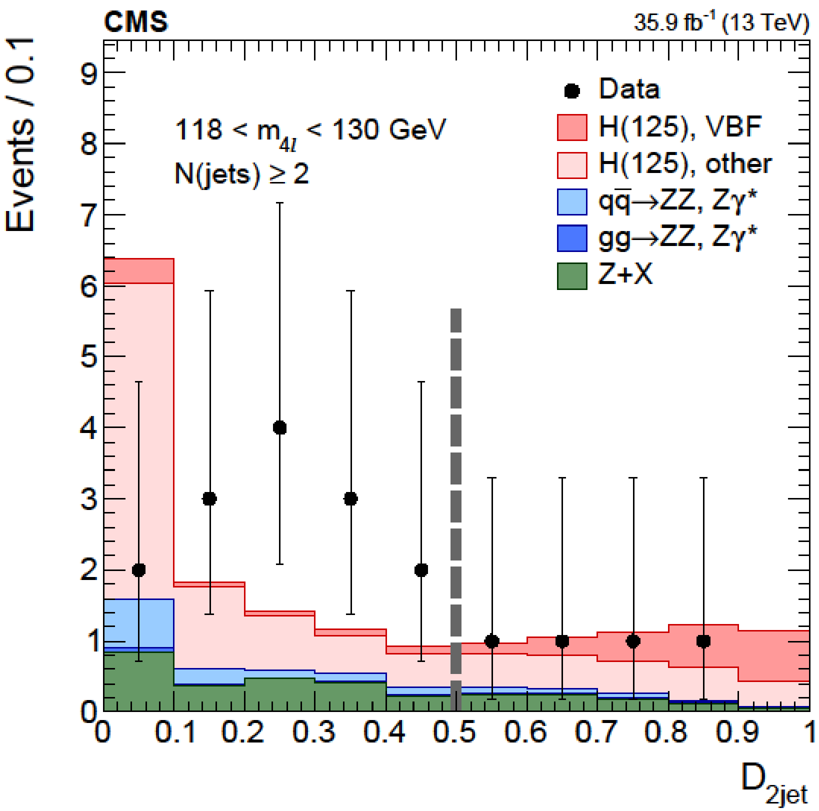
  → Need to do this for different anomalous couplings in HVV (or Hff) as well

- We would also like to ensure consistency of methods in the different measurements:
  → Essentially need understanding of all ingredients from <100 GeV to >3 TeV.

Run-II needs: Categorization

→ Increase in luminosity and $\sqrt{s} = 13$ TeV provides better opportunity to study Higgs production via associated particles

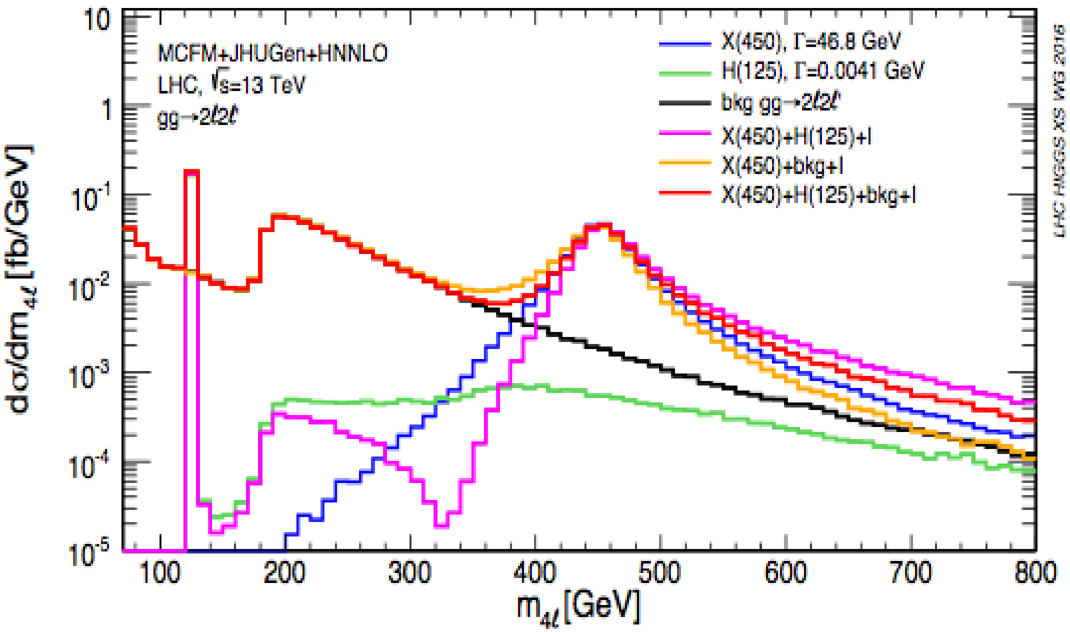




→ Need to have reliable knowledge and a good uncertainty estimate in all kinematic observables, not just m_{ZZ}

→ Only extractable from event simulation

Run-II needs: High mass

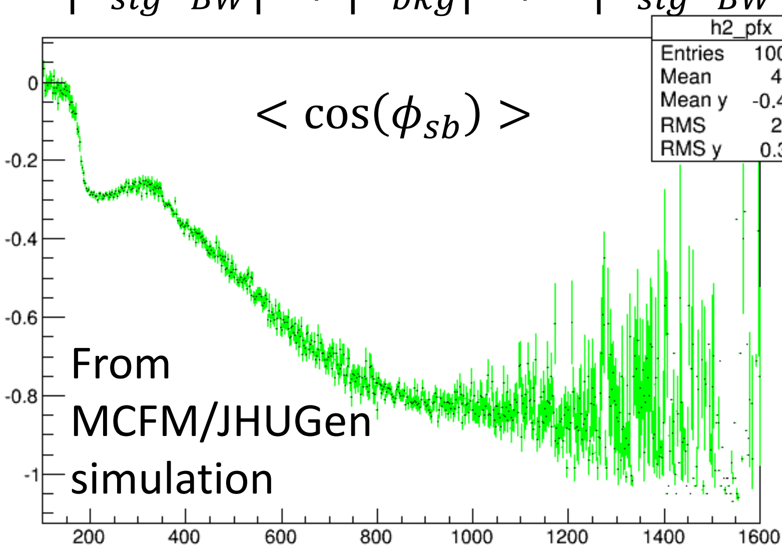


→ Interference effects shown to be important in high mass searches, not just with background but with H(125) as well (see red vs orange).

→ A high mass spin-0 resonance behaves just like H(125), but with a different propagator.

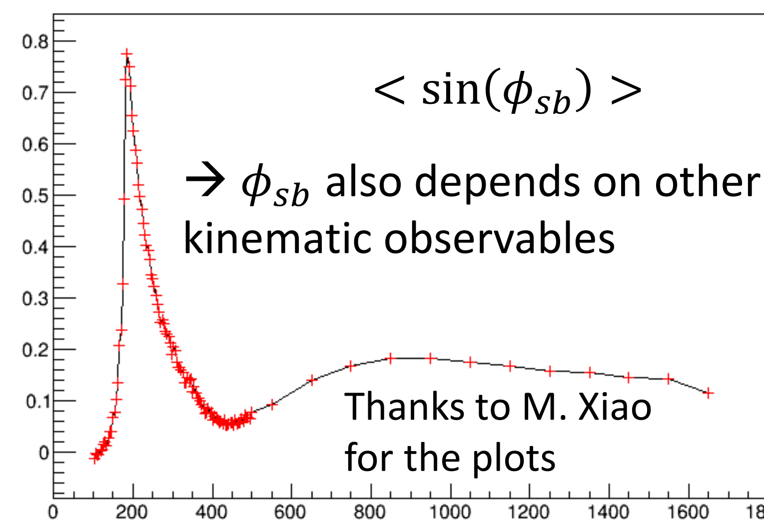
→ A single K_{int} would only be computed for a particular BW.

$$|A_{sig}P_{BW}|^2 + |A_{bkg}|^2 + 2\,|A_{sig}P_{BW}||A_{bkg}| \times (\cos(\phi_{sb})\cos(\phi_{BW}) - \sin(\phi_{sb})\sin(\phi_{BW}))$$



$< \cos(\phi_{sb}) >$

From MCFM/JHUGen simulation



$< \sin(\phi_{sb}) >$

→ ϕ_{sb} also depends on other kinematic observables

Thanks to M. Xiao for the plots

Run-II needs: HVV anomalous couplings

$$A(HVV) \sim \left[\boldsymbol{a_1} - e^{i\phi_{\Lambda Q}} \frac{q_H^2}{\Lambda_Q^2} - e^{i\phi_{\Lambda 1}} \frac{(q_{V1}^2 + q_{V2}^2)}{\Lambda_1^2} \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^* + \mathrm{a}_2 \mathrm{f}_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \mathrm{a}_3 \mathrm{f}_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

→ The total amplitude includes additional terms to SM ($\propto a_1$)

→ Interference effects are very different with the background.

→ Ex. Take the pseudoscalar contribution ($\propto a_3$): Projection of signal-bkg. interference and signal scalar-pseudoscalar interference terms on CP-insensitive variables (e.g. m_{ZZ}) should be exactly 0.

→ On-shell analysis published by CMS already uses categorization for VBF and hadronic VH-tagged events. Important to use same method for off-shell measurements.

On-shell AC measurements:

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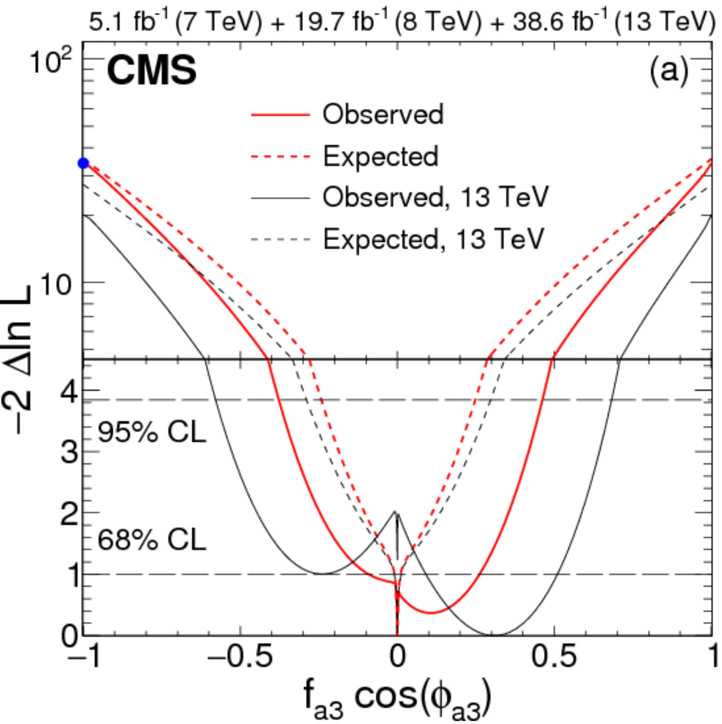
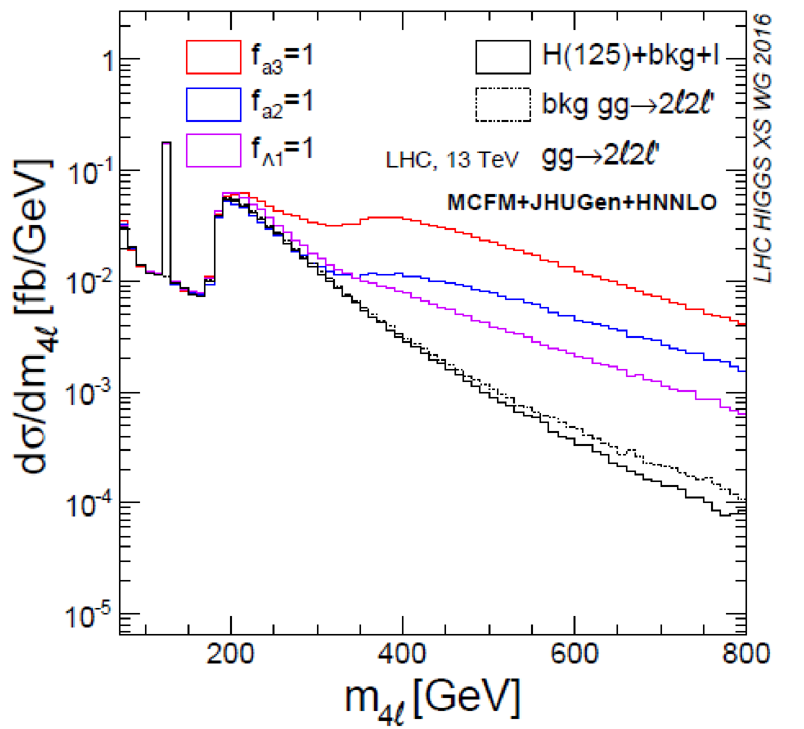
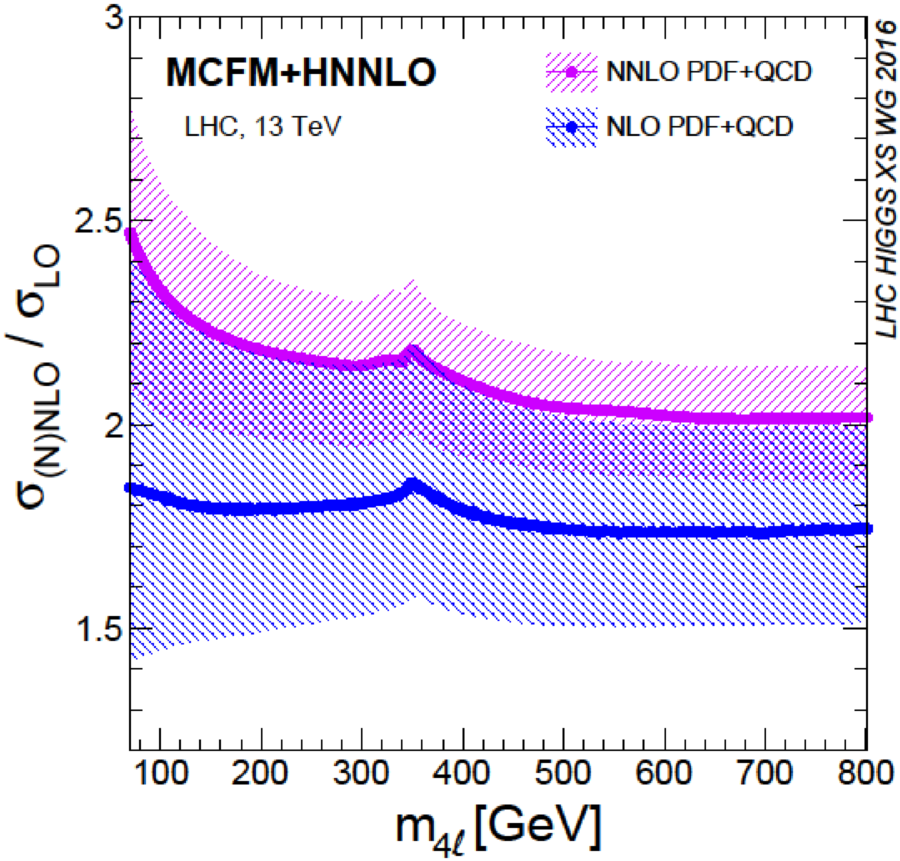


$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j}$$



Best knowledge: Signal

- Signal and interference lineshapes may be modified based on the anomalous couplings.
  → If anomalous couplings are in the HVV vertex, signal gg production side does not change.
- Signal normalization known best at N3LO only at and around 125 GeV.
- Information on associated particle kinematics known from NLO POWHEG simulation.



m_{ZZ} lineshape critical for all analyses aforementioned:
→ m_{ZZ}-dependent K factors computed for NLO and NNLO using HNNLO v2 by Grazzini et al. from 70 GeV to beyond 3 TeV
→ Features full quark mass effects at NLO, infinite top mass for the NNLO-NLO contribution.
→ Central value chosen to have consistent parameters and scales ($\mu_{R,F} = m_{4l}/2$)
→ Different mass-dependent variations are obtained for the following components based on latest [PDF4LHC recommendations]:

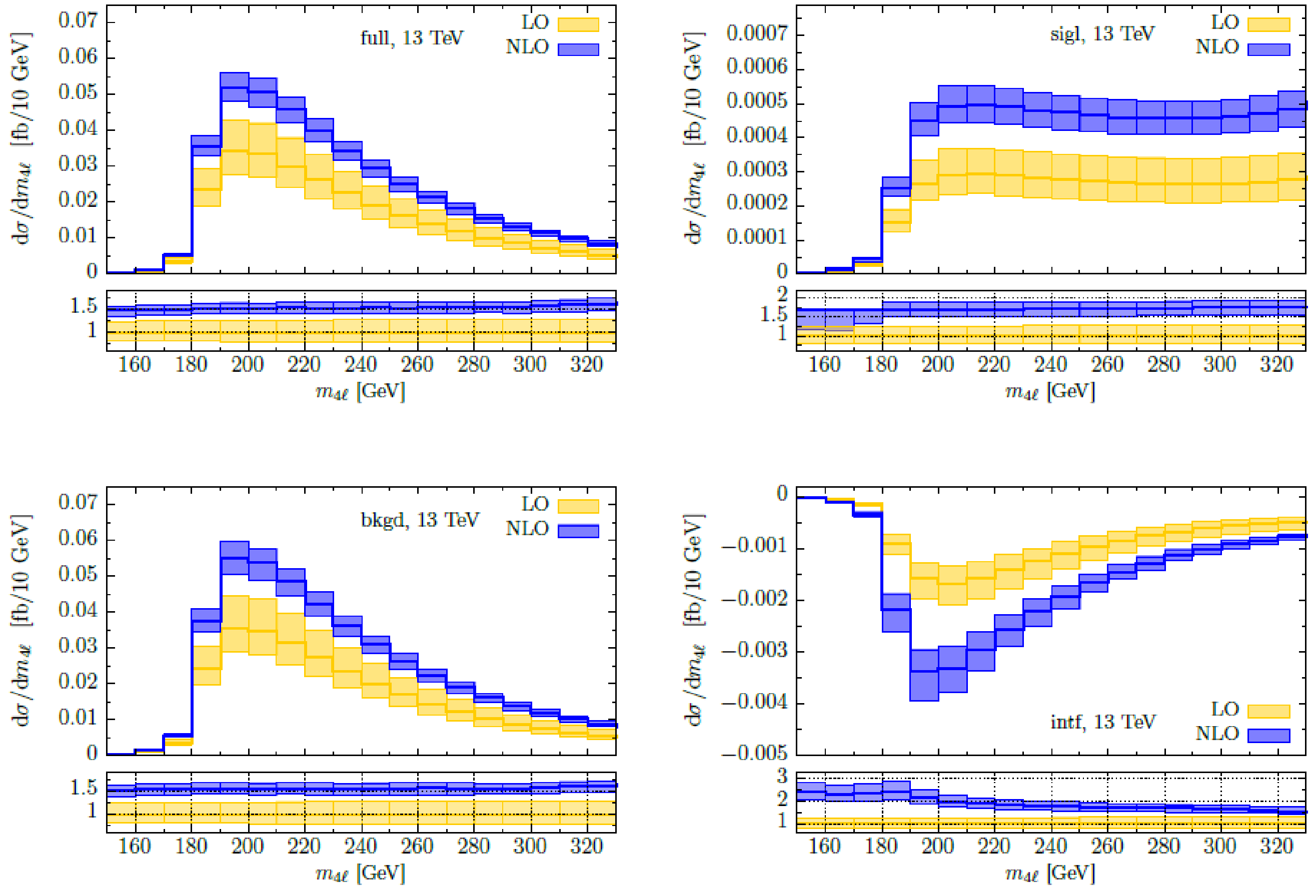
a) Renormalization scale
   (dominant uncertainty at lower masses)
b) Factorization scale
c) Uncertainty in $\alpha_s(m_Z)$ (C.V. 0.118)
d) 100 PDF variations from NNPDF 3.0
   (dominant uncertainty at higher masses)

Best knowledge: Background and interference

- Knowledge from Run-I from Li et al., Bonvini et al., and communication with F. Caola, K. Melnikov already indicate interference background K factors are close to signal within ~10%.
  → Recall that we also need to model interference for different coupling choices, not just SM.

- While recent computations by Caola et al. (arxiv 1509.06734, 1511.08617, 1605.04610) indicate signal, background and interference NLO K factors may be slightly different, they are still close to each other within O(10%) approximation.
  → Agreement better above $2m_z$ threshold, where background is much larger and interference effects become more relevant.
  → Computation valid only up to $m_{ZZ} < 2m_t$

Best knowledge: Background and interference



Caola et al.

[arxiv 1605.04610]

Figure 6: Four-lepton invariant mass distributions in $gg \to ZZ$ processes at the 13 TeV LHC The full result is shown as well as contributions of signal, background and interference separately LO results are shown in yellow, NLO results are shown in blue, and scale variation is shown foı $m_{4\ell}/4 < \mu < m_{4\ell}$ with a central scale $\mu = m_{4\ell}/2$. The lower pane shows the K-factors.

Strategy in ZZ

- Driven by the needs of the different analyses aforementioned:
  → Ideally, need simulation at NNLO QCD for background with consistent signal-background interference treatments with different anomalous couplings, but lack a full NNLO QCD simulation in signal and background
  → Do not have best K factors at consistent orders (NNLO for signal, NLO for bkg.)
  → NLO K factor for background has limited validity range in m_{ZZ}
  but
  → Know since Run-I that signal and background K factors are within 10%
  → Have full NLO QCD simulation for the signal from POWHEG, and N3LO total signal cross section at around 125 GeV
  → Physical treatment of interference plausible with $K_{int} = \sqrt{K_{sig}K_{bkg}}$, unless corrections on ϕ_{sb} (+ under different anomalous couplings) are large at NLO or NNLO.

- With the best current knowledge, we choose to pursue the following strategy in ZZ:
  → Apply NNLO signal K factor on signal, background and interference as a function of m_{ZZ}
  → Apply single N3LO/NNLO (125 GeV) flat factor on overall yield, fractional uncertainties kept the same as in NNLO
  → Other kinematic observables of associated production and categorization efficiency + uncertainties are taken from POWHEG signal simulation at NLO QCD, applied the same on all different contributions