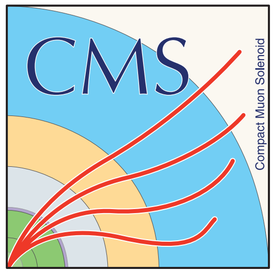
Summary of the HH parallel sessions



UF | UNIVERSITY of FLORIDA

Fermilab

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16th LHC HXSWG workshop
CERN, October 18th, 2019

Organisation of the parallel sessions

- We organised three parallel session as follows:
  - **joint session HH - WG2** : H and HH combined EFT interpretations
  - **joint session HH - WG3** : HH/SH/SS resonant signatures
  - **HH session** : MC and technical tools

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H and HH EFT interpretations

Which operators enter in HH?

	Constraints
$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right)(\bar{Q}t)\,\tilde{\phi}\,,$	Inclusive H, Higgs plus jets, ttH
$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$	Inclusive H, Higgs plus jets, ttH
$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}$	tt, ttH, ttV….
$O_6 = -\lambda(\phi^\dagger\phi)^3$	HH (single Higgs@NLO)
$O_H = \frac{1}{2}(\partial_\mu(\phi^\dagger\phi))^2$	All Higgs couplings H decays, VH, VBF…

All but one operator will receive constraints from another processes (at LO)

- If a high scale BSM physics exists, it may induce important modifications in HH production
- 5 operators affect HH production, but 4 of them are also constrainable from single Higgs
  - however, in single Higgs further operators must be also constrained simultaneously

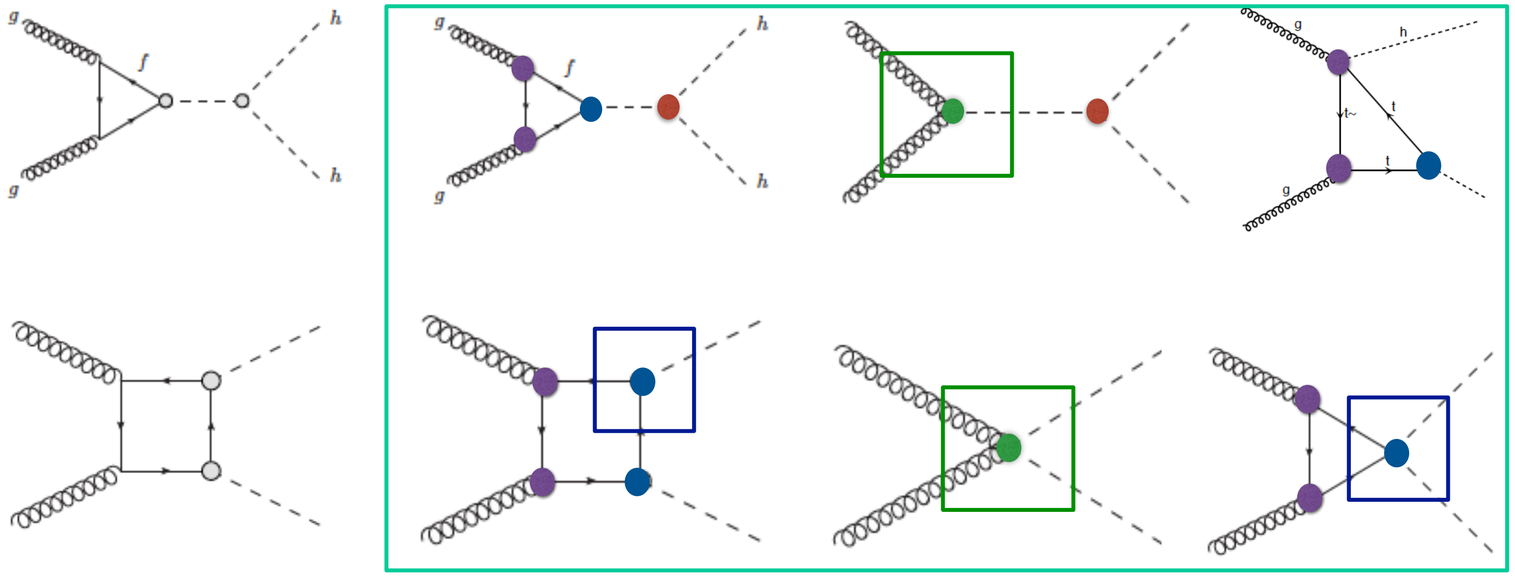
Just κ_λ and κ_t ?

- A generic EFT also predicts new types of contact interactions
- Depending on the EFT considered, some of these interactions are correlated as they depend on the same operator

SMEFT in HH

SM

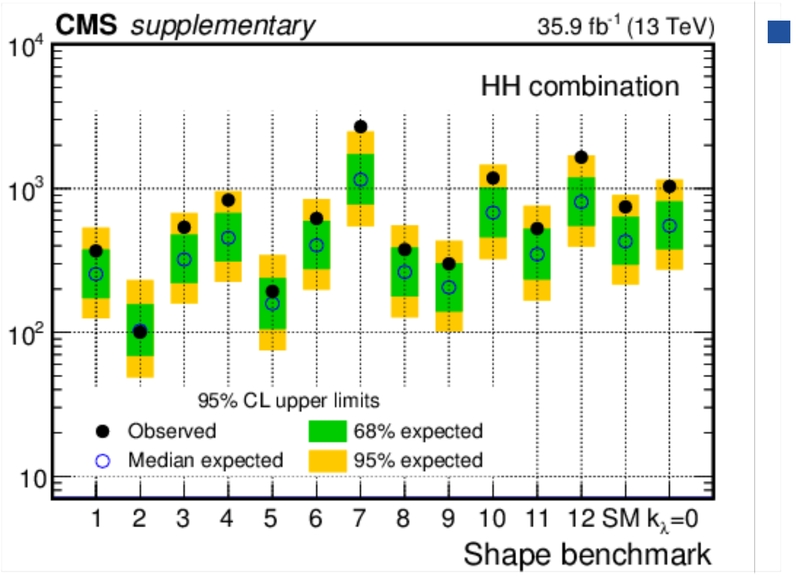
SMEFT



c.f. in EWchL (Buchalla et al arXiv:1806.05162) c_{gghh}-c_{ggh} and c_t-c_{tt} are independent, with c_{gghh}, c_{tt} and c_{hhh} to be determined by HH

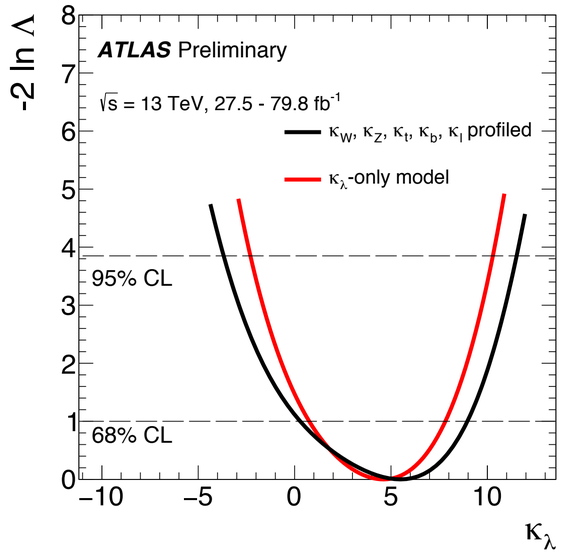
Where do we stand experimentally?

Signature-based approach in HH



- Shape benchmarks: each point represents a characteristic HH signal shape in the EFT param space
- Instructive about large variations of sensitivity depending on the EFT region probed, captures the contact interactions effects
- Hard to reinterpret in practice

Fitting kappas in H + HH



- H + HH combination in a κ-framework: floating κ_λ, κ_V, κ_f
- Allows us to get the best out of our current data by combining two types of measurements
- Limited access to possible BSM effects
  - no consistent EFT predicts only SM coupling variations without the new contact interactions
  - combines LO and NLO effects in the two measurements within a κ-framework

EFT fit based on operators as the way to get the best out of our H and HH measurements

Discussion items

- Validity of a κ-framework approach for NLO effects in single H and how to go beyond this approach

- Definition of an experimental procedure to perform such fits
  - A very large number of operators must be constrained simultaneously
  - some assumptions needed when selecting which ones to fit in a H + HH combination
  - how to consider operator variations? only one at the time, simultaneous fit, …

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Experimental status of resonant searches

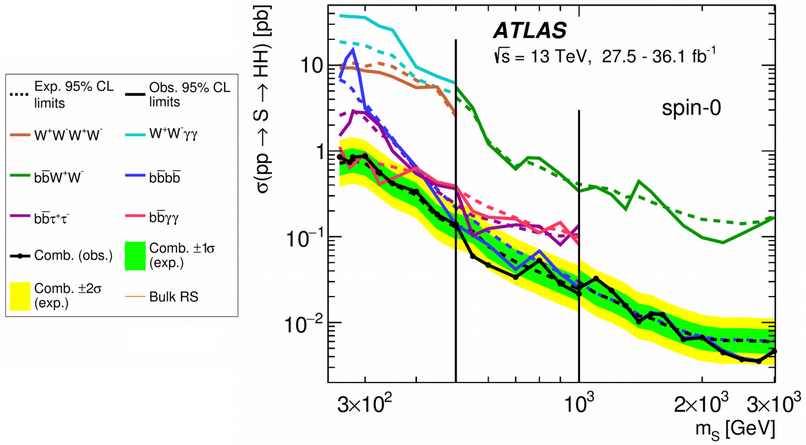
- X→HH systematically probed in several channels by both experiments
  - assuming so far a narrow width for spin 0, different assumptions by the experiments for spin 2
- SS probed only in WWWW by ATLAS
- No experimental searches for SH so far

Resonant HH Combination

ATLAS

arXiv:1906.02025

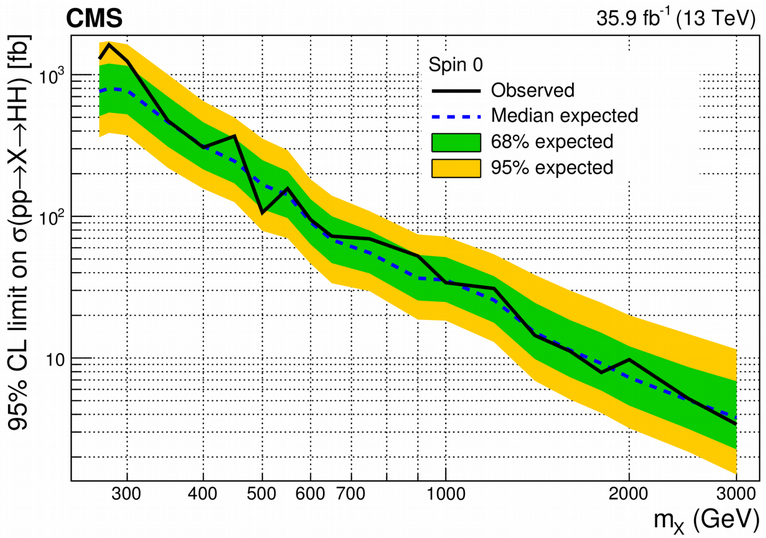
- Narrow-width spin-0 (S)
  - hMSSM and EWK-singlet interpretations
- Spin-2 Bulk graviton (G)
  - W.E.D. Interpretations
- Mass range: 260 GeV to 3 TeV



CMS

PRL 122, 121803 (2019)

- Narrow-width Spin-0 and Spin-2 (X)
- Mass range: 250 GeV to 3 TeV



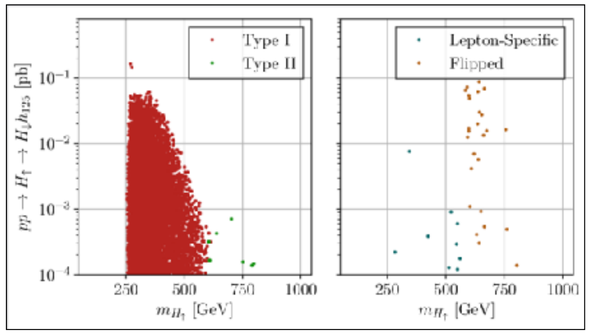
No significant excess is observed with respect to the SM prediction

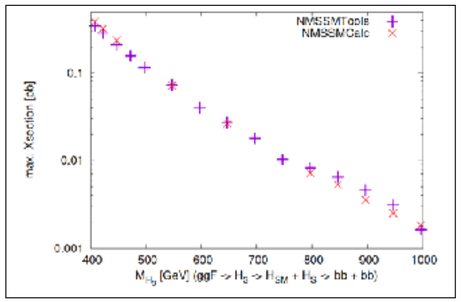
Extra scalars

- Signatures with extra Higgses and scalars are possible
  - and even more exotics with > 2 scalars in the final states are possible!
- A broad set of models and benchmark points presented in the parallel session
  - cross sections in the range 10 fb - 1 pb : we can be sensitive with the full Run 2 LHC dataset
  - full list in slide 18 of Maggie's talk this morning (link)
  - diversity of channels is important: many models have enhanced couplings of new scalars to specific particles

Talks at this Workshop

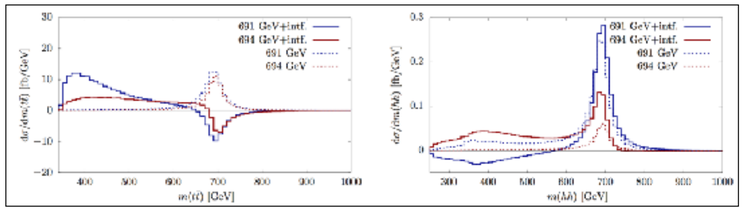
D. Fontes, C2HDM

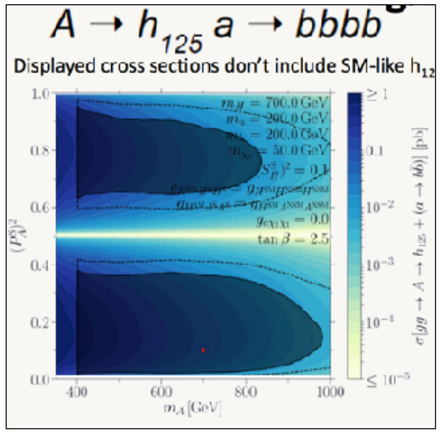




Basler, Ellwanger, MM maximumm possible Cxn in NMSSM

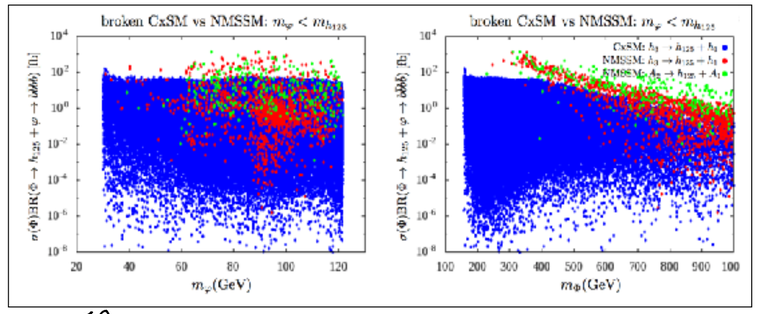
C. Englert, Interplay of interference effects





N.Shah, 2HDM+S

MM, Singlet extensions, NMSSM



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Discussion items

- We have so far discussed benchmark resonant points (i.e. specific mass values and couplings), but benchmark planes would be more interesting for interpretations
  - experimentally, only the masses and width are needed (generally following a model-independent approach). In case no signal is seen and upper limits are set on the xs, these can be used to reinterpret the results
  - some choice of other parameters of models must be done to define suitable planes

- Complementing the set of interesting final states
  - if the extra scalars are “Higgs-like”, the current HH main decay channels (bbbb, bb$\tau\tau$, bb$\gamma\gamma$) have high sensitivity
  - decays to e.g. vector bosons can be enhanced in many scenarios: interesting tho identify those cases
  - analyses in final states with incomplete reconstruction (with ν) can be easier to generalise from HH to SH/SS

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Overview of generators

- Generators available for several production modes and spin hypotheses
- Experiment choices generally aligned
  - some differences in the choice of hadronisation, but not specific to HH

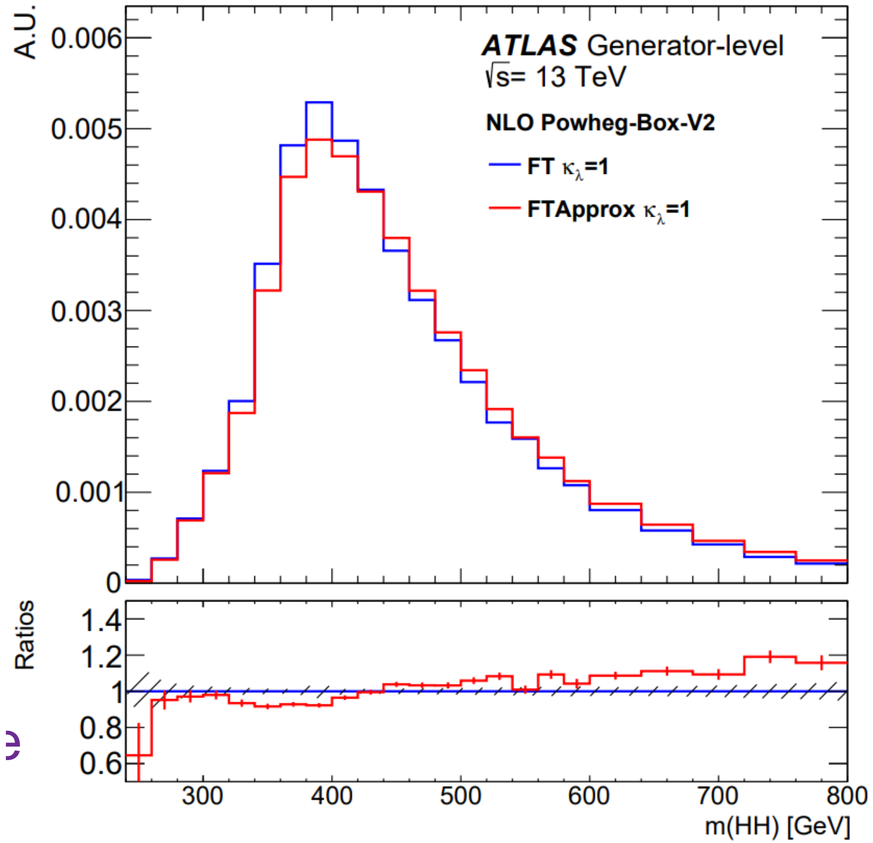
Introduction

- 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

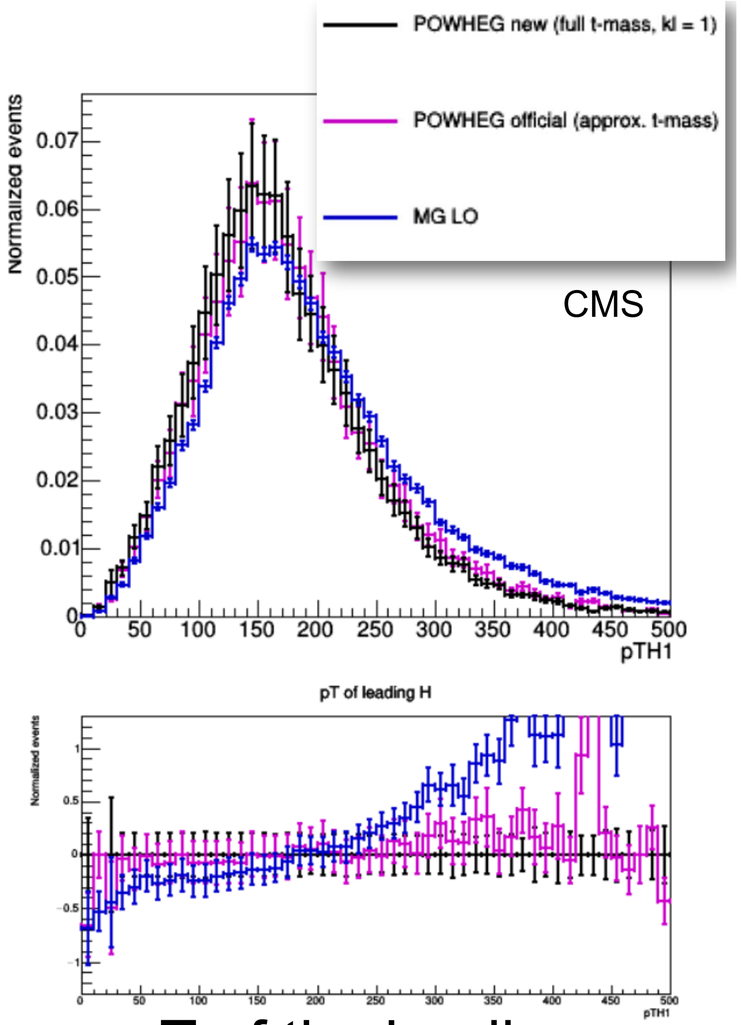
	ATLAS	CMS
Non-resonant (ggF)	**NLO+FT** Powheg-Box-V2 (vary κ_λ)	
	Herwig7	Pythia8
Non-resonant (VBF)	**LO** MG5_aMC@NLO (vary κ_V κ_{2V} and κ_λ)	
	Herwig7	Pythia8
Resonant spin0 X→HH (ggF)	**LO** MG5_aMC@NLO Heavy scalar, narrow width	**LO** MG5_aMC@NLO Radion, narrow width
	Herwig7	Pythia8
Resonant 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

MC tools

- HH MC at NLO with m_t effects available and validated in both experiments
  - sizeable effects w.r.t. the LO one



m(HH) at fixed-order NLO



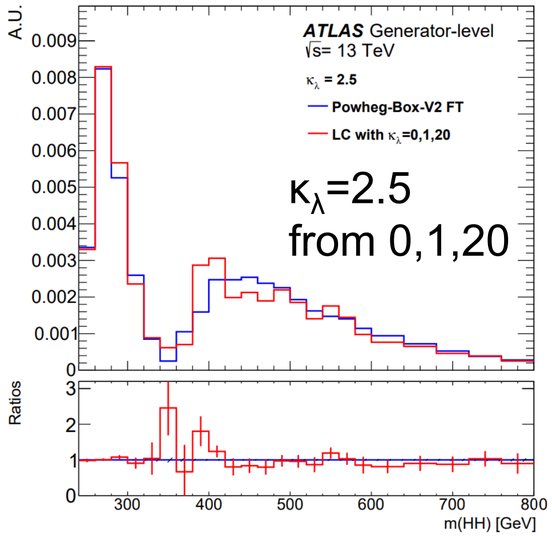
pT of the leading Higgs, after shower

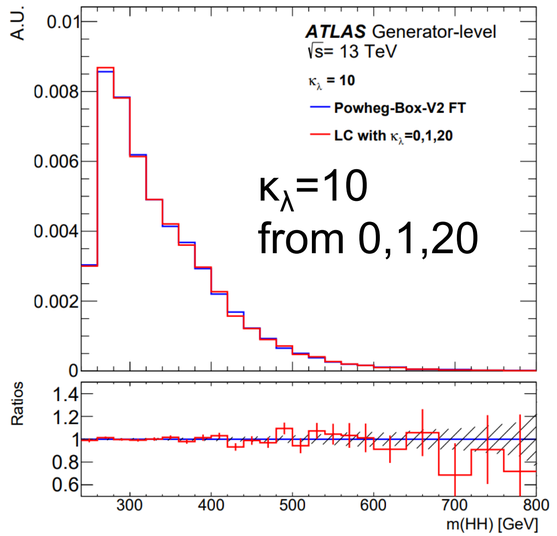
Modelling anomalous self-coupling

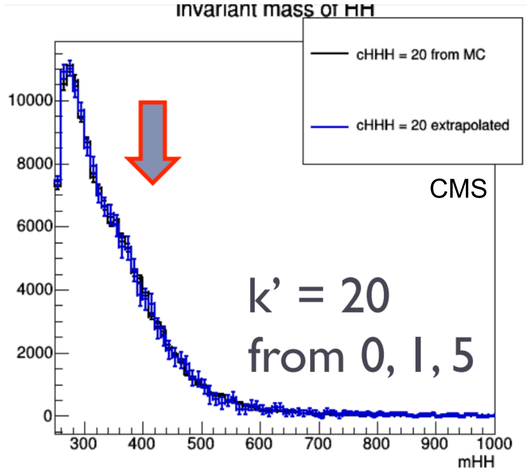
- Both experiments have implemented and validated a method to model κ_λ variations with the NLO MC
  - obtained by summing three HH samples scaled by adequate functions of (κ_λ, κ_t)
  - some finer tuning may be helpful to minimise the statistical error in the procedure

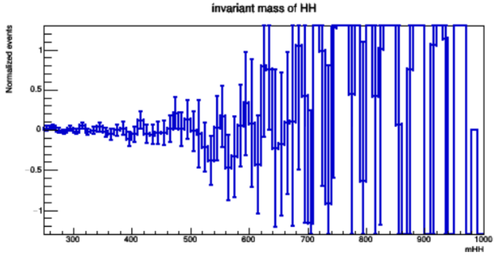
Closure of LC

- 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







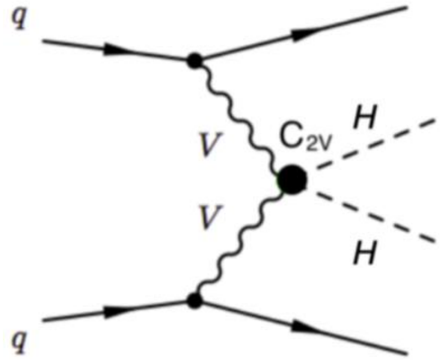


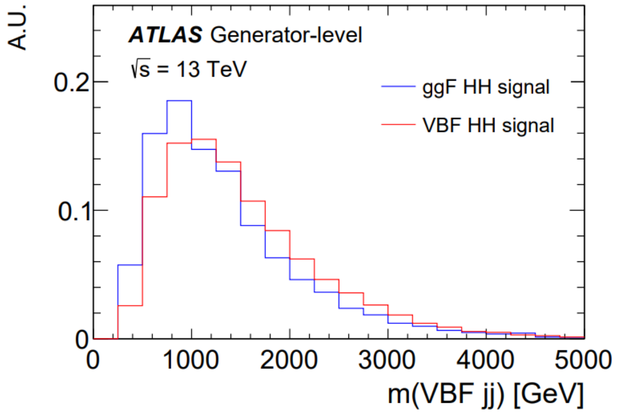
$$\sigma(pp \to HH) \sim k_t^4 \left[|B|^2 + \frac{k_\lambda}{k_t}(B^*T + TB^*) + \left(\frac{k_\lambda}{k_t}\right)^2 |T|^2 \right]$$

Vector boson fusion

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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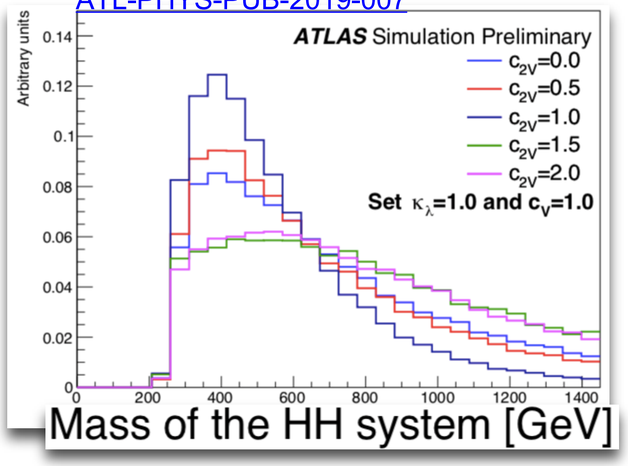

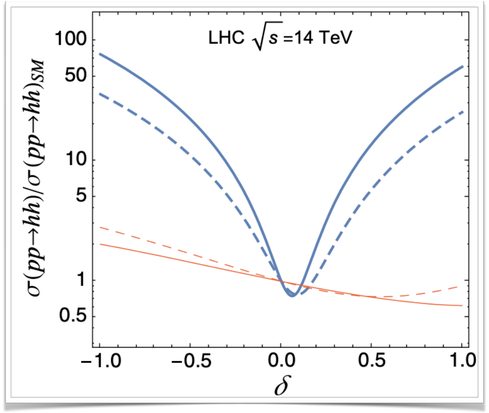

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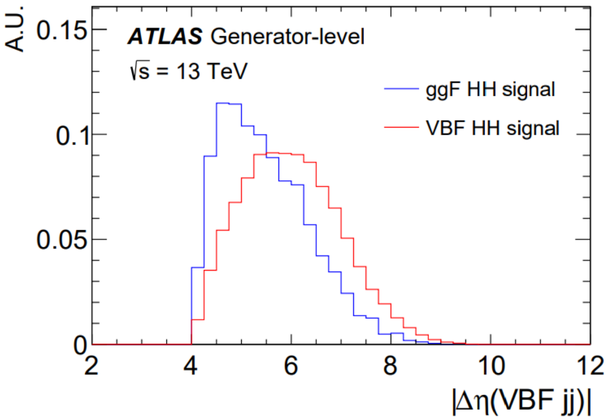

- Interesting to measure the VVHH interaction
  - longitudinal scattering amplitude suppression by C_V^2 - C_{2V} : large sensitivity to anomalous C_{2V}
  - MC modelling procedure defined inside both experiments
  - already applied for a full Run 2 ATLAS search

Discussion items

- Generation of gg -> HH + jj at LO to better model contamination in the ggF phase space
- Overlap between the V(had)HH and VBF production modes
- Uniforming the choices of the two experiments
  - how would the different hadronisation / uncertainties schemes impact a combination?
  - ATLAS: compare two hadroniser codes with different tune -> systematic variations due to the change of shower method, but also involve changes of other parameters
  - CMS: vary the hadronisation scales, but within the same generators
  - need also to check uncertainties in matching for the new NLO sample

Conclusions

- Broad discussion ongoing on several HH and related topics
- HH as part of a broader Higgs and BSM picture : joint sessions with WG2 and WG3
- Nonresonant HH well advanced in terms of tools
  - NLO MC of ggF, including anomalous klambda
  - NNLO FTapprox cross section prediction
  - modelling of VBF processes
- Good opportunities for resonant signatures with the full Run 2 dataset
  - discussion about the interest of spin 2 HH searches (although model independent approach remains)
  - plan to extend the current searches to SH / SS
  - ongoing work to define benchmark points. Benchmark models / phase space regions to interpret would be good from the experimental point of view