Offshell Subgroup: Theory Summary

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LHC Higgs Working Group General Meeting

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Introduction

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

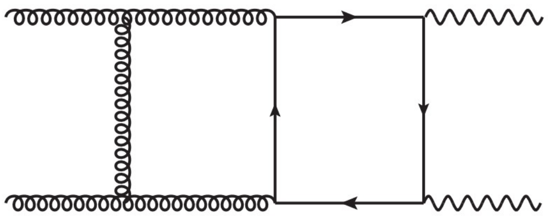
  10% of events above the $2m_V$ threshold. [NK, Passarino ('12)]
- Large offshell rates also in EW production (*VH*, VBF).

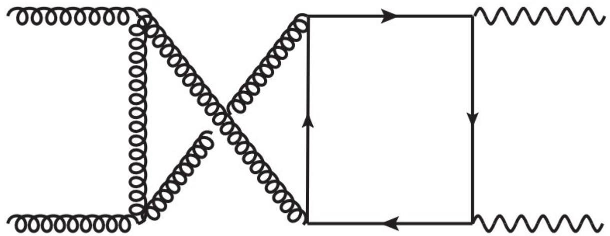
  [cf. Campbell, Ellis ('15); Gritsan *et al.* (20)]
- Allows the exploration of the Higgs properties in a new kinematic regime:
  - Width [Caola, Melnikov ('13)]
  - Couplings
  - Unitarization properties
  - ...

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 $gg \rightarrow (H) \rightarrow ZZ$ 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, Röntsch (‘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)]

- Offshell Higgs production at LHC as probe of trilinear Higgs coupling [Haisch, Koole (‘21)]

Focus 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.

Write-Up: Models, EFTs and Interpretations

- Summary of the Higgs basis parametrization of the SMEFT (finalized)
  - significantly revised presentation and discussion of the Higgs basis [see also: Talk]

[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 (finalized)
  - Studies using SMEFT@NLO implementation of SMEFT operators with `MG5_aMC@NLO`

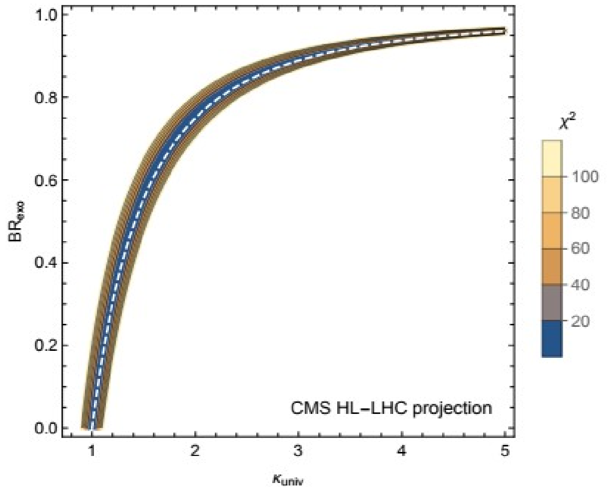
[M. Thomas, E. Vryonidou]

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?

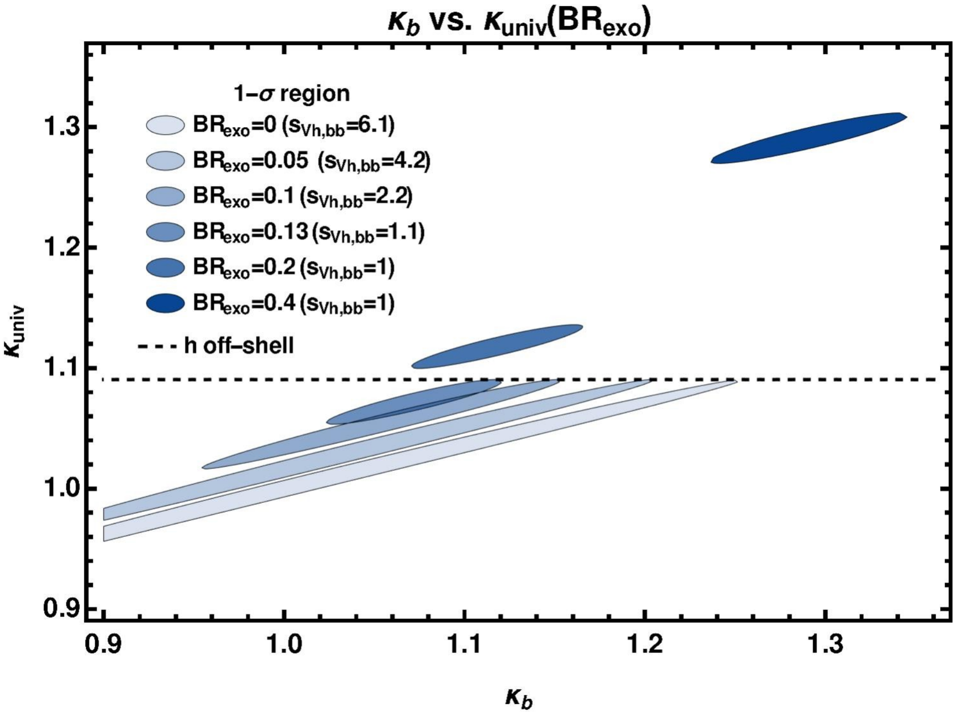
- Realize flat direction in a concrete BSM setup.
- BSM model with real scalar that decays predominantly to *gg* / hadrons

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

- two conditions for existence of universal flat direction: increased Higgs couplings relative to SM, scaling violation (not $\kappa^2_{\rm univ}$) for total Higgs width due to new BSM contribution
- 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?

Below the dashed line: allowed range of κ_{univ} as found from the off-shell contribution to $gg \rightarrow$ *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.

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

Brief review of *explicit* models testable in off-shell production

SMEFT effects in gg→ZZ

- sensitivity of off-shell measurements to SMEFT dim-6 operators for the gg→ZZ process, detailed discussion for CP-even couplings
- 9 CP-even and 5 CP-odd coefficients (Higgs basis):

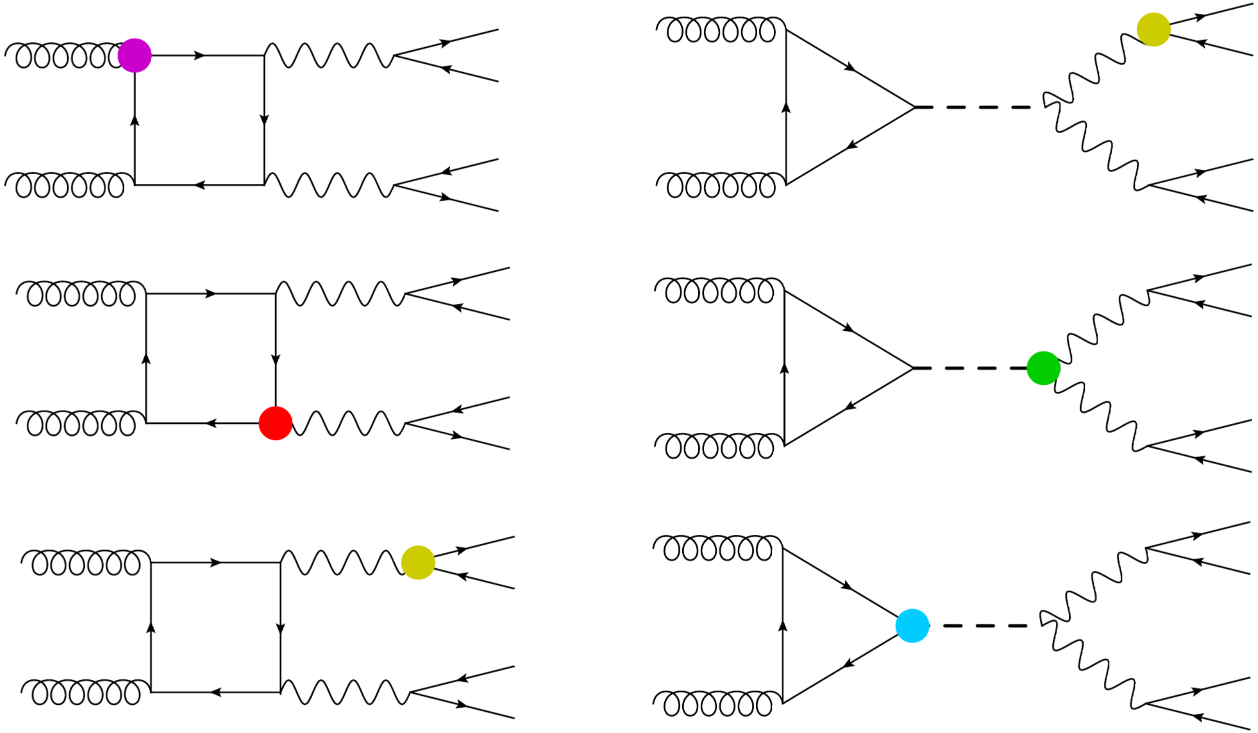
$$\Delta\mathcal{L} = \frac{h}{v}\Big(c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^{\mu\nu\,a} - m_t\underline{[\delta y_u]_{33}}\bar{t}_L t_R + \text{h.c.} + \delta c_z\frac{g_Z^2 v^2}{4}Z_\mu Z^\mu + c_{zz}\frac{g_Z^2}{4}Z_{\mu\nu}Z^{\mu\nu} + c_{z\Box}g_L^2 Z_\mu\partial_\nu Z^{\mu\nu}$$
$$+\tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\widetilde{G}^a_{\mu\nu} + \tilde{c}_{zz}\frac{g_Z^2}{4}Z_{\mu\nu}\widetilde{Z}_{\mu\nu}\Big) - g_Z(\delta g_L^{Zu})_{33}Z_\mu\bar{t}_L\gamma^\mu t_L - g_Z(\delta g_R^{Zu})_{33}Z_\mu\bar{t}_R\gamma^\mu t_R$$
$$-\frac{m_t}{4v^2}\Big(1+\frac{h}{v}\Big)\Big(g_s\bar{t}_R\sigma^{\mu\nu}T^a\underline{[d_{Gu}]_{33}}t_L G^a_{\mu\nu} + g_Z\bar{t}_R\sigma^{\mu\nu}T^a\underline{[d_{Zu}]_{33}}t_L Z_{\mu\nu}\Big) + \text{h.c.},$$

Off-shell Higgs production in the SMEFT

M. Thomas, E. Vryonidou

gg→4 leptons via off-shell Higgs: interesting interplay of Higgs and top interactions, significant interference with background

Typical Feynman graphs (SMEFT insertions as colored blobs, also H and Z,W width):



Off-shell Higgs production in the SMEFT

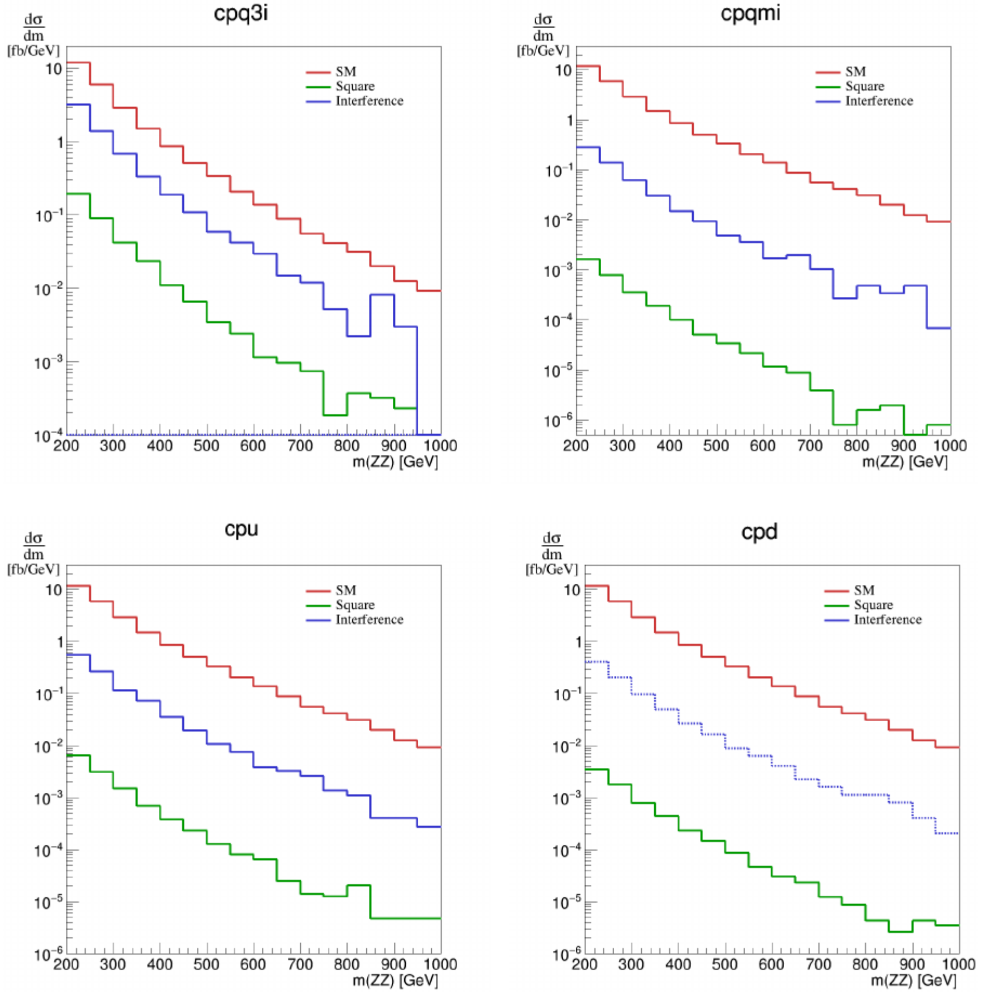
- Study gg→4 leptons via off-shell Higgs (signal and background contributions at 1-loop) in the SMEFT using MG5_aMC@NLO with the SMEFT@NLO implementation of SMEFT operators
- Note includes listing of all appearing operators, instructions how to carry out computations and representative integrated cross sections (squared and interference terms) and differential distributions for gg→ZZ (decay neglected) turning on one coefficient at a time assuming Λ = 1 TeV, results for gg→4 leptons can also be obtained following the instructions
- Operators with the **largest contributions** at interference level:

$$\mathcal{O}_{\varphi WB},\ \mathcal{O}^{(3)}_{\varphi q},\ \mathcal{O}^{(3)}_{\varphi Q}\ \text{and}\ \mathcal{O}^{(-)}_{\varphi Q}$$

- These also enter in many other processes: sensitivity comparison required
- Differential study (potential significant changes in high-energy regions)

Off-shell Higgs production in the SMEFT

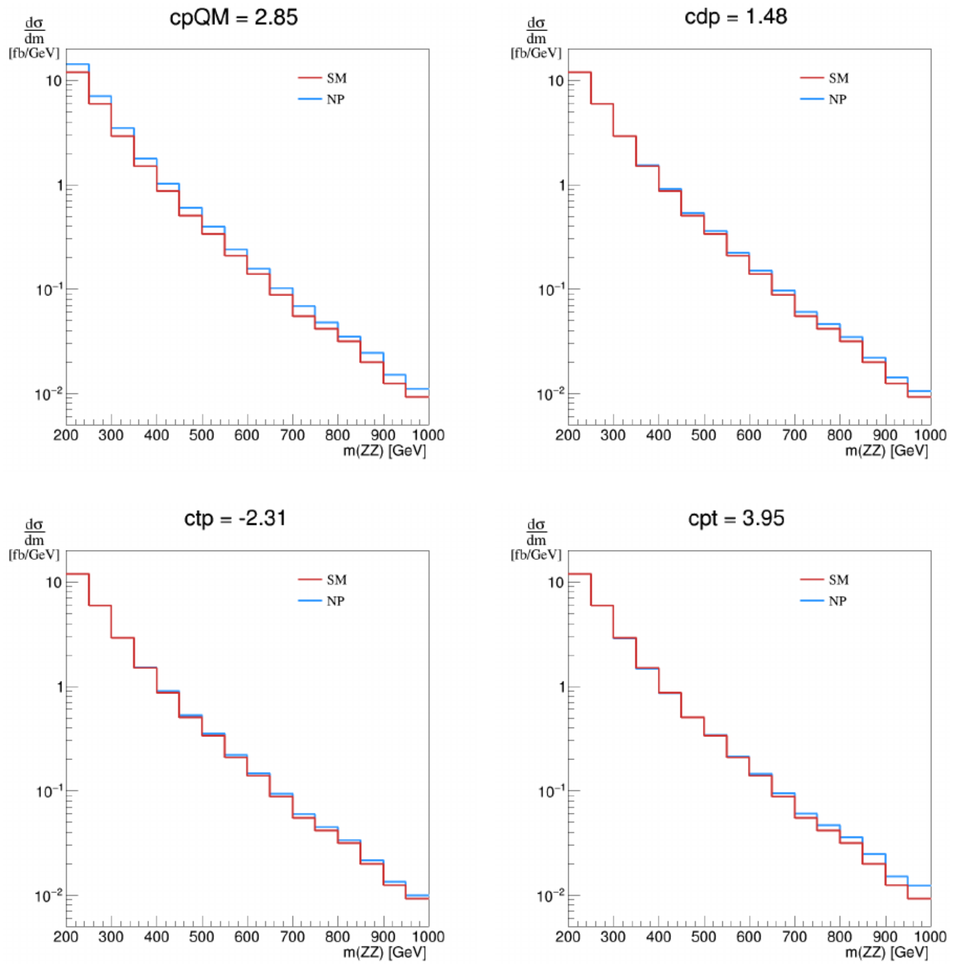
$\mathcal{O}_i$	UFO	Squared term (fb)	Interference term (fb)
$\mathcal{O}_{\varphi WB}$	cpwb	2.797(7)	118.9(3)
$\mathcal{O}_{\varphi d}$	cdp	1.273(3)	0.921(4)
$\mathcal{O}_{\varphi W}$	cpw	1.162(3)	16.83(7)
$\mathcal{O}_{\varphi B}$	cpbb	0.1083(4)	5.17(1)
$\mathcal{O}_{\varphi q}^{(3)}$	cpq3i	23.04(5)	370.0(7)
$\mathcal{O}_{\varphi q}^{(-)}$	cpqmi	0.1973(1)	34.18(7)
$\mathcal{O}_{\varphi Q}^{(3)}$	cpq3	5.78(1)	185.1(2)
$\mathcal{O}_{\varphi Q}^{(-)}$	cpqm	1.800(4)	94.5(2)
$\mathcal{O}_{\varphi u}$	cpu	0.788(2)	68.07(4)
$\mathcal{O}_{\varphi t}$	cpt	0.4794(7)	−1.85(1)
$\mathcal{O}_{\varphi d_i}$	cpd	0.434(1)	−50.5(1)
$\mathcal{O}_{t\varphi}$	ctp	0.3245(6)	−0.51(4)
$\mathcal{O}_{tZ}$	ctz	0.1546(3)	−3.53(1)
$\mathcal{O}_{tG}$	ctg	45.18(4)	0.47(6)
$\mathcal{O}_{\varphi D}$	cpdc	0.03983(3)	8.23(4)



Off-shell Higgs production in the SMEFT

Analysis of prospects of complementary off-shell constraints to those set in global fits

- employ the marginalised constraints set in [J. Ethier et al. ('21)]
- select the 95% CL marginalised bounds and show corresponding differential distributions
- Shown: the operators where allowed values of the coefficients can lead to potentially measurable deviations
- can potentially breaking degeneracies between operators

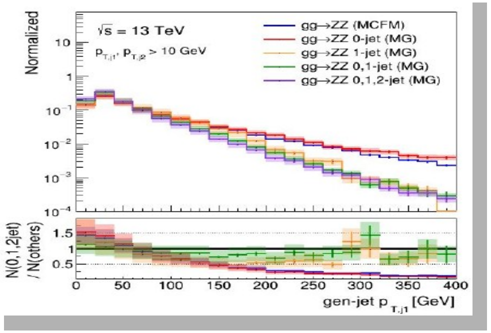


Higher Order Corrections: Jet Merging and PS

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

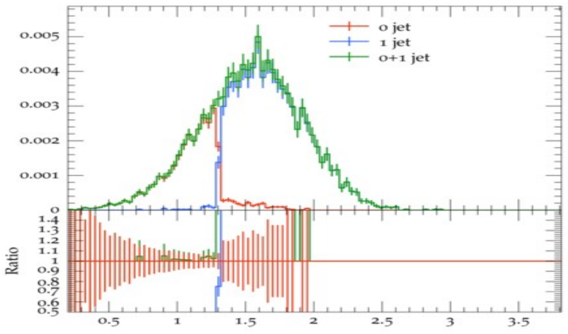
Massive increase in computational time for 2 jet emission!

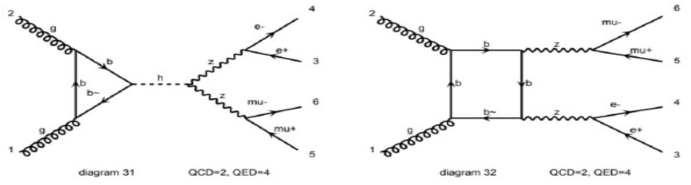
Higher Order Corrections: Jet Merging and PS

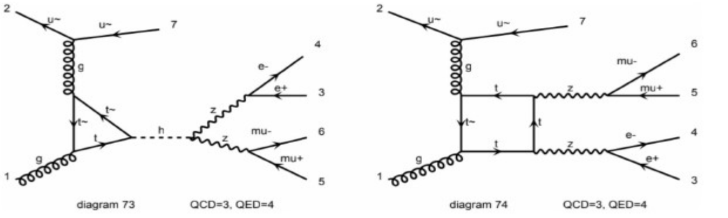
Use merging to simulate effect of additional radiation.

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:

[Röntsch 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 is in initial stages

Conclusions

- Impressive progress towards higher-precision predictions for off-shell Higgs production
- Progress how off-shell Higgs events can provide insights into BSM physics:
  - Detailed study going beyond a universal flat direction for on-shell Higgs rates
  - Tools (incl. 1-loop) for off-shell SMEFT computations validated & publicly available
  - Systematic analysis of the off-shell sensitivity to SMEFT operators initiated
  - Clarification of theoretical aspects of SMEFT analyses facilitated (Higgs basis)
- Comparative study of jet merging and parton showers for additional QCD radiation (early stages)
- Eagerly awaiting more results using Run-II data

Thanks to all authors of contributions to the write-up!