MC harmonisation for Higgs analyses: experience in HH

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ATLAS EXPERIMENT

CMS Compact Muon Solenoid

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Introduction

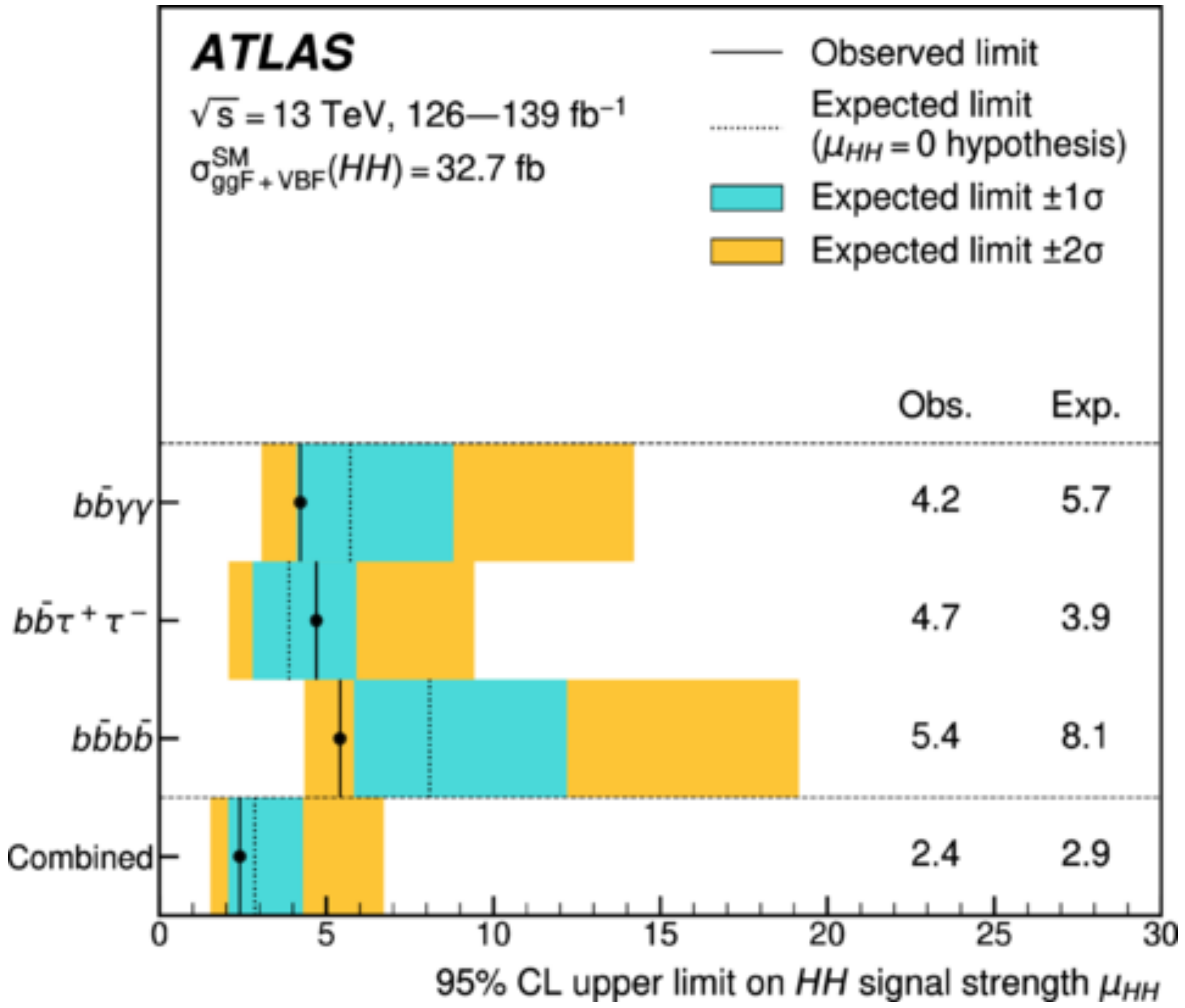
- This talks will introduce the motivation and benefits of harmonising MC generators between ATLAS and CMS

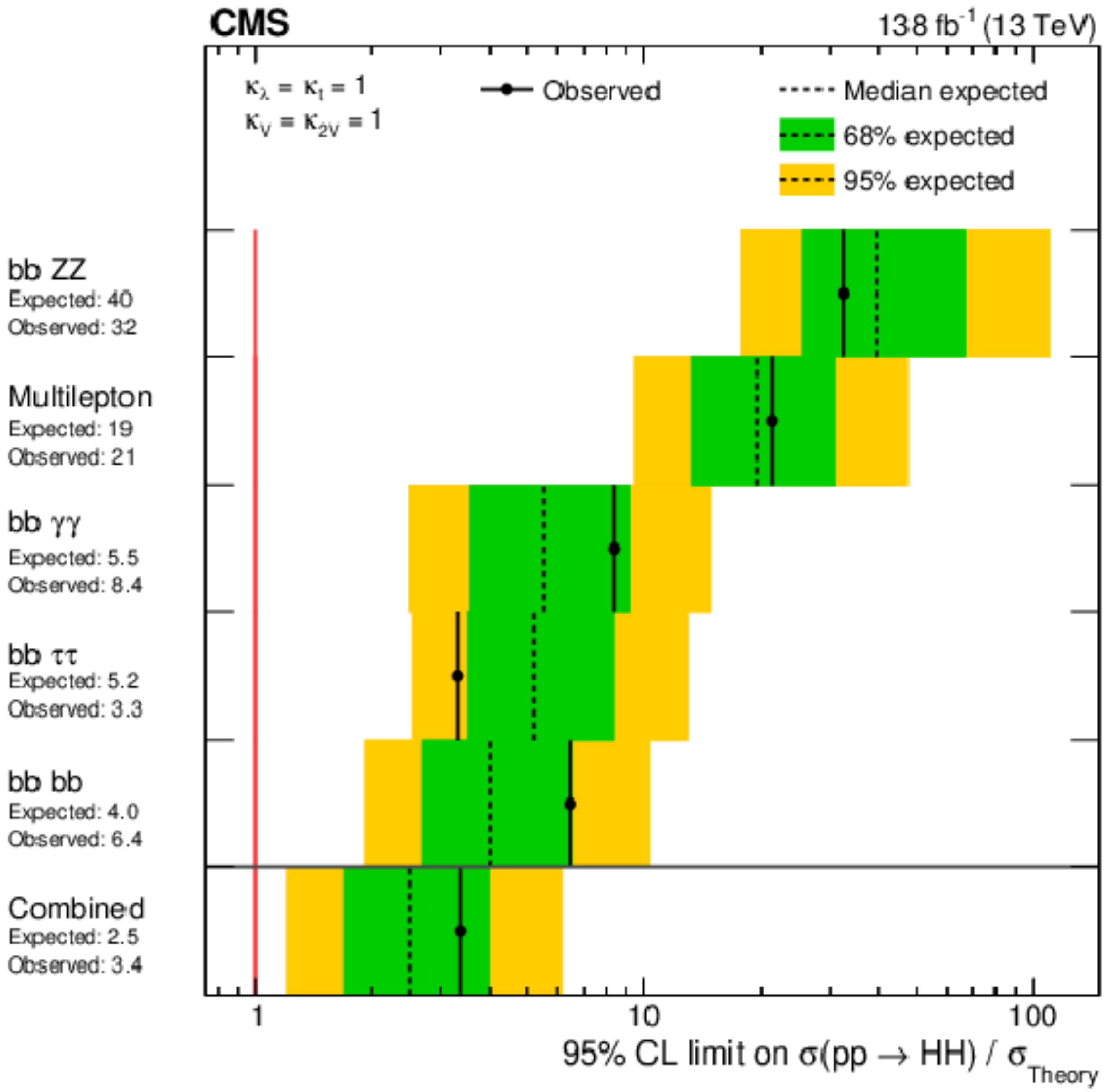
- Based on the experience mainly from ATLAS+CMS MC HHarmonisation, we will see what we went through in the past, which could be helpful for a possible MC generator harmonisation to a larger extend, such as Higgs analyses

- We will also look into some technicalities in generator harmonisation

The motivation of MC harmonisation

- If the MC generator is harmonized, the benefits could involve the following
- Direct comparison of experimental results
  - Limits, cross-section, coupling





Using the same generator ensures that the difference is not coming from MC but on the actual performance and sensitivity

Phys. Lett. B 843 (2023) 137745

Nature 607 (2022) 60-68

The motivation of MC harmonisation

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- Direct comparison of experimental results of ATLAS and CMS
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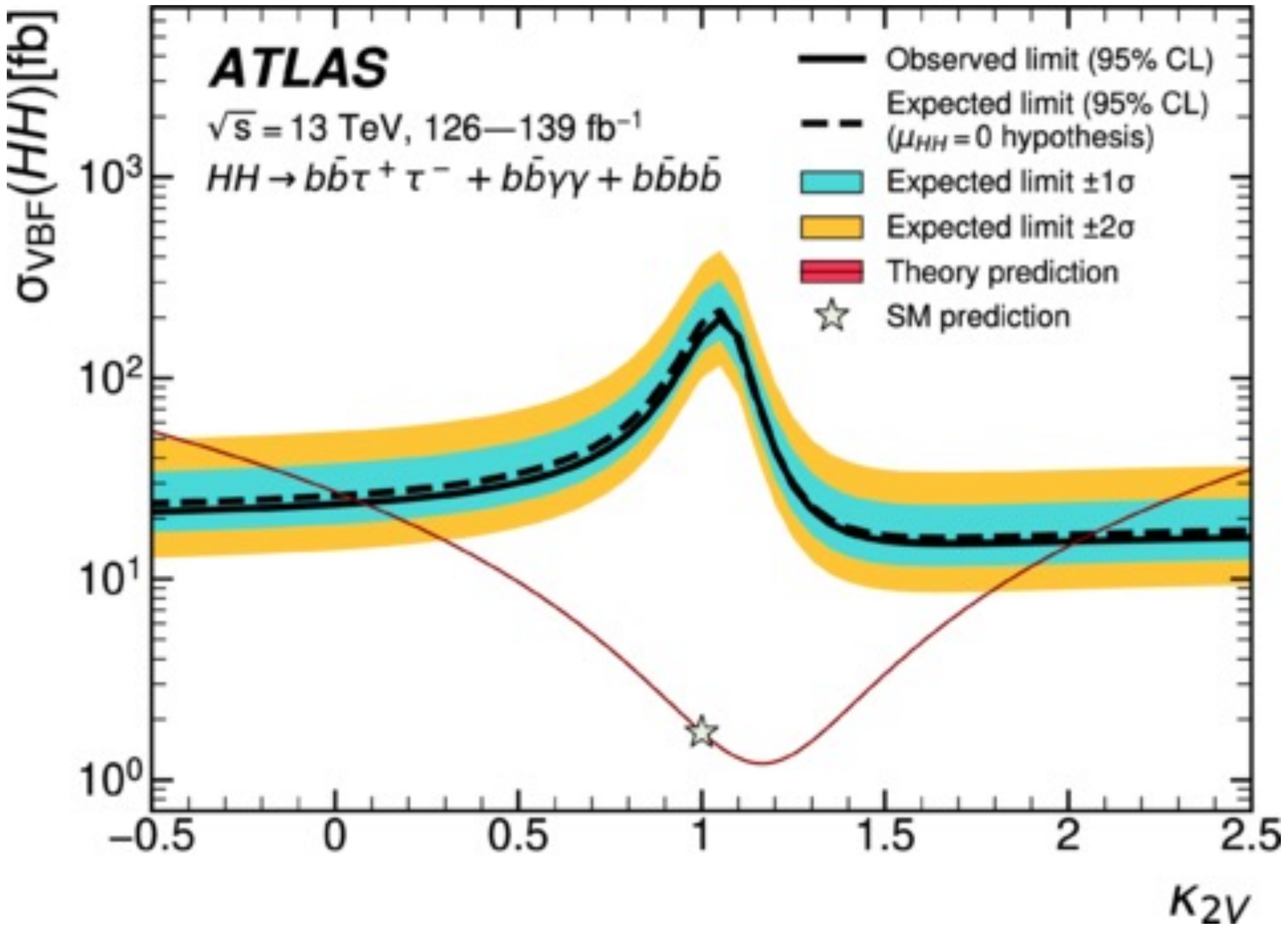
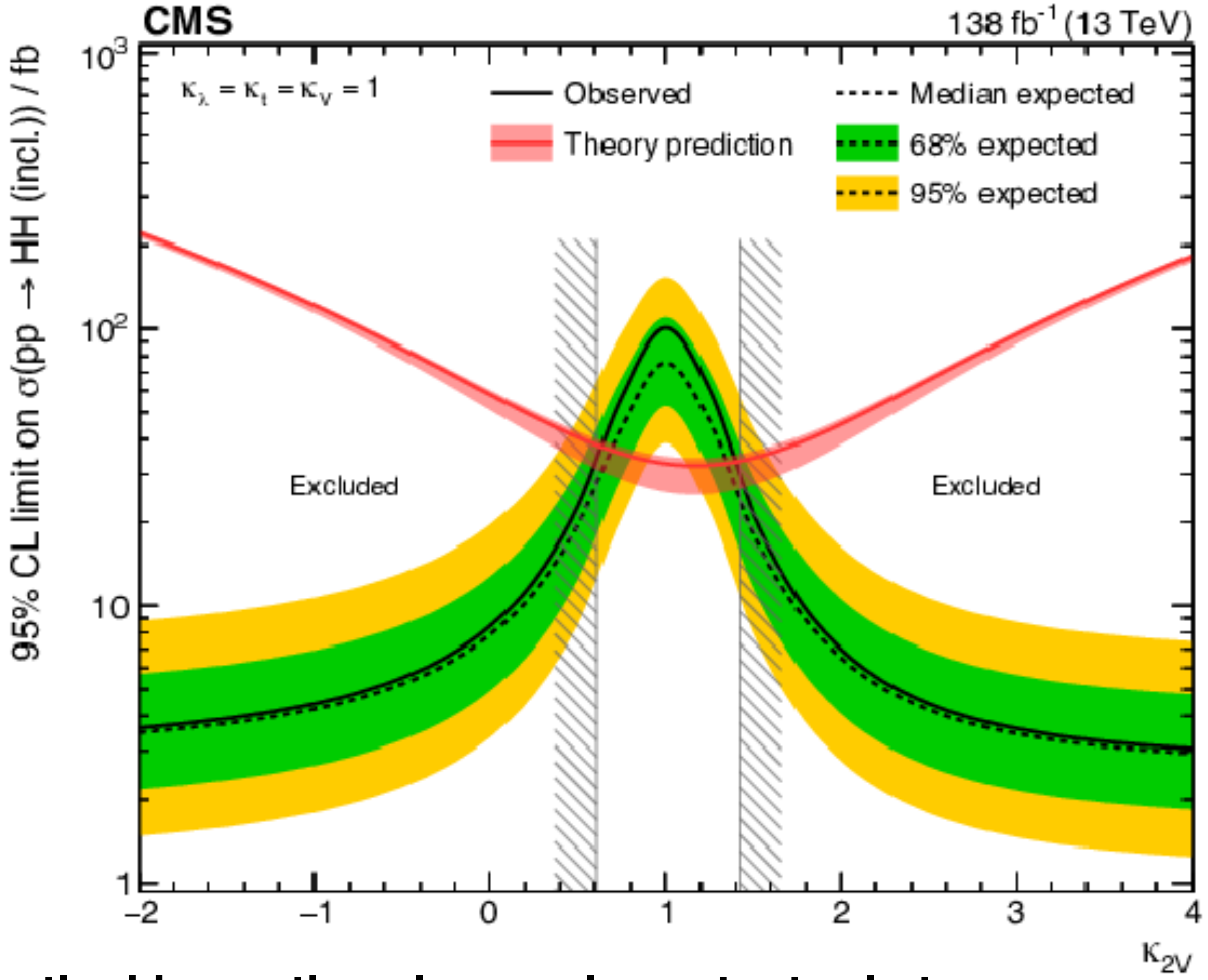




The same applies to the coupling constraints, where the kinematics plays an important role too.
Using the same MC generator ensures the same dependence on the coupling

[Phys. Lett. B 843 (2023) 137745](#) [Nature 607 (2022) 60-68](#)

The motivation of MC harmonisation

- If the MC generator is harmonized, the benefits could involve the following
- Consistent (easier) treatments of the systematic uncertainties between the experiments
  - Alternative generator difference, factorisation/renormalization (on the acceptance and shape), PDF+alpha_S (on the acceptance and shape)
  - Pave the way to correlating MC generator uncertainties in ATLAS+CMS combination

Category	ATLAS	CMS	Correlate
QCD scale ggF	TheorySig_QCDscale_ggF	THU_ggH_Mu (xs)	+
	TheorySig_QCDscale_ggF_pTt		
	TheorySig_QCDscale_ggF_relpT		
	TheorySig_QCDscale_ggF_vbf[2,3]j		
	TheorySig_QCDscale_ggF_VBFModel		
		THU_ggH_Res	
QCD scale others	TheorySig_QCDscale_ttH	THU_ttH_Yield	
	TheorySig_QCDscale_VBFH (xs&acc)	THU_VBF_Yield (xs)	
	TheorySig_QCDscale_WH	QCDscale_WH	
	TheorySig_QCDscale_ZH	QCDscale_ZH	
PDF	TheorySig_PDF_[ttH,VBFH,WH,ZH]		
	TheorySig_PDF4LHC_NLO_30_EV[1-30]		
		pdf_Higgs_ttH	
		pdf_Higgs_qqbar	
		pdf_Higgs_gg	
QCD alphaS	TheorySig_QCDalphaS		
	TheorySig_QCDalphaS_[ttH,VBFH,WH,ZH]		
BR	TheorySig_BR_Zy	BR_hzg	+
UEPS	TheorySig_UEPS_ggH		
		UnderlyingEvent_norm	
		PartonShower_norm	
Higgs Mass	ATLAS_LHCmass		

Snapshot of syst corr scheme in ATLAS+CMS HZgamma

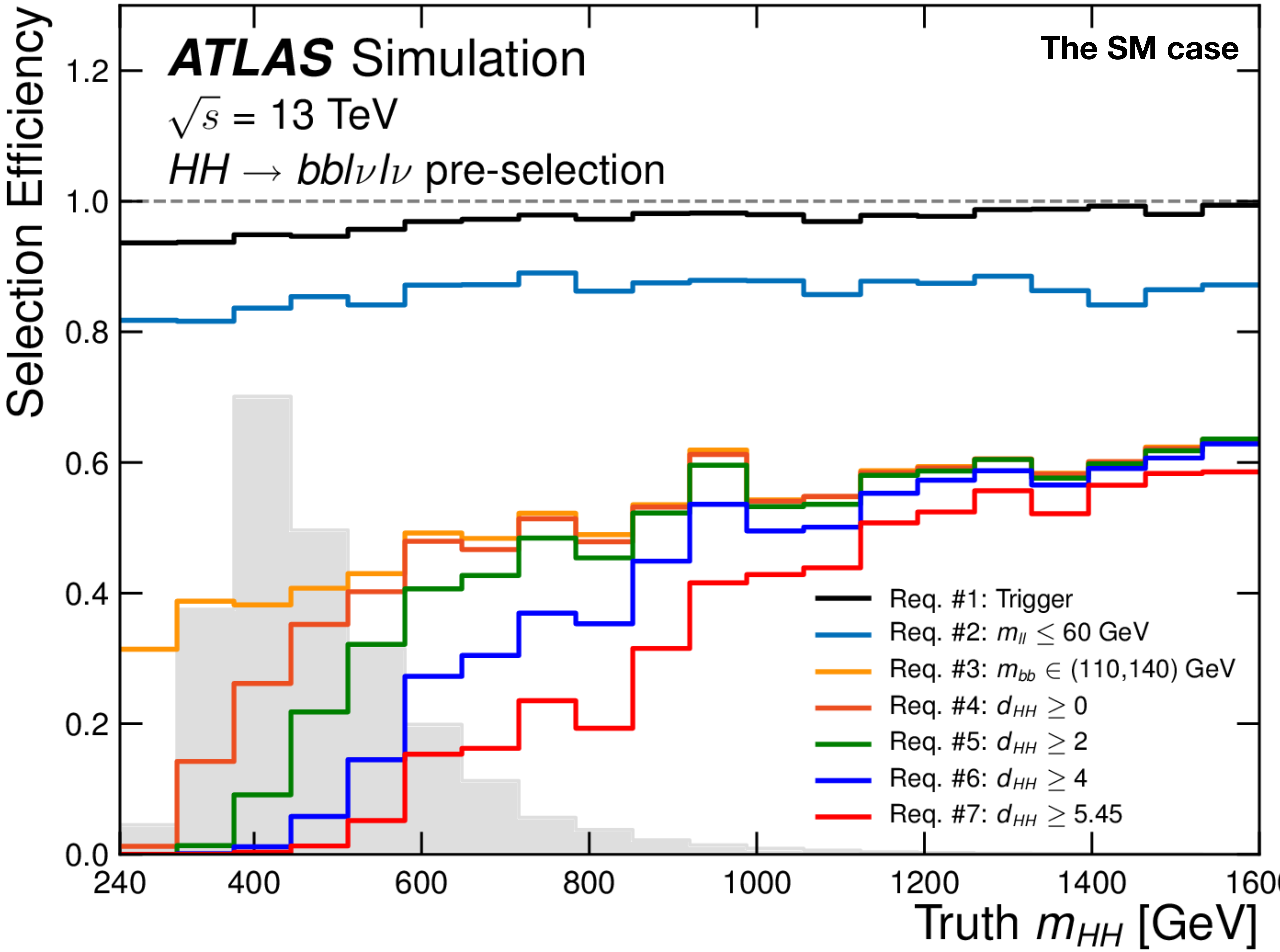
Scale uncertainties on the acceptance will need to be completed and correlated

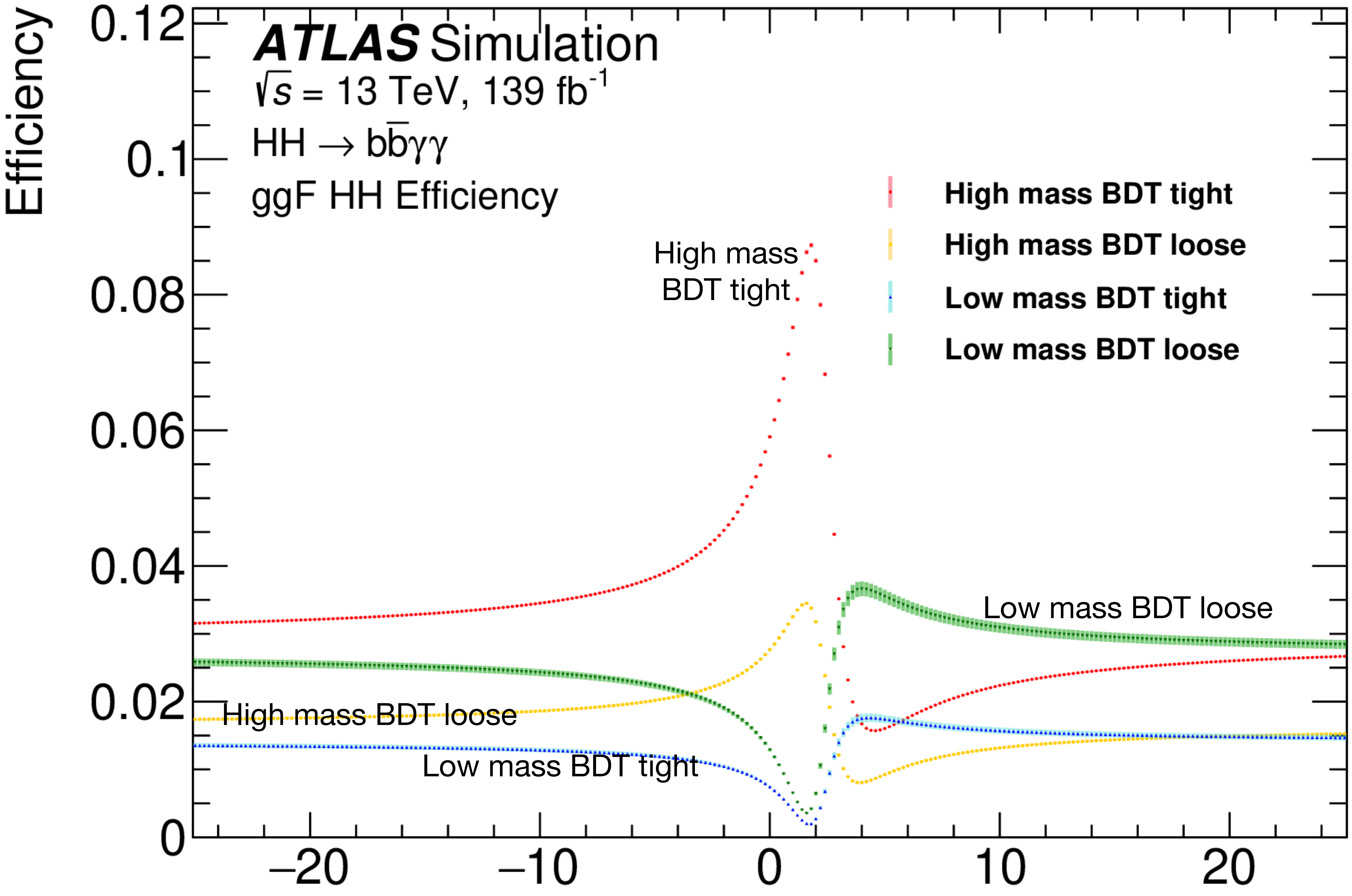
The motivation of MC harmonisation

- If the MC generator is harmonized, the benefits could involve the following
- Deeper understanding of the performance between ATLAS and CMS
  - Detector and reconstruction impacts: kinematics under similar cuts
  - Efficiency&acceptance
  - Trigger impact
  - Analysis phase space: signal regions
    - How much do ATLAS and CMS phase space differ?

- With the same generator, the efficiency and acceptance can be directly compared between ATLAS and CMS
- This plots assists well to understand the selection impacts in different mHH, thus for different self-coupling, across the experiments
  - encourage both experiments to consider such efficiency vs mHH plots

Phys. Lett. B 801 (2020) 135145





This should be compared between experiments

[Phys. Rev. D 106 (2022) 052001]

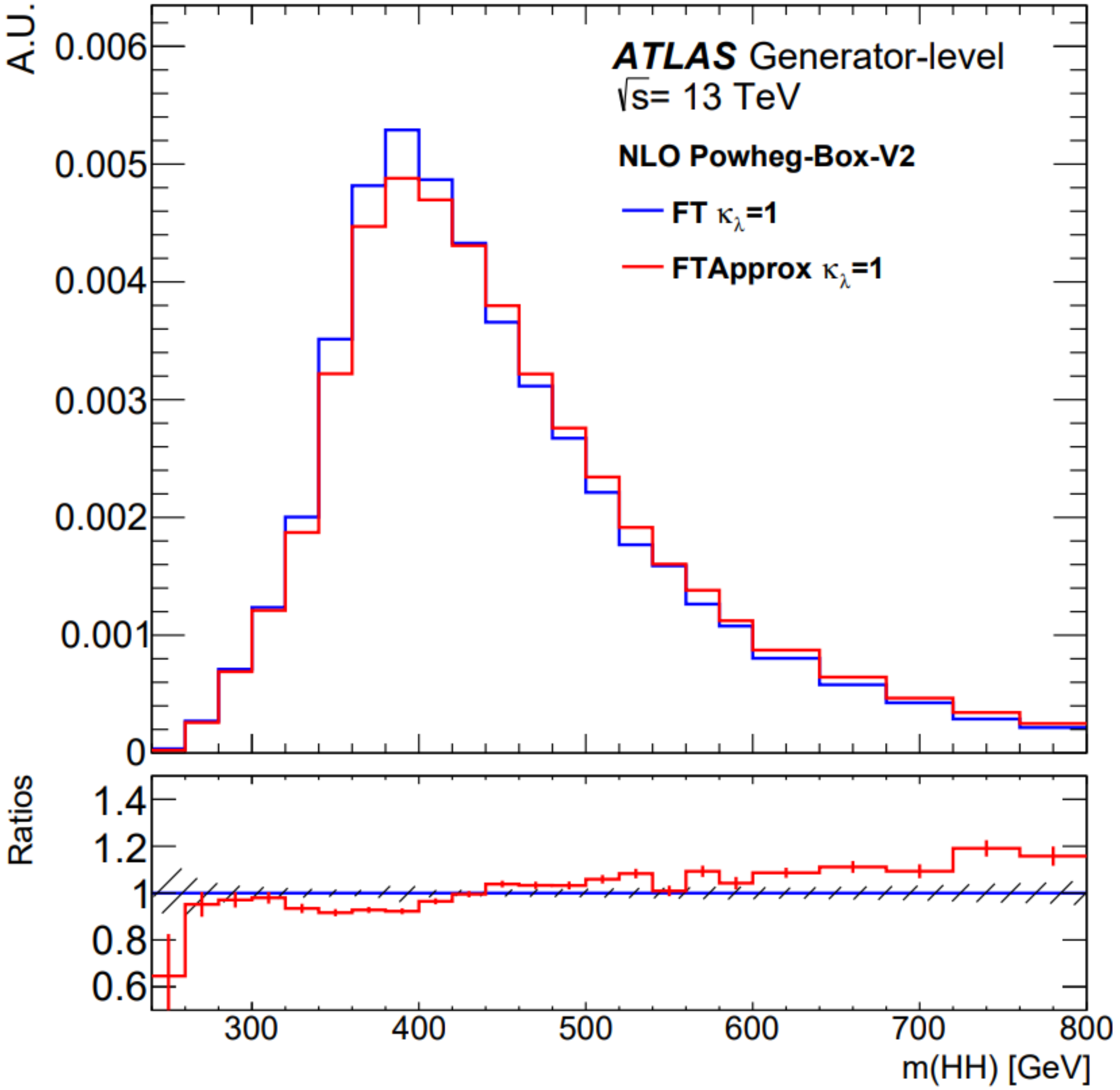
HHarmonisation

- Most of the HHarmonisation activities happened across the year of 2019, when the analyses were updating from 36/fb to full Run2 (summarized in the 16th workshop)
  - Good timing as most of channels needed new MC samples for full Run2
  - Could be a good timing now for Higgs MC harmonisation, when switching to Run3 analyses
- Over the year, we experienced many updates with two highlights below
  - The ggF HH generator from NLO FTApprox in MG5_aMC@NLO to NLO FT in POWHEG-BOX-V2 (20% in the mHH tail, but right in the selected phase space)
    - FTApprox with MG5_aMC@NLO -> FTApprox with Powheg-Box-V2 -> FT with Powheg-Box-V2
  - The ggF HH generator with self-coupling variation from LO MG5_aMC@NLO+Pythia8 to NLO FT POWHEG-BOX-V2

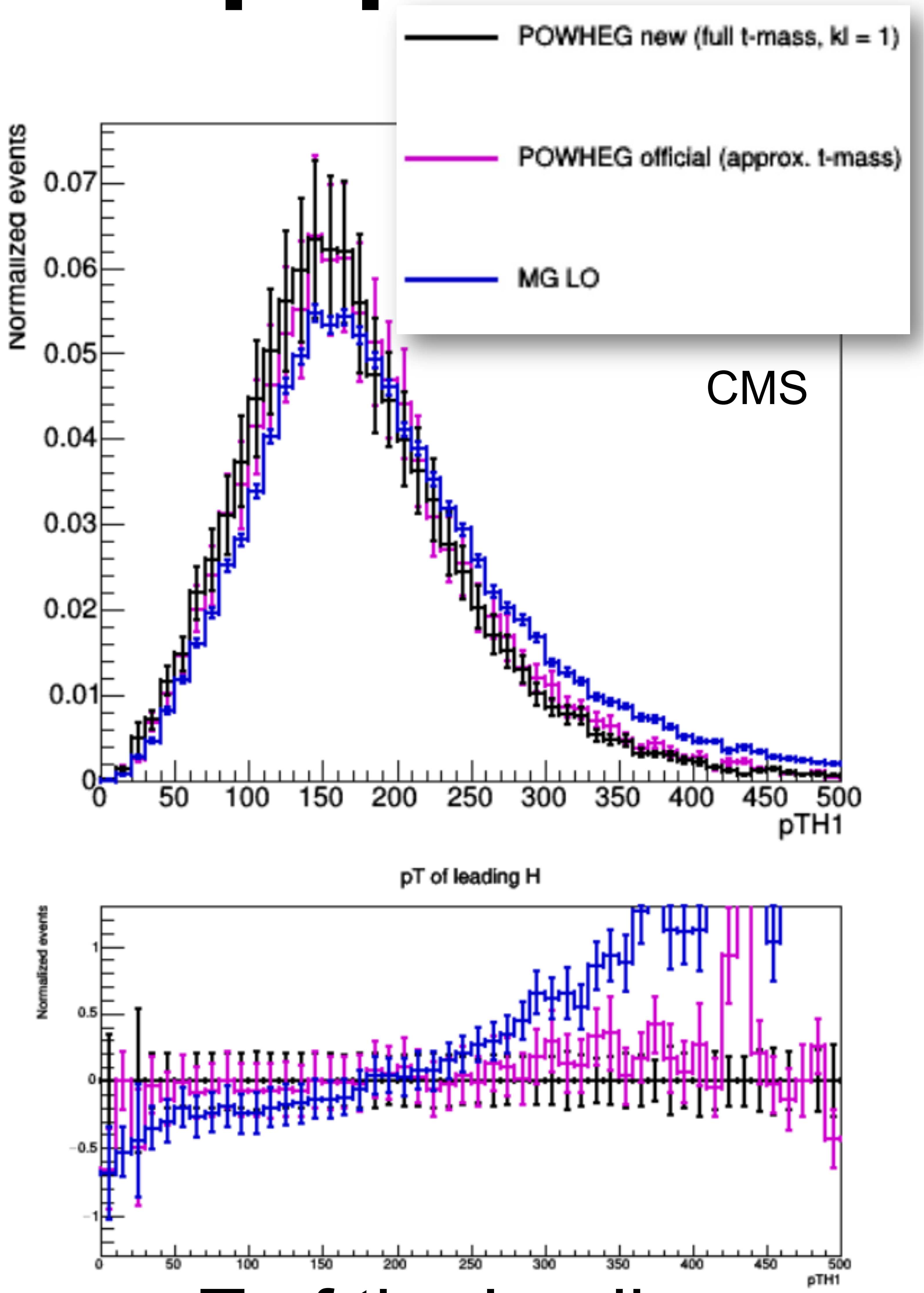
Recap of FTApprox -> FT

2019

- The update for full Run2 analyses is NLO FTapprox → FT, i.e. implementation of finite top mass in the virtual loop, with efforts of theorists in close contact of LHCHWG (helpful iterations between ATLAS, CMS and theorists in LHCHWG workshop and ATLAS/CMS HH workshop)
  - Validation done in both ATLAS and CMS at the same time
- 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)



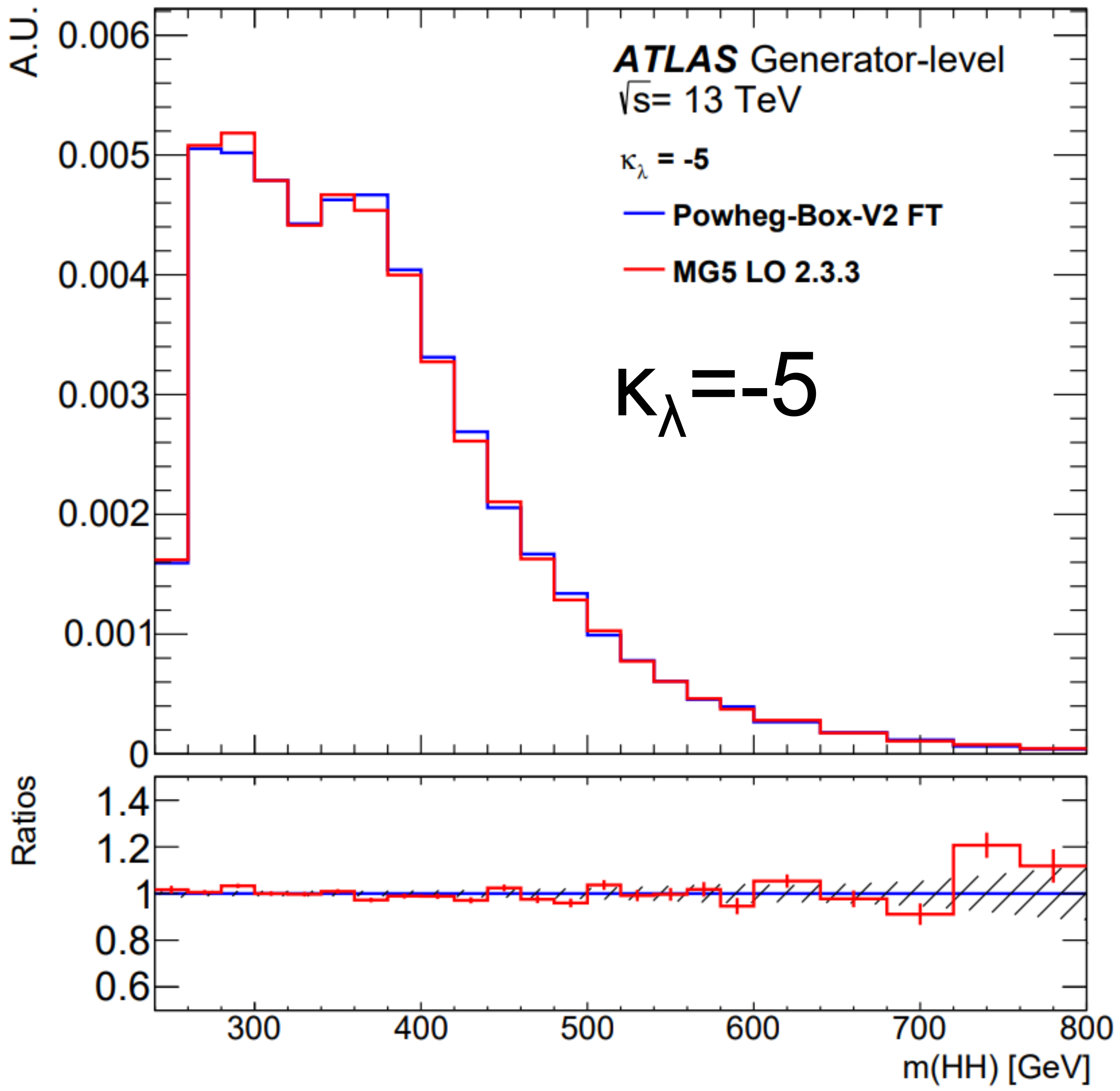
m(HH) at fixed-order NLO

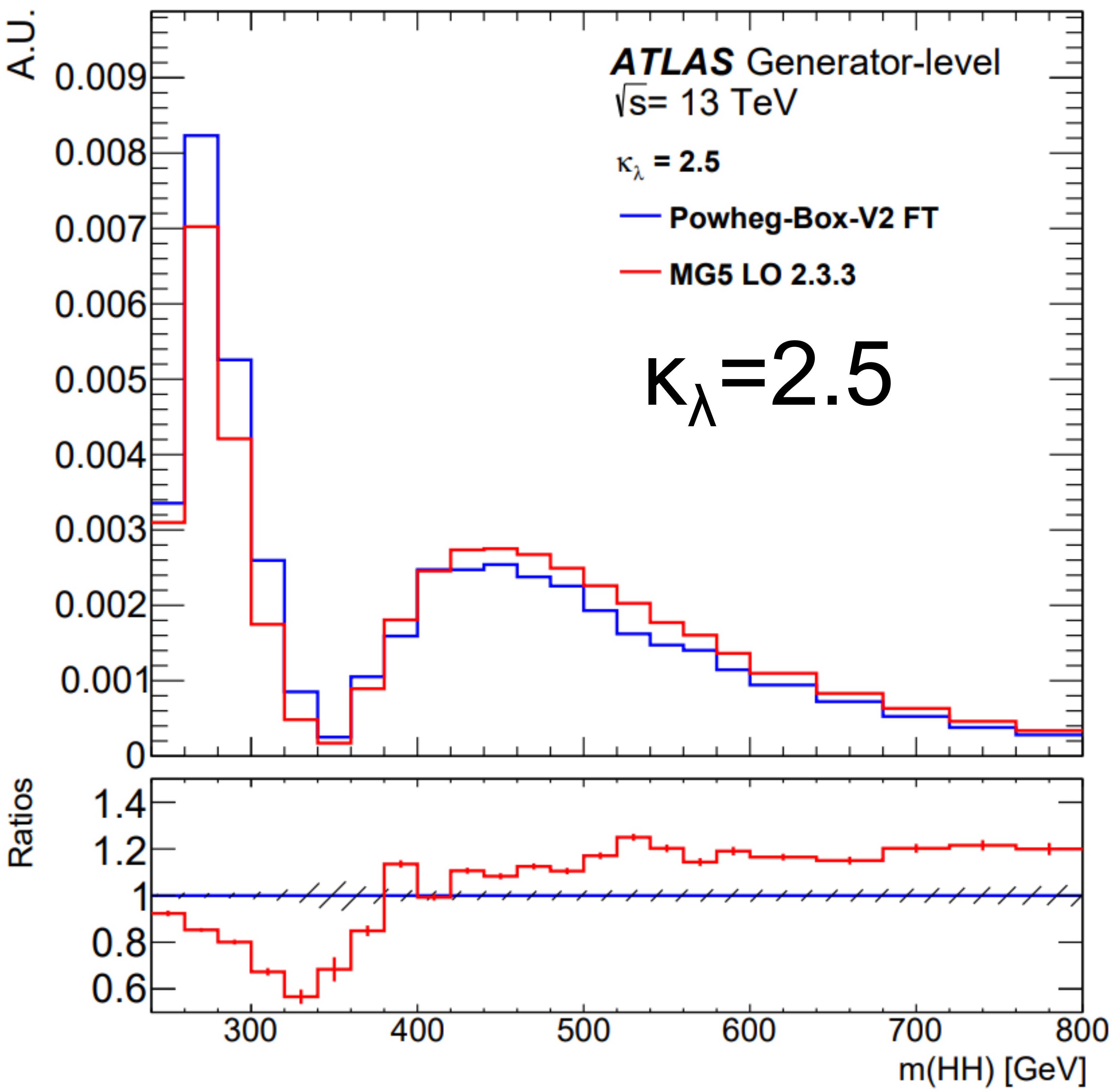


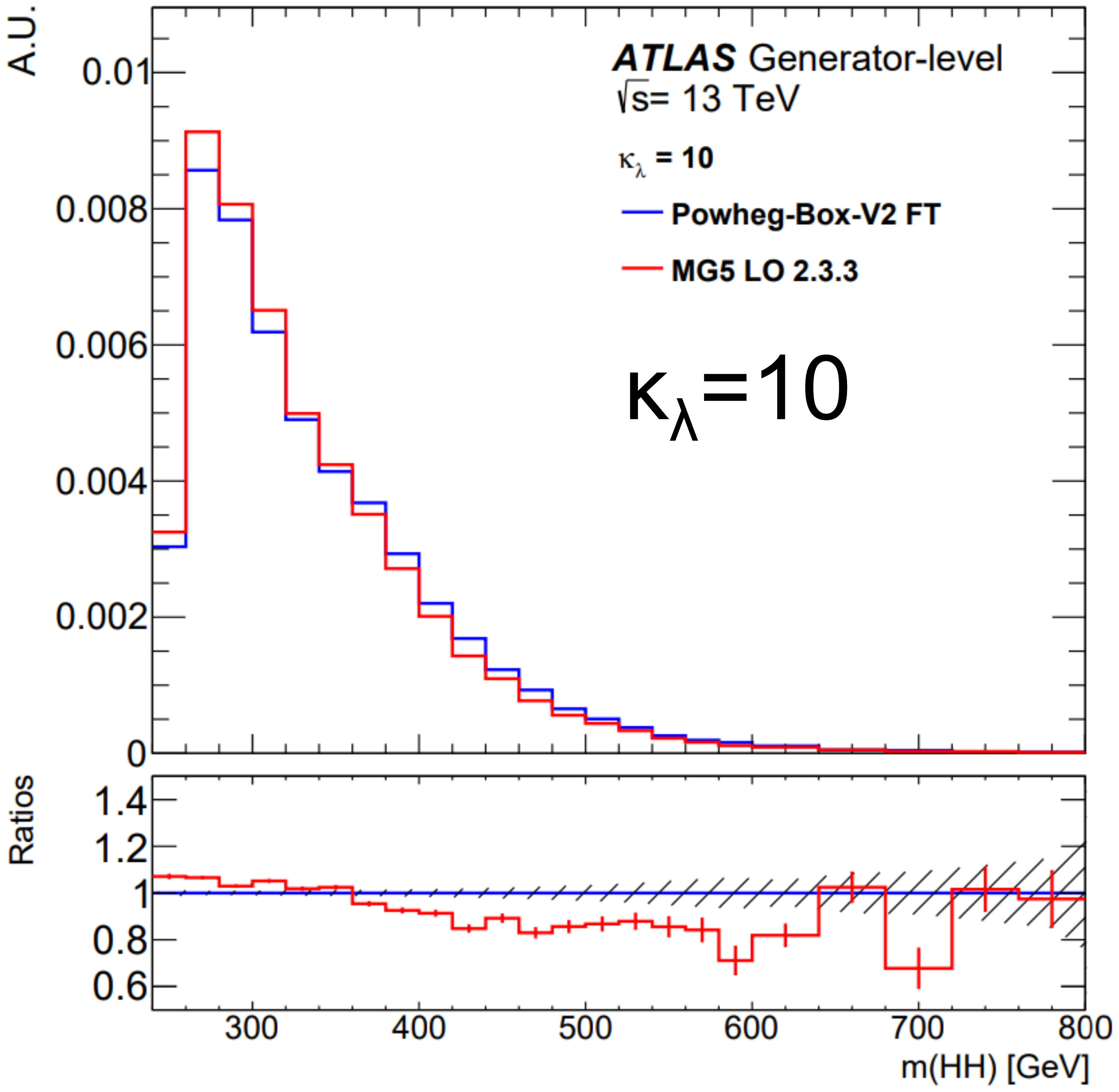
pT of the leading Higgs, after shower

Recap of LO -> NLO FT for κ_λ variation

- 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 at the same time
- Compare MG5 LO and Powheg NLO+FT with λ variations, at fixed-order NLO





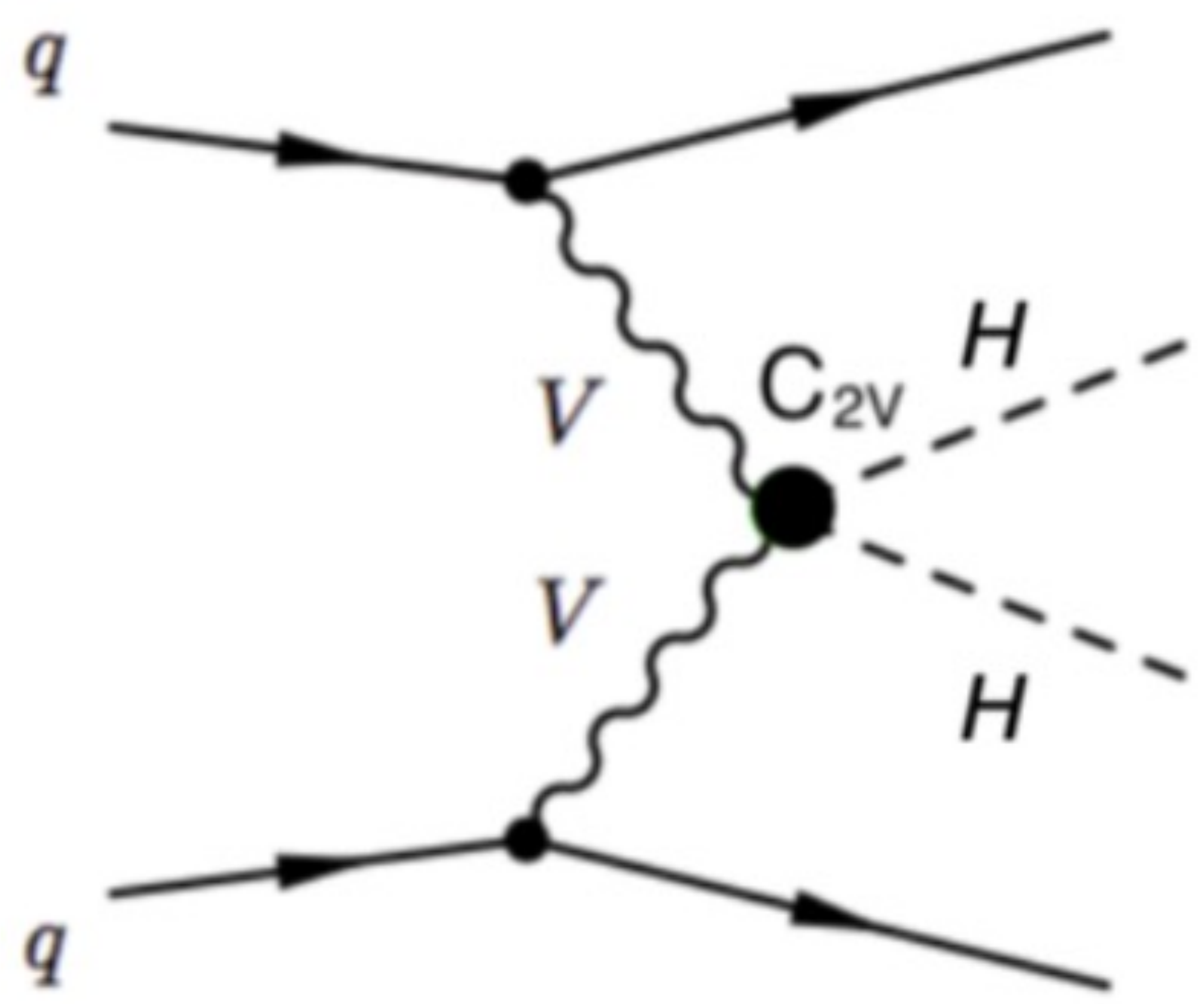


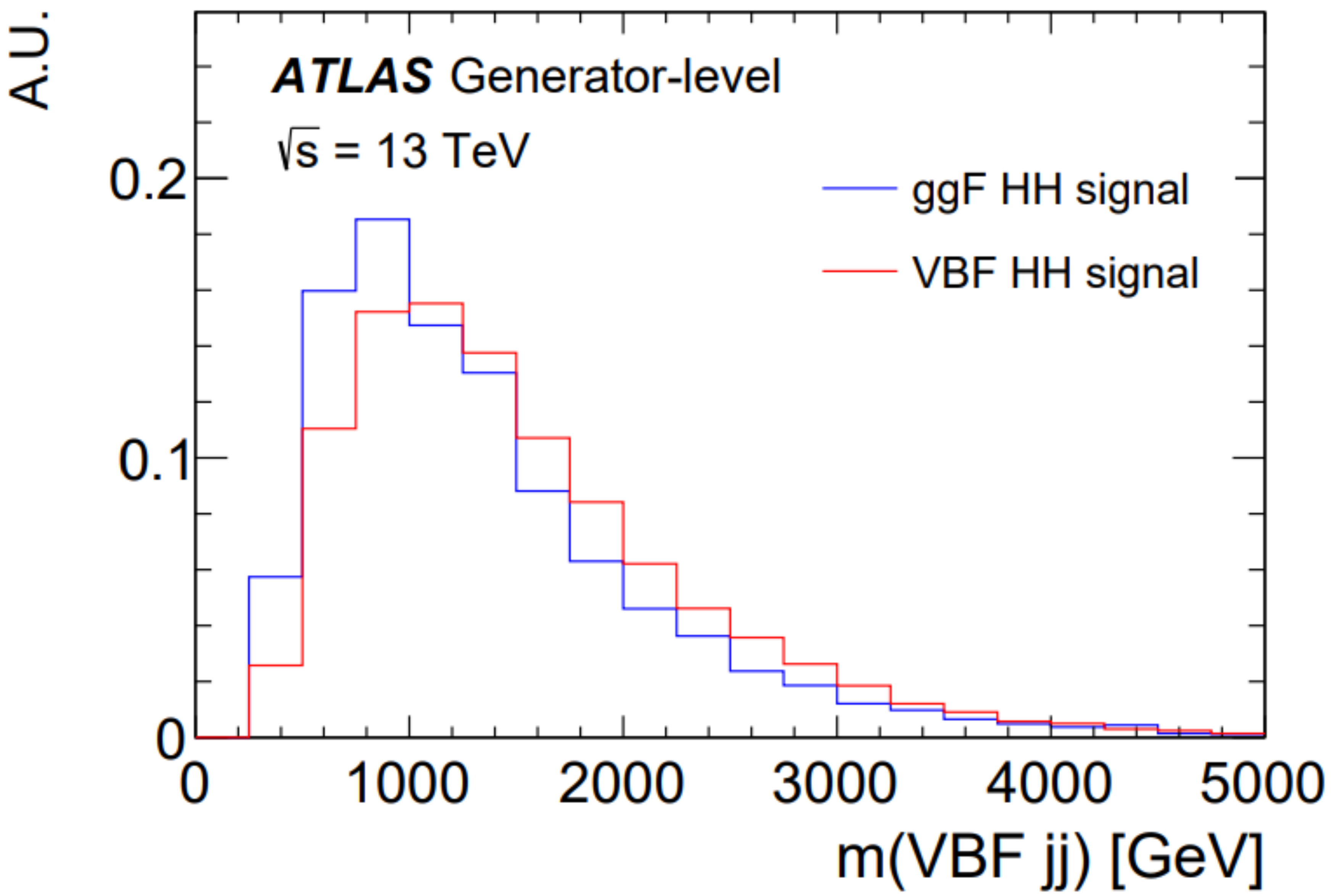
Recap of HHarmonisation in 2019

	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

Non-resonant VBF HH

- The second leading HH production
- Particularly interesting, sensitive to constrain c_{2V}
- LO generator in use for VBF HH and also VHH





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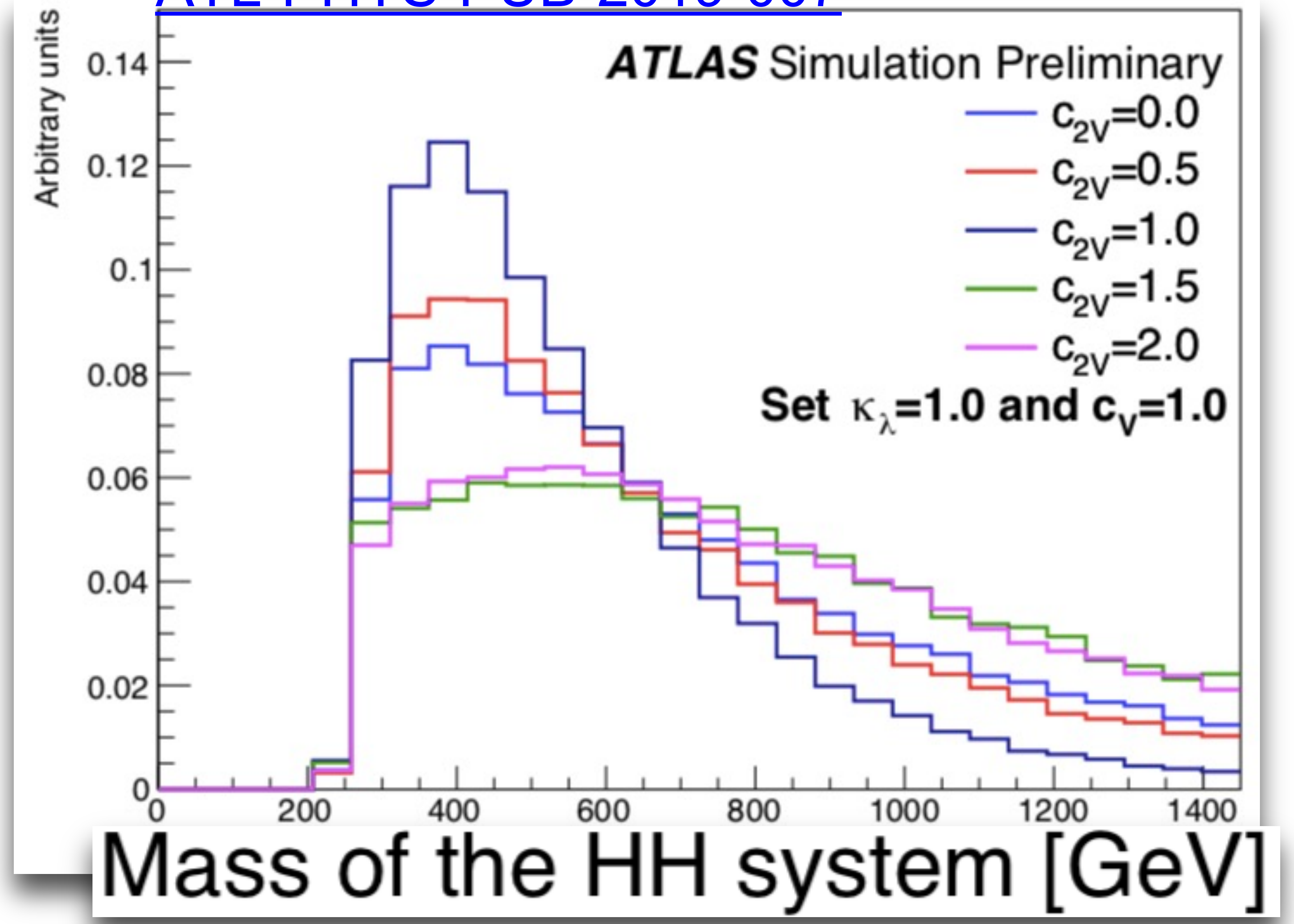

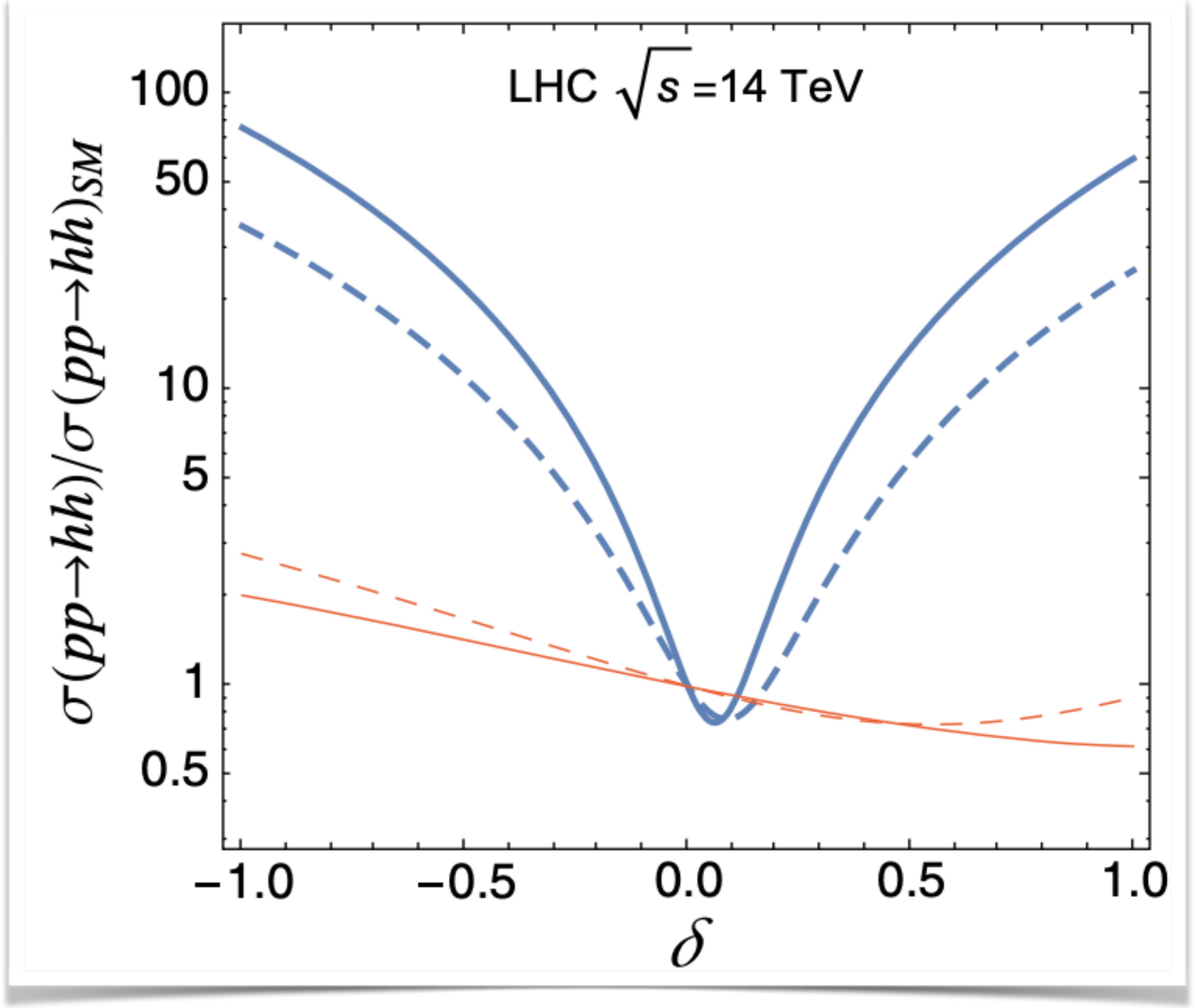

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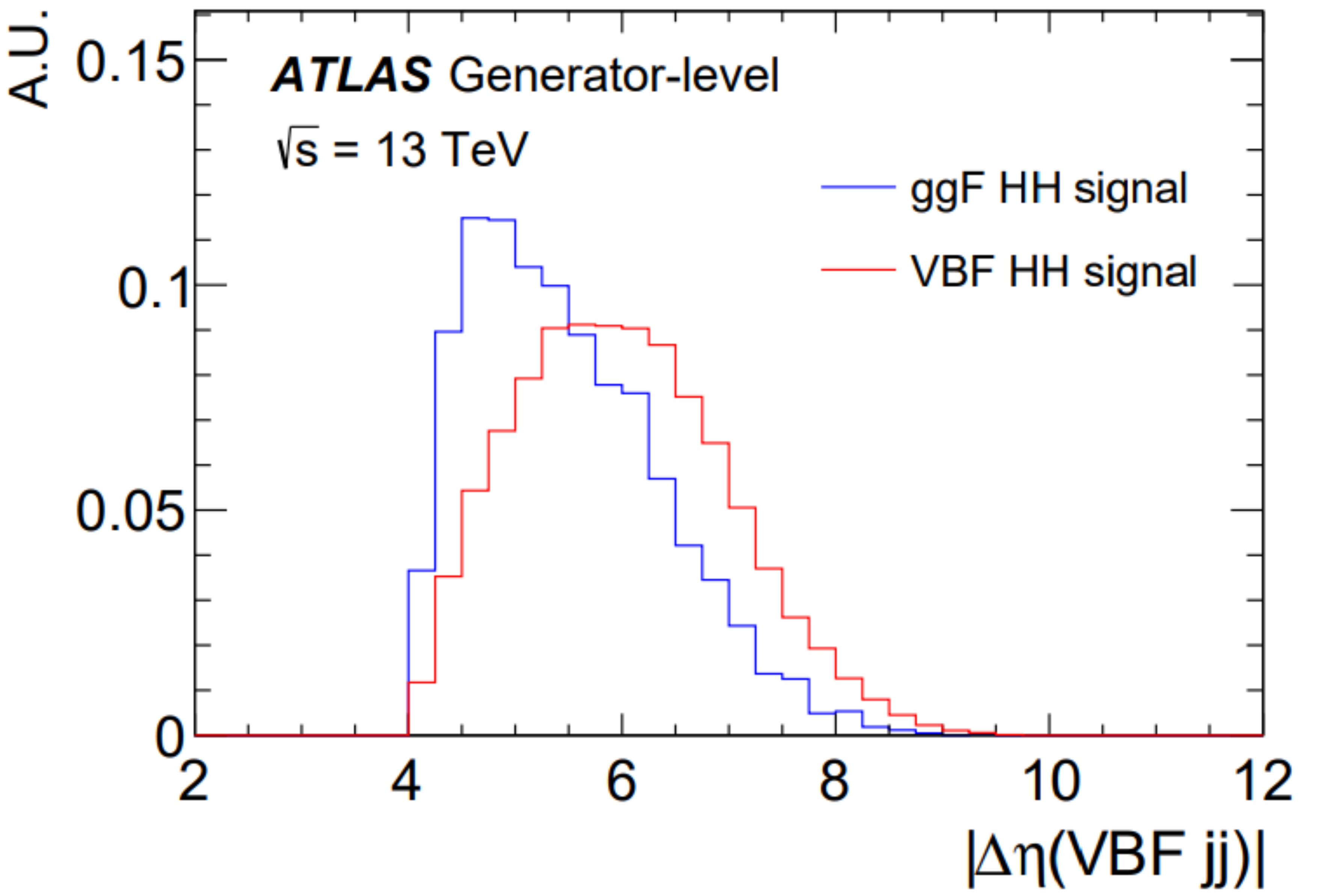
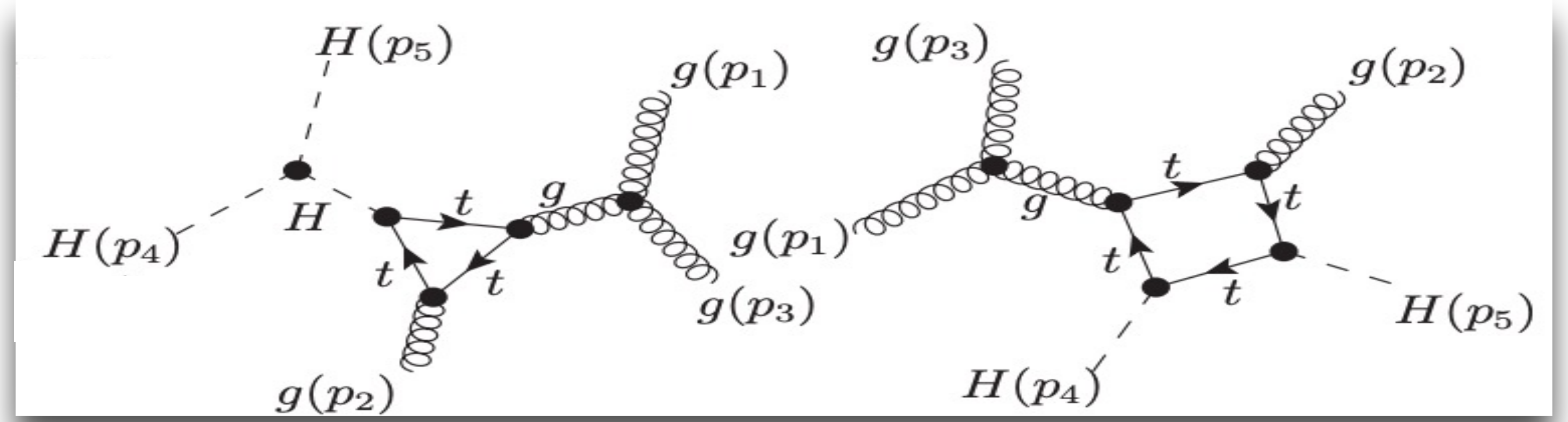
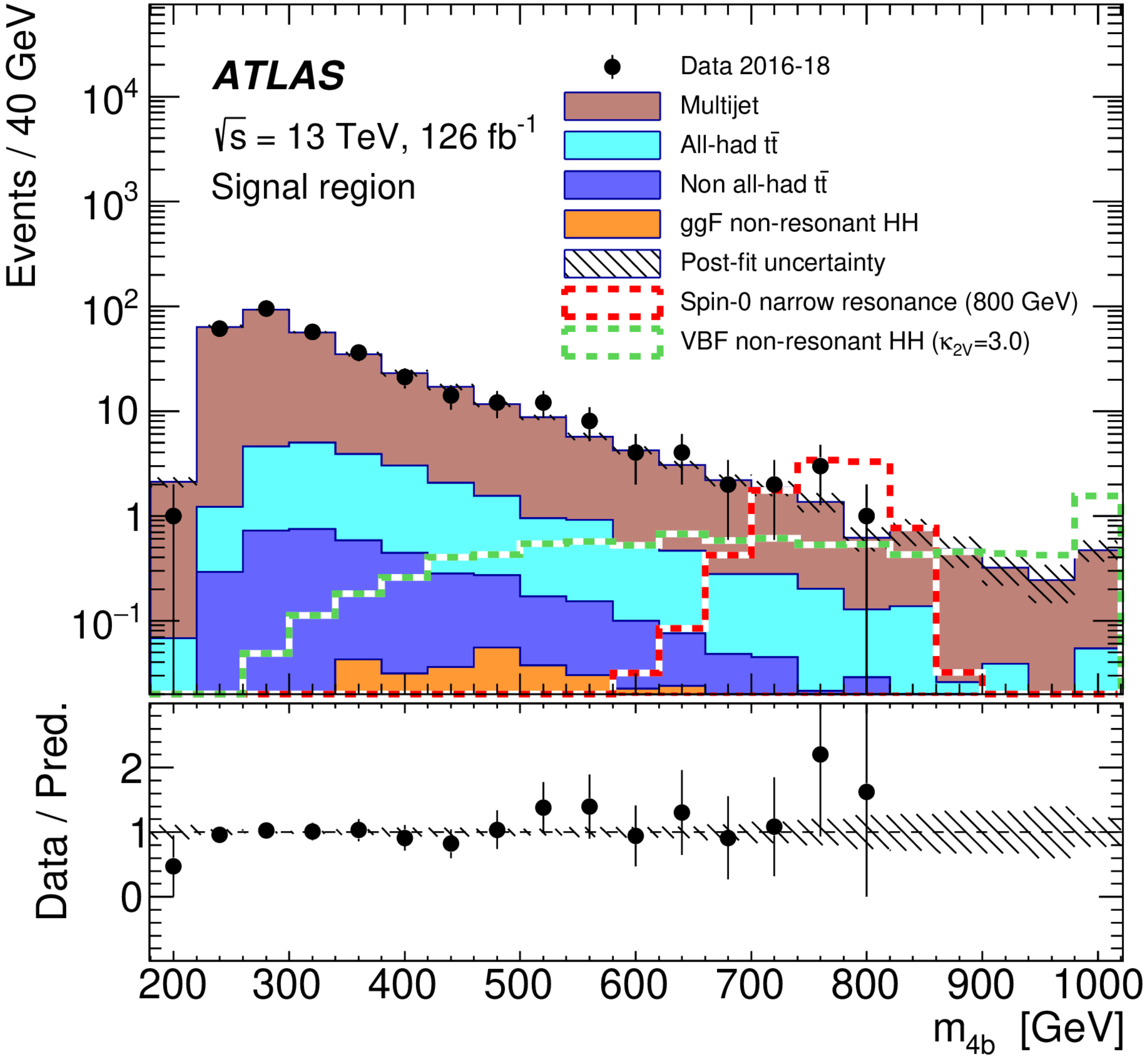


ggF HHjj entering VBF region



- 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 generators (Sherpa+OpenLoops), but costy; possible shared production of LHE between ATLAS and CMS



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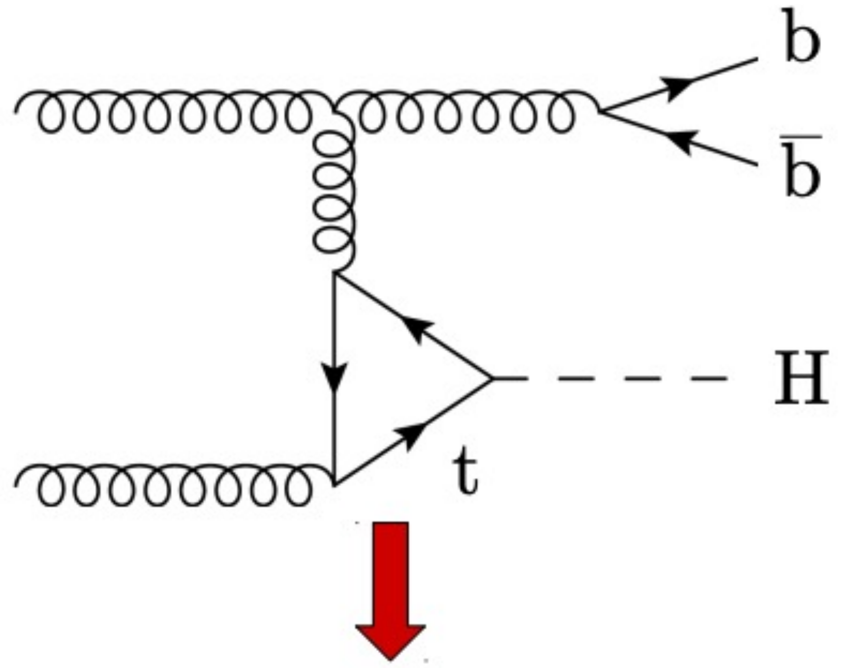
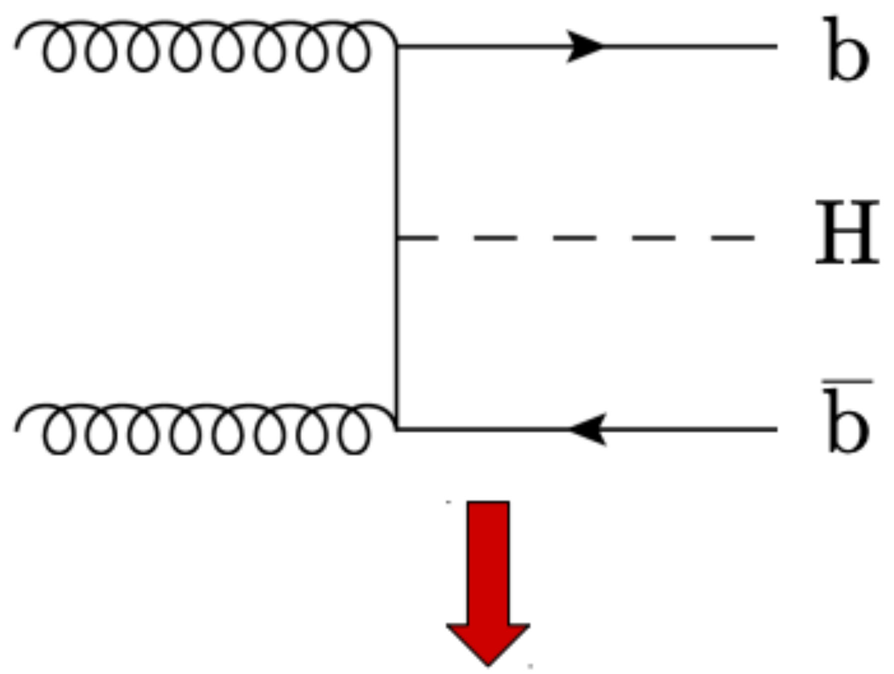
HF+Higgs as bkg

- 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):
  - Simulated with NNLOPS ggH (LO accurate in 2 jets configuration) for the y_t contribution & bbH simulation with Powheg for the y_b contribution
  - +100% uncertainty on top of ggH yield to cover for possible mis-modelling (similar in ttH analyses) givens its LO
  - Not negligible contribution when compared to signal
- New work with bbH at NLO including both y_t and y_b, reducing the uncertainty to ~50%, bringing an improvement on HH (bbyy) limits by 10%-20% possibly, see Javier Mazzitelli's talk (2307.09992)



$\mathcal{O}(\alpha_s^4 y_t^2)$



$\mathcal{O}(\alpha_s^2 y_b^2)$

Summary

- HHarmonisation coordinated from HH conveners from both experiments and LHCHWG successfully synchronized the HH generator setups in ATLAS and CMS (many thanks for our theorists in contact!)
  - Making the comparisons of final results and performances easy
  - Leading to consistent treatment of signals and uncertainties
  - Saving computing resources for those expensive ones (ggF HHjj) by sharing the LHE production possibly across the experiments
  - Paving the way to combination in the future
- This talks tries to recap what we learnt from HHarmonisaion and can possibly be helpful to a larger extend such as Higgs analyses in both ATLAS and CMS
- Many things were not covered or discussed extensively in the talk:
  - EFT recommendation in 2023 https://cds.cern.ch/record/2843280/ : HEFT and SMEFT at NLO (with full top quark mass dependence) are available in Powheg (2006.16877 and 2204.13045)
  - BSM signal generators etc.

Backup

HZgamma combination

QCD scale : In ATLAS, the QCD scale for ggF are evaluated from several sources: a total uncertainty in the cross section is taken from LHC HXSWG [11]; migration effect (including overall acceptance) due to cuts on $p_{\mathrm{T}t}$ and $p_{\mathrm{T}}^{\gamma}/m_{ll\gamma}$; ggF contaminating into the VBF-enriched category; uncertainties affecting the BDT response that is used to define categories. In CMS, only the total uncertainty in the ggF from the theoretical cross section calculation is included, and will be correlated with the corresponding component in ATLAS. For the other processes, such as VBF, WH, ZH, ttH, ATLAS considers both uncertainties on the theoretical cross section calculations and acceptance while CMS considers only the uncertainty on the theoretical cross section calculations that are taken from the LHC HXSWG, therefore they are all uncorrelated, respectively. (A test by correlating VBF, WH, ZH and ttH QCD scale uncertainties shows negligible impacts on final results, see Appendix B).

PDF : In ATLAS, the uncertainties on PDF for ggF are decomposed into 30 uncorrelated nuisance parameters. And for the VBF, WH, ZH, ttH processes, each of them has one corresponding PDF nuisance parameter. In CMS, three PDF (plus QCD α_S) related components are available which are for "gluon-gluon", "q-qbar", and "ttH" respectively. Since the sources considered in both experiments are different, we decided to not correlate them. However, a test is performed on correlating this uncertainty, see Appendix B.2.

QCD α_S : Uncertainties stemming from QCD α_S is evaluated in ATLAS in each production mode. In CMS, they are covered by the PDF above. Therefore nothing to be correlated in this source.