A status report of DiHiggs MC generators in ATLAS and CMS

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On behalf of the ATLAS and CMS collaborations
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Introduction

- This talk reviews the status of DiHiggs (HH) MC generators used in both experiments
- Discuss commonalities and differences
- Spot uncovered corners
- Harmonise generators
  - Consistent comparisons of future results
  - Smoother (potential) combination effort of ATLAS+CMS HH

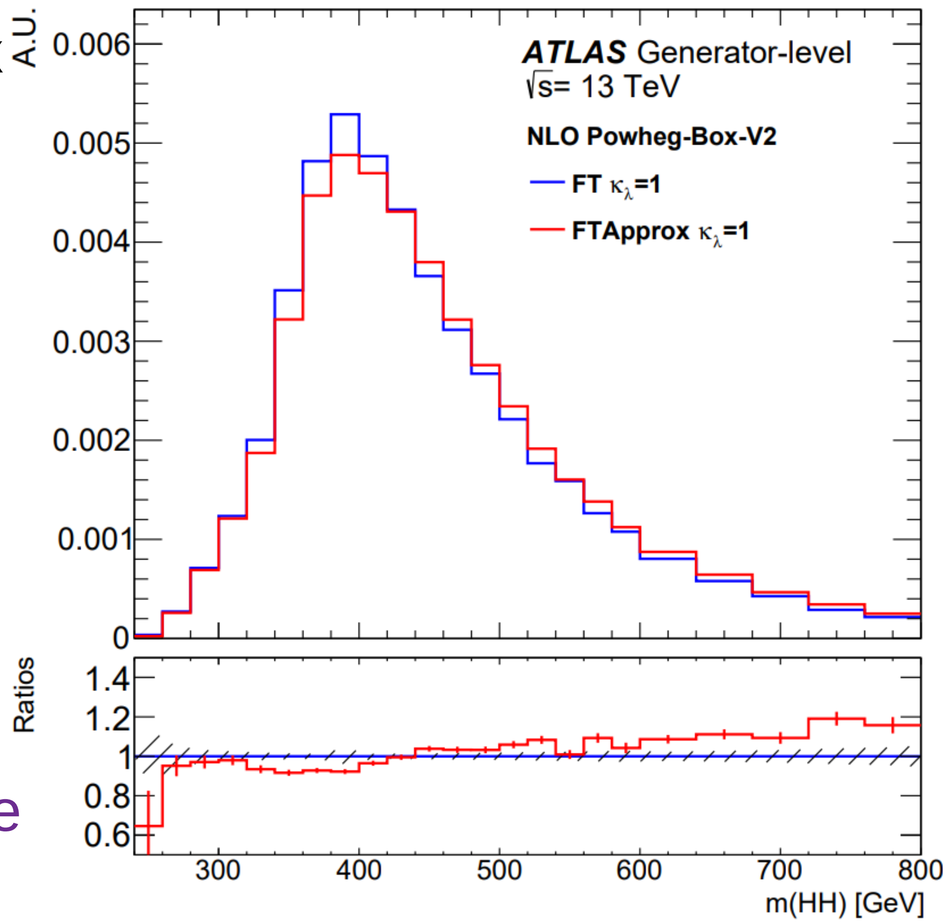
	ATLAS	CMS
Non-resonant (ggF)	**NLO+FT** Powheg-Box-V2 (vary κ_λ)	
	Herwig7	Pythia8
Non-resonant (VBF)	**LO** MG5_aMC@NLO (vary κ_V κ_{2V} and κ_λ)	
	Herwig7	Pythia8
Resonant spin0 X→HH (ggF)	**LO** MG5_aMC@NLO Heavy scalar, narrow width	**LO** MG5_aMC@NLO Radion, narrow width
	Herwig7	Pythia8
Resonant spin0 X→HH (VBF)	**NLO** Powheg-Box-V2 Heavy Higgs, narrow width	**LO** MG5_aMC@NLO Radion, narrow width
	Pythia8	Pythia8
Resonant spin2 X→HH (ggF)	**LO** MG5_aMC@NLO, graviton, narrow width	
	Pythia8	
Resonant spin2 X→HH (VBF)	-	**LO** MG5_aMC@NLO graviton, narrow width
	-	Pythia8
X→SH/SS	**LO** Pythia8 (m_S>m_H)	**NLO** MG5_aMC@NLO generalized NMSSM
	Pythia8	Pythia8

Recap the last versions (ME)

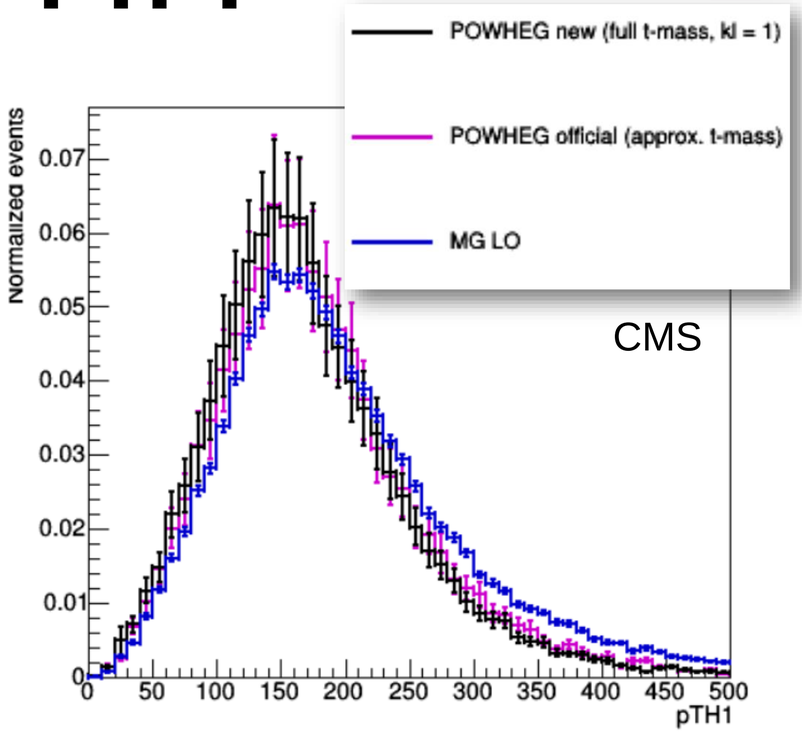
	Last versions (36/fb early Run2)	Now (140/fb full Run2)
Non-resonant (ggF)	**NLO+FTApprox** MG5_aMC@NLO, **LO** MG5_aMC@NLO for κ_λ variation (ATLAS) **LO** MG5_aMC@NLO with EFT (CMS)	**NLO+FT** Powheg-Box-V2 (vary κ_λ) EFT unchanged, under discussion
Non-resonant (VBF)	-	**LO** MG5_aMC@NLO (vary κ_V κ_{2V} and κ_λ)
Resonant spin0 X→HH (ggF)	**NLO** MG5_aMC@NLO (ATLAS)	**LO** MG5_aMC@NLO
	LO MG5_aMC@NLO (CMS)	
Resonant spin0 X→HH (VBF)	-	**NLO** Powheg-Box-V2 (ATLAS) **LO** MG5_aMC@NLO (CMS)
Resonant spin2 X→HH (ggF)	**LO** MG5_aMC@NLO	
Resonant spin2 X→HH (VBF)	**LO** MG5_aMC@NLO	
X→SH/SS	-	**LO** Pythia8 (ATLAS) **NLO** MG5_aMC@NLO (CMS)

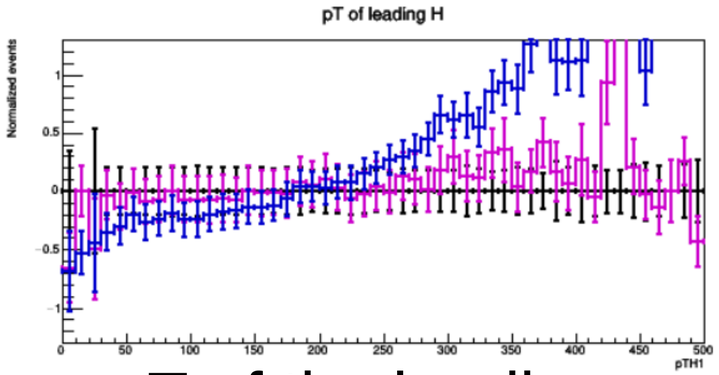
Non-resonant ggF HH

- The update for full Run2 analyses is NLO FTapprox → FT, i.e. implementation of finite top mass in the virtual loop
  - Validation done in both ATLAS and CMS
- The implementation is available in Powheg and MG5_aMC@NLO (1604.06447, 1803.02463)
  - Use Powheg as baseline
- The difference of FT vs FTApprox is found consistent with theory prediction (1604.06447)



m(HH) at fixed-order NLO

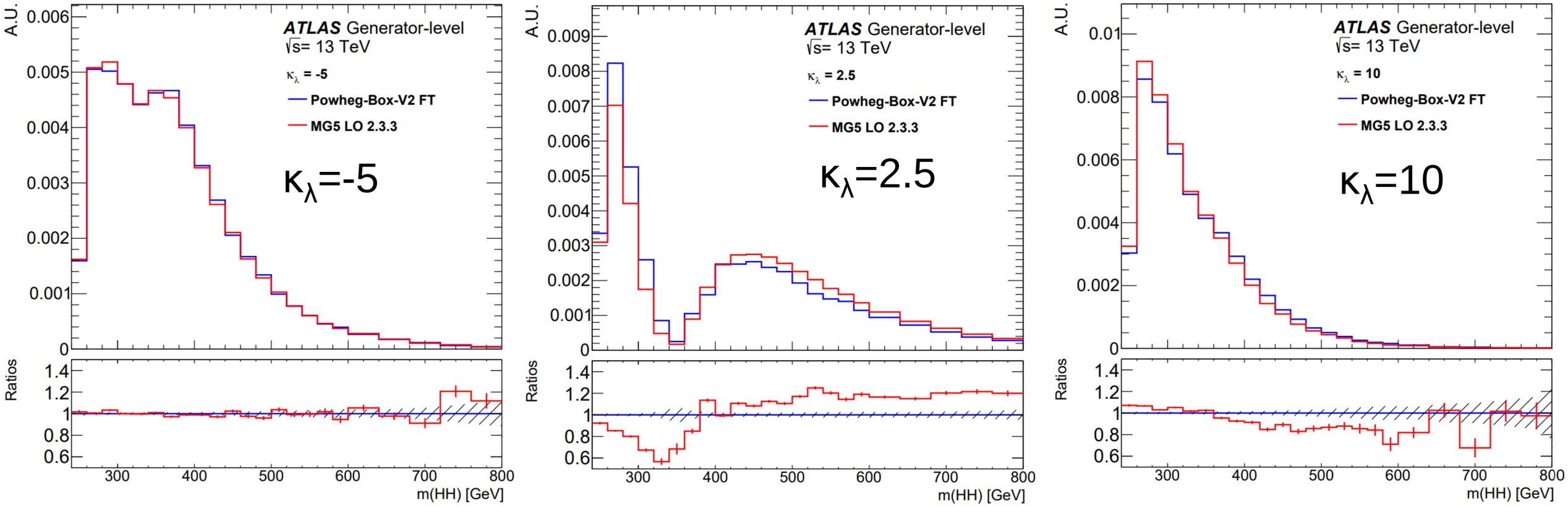




pT of the leading Higgs, after shower

Non-resonant ggF HH with non-SM κ_λ

- The update for full Run2 analyses is λ-variation at LO → NLO+FT, same generator as last page allows this: validation done in both ATLAS and CMS
- Compare MG5 LO and Powheg NLO+FT with λ variations, at fixed-order NLO

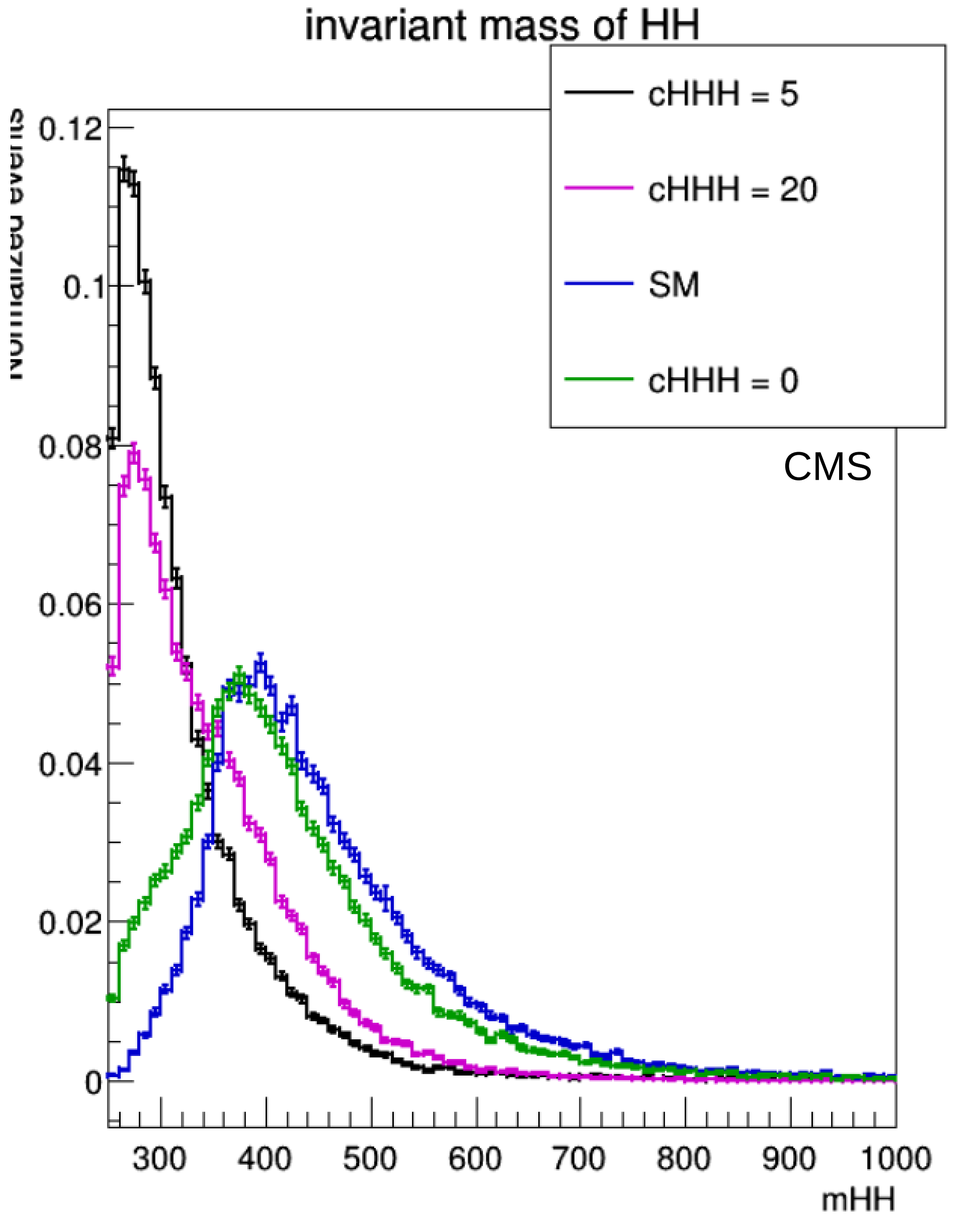


Linear combination for κ_λ variations

- Both ATLAS and CMS use similar methods to linearly combined (LC) MC samples with fixed κ_λ, κ_t to make MC samples with arbitrary κ_λ, κ_t

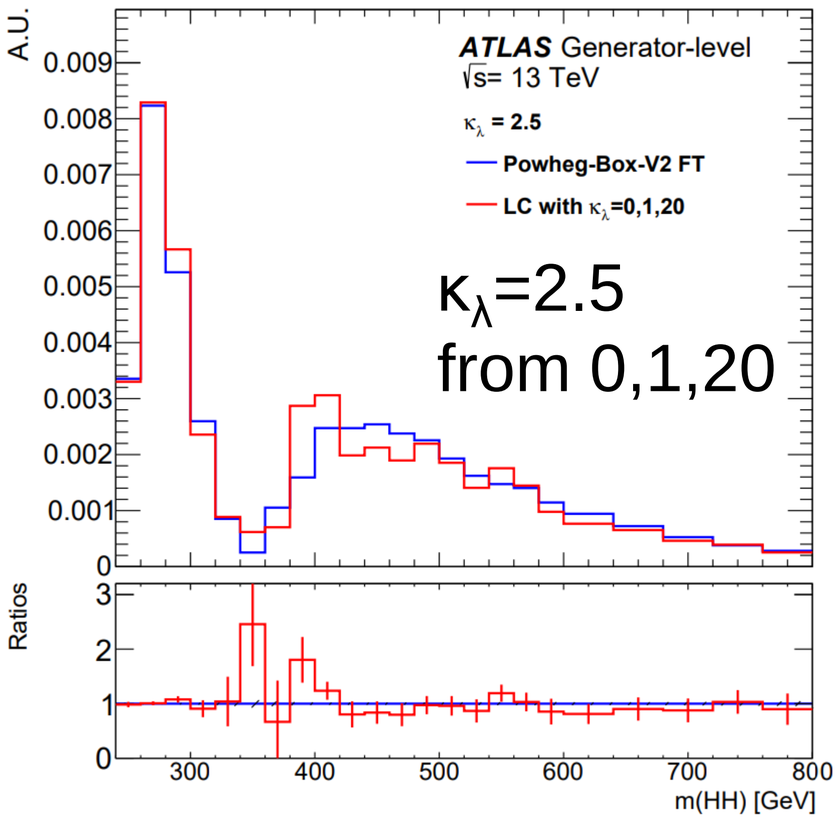
$$\sigma(pp \to HH) \sim k_t^4 \left[|B|^2 + \frac{k_\lambda}{k_t}(B^*T + TB^*) + \left(\frac{k_\lambda}{k_t}\right)^2 |T|^2 \right]$$

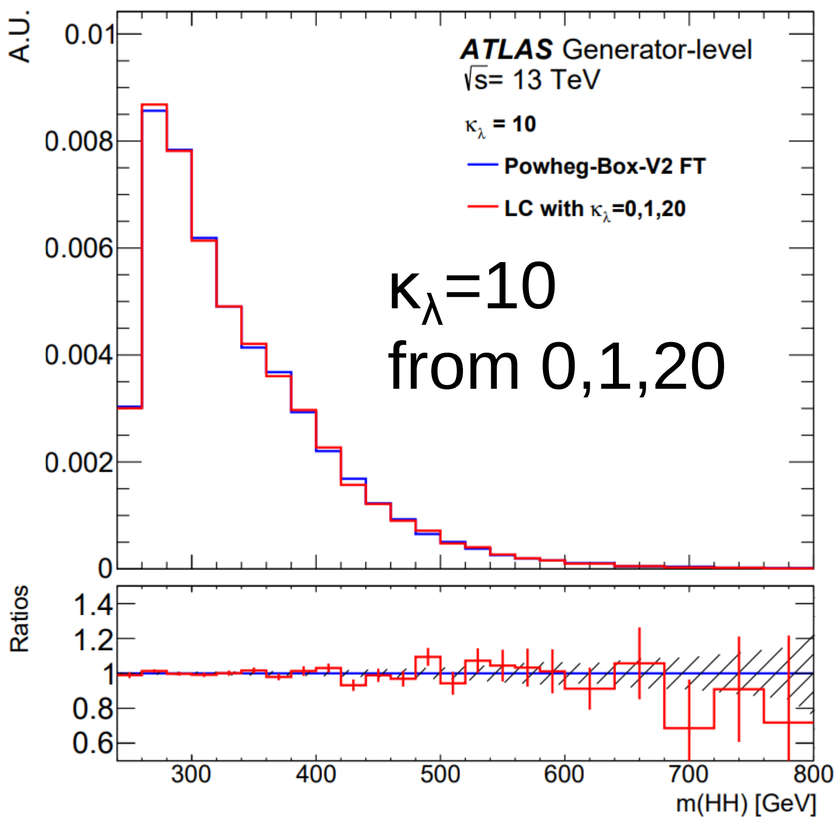
- The base samples for LC are free to choose
  - Previously (36/fb) used: (κ_t, κ_λ) = (1,0), (1,1), (1,20) [(1,2) for κ_λ~2]
  - Testing (1,0), (1,1), (1,5), (1,20) …
  - Good to harmonise

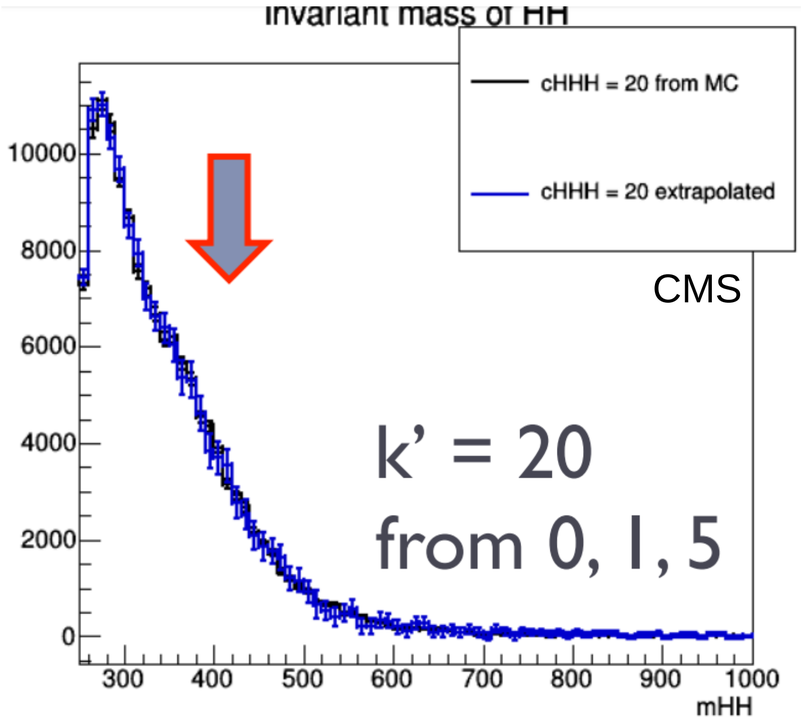


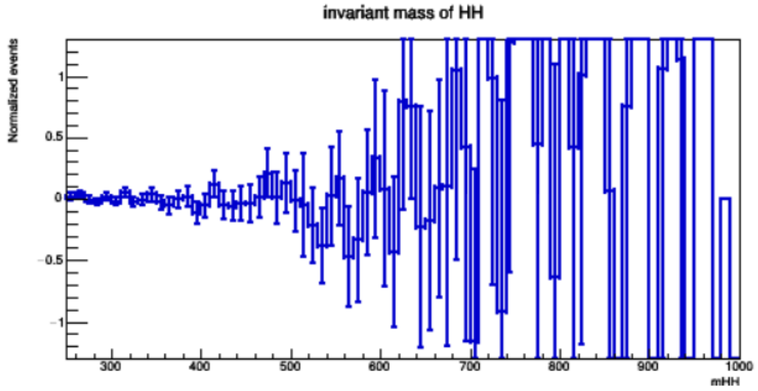
Closure of LC

- LC is compared to MC samples generated with the actual κ_t, κ_λ values
- In general closure, although statistical error can be large for maximal interference κ_λ~2.5 if using κ_λ=0,1,20



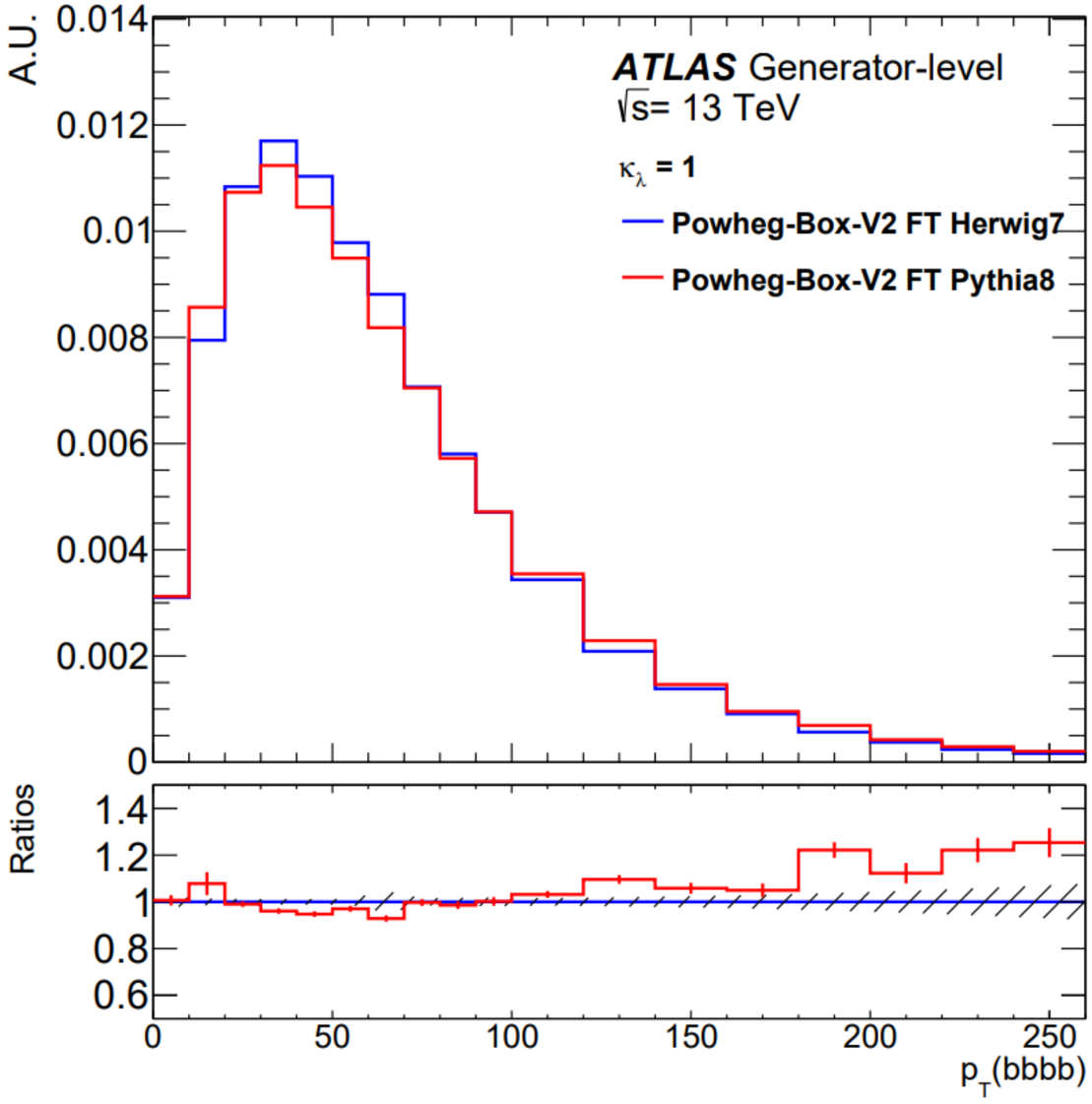






Non-resonant ggF HH with shower

- ATLAS:
  - Herwig7 (H7-UE-MMHT) is used as the baseline
  - Pythia8 (A14 NNPDF23LO) is used as an alternative to evaluate the systematic uncertainties
- CMS:
  - Pythia8 is used as the baseline
  - Vary hadronisation parameters in Pythia8 for uncertainties

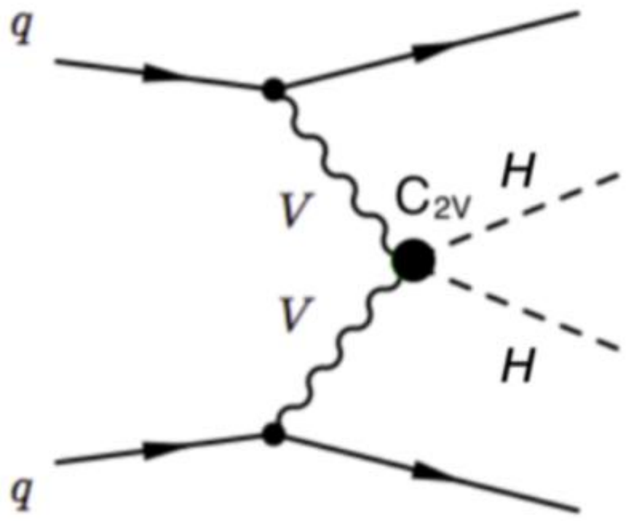


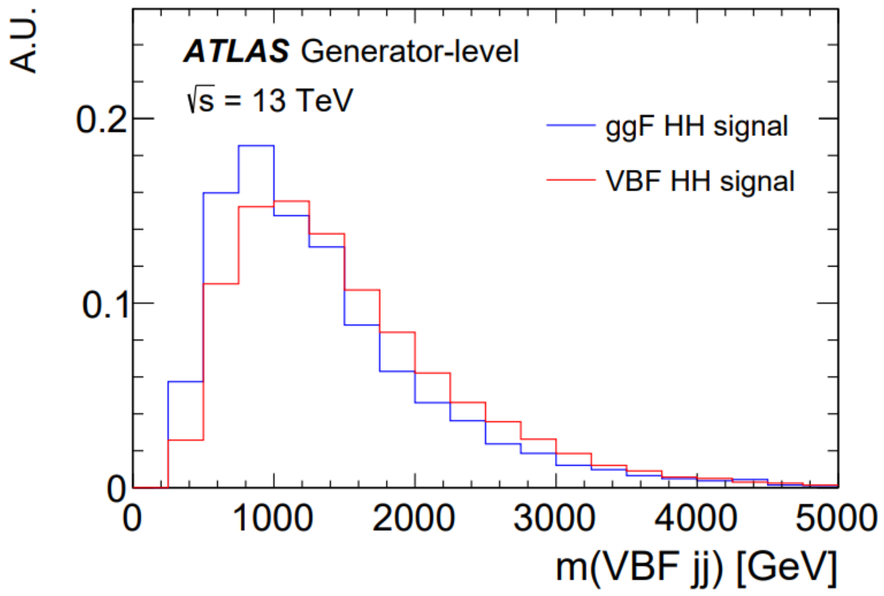
Background: HF single Higgs

- The single Higgs production with heavy-flavour (HF) radiation (H+1b, H+2b etc.) is among our backgrounds, as many of us require one of Higgs H→bb
- Currently ATLAS treatment on the HF single Higgs is (for example bbγγ that has single Higgs backgrounds just under the γγ-125 peak):
  - Assign 100% uncertainty to ggF, VBF and WH single Higgs, based on studies of HF quarks associated with tt [1304.6386] and W [1302.2929]
  - No uncertainty on ZH and ttH single Higgs, as the dominant heavy-flavour production is considered at LO
- ggF [1509.05843] and bbH can be generated in Powheg separately
  - Need to deal with the overlap between ggF (H+bjets) and bbH

Non-resonant VBF HH

- The second leading HH production
- Particularly interesting, sensitive to constrain c_{2V}
- Very different kinematics given the VBF jets





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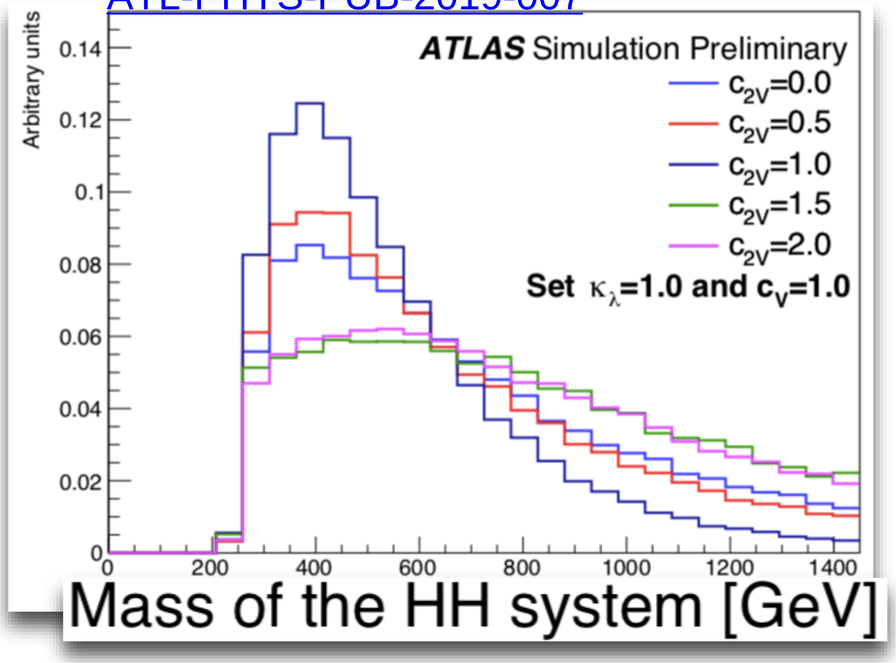

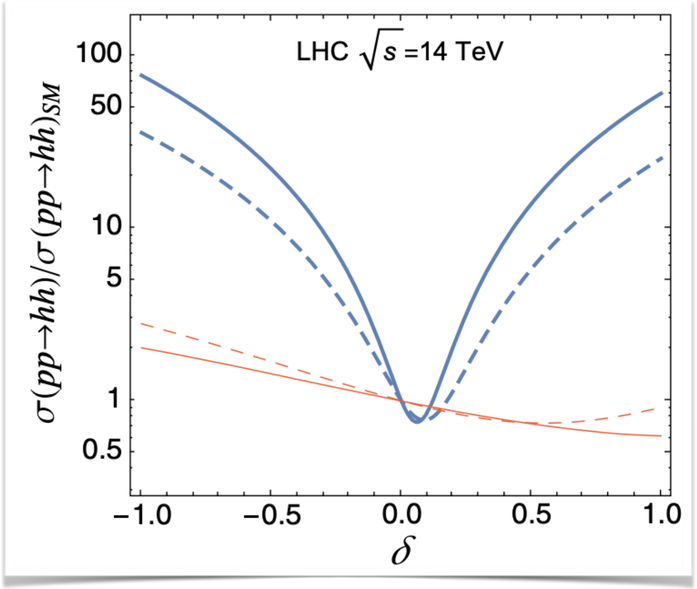

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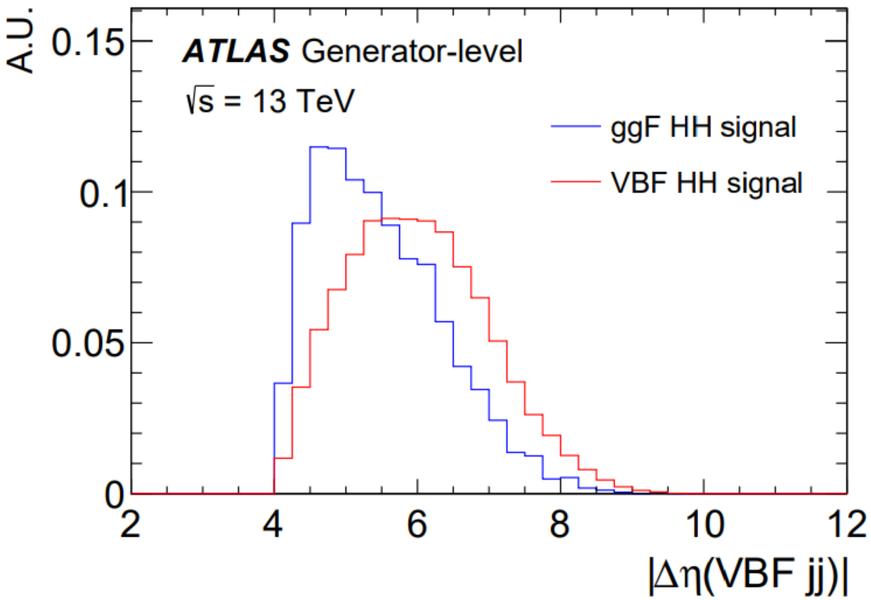
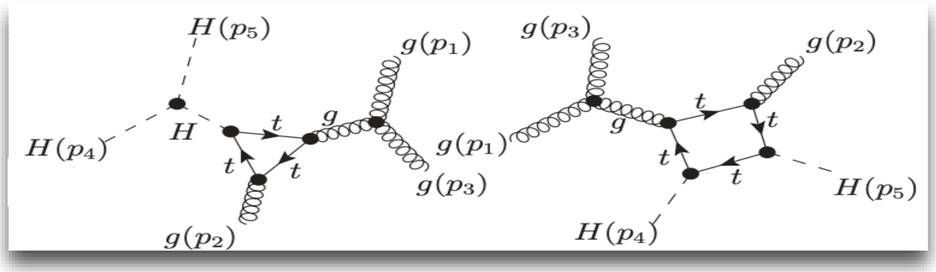
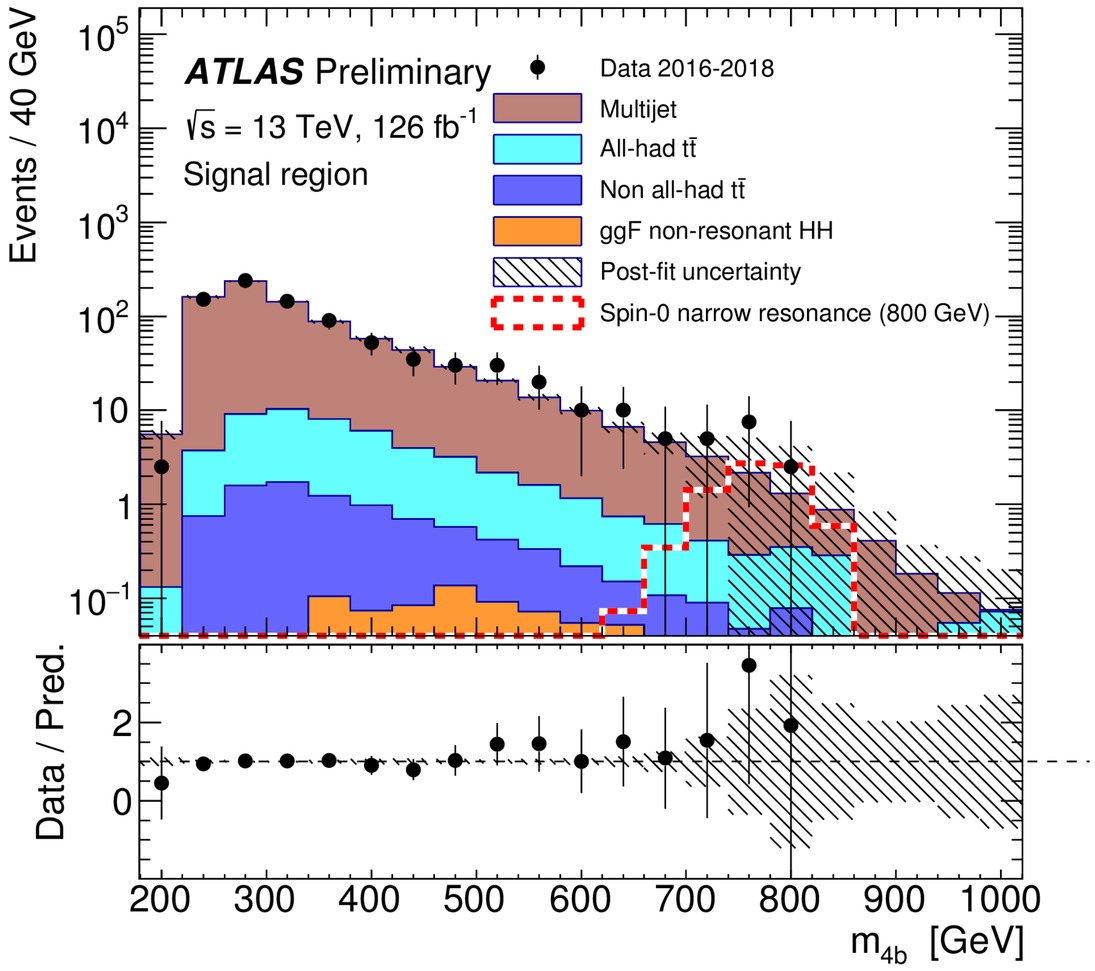


ggF HHjj entering VBF region



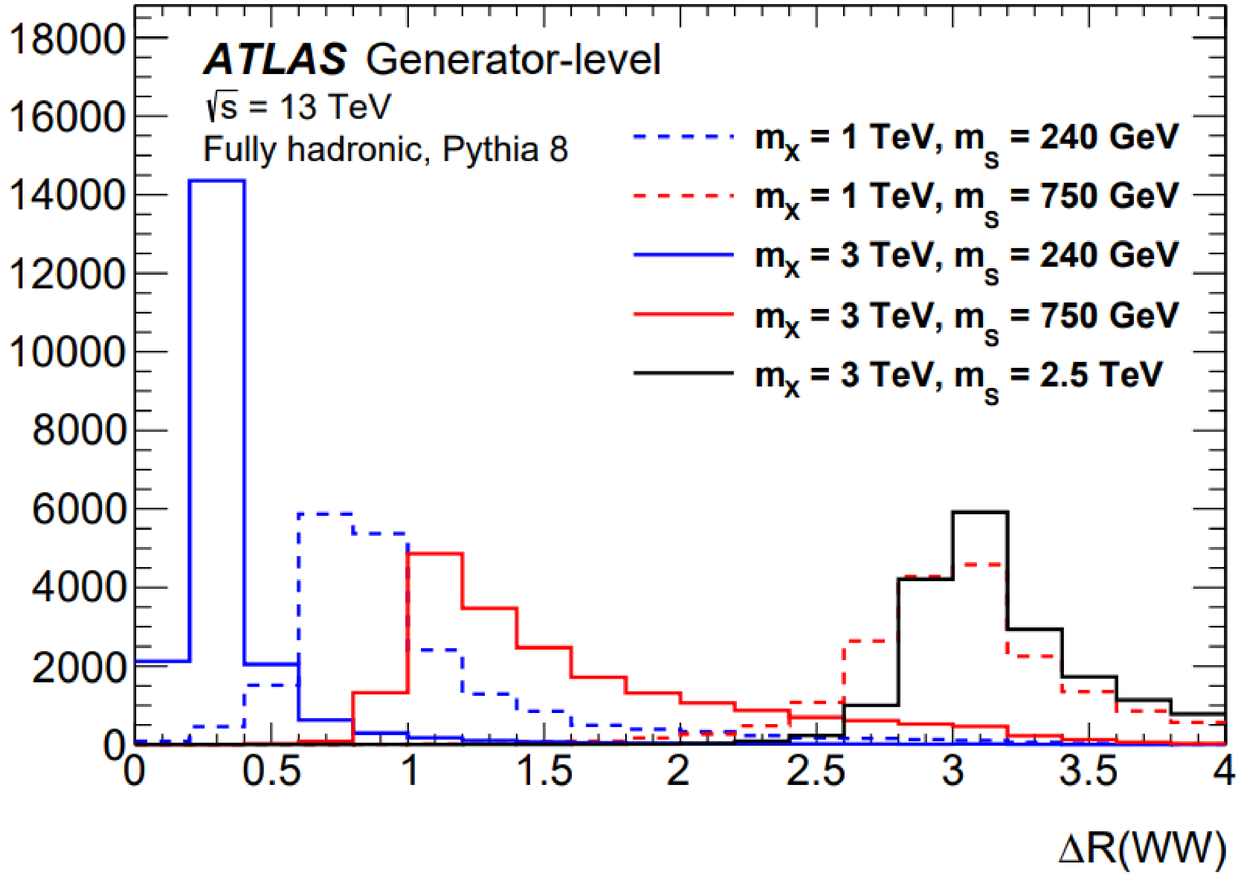
- ggF HHjj has the same final state as VBF HHjj
  - Compared to other backgrounds, ggF HHjj is not large, but to VBF, it is large
- The cross-section of ggF HHjj is >~ 2x of VBF HHjj, and can be 1/3 of VBF HHjj yields after VBF selections (1506.08008): m(HH) > 400 GeV, Δη (j1,j2) > 5
- Current estimate uses
  - ggF HH NLO HH+j (ME) + j (PS)
- Available generator from theorists:
  - Sherpa+OpenLoops, expensive to run, need to test it



ATLAS-CONF-2019-030

SH/SS

- X→SH/HH is of great interests
- Higher mass of S enhances S→WW branching ratio
- ATLAS Pythia8: use BSM process A→Hh (where H is heavier and h is 125) to realise X→SH
- CMS MG5_aMC@NLO: use a generalisation of the NMSSM model for H→aa to account for the presence of another scalar X→SH



Higher mass of S and X tend to have merged final states where boosted techniques can be applied

EFT HH

- Status:
  - LO implementation of HH in place, as CMS published setting limits on benchmarks
  - Machinery of reweighting at ME level available at LO (1710.08261)
- Open for discussions:
  - SMEFT or HEFT
  - Which EFT couplings are interesting or feasible
  - Will the benchmark point tests or a N-dimensional coupling scan be performed
  - If going with the benchmark point tests, will benchmark needs updating
  - What can be constrained if use both HH and H

Summary

- A wide range of HH programs are ongoing, benefitting from the availability of a big variety of MC generators on the market (many thanks to our theorists!)

- In general, ATLAS and CMS are consistent in ME generator choices
  - Some aspects left to harmonise: κ_λ base samples, EFT treatment etc.

- Beyond the limit with the current dataset, many unexplored areas are on the way
  - Smaller production modes: ttHH VHH etc.
  - Constrains on Higgs self-coupling and EFT from all of the production modes

* According to ATLAS rules all the Generator-level plots are published through the collaboration approval [cds.cern.ch]

Backup