Update on Offshell Studies

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WG1 Fall Meeting

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Introduction

- Focus on processes with sizeable contribution from offshell Higgs.
- E.g: $gg \to H \to VV$:

  10% of events above the $2m_V$ threshold. [Kauer, Passarino ('12)]
- Large offshell rates also in EW production (*VH,* VBF).

  [cf. Campbell, Ellis ('15); Gritsan *et al. (*20)]
- Allows the exploration of the Higgs properties in a new kinematic regime:
  - Width [Caola, Melnikov ('13)]
  - Couplings
  - Unitarization properties
  - ...

Experimental Status

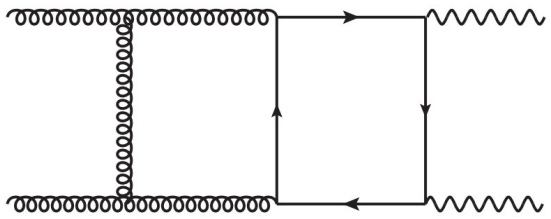
- ATLAS
  - $H \to ZZ$ offshell analysis ongoing and quite mature. Two final states, *4l* and *2l2ν*, are used and will be combined.
  - $H \to WW \to l\nu l\nu$ offshell analysis still in the very early stage.
  - Interferometry in the on-shell diphoton channel also under development.
- CMS
  - Continuing investigations of Higgs width measurements in a number of decay channels.

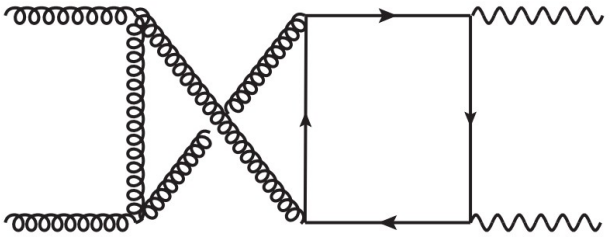
No updates with full Run-II data presented yet

Theory Status and Progress (I)

- Offshell predictions for $gg \to H \to VV$ require background $gg \to VV$ process to be taken into account.
  - Makes higher order corrections very difficult to compute!
- Two-loop QCD amplitudes for $gg \to ZZ$ and $gg \to WW$ including massive quark effects now known.

  [Agarwal, Jones, von Manteuffel (‘20); Brønnum-Hansen, Chen (‘20,’21)]





- Substantial computing resources required: still not used in cross section calculations...

Theory Status and Progress (II)

- NLO corrections in *gg → (H) → ZZ* combined with NNLO QCD + NLO EW corrections to ZZ production.

  [Grazzini, Kallweit, Wiesemann, Yook (‘21)]

  - Massive two-loop amplitudes through reweighting.
- Offshell Higgs production (incl. interference effects) matched to parton shower in POWHEG-BOX.

  [Alioli, Ferrario Ravasio, Lindert, RR (‘21)]

  - Massive loops using $1/m_t$ expansion and through reweighting
- WW production in NNLO+PS using MiNNLO$_{PS}$.

  [Lombardi, Wiesemann, Zanderighi (‘21)]
- Pheno study of offshell Higgs production at HL-LHC using effective field theory framework and non-local Higgs-top coupling form factor.

  [Gonçalves, Han, Leung, Qin (‘20)]

Focuses of Offshell Subgroup

- Interpretation of offshell measurements:
  - Width extraction *not* model independent – **constraints on NP through EFT operators** + width determinations?
- Tools for simulations:
  - Account for higher order corrections?
  - Include EFT effects.
- Theory uncertainties:
  - **Inclusion of extra radiation through jet merging.**
  - Combining QCD and EW corrections in *VV* background.
  - EW corrections in *VV* background.

Overlap between these areas!

- Documentation of studies in progress – thanks to our theory, ATLAS, and CMS colleagues who have contributed!
- See our Twiki for more information.

Models, EFTs, and Interpretations

- Summary of the Higgs basis parametrization of the SMEFT [finalized]

  [A. Falkowski]

- What can off-shell Higgs measurements tell us about BSM physics? [finalized]
  - use off-shell observables to lift universal flat directions of on-shell Higgs rates
  - when giving up coupling universality: off-shell can have leading resolving power in certain scenarios)

  [A. Azatov, J. de Blas, C. Grojean, E. Salvioni]

- Off-shell Higgs production in the SMEFT [draft]
  - Studies using SMEFT@NLO implementation of SMEFT operators with `MG5 aMC@NLO`

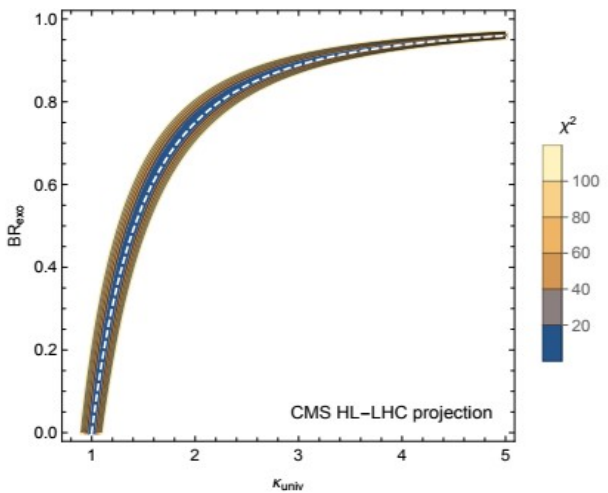
  [E. Vryonidou]

What can off-shell Higgs measurements tell us about BSM physics?

A. Azatov, J. de Blas, C. Grojean, E. Salvioni

- Re-examine the potential impact of off-shell Higgs measurements on BSM physics.
- Off-shell data can lift a flat direction plaguing onshell Higgs measurements @ LHC under universal Higgs coupling rescaling κ_{univ}. [Caola, Melnikov ('13)]
- Genuinely new contributions to Higgs width can be classified as "invisible" or "untagged".

- Invisible constrained by direct search to $BR_{inv} < 0.13$ @ 95% CL.
- Focus on "untagged" partial width



χ-squared contours for the projection to the HL-LHC of CMS on-shell Higgs measurements, assuming a universal coupling rescaling κ_{univ} and the presence of an untagged branching ratio.

[de Blas *et al.* ('19)]

What can off-shell Higgs measurements tell us about BSM physics?

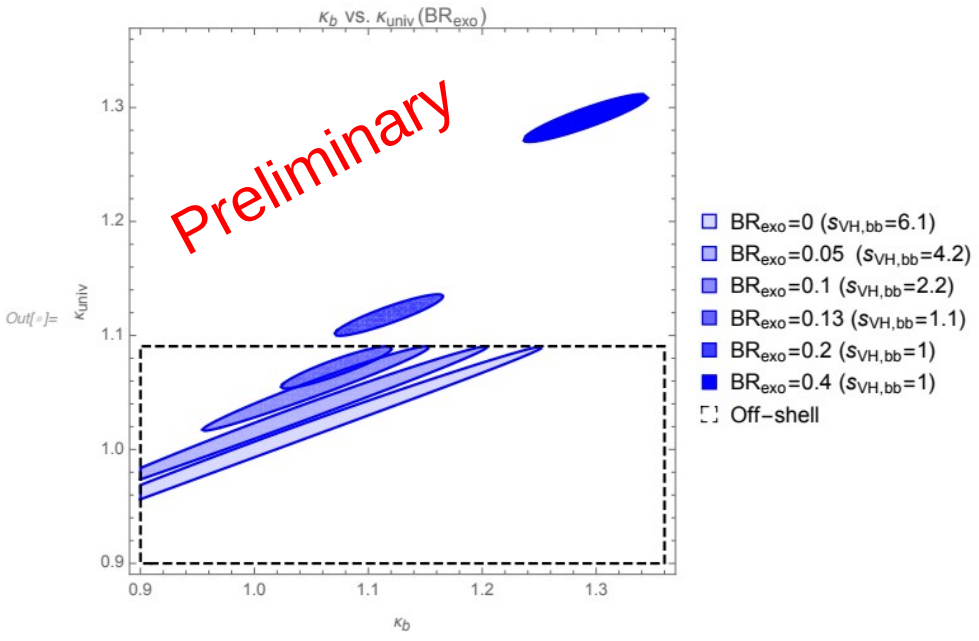
- Realize flat direction in a concrete BSM setup.
- BSM model with real scalar that decays predominantly to *gg* / hadrons

$$\mathcal{L}_{\rm BSM} \ni \frac{c_H}{2f^2}(\partial_\mu |H|^2)^2 - \lambda_{H\varphi}|H|^2\varphi^2$$

- Discussed examples make it clear that a BSM theory needs to satisfy specific conditions in order for a universal flat direction to be realized.
- Can fit to on-shell Higgs data allow for (approximately) flat directions even when the assumption of coupling universality is relaxed?
- Introduce non-universal *hbb* rescaling κ_b as decay mode dominates SM Higgs width.
- Flat direction: for given $\kappa_b<1$, a compensating value of untagged BR_{exo} exists, such that Higgs has a SM-like total width.
- Degeneracy lifted by $H \to b\bar{b}$ observables in *ZH* and $t\bar{t}H$ production.
- In this context: complementary information from off-shell Higgs production.

What can off-shell Higgs measurements tell us about BSM physics?

Dashed contour encloses the allowed range of κ_{univ} as found from the off-shell contribution to gg→ *4l* at the HL-LHC.



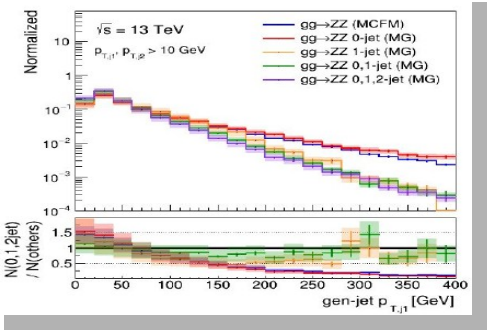
- For large untagged BR_{exo} = 0.2:
  - off-shell data has stronger sensitivity than *VH.*
- For medium BR_{exo} = 0.1:
  - off-shell data can provide genuinely new information.
- For small BR_{exo} = 0.05:
  - off-shell data is most likely not competitive.

Higher Order Corrections: Jet Merging and PS

Use merging to simulate effect of additional radiation.

[Li *et al.* '20] [Talk by Congqiao Li]

- Merging of 0, 1- and 2-jet samples in gluon fusion $gg \rightarrow ZZ$.
- Higgs-mediated diagrams not **(yet)** included [work in progress].
- Z decay not included yet [work in progress]
- MadGraph for matrix element simulation, matched to Pythia with MLM scheme.



sub-process	core-hour
0-jet	0.085
1-jet	10.9
2-jet	15300

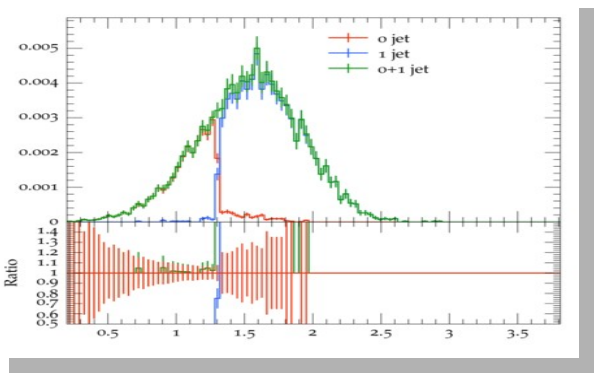
Massive increase in computational time for 2 jet emission!

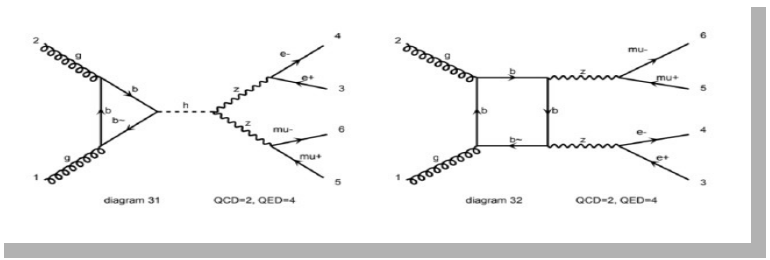
Higher Order Corrections: Jet Merging and PS

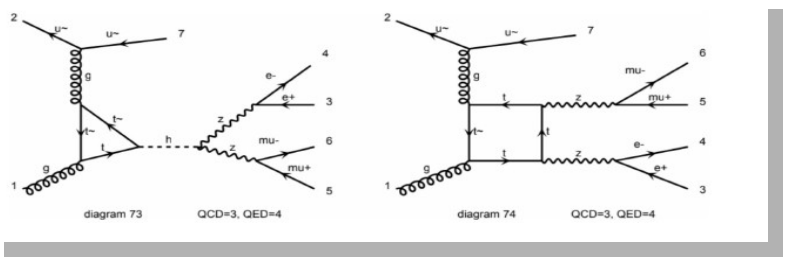
Use merging to simulate effect of additional radiation.

Talk by Jay Sandesara

- Includes prompt *ZZ* production as well as Higgs-mediated ("*SBI*").
- Leptonic decays included*.
- MLM merging to Pythia.







* 2 jet sample has onshell Z decays and no spin correlations.

Higher Order Corrections: Jet Merging

Combined study of jet merging and parton shower effects:

[with R. Coelho Lopes de Sá, S. Ferrario Ravasio, C. Li, J. Sandersara]

- Merging:
  - Up to 2 jets, generated according to matrix elements.
  - Virtual corrections not included.
- PS matching:
  - Hardest jet generated according to matrix elements.
  - Softer jets generated through PS.
  - Virtual corrections included.

Study in initial stages – watch this space!

Conclusions

- Impressive progress towards higher-precision predictions for offshell Higgs production.
- Improved understanding of how offshell Higgs events can provide insights into BSM physics:
  - Width constraints
  - Non-universal couplings in EFT approach
- Comparative study of jet merging and parton showers for additional QCD radiation (early stages)
- Eagerly awaiting results using Run-II data

Please visit our Twiki for more information